# Adapting the Wetting Front Detector to small-scale furrow irrigation and providing a basis for the interpretation of salt and nutrient measurements from the water sample

Report to the
**Water Research Commission**

by

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# EXECUTIVE SUMMARY

The Wetting Front Detector (WFD) was originally developed as a simple irrigation scheduling tool to fill a perceived gap in the market. This 'gap' was perceived to be for a tool that made 'intuitive' sense to farmers and linked water management with salt and nutrient management The FullStop WFD is a funnel shaped device that is buried in the soil and provides a visual signal when the soil water suction falls to 2 kPa during an irrigation event. The FullStop collects a water sample from the wetting front, which can be analyzed for water quality parameters, such as electrical conductivity (EC) and nitrate levels (see www.fullstop.com.au).

Much progress was made between 2000 and 2003 through the Water Research Commission Project no. 1135 "Building Capacity in Irrigation Management with Wetting Front Detectors" (Stirzaker et al., 2004b) which involved the testing of the device under controlled conditions, on-farm evaluation, and obtaining feedback from irrigators. The initial research and on-farm experience showed enormous promise and the device was commercialised in a relatively short space of time. In 2003, the FullStop won the international prize for "Outstanding contribution to water saving and water conservation in Agriculture" presented by the International Commission on Irrigation and Drainage in France. It was released onto the market in 2004 and over 13 000 units have been sold world-wide.

Results from WRC Project 1135, together with a follow-up WRC consultancy and experiences from the early stages of commercial release, have highlighted three areas requiring further work. These three areas form the subject of this project report.

## 1. NEW DESIGN OF WFD FOR FURROW IRRIGATION

The commercially available FullStop design was well suited to drip irrigation and had been used with some success under sprinklers, but it was not particularly well suited to furrow irrigation. A design that could be placed deeper in the soil, was more sensitive to weak wetting fronts, and caused less soil disturbance, was needed. Fronts get weaker as they move down through the soil as each soil layer retains and slowly releases some of the infiltrating water. When the flux is low, a funnel shape is not the best option for producing free water from unsaturated soil. When there is low flux, convergence is less effective, and the shallow depth of the funnel does not counteract emptying by capillarity. In these cases, a pipe-like design is more appropriate than a funnel, since sensitivity at low flux rates is determined by length of the detector.

The modified WFD, called a Tube Detector (TD), was developed and tested in the laboratory, at the Hatfield experimental farm, at UNIVEN and in farmer's fields at the Dzindi irrigation scheme. The research evaluated i) the properties of the material needed to fill the Tube Detector, ii) the sensitivity of the several Tube Detector designs, iii) a comparison of FullStop and Tube WFDs, iv) different placements within a furrow irrigation setup, and v) the usefulness to small-scale irrigators.

The Tube Detector proved to be an extremely sensitive wetting front detector and operated exactly according to theory. A robust understanding of how to build and use the Tube Detector, something that was considered essential before embarking on another commercialisation venture was developed. Tube Detectors identified severe over-irrigation in farmer's fields, although more work is needed to fully evaluate their potential for the small-scale furrow irrigation sector.

## 2. SOIL SOLUTION MONITORING

The second objective of this project was to provide a basis for interpreting the soil solution electrical conductivity and nitrate measurement. From the start, surveys showed that leading irrigators were more interested in the WFD as a solute measuring device than an irrigation device. The FullStop can be considered as passive lysimeter, since no suction force needs to be applied to collect a water sample, as is required for the standard ceramic suction cup. The task of this study was to compare the performance of the WFD to the standard, but more cumbersome technique of obtaining a soil solution sample by suction cups (SC).

This work was carried out both in the field (stone fruit and citrus orchards) and in large outdoor drainage lysimeters. The lysimeter data lent support to the theory that SC solute concentrations are more indicative of what crop roots are exposed to (resident water), while WFDs are more indicative of solute concentrations in the percolating soil water (moving water). However, there were other factors involved, which could lead to the two methods giving somewhat different results. For example, the WFD collects water over a short period as the front passes and picks up salt or nitrate 'bulges' if they are present, which the slowly collecting SC appears to miss.

The solute movement data, or solute signatures, can be used in their own right to give feedback on irrigation performance. Generally, a build-up of salts lower in the root zone indicates that excess irrigation has not been applied. No build-up or sudden drops in nitrate concentrations indicate that the crop is being over-irrigated.

Good data from SC and WFD were obtained in the orchard trials, with both devices usually indicating very similar trends. An advantage of the WFD was that the operator did not have to prime the cup with suction to obtain the sample – it was collected and stored automatically by the WFD. The latest development of installing prototype electrodes in the reservoirs of FullStops enabled the successful automatic reading and logging of soil water EC. This continual EC logging provided further insights into the movement of solutes in the soil, and is a significant advance to the deployment of WFD in agriculture.

## 3. TRAINING GUIDELINES

The phenomenal adoption of the WFD in the first couple of years has had its downside. So much was happening so fast that it was impossible to respond to user experiences, especially those from soil-irrigation combinations for which there were no previous personal experience. Now, in the fifth year since product release, two trends were observed. First, overall sales have declined to around 1000 units per year. Second, farmers who were keen at the very start, and with whom direct interaction constantly took place, have continued to use the WFD successfully.

Meanwhile the project team's research experience continues to grow with improvement to the interpretation guidelines and the focus on situations where the WFD can make a major contribution to irrigator practice. With almost a decade of experience, an understanding has been reached which, it is believed, can unlock more of the potential of the device within the irrigation industry. This understanding is built around the following three findings:

1. When people first see a WFD it looks incredibly simple. Most feel they know exactly how it works and that it should be a simple solution to the difficulties of managing water, salt and nitrate.
2. The physics underpinning operation of the WFDs is difficult. It even takes highly trained soil physicists some time to grasp how the two versions actually work, how the shape relates to sensitivity and how the sensitivity relates to deployment and interpretation in different situations.
3. Definitive instructions on how to use the WFD for each particular situation cannot be provided. All other tools come with an interpretation method, such as threshold suction or a refill point. Yet it is not possible to say *a priori* how frequent a detector at each soil depth should respond to irrigation.

The above seems like a paradox. If the WFD looks simple to farmers, why is it not immediately apparent how to deploy it (depth and frequency of response) and to interpret the response? Why do some growers find them extremely useful and others lose enthusiasm? We believe the answer is that the WFD must be a learning tool before it can become a 'solution'.

The WFD helps the irrigator to understand their current irrigation strategy, and to organise their experiential knowledge. Irrigators build their own rules of thumb around the response of the WFD. They combine their existing knowledge, built up within the constraints of their own systems, to come up with WFD responses that help them to balance accuracy with risk. They use the WFD to evaluate different fertigation or leaching strategies in a learning-by-doing approach.

Since the WFD is a learning tool combining water, salt and nutrients, a comprehensive training package for farmers and advisors was developed. This package is laid out as a PowerPoint presentation containing 10 modules with five slides each. Each module is a concise summary of principles, followed by real on-farm case studies. It is believed that this simple training package will help many irrigators to understand their craft, and to get much more benefit from their detectors.

## 4. KEY POINTS

1. This ability to detect weak fronts together with the cheap cost of constructing Tube Detectors means that these detectors could be deployed to guide irrigation management in furrow irrigation systems.
2. Monitoring EC using FullStops has provided valuable practical information on soil salinity, leaching fractions and nutrient leaching.
3. The use of simple electrodes inside the WFD for continuous logging shows promise as an easy, cost-effective method of monitoring wetting fronts and soil solute levels.
4. WFDs can play an invaluable role as a learning tool, complimenting years of farmer experience.
5. A training package has been produced around the WFD as a learning tool. It will help to organise irrigator's existing knowledge, help them to make sense of new information, and help them to develop management strategies that will improve water, salt and nitrate management.

## 5. RECOMMENDATIONS

1. Although the Tube Detector performed exceedingly well, commercialisation at this stage is not recommended until more feedback from users has been received. Any number of Tube WFDs can, at short notice, be provided for further evaluation.
2. Research learning over a 10 year period was captured in the training course. This knowledge was grounded in farmer experience and it is strongly recommend that the course be presented to irrigator groups to help improve water, nitrate and salt management.

## ACKOWLEDGEMENTS

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# CHAPTER 1 - INTRODUCTION

## 1.1 BACKGROUND

The Wetting Front Detector (WFD) was developed for three reasons (Stirzaker et al., 2000; Stirzaker, 2003a):

1) many irrigators struggle with the concepts like volumetric water content and matric suction and do not find it easy to interpret graphs showing this kind of data
2) irrigators conceptualise their practice as the depth that water infiltrates into the soil following irrigation, which can be simply illustrated by a WFD
3) the WFD combines water, salt and fertiliser management

The FullStop WFD consists of a specially shaped funnel, a filter and a mechanical float mechanism. The funnel is buried in the soil within the root zone of the plants or crop. When the infiltrating water converges inside the funnel, the soil at the base becomes so wet that water seeps out of it, passes through a filter, and is collected in a reservoir. This water activates a float, which in turn operates an indicator flag above the soil surface. The instrument was patented in 1997.

A large amount of work was conducted in Australia and South Africa under controlled conditions and this demonstrated the potential of the WFD for scheduling irrigation (Stirzaker, 2003b; Stirzaker et al., 2004b; Stirzaker and Hutchinson, 2005). Much of the research and development underpinning the WFD has been funded by the Water Research Commission, in particular WRC Project No.1135 “Building Capacity in Irrigation Management with Wetting Front Detectors” (Stirzaker et al., 2004b). Not only was the WFD evaluated under controlled conditions, but a huge effort was put into getting the detector installed on farms and getting farmer feedback (Steyn et al., 2002; Maeko et al., 2003; Nkgapele et al., 2003; Stirzaker et al., 2003a,b; Maeko et al., 2004; Mpuisang et al., 2004; Steyn et al., 2004; Stirzaker et al., 2004a,b).

The South African company Agriplas obtained the exclusive rights to develop the WFD into a commercial product in 2002. The project was nominated by the South

African National Committee on Irrigation and Drainage (SANCID) as contender for the WATSAVE award and won the international prize for "Outstanding contribution to water saving and water conservation in Agriculture" presented by the International Commission on Irrigation and Drainage (ICID)in France in 2003. The commercial version was released onto the market in 2004 and over 13000 units have been sold around the world.

This project has it roots in two major findings from the Water Research Commission Project No.1135. First we wanted to reach the small-scale sector and most of them operated short furrow flood systems. Very little of our work had been done in flood systems, and our experience combined with theory showed a different design would be needed.

Secondly, many who showed initial enthusiasm for the WFD wanted it for nutrient monitoring. This demand came from the sophisticated end of the irrigation market, but we had no research experience to guide them.

There was also a third important factor that we had overlooked. Most irrigation scheduling tools or techniques (tensiometry, neutron scattering, granular matrix, heat dissipation, time domain reflectometry, capacitance) have undergone many years of research and testing at multiple locations around the world before being released onto the market. In contrast the WFD is the product of a small team operating over a few years. We urgently needed to develop training aids so we could consolidate our experience and communicate it to farmers.

## 1.2 APPLICATION OF THE WFD UNDER FURROW IRRIGATION SYSTEMS

At the onset of this project, most of the research work on the WFD had been carried out on drip and sprinkler systems. For drip and sprinkler irrigation the source of irrigation water is directly above the detector. Water is supplied at rates lower than the saturated conductivity of the soil, so the velocity of the wetting front is influenced mostly by the initial water content of the soil and only weakly by any changes to soil structure that might have occurred during installation.

Furrow irrigation requires a reasonable amount of water to be applied at one time to attain uniformity; the water cannot simply be turned off when the wetting front reaches a set depth as it can be in the case of drip or sprinkler irrigation. A number of problems surfaced from an original user survey related to furrow irrigation, but some case studies showed that small scale farmers who used detectors in furrow irrigation saved water (or diesel), or produced higher yields and made greater profit.

The obvious research questions were where to locate the detector for furrow irrigation – under the bed, under the furrow or half of each – and how deep did they need to be? Deeper positioning further from the furrow had obvious implications for the required sensitivity. Whereas the FullStop located right under a dripper experiences a relative 'strong' front, a deep placement under the ridge irrigated from a furrow may need to detect wetting fronts at 6 to 10 kPa suction.

We had already prototyped a more sensitive WFD, the tube-shaped LongStop, which was theoretically better suited to furrow irrigation (Stirzaker, 2008). It could be placed deeper in the soil (irrigation amounts and therefore wetting depth tends to be greater in furrow) and with less soil disturbance than a FullStop (important for when water is applied at rates greater than the saturated conductivity of the soil). Moreover the LongStop does not reset until the sub-soil starts to dry, and may therefore be used to show the farmer when to start the next irrigation. Further work was therefore also required to compare the sensitivity and suitability of FullStops and LongStops in furrow irrigation, as well as to compare different fill materials, as the hydraulic properties of materials inside the detectors has major implications for their operation and sensitivity.

### 1.3 SOLUTE MONITORING AND INTERPRETATION OF DATA

Pilot studies have demonstrated that the monitoring of salt and nitrate can provide useful information to farmers (Stirzaker and Wilkie, 2002; Stirzaker, 2003; Stirzaker et al., 2004a,b,c). When 54 people using WFDs were asked in a survey why they were interested in the technology, 20% replied that their interest lay in monitoring electrical conductivity (EC) and nutrients (especially nitrate) in the soil water sample collected by the detector.

The suction cup has been the standard technique for soil solution monitoring since it was invented over 100 years ago. A lot is known about cups, and in the case of salt there are some published thresholds for leaching. Although the suction cup is simple and well understood, it is hardly used outside a research environment. An advantage of the WFD over the cup is that the operator does not have to prime the cup with suction after irrigation and then return again to retrieve the sample.

The obvious starting point is to compare the performance of the suction cup and WFD under controlled conditions and on commercial farms. Ceramic suction cups can theoretically collect soil solution up to 100 kPa suction (a vacuum), although in practice 20 to 30 kPa is usually the limit. Cups can take a few hours to several days to collect a sample, depending on the water potential. In contrast, WFDs collect water very quickly when they experience a front in the 0 to -3 kPa range. Therefore WFDs sample at similar water contents and sample similar suctions and hence similar pore sizes, potentially giving more consistent results.

We do not know how well the solutes in the soil water mix with the relatively fresh irrigation water. Interpretations may also vary under different irrigation systems. In the case of drip irrigation the detector is situated in the most leached position of a field, right underneath a dripper. Solutes would therefore tend to accumulate between the drippers. Lastly the saturated extract method used in the laboratory to determine how much salt is in the soil typically extracts water from soil that is at 1 kPa suction or wetter. The salinity thresholds from WFD samples, which can sample from drier soil, may be higher than those published in the literature. For more information on soil solution samplers see reviews by Litaor MI (1988) and Paramasivam et al. (1997).

## 1.4 PROJECT AIMS

The aims of the current project can be summarized as follows:

- To develop and test a modified Wetting Front Detector (LongStop) dedicated to the needs of small-scale furrow irrigators
- To determine by theory and experimentation the optimal location for FullStop and LongStop detectors in furrow irrigation and a comparison of the two versions for cost and efficacy
- To define the sensitivity of the WFD (the amount of water that could pass the detector without activating it) and to compare the sensitivity of the two versions
- To support the Limpopo Revitalization (RESIS) program by providing a locally based expert in furrow irrigation to work alongside farmers and extension workers
- To compare the concentration of solutes from WFD samples with those of suction cup samples
- To provide a basis for interpreting salt and nutrient concentrations from water samples collected in WFDs
- Although not a specific objective, one of the deliverables of the project was to provide guidelines for the optimal use of WFDs for irrigation, salt and nitrate management

## 1.5 APPROACH

Finding the best material to fill LongStops required laboratory experimentation and was carried out at the University of Pretoria Department of Plant Production and Soil Science’s facilities. Detailed monitoring of wetting patterns was carried out at the University of Pretoria and University of Venda Experimental Farms. Field trials in furrow irrigation were situated on Dzindi scheme as directed by the Limpopo Department of Agriculture. Solute movement studies were carried out at the drainage lysimeter facilities at the University of Pretoria Experimental Farm and at a commercial orchard (on peaches, plums and nectarines) in Rustenburg.

# CHAPTER 2 – SENSITIVITY ANALYSIS OF WETTING FRONT DETECTORS AND LABORATORY STUDIES ON HYDRAULIC PROPERTIES OF WICK MATERIALS

## 2.1 INTRODUCTION

The science of irrigation scheduling is well developed but the translation of information from these tools into decision on how much and when to irrigate is still not easy for most irrigators. Different irrigation scheduling products were developed and made available in the market. However, irrigators experienced difficulty in applying the concepts of soil matric suction and volumetric water content into their irrigation decisions, which resulted in the low uptake of irrigation technologies. This low adoption rates could be attributed to the failure of scientists to understand the relationship between scientific techniques and farmers' goals and constraints under which they operate (Stirzaker et al., 2009). Considering the above problem, an alternative approach was developed to bridge the gap between the existing scientific knowledge and irrigation practices by farmers. This approach was related to how farmers visualize water movement below the soil surface.

The wetting front detector was developed as a tool to provide simple information, like the depth of water infiltration or redistribution, which could potentially be useful for irrigation decisions. Wetting front detectors (WFDs) make intuitive sense to the farmer, as they measure the depth of water penetration into the soil, and could therefore potentially be used for water, nutrient and salt management. The funnel-shaped device, commercially known as the FullStop wetting front detector (Figure 2.1), is filled with soil and buried at an appropriate soil depth, where it can detect when a wetting front with strength of 30 cm (-3 kPa) or wetter moves past that depth. This wetting front detector comprises of a funnel, a filter, floats and an indicator that works on the principle of flow line convergence (Stirzaker et al., 2009). As water moves into the funnel, the funnel-shaped detector (Figure 2.1) produces free water at its base and the free water flows through a filter into a small reservoir to activate an indicator that is visible above the soil surface (Stirzaker, 2003; Stirzaker and Hutchinson, 2005; Stirzaker et al., 2009).

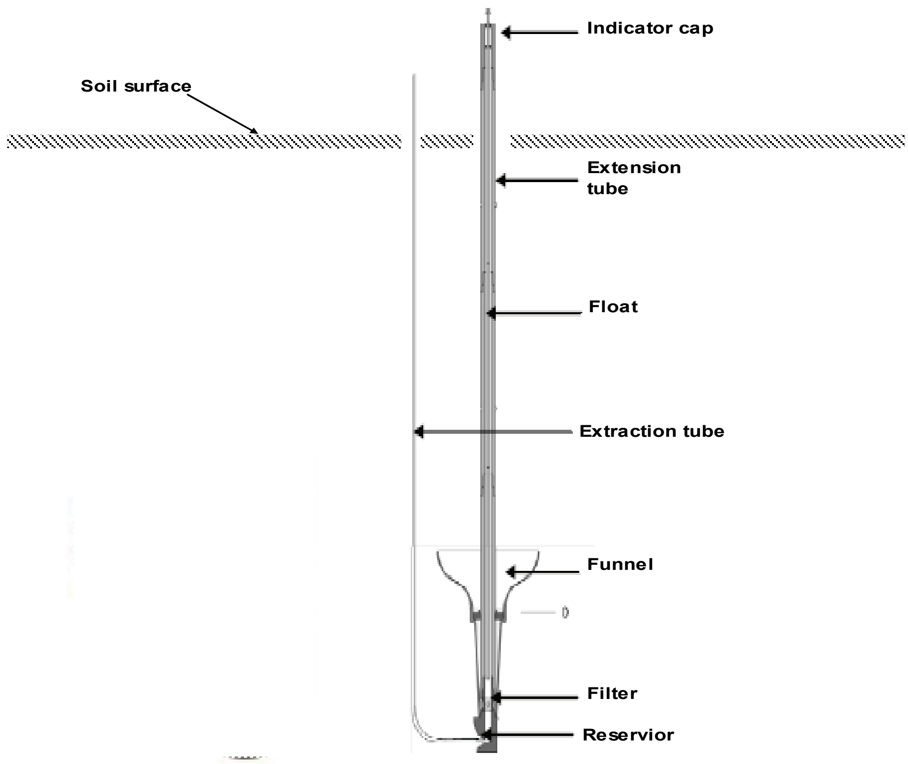



**Figure 2.1** Components of the FullStop wetting front detector

However experience has shown that the funnel-shaped design operates reasonably well under very wet conditions (≤ 30 cm soil tension). Such wet conditions do however not occur under flood irrigation or sprinkler irrigation when deep placement is required. During unsaturated conditions at tensions drier than 30 cm, water may bypass the funnel-shaped design WFD undetected and the volume of water required to refill the soil profile to a certain depth will be overestimates. Hence, the convergence effect of the funnel was not efficient under such conditions. Consequently, prototype designs other than the commercially available funnel-shaped detector have been developed for specific applications. These prototypes were believed to theoretically respond better to weak redistributing fronts at deeper placements depths, as required for flood irrigation.

Two improved versions of the funnel-shaped wetting front detector were developed. These two prototypes are commonly referred to as tube and hybrid (comprising both funnel and tube features) wetting front detectors. The designs and operating principles of each prototype are explained below.

A tube-designed wetting front detector is a prototype design, comprising of two concentric tubes, a filter, wick material and contact material (Figure 2.2). The mouth of the outer tube (50 mm outer diameter) is buried in the root zone, with the inner pipe (20 mm outer diameter) visible above the soil surface.

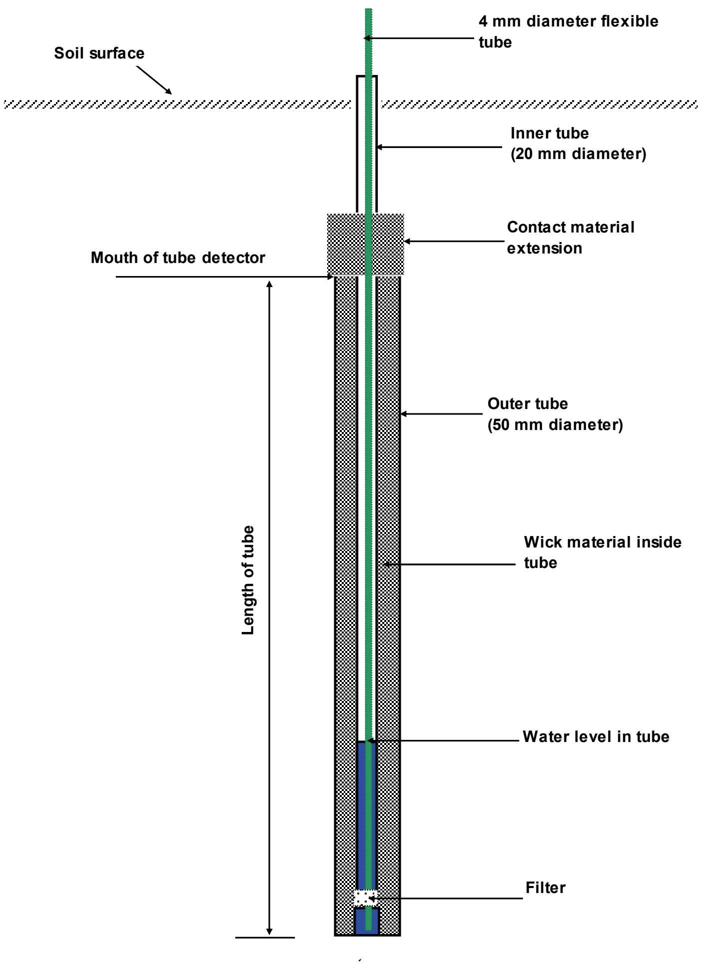



**Figure 2.2** Components of a tube-shaped wetting front detector

The tube-shaped detector gives a “yes” or “no” answer to the irrigator, or informs the irrigator whether the wetting front strength (the degree of wetness) of infiltrating water was within the sensitivity limit (depending on the tube length) of the specific WFD. The wick material, which is used to fill the space between the two concentric tubes, enables lateral water flow into the mouth of the tube, thereby producing a “hanging column” of water which applies tension on the soil above it. A contact material (made from the same material as the wick material) is placed above the mouth of the tube detector to provide hydraulic contact between the wick and the surrounding soil. Infiltrating water is intercepted by the contact material and conducted into the tube detector, resulting in a water level rise inside the inner tube. The water level in the inner tube rises until a “no flow” condition is established between the contact material and surrounding soil.

When the surrounding soil in contact with the contact material dries out, water will flow out of the inner tube to the surrounding soil until a “no flow” condition is attained (or a zero water table level in the tube is reached). The water level will keep dropping until equilibrium between the contact material and the soil is established and a new hydrostatic pressure within the tube is attained (Figure 2.2). The length of the outer tube determines the maximum measurable tension by determining the water table level in the tube. Therefore, the sensitivity of this WFD design is equal to the length of the outer tube filled with wick material. The water level in the inner tube is determined using either a dipstick or by measuring the water volume with a syringe and converting to a depth of water (cm), using a conversion factor of 2.34 ml $cm^{-1}$ (the volume of water in a 100 cm long tube of 20 mm outer diameter was measured and divided by 100 cm to get 2.34 ml $cm^{-1}$). The measured difference in elevation between the static water level in the inner tube and the mouth of the tube can be directly converted to matric suction (tension) at the mouth of a tube, representing the tension of the surrounding soil and using a hydrostatic pressure gradient of 9.8 kPa $m^{-1}$ (Nichol et al., 2008).

The hybrid wetting front detector is another prototype design made up of a 33 cm long extension pipe (71 mm in diameter) placed above the top of the funnel neck (22 cm from funnel base to the neck), a filter, float and an indicator. The mouth of the extension pipe is buried in the root zone, with the indicator visible above the soil surface (Figure 2.3). The operating principle of the hybrid detector is similar to that of the tube detector, but it uses a float mechanism to indicate activation (similar to the funnel-shaped WFD). The extra length of pipe minimizes divergence of flow during unsaturated conditions. The hybrid detector has a total length of 55 cm (base to the mouth of the device) and is expected to have a sensitivity value of 55 cm. The space between the outer extension pipe and inner pipe is filled with a selected wick material. A contact material (from the same material as the wick) is placed above the top of the 71 mm diameter pipe to provide hydraulic contact between the wick in the hybrid WFD and the surrounding soil.

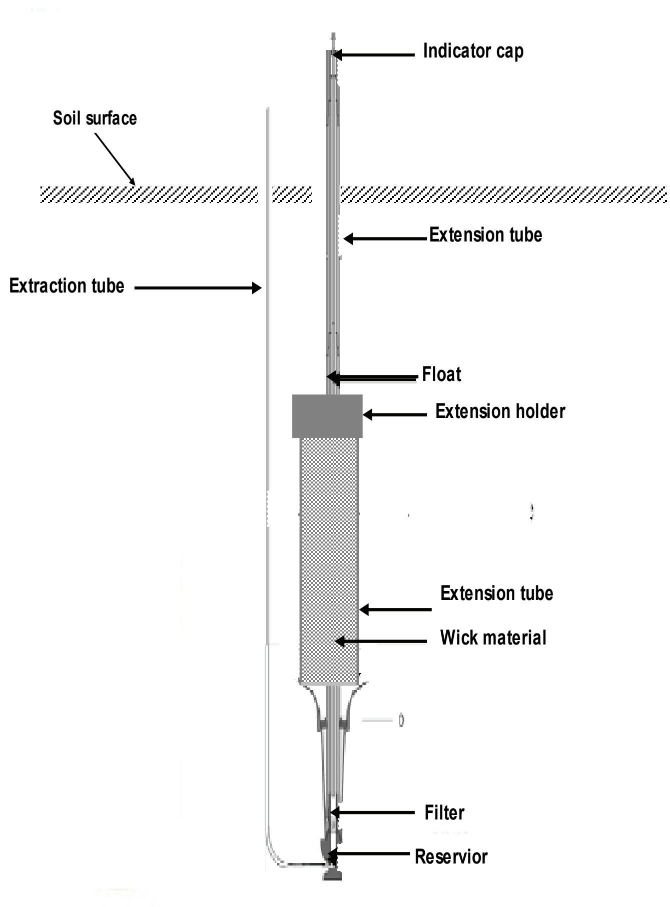



**Figure 2.3** Components of a hybrid wetting front detector

This chapter of the report focuses mainly on the testing and evaluation of three design lengths of the prototype tube-shaped wetting front detector. The different tube lengths represent different instrument sensitivity levels, aimed at detecting weak infiltrating or redistributing wetting fronts. Furthermore, different designs of the prototype hybrid wetting front detector were tested and evaluated for their suitability to detect weak redistributing wetting fronts.

The objectives of this chapter were (1) to test and evaluate the performances of two improved versions of wetting front detectors (both prototypes) under field conditions and (2) to describe the hydraulic properties of potential wick materials to be used in a tube wetting front detector and hybrid wetting front detector, using analytical and empirical techniques, a numerical based model (Hydrus-2D) and RETC methods. Soils of two depths from the Hatfield experimental site (University of Pretoria) were described using similar methodologies as for the wick materials. The determined hydraulic properties of the wick and soil materials were then used as model inputs to conduct scenario analysis and performance evaluation of the different wetting front detector designs under field conditions.

Additionally, two potential filter materials were tested under field conditions to establish whether different filter sands would impact on the sensitivity of the funnel-shaped detector.

## 2.2 LABORATORY STUDIES, NUMERICAL APPROACH AND EMPIRICAL OBSERVATIONS

### 2.2.1 Laboratory studies

The hydraulic properties of a wick material have been shown to significantly influence the performance of especially tube wetting front detectors. Wick material should be physically stable and chemically inert to ensure a linear hydrostatic pressure profile within the tube. Wick material selection, therefore, has a critical influence on performance of the newly designed prototype detectors; however, the basic hydraulic properties of the ideal wick material have not yet been well defined.

The water retention characteristics, hydraulic capacity and hydraulic conductivity of any wick material are important considerations to ensure proper operation of a tube-designed detector of any length. The wick material to be used in the detectors should remain chemically inert, be easy to install and be physically stable after installation. A wick material should also have a high air entry value over the length of the tube in order to respond to a weak redistributing front. The material should also be highly conductive in most unsaturated soils over the length of the tube to produce preferential flow into the mouth of the tube and develop a water table in the inner tube in response to the tension in the mouth of the detector.

Laboratory tests involving analytical techniques and numerical based models such as Hydrus-2D and the RETentionCurve (RETC) computer programme were used to better quantify the hydraulic properties of different materials. At the end of the analysis, several tube-designed detectors were filled with selected wick materials and instrumented with tensiometers placed in the contact material in the mouth of tube detectors for tension measurements and to perform empirical observations and analyses.

**Materials**

Five potential wick materials and soil from two depths were characterized in terms of their water retention characteristics and unsaturated hydraulic conductivity functions, using standard laboratory methods and some numerical based models. Two wick materials, Diatomaceous Earth (DE) and very fine sand (D36) were sourced from Pretoria, South Africa. DE was selected because of its wide application for filtration processes in the saturated flow range and because of its commercial availability. The very fine sand was chosen due to its physical stability and chemical inertness. Three other physically stable and chemically inert wick materials (Sand1, Sand2 and Sand3), were also evaluated. Sand1 (fine sand) was sourced from B & E Silica Pty-Pretoria, Sand2 was a silica sand sourced from the University of KwaZulu-Natal (Pietermaritzburg) and Sand3 was a crushed and pulverized silica sand. Furthermore, soil sampled from two depths (0-60 and 60-120 cm) of the Hatfield experimental farm site where wetting front detectors were installed, were included.

## Methods

***Particle size analyses***

The selected wick and soil materials were analysed for particle size distribution, using the sieve method for all sands and the hydrometer method for DE and the two soil materials.

***Controlled outflow cells***

The water retention characteristics of each sample were determined using the controlled outflow cell method over the 0-10 kPa tension range. The method establishes each point on the retention curve by equilibration of the capillary pressure at a fixed saturation. Also water retention curves were determined using equilibration by continuous drainage at a fixed applied pressure.

For the determination of the water retention characteristics, a sample of each material was packed into a metal sampling ring (volume of 54.287 $cm^3$) at a specified bulk density. Each packed sample was placed in a 2.8-cm depth of de-aired water that was sitting in a plastic container. Samples were allowed to saturate slowly from the bottom upwards, where after samples were placed on top of a porous plate that had been pre-soaked in de-aired water to ensure good contact between the two surfaces. The cap was secured and the air hoses connected to the cap and dry port of a transducer. The glass T-piece and transducer were filled with de-aired water in order to establish a continuum of water between the soil sample and the burette (Figure 2.4). The sample was allowed to equilibrate overnight with the stopcock of the air hose in the closed position.

Air pressure was applied with the outflow stopcock in the open position. The height of the column of water between the sample and transducer was adjusted to calculate the capillary pressure. After the final point of reading, the sample was removed and weighed before and after drying. The same methodology was used for all wick and soil materials to measure the water release curve of each porous medium.

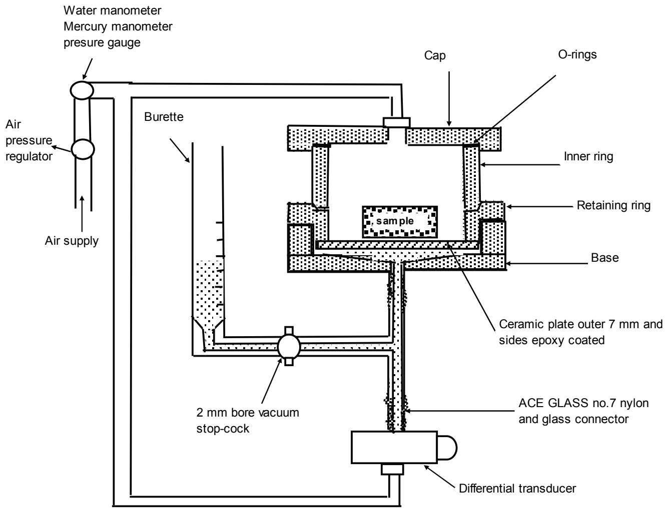



**Figure 2.4** Schematic of the Controlled Outflow Cell assembly (Lorentz et al., 2001)

***Bruce-Klute test***

One of the direct measurement methods of unsaturated hydraulic conductivity is to conduct the standard Bruce-Klute analysis test to establish the soil water diffusivity function. The theory on which this evaluation is based is described in Appendix 2.1.

A column of 11 Bruce-Klute transparent cells was packed homogeneously with the required sample to the desired bulk density as indicated in Figure 2.5. Each cell ring has a volume of 39.27 $cm^3$. The inlet chamber of the column was connected to the supply flask to establish zero head at the centre of the sample. An instantaneous supply of water was applied to the column from a funnel with immediate shift to the supply flask as soon as the inlet chamber was filled. Starting time was recorded and the advance of wetting front observed. The source of water was removed as soon as the wetting front reached the second last ring and the time was recorded. The 11 rings were quickly sectioned and placed into separate aluminium weighing rings and wet and oven-dry masses were taken in order to determine the water content of each sample. The five wick materials and two soils were tested using this method.

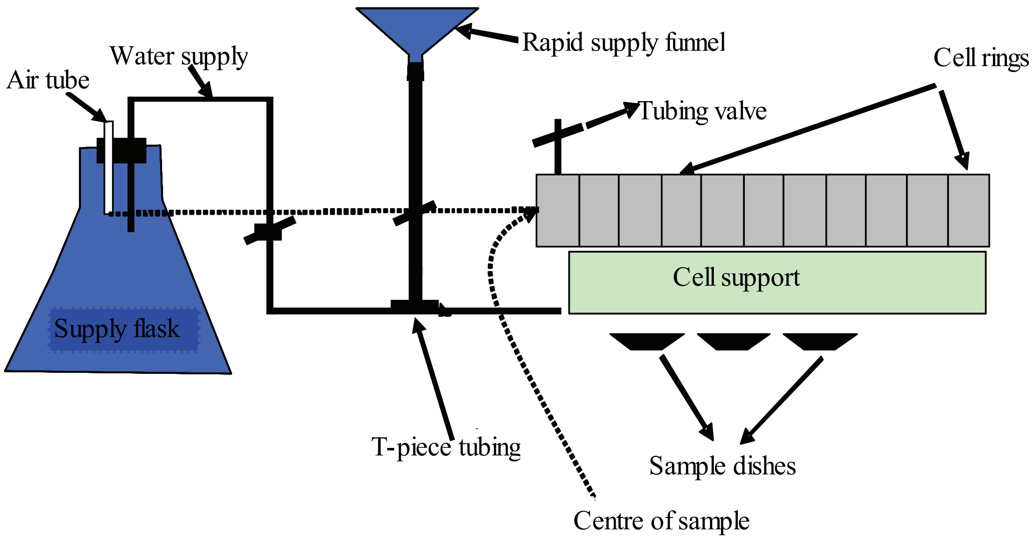



**Figure 2.5** Schematic of the Bruce-Klute diffusivity test

### 2.2.2 Numerical approaches

***RETC (RETention Curve)*** is a computer program developed by the US salinity laboratory for analyzing the soil water retention and hydraulic conductivity functions of unsaturated soils (Hollenbeck et al., 1999). The hydraulic parameters of the materials in this study were estimated by making use of the van Genuchten parametric model. Such theoretical models generally base predictions on statistical pore-size distribution, which assumes water flow through cylindrical pores and incorporate the Darcy and Poiseuille equations. This model uses the soil water retention curve and the theoretical pore size distribution model (Mualem hydraulic conductivity model) to predict the unsaturated hydraulic conductivity function from the observed soil water retention data. This model also uses the independently measured saturated hydraulic conductivity ($K_s$) value of the material.

***Hydrus-2D modelling***

Numerical evaluations of the Bruce-Klute test were performed using the Hydrus-2D model to simulate the hydraulic properties of wick and soil materials. The water flow parameters for each material were a prior requirement for the Hydrus-2D model to simulate the Bruce-Klute test. The model makes use of the van Genuchten water retention model parameters.

**Model Setup**

The inlet boundary condition was set at a constant pressure to allow constant supply of pressure head to the horizontal column, 22 cm in length and with a 5 cm internal diameter for 0.15 hour, with the wetting front assumed not to reach the end boundary of a packed column. The centre of the inlet sample was set at a zero pressure head. The end boundary condition was set as a seepage boundary under the assumption that any infiltration was free to pass the seepage face of the horizontal column. The flow geometry was set as a horizontal plane and the top and bottom sides of the column were regarded as a no flux boundary condition. The van Genucthen-Mualem hydraulic model (air entry value = -2 cm) and no hysteresis were selected from the hydraulic model options to estimate the hydraulic properties of the materials.

***The van Genuchten water retention model***

The Hydrus-2D model implemented the van Genucthen equation (1980) that uses the statistical pore size distribution model of Mualem (1976) to estimate the unsaturated hydraulic conductivity function in terms of soil water retention parameters. The van Genuchten water retention model is presented as follows:

$$\theta(h) = \theta_r + \left( \frac{\theta_s - \theta_r}{\left(1 + (\alpha h)^n\right)^m} \right) \qquad h < 0 \qquad [1]$$

$$= \theta_s \qquad h > 0$$

$$K(h) = K_s * S_e^{\,l} * \left(1 - \left(1 - S^m{}_e\right)^m\right)^2 \qquad [2]$$

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \qquad [3]$$

$$m = 1 - \frac{1}{n} \qquad n>1 \qquad [4]$$

Where $\theta_s$ and $\theta_r$ are saturated and residual water contents respectively, $S_e$ is relative saturation, $\alpha$ = air entry parameter, ($cm^{-1}$), h = matric pressure head, (cm), n = pore size distribution index, l = pore connectivity parameter (assumed as 0.5 for most soils), m is given by 1-1/n, K (h) = unsaturated hydraulic conductivity, (cm $s^{-1}$), and $K_s$ = saturated hydraulic conductivity, (cm $s^{-1}$).

### 2.2.3 Empirical observations

The data from the empirical tests were used to validate the hydraulic characteristics of Diatomaceous Earth (DE) and the very fine sand (D36), which were determined using the different methods described above. The empirical test was carried out to meet the following aims:

1) To show that the soil tension in the contact material at the mouth of the tube is related to the depth of water in the tube
2) To determine the effect of the wick material on the rate of water loss from the tube WFD, i.e. whether the water loss is energy or conductivity limited

***Non-weighing tube detector: Indoor test***

The wick materials used in these transient evaporation experiments were packed to bulk densities of 0.433 g $cm^{-3}$ for DE and 1.318 g $cm^{-3}$ for the very fine sand. The evaporation experiment was set up indoor, using tube-shaped detectors. The rate of drying was therefore controlled by the indoor conditions. A 90 cm long tube detector was filled with Diatomaceous Earth (DE) and a 50 mm diameter extension wick of DE was placed on the mouth of the tube (Figure 2.6a). A second 90 cm long detector tube was filled with DE and a 200 mm diameter funnel filled with DE was placed on the mouth of the tube (Figure 2.6b). Both detectors were saturated from their bottoms. Similar setups were made with very fine sand instead of the DE. The objective was to establish whether the different contact material diameters have an impact on the rate of water loss from the tube under similar environmental conditions (indoor test).

Water was applied to the WFDs via the inner 20 mm tube so that water moved into the wick via a fine nylon mesh glued 4-cm from the bottom of the inner tube. The process of upward infiltration wet the wick material filled between the two concentric tubes. Wetting from below avoided entrapped air and the wick samples were kept near zero suction for several days. A tensiometer was placed right in the contact material on the mouth of each tube WFD. The ceramic cup of each tensiometer was buried within the contact material to give suction readings at that specific position. The suction in the tensiometer was measured using a pressure transducer gauge with a precision of ± 1 cm. Saturation of the wick was confirmed when the tensiometer placed in the wick gave a reading close to the height of water in the tensiometer tube.

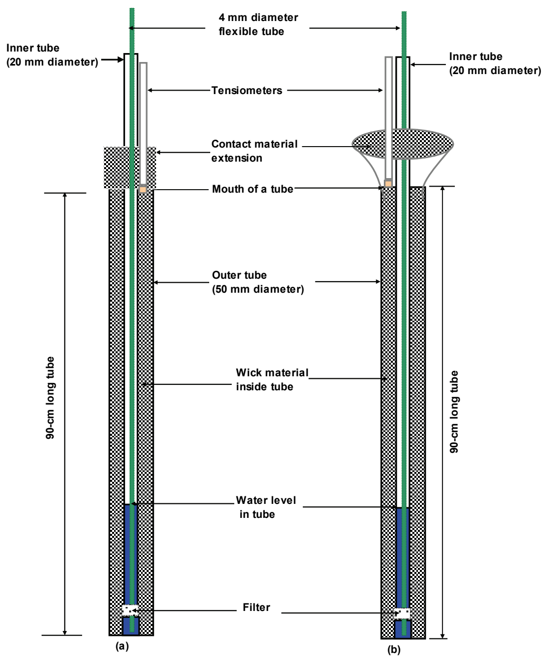



**Figure 2.6** A schematic presentation of a 90-cm tube detector filled with a wick material and (**a**) 50 mm diameter contact material and (**b**) 200 mm diameter contact material placed on the opening of the tube and subjected to a drying process after saturating the wick in the column

The set-ups were then allowed to dry out from saturation until the water level in the inner tube gave a zero reading. Water level in the inner tube was measured using two methods: firstly the water level was read directly from a piezometer scale (clear tube of 3 mm diameter connected to the inner tube and held upright against the outer tube) (not shown in Figure 2.6). Secondly, the water volume in the tube was measured (water sucked out with a syringe via a flexible tube and the volume of water was divided by 2.34 ml/cm to obtain the water level in cm). The water extracted with the syringe was returned to the inner tube after each reading.

## 2.3 FIELD STUDIES

The field experiment was a platform to create and evaluate different strengths of wetting fronts, especially tensions in the range of 0-100 cm using different forms of water applications in order to evaluate the sensitivity of each detector design. The aim of this experiment was to evaluate under field conditions whether the different detector prototypes (tube and hybrid designs) are more sensitive than the commercially available funnel-shaped detector (FullStop WFD).

### 2.3.1 Field site

The study was carried out at the Hatfield experimental farm of the University of Pretoria, South Africa ($25^0$ 64'S, $28^0$ 16'E and altitude of 1370 m). Plots were located under a rain-shelter facility to screen out rainfall that could possibly interfere with measurements. The facility consisted of plots with dimensions of 2 m x 2.5 m, which were hydrologically isolated by fibre cement sheets to a depth of 1.2 m. The soil had a sandy loam topsoil layer (0 to 20 cm), containing 15% clay, 5 % silt, and 79% sand and a sandy clay loam subsoil (20 to 120 cm soil layer), consisting of 25% clay, 15% silt and 60% sand. Weather variables required for computing reference evaporation were collected using a nearby (50 m from experimental field) automated metrological station. Of the 60 plots in the rain-shelter, 15 of the inner plots were selected for the trial, leaving two border rows of plots on either side. The five designs of detectors (three lengths of tube detectors, a hybrid detector and a FullStop detector) were each replicated three times and allocated to the 15 pots in a completely randomized block design (CRBD). Soil tension and water content measuring devices were installed in the plots where the different designs of detectors were buried (Figure 2.8). These installations enabled *in situ* measurement of soil water content, soil tension and WFD response to passing wetting fronts of various strengths.

### 2.3.2 WFD Installations

***Tube wetting front detectors***

Three lengths of tube detectors (45 cm, 60 cm and 90 cm), referred to as TD45, TD60 and TD90, were tested during the field experiment. In each tube detector treatment plot, 6 tube detectors of the same length were installed: 3 filled with DE and the other 3 with very fine sand. Detectors were buried with their mouths positioned at depths of 30, 60 or 90 cm below the soil surface (Figure 2.7). All tube detectors were installed in a grid of 0.5 × 1.0 m within a plot (Figure 2.8). The tube detectors were installed using an auger (55 mm diam.). The above installation was replicated 3 times for each length. The contact material is the same as the wick material filled in the tube.

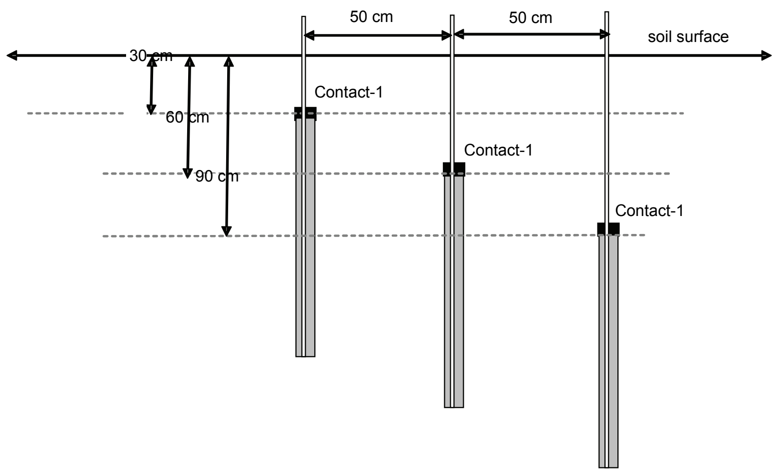



**Figure 2.7** An example of 90-cm-long tube detectors (TD90) filled with either DE or very fine sand installed in a plot at three depths (30, 60, 90 cm) from the soil surface, with 50 cm horizontal distance between each detector and the mouth of the tube (dashed line) indicating the depth of placement

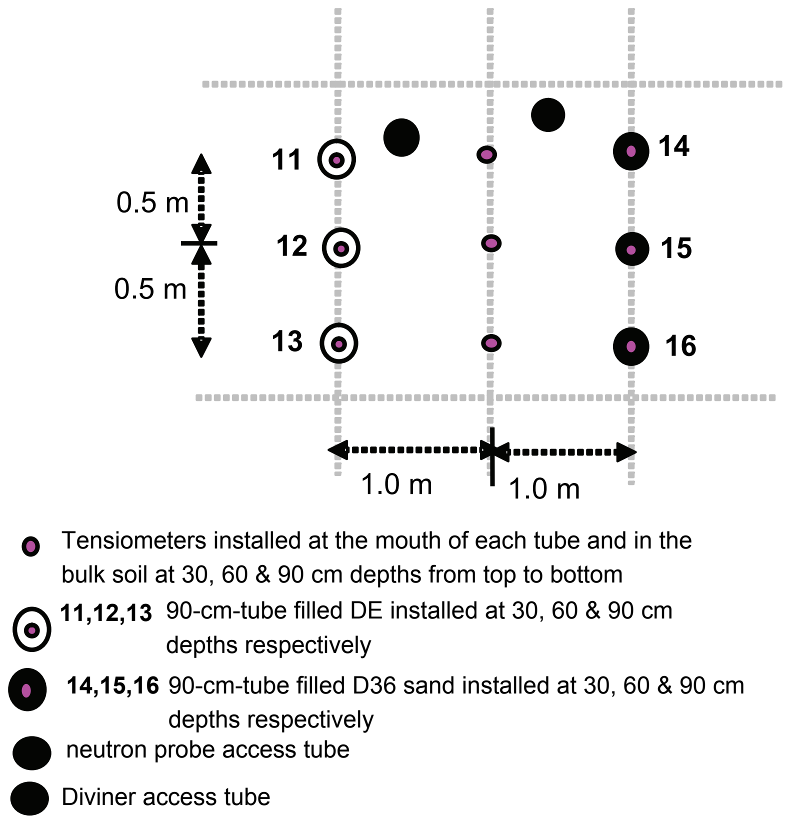



**Figure 2.8** Plane view showing the positioning of tensiometers, neutron probe access tube, Diviner 2000 probe access tube and 90cm long tube detector within a plot

***Hybrid and FullStop wetting front detectors***

In the hybrid design plots, 6 hybrid detectors were installed: 3 were filled with local soil and another 3 with very fine sand. Hybrid detectors were buried with their mouths positioned at depths of 30, 60 or 90 cm below the soil surface (Figs. 2.9a & 2.10a). The hybrid detectors were installed using auger sizes of 75 mm and 45 mm diameter. Similarly, 8 funnel-shaped WFDs were installed in a grid of 0.5 m × 1.0 m within applicable plots: 4 were filled with fine sand and another 4 with DE filter material (Figs. 2.9b and 2.10b). The funnel detectors were installed with auger sizes of 200 mm and 45 mm diameter. The above installations were replicated 3 times for each design.

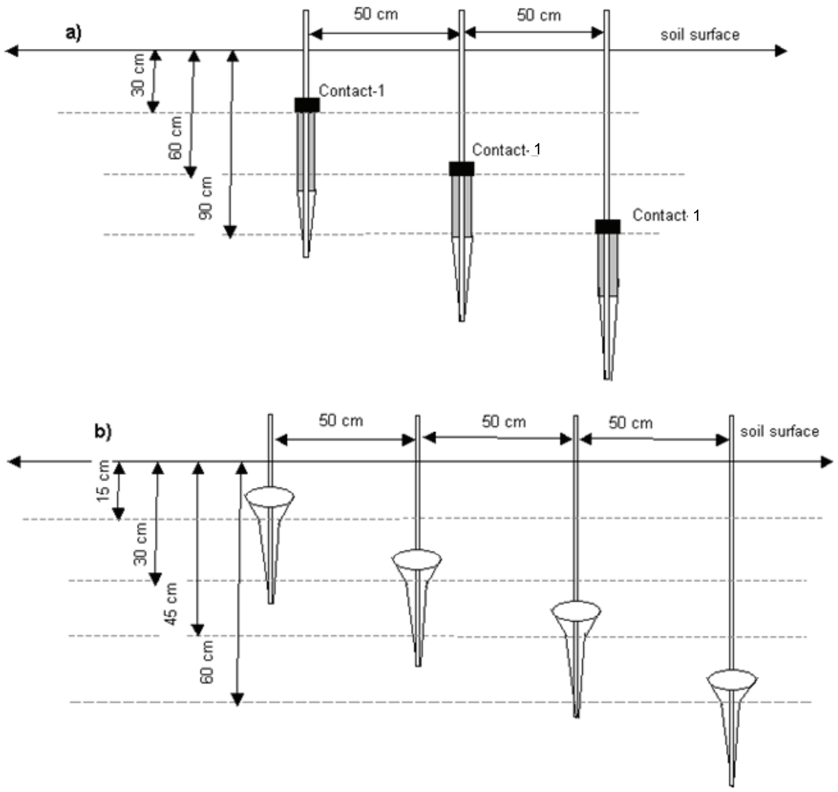



**Figure 2.9** Diagram illustrating (a) the field layout of the hybrid wetting front detectors (HD) filled either with soil or very fine sand and installed at 3 depths (30, 60, 90 cm; dashed horizontal lines indicate the depth of placement) from the soil surface, with 50 cm horizontal distance between each hybrid and (b) funnel-shaped wetting front detectors (FS$^{TM}$) filled with fine sand or Diatomaceous Earth filter material installed at 4 depths (15, 30, 45, and 60 cm; dashed horizontal lines indicate the depth of installations) from the soil surface, with 50 cm distance between funnel detectors

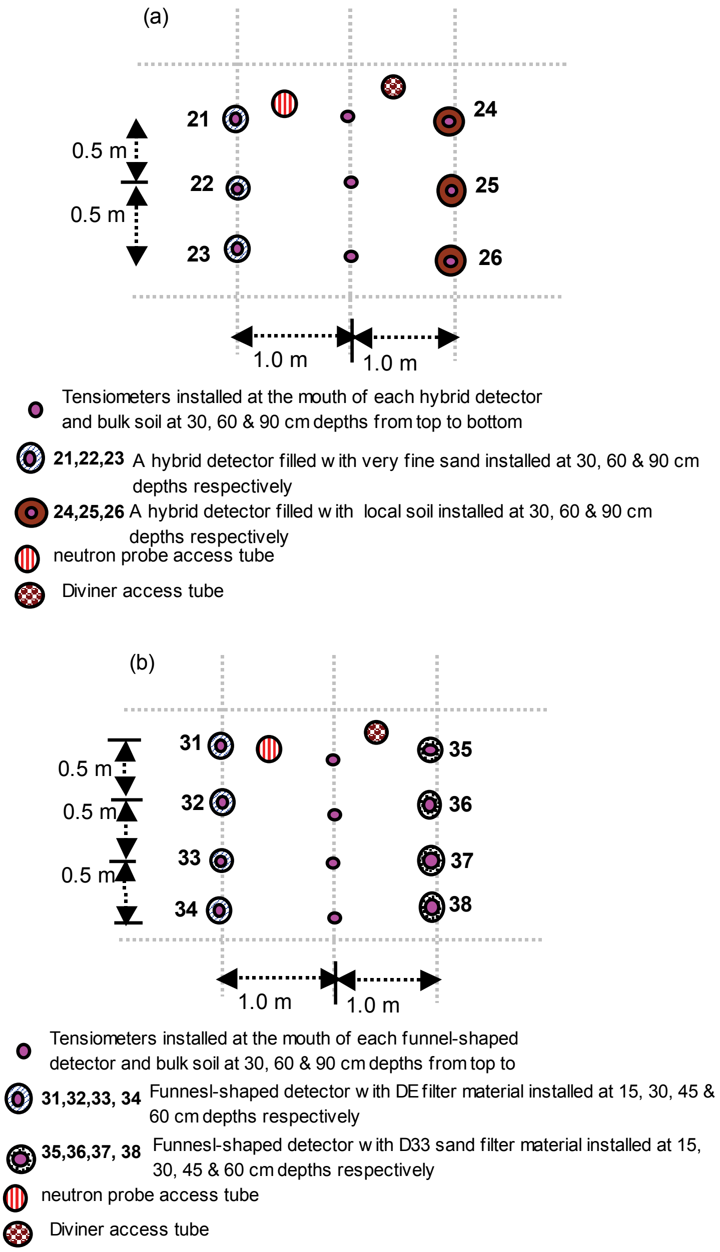



**Figure 2.10** Plane view showing the positioning of the tensiometers, neutron probe access tube, Diviner 2000 probe access tube in (a) hybrid detector plots and (b) funnel-shaped detector plots

***Soil water monitoring tools***

Neutron and diviner probes were used to measure soil water contents. Access tubes for the Diviner probe were installed using the installation kit supplied with the Diviner 2000 instrument. Aluminium access tubes of 1.5 m length were installed using an auger (50 mm diam.) for neutron probe measurements.

The manual and automatic tensiometers were installed using a 45 mm diameter auger after saturating the ceramic tips for 24 hours. All access holes were backfilled with slurry prepared from the same soil to ensure good contact between the tensiometer cup and soil. Tensiometers were used to measure soil tension in the bulk soil and in the contact material at 3 depths (Figs. 2.8 and 2.10a). Each tube detector plot consisted of 9 tensiometers (6 in the contact material and 3 in the soil) to measure changes in soil tension. Automatic tensiometers were installed according to the manual for the operation of tensiometer nests, using the HOBO logger system. For the tube and hybrid detector plots, one plot from each treatment was instrumented with automatic tensiometers to monitor the time series of soil tension fluctuations in the bulk soil adjacent to each detector at four depths (30, 45, 60 and 90 cm). However, the monitoring depths for the funnel-shaped plot were at 15, 30, 45 and 60 cm to match the depth of the FullStop wetting front detectors installations (Figure 2.10b). Therefore, a total of 128 manual tensiometers, 20 automatic tensiometers, 15 neutron probe access tubes and 15 diviner probe access tubes were installed.

### 2.3.3 Water application

One of the water application methods used was rainfall, because a very uniform application of small amounts was needed (which may not be possible with an irrigation system). Rainfall did produce a very uniform distribution over all the plots under the rainshelter, ranging from 1.0 mm $d^{-1}$ to 41.8 mm $d^{-1}$. The rainshelter facility was opened on 3 November 2006 in order to evaluate all the detectors under rainfall conditions. The rainfall data for analysis was taken from the automatic weather station near the rainshelter facility. Moreover, manual rain gauges were placed within the rainshelter facility to record the rainfall amounts as a check. There were 45 rainfall events amounting to 337 mm from the beginning of November 2006 until 19 April 2007. Rainfall greater or equal to 1 mm was considered a rainfall event. Of the rainfall events, 88% were below 15 mm, 7% between 15 and 30 mm, and only 5% were above 30 mm. Of the 15 measurements made, 10 were with rainfall events (9 events were 1 to 15 mm and only one event was above 15 mm) and 5 measurements were from non-rainfall events.

The second water application method used was sprinkler irrigation that produced a distribution uniformity of 70-80% with two lateral lines each consisting of 3 sprinkler stands (full rotation) at 6 × 12 m spacing. During the evaluation period when irrigation was used, 750 mm of water was applied in 19 irrigation events from 21 August 2007 to 28 November 2007. The irrigation events over the trial period could be classified four categories. The first category of irrigation includes 9 irrigation events (total of 479.5 mm) applied on a weekly basis at a rate of 7.8 – 10.4 mm $h^{-1}$. The amount applied per event varied between 25 and 98 mm. The second category of application was from 9 October to 18 October 2007, amounting to a total of 44.2 mm in 4 irrigation events and applied at a rate of 10.3-12 mm $h^{-1}$. The irrigation intervals between the events were 1, 2 or 3 days. The third category of irrigation includes 4 events amounting to a total of 119.6 mm, applied at intervals of 1, 3 or 10 days. The application rate ranged from 9.6-10.5 mm $h^{-1}$. The last category included 2 events amounting to a total of 106.7 mm and was applied at a rate of 17-18.7 mm $h^{-1}$ (sprinkler heads were changed from full rotation to a half rotation to avoid water wetting other trial plots adjacent to the rain shelter facility).

The distribution uniformity (DU) and the coefficient of uniformity (CU) were calculated for all irrigation events using 60 catch cans (one placed in each plot) in a grid of 3.0 by 3.0 m within the rain shelter facility. The DU and CU for the 17 events were on average 70 and 80% respectively. For the last two events, however, the DU and CU values were very low after changing the sprinkler heads from full to half rotation.

### 2.3.4 Measurements and monitoring

Measurements were taken the day after each rainfall event. However, measurements during the sprinkler irrigation evaluations were taken before, immediately and on a daily basis after irrigation. Measurement parameters included soil water content, soil tension and volume of water in the detectors. It also included observations of visual responses by funnel-shaped and hybrid detectors.

Soil water content was measured using the neutron probe and Diviner probe methods. The neutron probe (Model503DR, Campbell Pacific Nuclear International Martinez, CA) was calibrated for the local soil. The count readings were taken manually from the display screen. Factory calibration functions were used for the Diviner probe (Diviner2000 series II, Sentek Sensor Technologies). Readings were taken at 10 cm intervals down the soil profile (10-160 cm) and data was stored in the Diviner 2000 memory.

The soil tensions were measured using tensiometer pressure transducers which had a resolution of ± 1cm (IrriCrop Technologies Pty. Ltd., Australia) for all the measurement periods. The tensiometers in the bulk soil and contact materials indicated the direction of the lateral gradient to establish if flow was away from or towards the detector's opening. The measured tensions were also used to validate equilibrium between the contact and the bulk soil. Time series measurements of soil tensions were automated using automatic tensiometers (Onset Computer Corporation, Bourne, MA02532).

Water volume inside the tube detectors was measured using a simple and inexpensive method. It required a syringe and a flexible tube that directly sucked water from the inner detector tube. The volume of water collected was related to the tension in the contact material. The water collected in the tube or the visual indicators in the up position for funnel-shaped and hybrid detectors at the time of measurement indicated response to infiltrating water during the rainfall and irrigation events.

### 2.4 Statistical analyses

All data regarding the measured contact material tensions, bulk soil tensions, water contents, and WFD response observations at all depths were subjected to ANOVA using the Statistical Analysis System (SAS Institute, 1999-2001). Significantly different treatment means (if ANOVA F-test means were significant) were separated using a t-Test (LCD) comparison wise error rate.

## *2.5 RESULTS AND DISCUSSION*

### 2.5.1 Laboratory data analyses

***Particle size distribution***

Sand size affects total porosity as well as the shape of the water retention curve of a porous material. Particle size distribution (PSD) analyses were conducted for all five potential wick materials and two soil depths for the Hatfield experimental site. Four of the sands (Sand1, Sand2, Sand3 and very fine sand) were analyzed using mechanical sieving, while the hydrometer method was used to determine particle size distribution for DE and soil samples from two depths (0-60 cm and 60-120 cm). Particle size analysis for the soils and wick materials are presented in Table 2.1.

**Table 2.1** Particle size distribution of potential wick materials and two soils from the Hatfield experimental site

| Type | Particle size distribution (%) | | |
|---|---|---|---|
| | **Sand (>0.05 mm)** | **Silt (0.05-0.002 mm)** | **Clay (<0.002 mm)** |
| Diatomaceous Earth (DE)[2] | 99.7 | 0.1 | - |
| Diatomaceous Earth (DE)[1] | 36.2 | 50 | 12.5 |
| Very Fine Sand (D36)* | 91.4 | 8.6 | - |
| Sand1* | 76.6 | 23.3 | - |
| Sand2* | 94.7 | 5.1 | - |
| Sand3* | 79.8 | 20.1 | - |
| Soil (0-60cm)[1] | 60.5 | 5 | 34.5 |
| Soil (60-120cm)[1] | 60 | 15 | 25 |

[1] UP Soil Science Lab results, [2]Particle size analysis (Bigelow et al., 2004)

* Sieve method

The PSD results showed that particle sizes fell predominantly (> 76%) in the sand size category for all the sand materials, while the two soil samples had about 60% sand and 25 - 34.5% clay content. The PSD for Diatomaceous Earth determined in the UP Soil Science Lab was very different from that reported by Bigelow et al (2004), which indicated that 99.7% of the particles fell in the sand size category (> 0.05 mm).

*Water retention curves*

Soil water retention data of the five potential wick materials and two soil samples that were determined using the controlled outflow method are plotted in Figure 2.11. For the water retention characteristics of wick materials (Figure 2.11a), DE showed much higher volumetric water content at saturation than the other porous media types, with little change in water content, at least over the tension ranges close to 100 cm. The shape of the water retention curve of all sands except very fine sand were very close to each other and stayed nearly saturated for very low-tension ranges. Very fine sand seemed to have a definite air entry potential (10 cm) but that was not the case for the other sands. The pore size distribution index (n) was highest for very fine sand, indicating that it contained more coarse sand. The water retention characteristics of the four sands (Sand1, Sand2, Sand3, and very fine sand) indicated that 50% of their water was lost at tensions between 90 and 190 cm. Diatomaceous Earth, however, had the lowest inverse air entry value, which enables it to stay fully saturated up to a tension of 114 ± 18 cm, and it loses 50% of its water when the tension exceeds 370 cm.

The soil material data (Figure 2.11b) showed that the 60-120 cm soil sample had a steep slope with lower air entry potential when compared to the 0-60 cm sample. The 0-60 cm soil sample tended to have a definite air entry potential (20 cm) and decreased in volumetric water content sharply thereafter. This has special significance to the hybrid detectors, as this local soil (besides the very fine sand) was used as a wick material to fill the extension pipes that were used to minimize divergence of water flow. The 0-60 cm soil sample (Figure 2.11b) was better for the hybrid detectors than very fine sand (Figure 2.11a) if the air entry potential requirement of the device is considered.

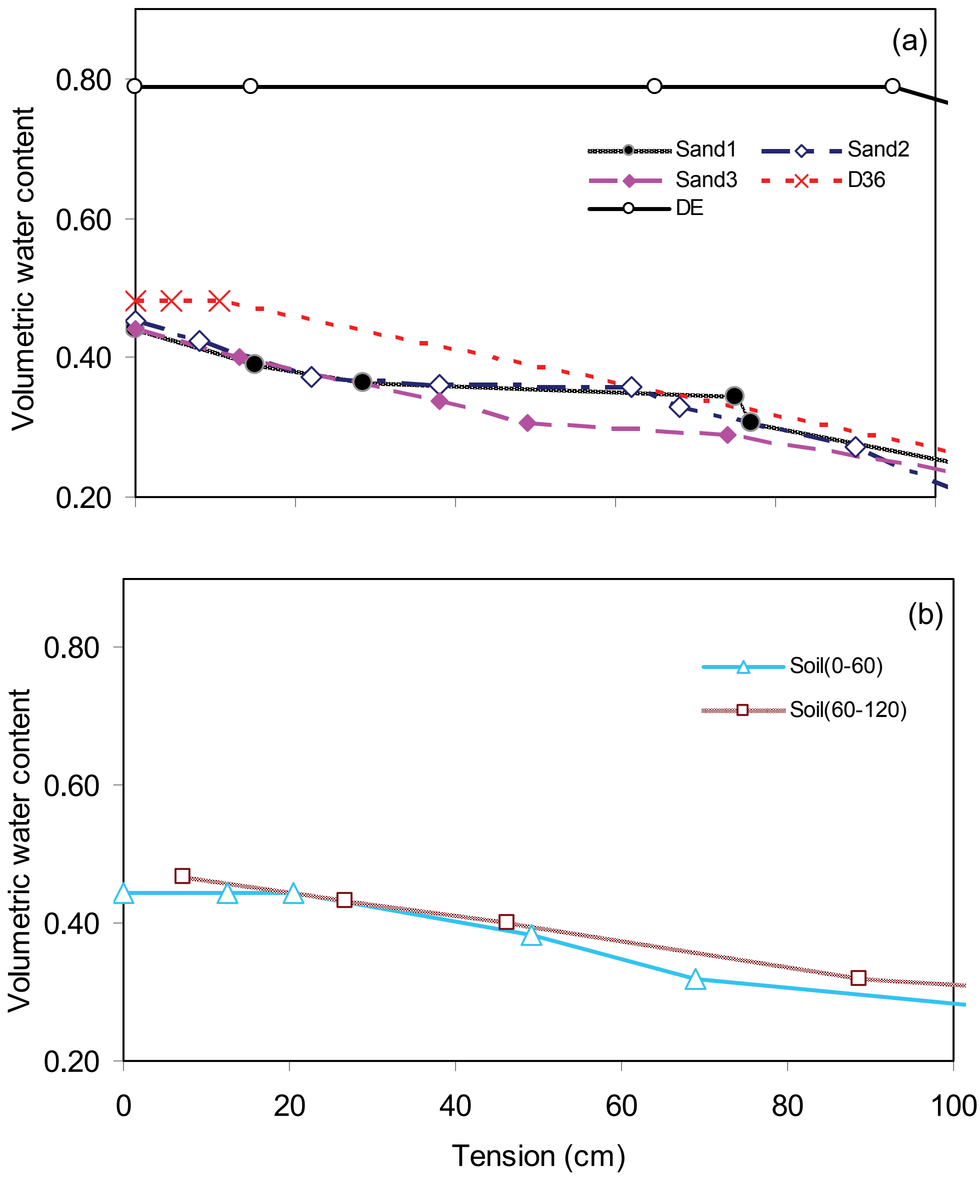



**Figure 2.11** Measured water retention characteristics for (a) wick materials and (b) soil materials

Water retention curves were fitted to the data using RETC to determine the hydraulic parameters of each tested material. Graphical presentations thereof can be seen in Appendix 2.2. RETC implements the van Genuchten (1980) retention model to estimate model parameters. Water content at saturation ($\theta_s$) was fixed to the porosity value of the material and m was calculated in terms of n as 1-1/n to minimize the number of fitting parameters. The residual water content ($\theta_r$), pore size distribution index (n), and inverse air entry value ($\alpha$) were fitted through the parameter estimation process using RETC. Besides fitting parameters, RETC provided information related to goodness of fit ($r^2$) between measured and fitted values, and statistical parameters (mean, standard error, and lower and upper 95% confidence limits).

The predicted water retention curves presented in Appendix 2.2 were in good agreement with the measured data for all the wick and soil materials ($r^2 > 0.97$) with the exception of Sand2 ($r^2 = 0.93$). The measured data was quite well reproduced by the van Genuchten retention model; hence the agreement between the fitted curves and measured data was very good.

The model parameters determined by fitting the analytical expressions to the measured retention data for the five wick and two soil materials are presented in Table 2.2. Results from Table 2.2 show that the pore size distribution index (n) for very fine sand (D36) was highest among the tested materials. The high n was related to the high sand fraction content of D36, which was exceeded by Sand2 only (Table 2.1). The inverse air entry value (α) was lowest for DE, which is related to a large fraction of very fine particles that enables the material to remain saturated over drier tensions (Table 2.2).

**Table 2.2** Water retention model parameters of potential wick materials and two soils from the Hatfield experimental site

| Type | van Genuchten model parameters | | | | |
|---|---|---|---|---|---|
| | $\theta_s$(cm$^3$ cm$^{-3}$) | $\Theta_r$(cm$^3$ cm$^{-3}$) | α(cm$^{-1}$) | n | m = 1-1/n |
| DE | 0.793 | 0.078 | 0.0036 | 2.56 | 0.61 |
| D36 | 0.48 | 0.09 | 0.012 | 3.6 | 0.72 |
| Sand1 | 0.44 | 0.045 | 0.022 | 1.51 | 0.34 |
| Sand2 | 0.452 | 0.045 | 0.015 | 2.33 | 0.57 |
| Sand3 | 0.44 | 0.045 | 0.022 | 1.91 | 0.48 |
| Soil* | 0.443 | 0.178 | 0.016 | 2.74 | 0.64 |
| Soil** | 0.467 | 0.213 | 0.020 | 2.13 | 0.53 |

*Soil* = 0-60 cm (sandy clay loam), Soil** = 60-120 cm (sandy clay loam)*

***Unsaturated hydraulic conductivity***

The unsaturated hydraulic conductivities of materials were determined using the following techniques: Bruce-Klute method, RETC analysis of retention data, and Hydrus-2D modelling of the Bruce-Klute test. The Bruce-Klute hydraulic conductivity results are presented in Figure 2.12. The hydraulic conductivities obtained from the Hydrus-2D simulations of the Bruce-Klute test can be found in Appendix 2.3.

The good agreement between the van Genuchten analytical expressions with the measured retention data shows the reliability of the model parameters (Table 2.2) estimated with the RETC fitting technique to predict the unsaturated hydraulic conductivity.

Direct measurement of conductivities using Bruce-Klute analysis was applied for DE, D36 and two soil depths (0-60 and 60-120 cm) to calculate the unsaturated hydraulic conductivities, using the theory described in Appendix 2.1. The three sands (Sand1, Sand2 & Sand3) were, however, excluded from the analysis, as the end boundary conditions were not maintained.

The Hydrus-2D simulated conductivities for D36 were over-predicted when compared to the standard Bruce-Klute results (Figure 2.12a). However, for DE, the Hydrus-2D and standard Bruce-Klute test results were very close to each other. In case of the two soil materials (Figure 2.12b), Hydrus-2D simulations overestimated conductivities for tensions wetter than 40 cm and underestimated it at soil tensions higher than 40 cm, when compared to the standard Bruce-Klute results. The results from Hydrus-2D and Bruce-Klute analyses also showed that D36 was the most conductive for tensions < 80 cm. Therefore, D36 was best suited to the requirements of prototype detectors for lengths < 80 cm, provided that the air entry potential requirement of the wick material is also fulfilled. The high conductivity of D36 could be attributed to the high particle size distribution index (n). As the tension becomes drier than 80 cm, however, DE was the most conductive.

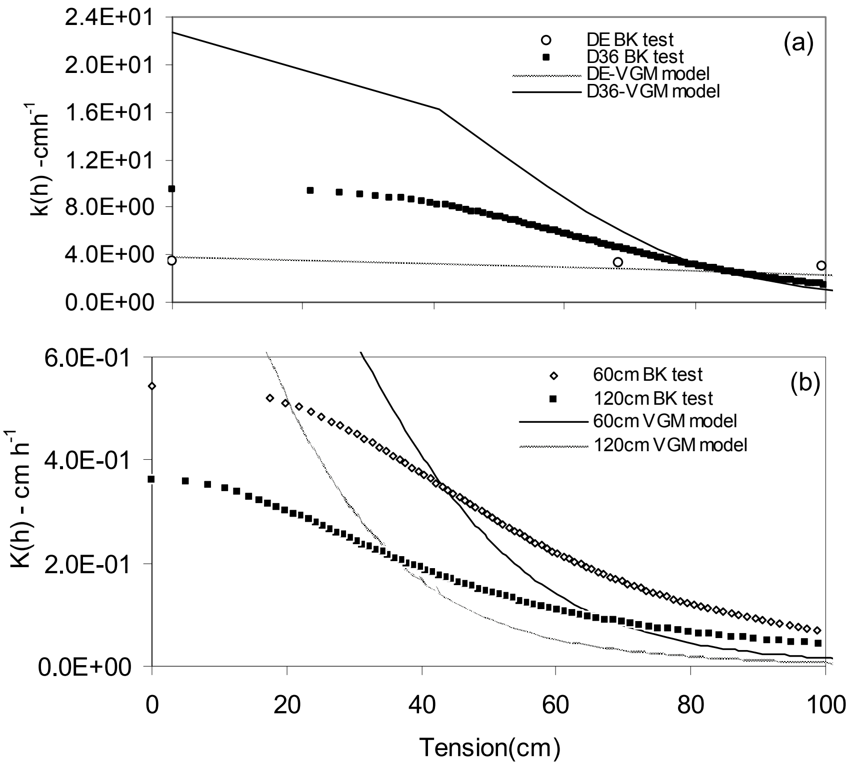


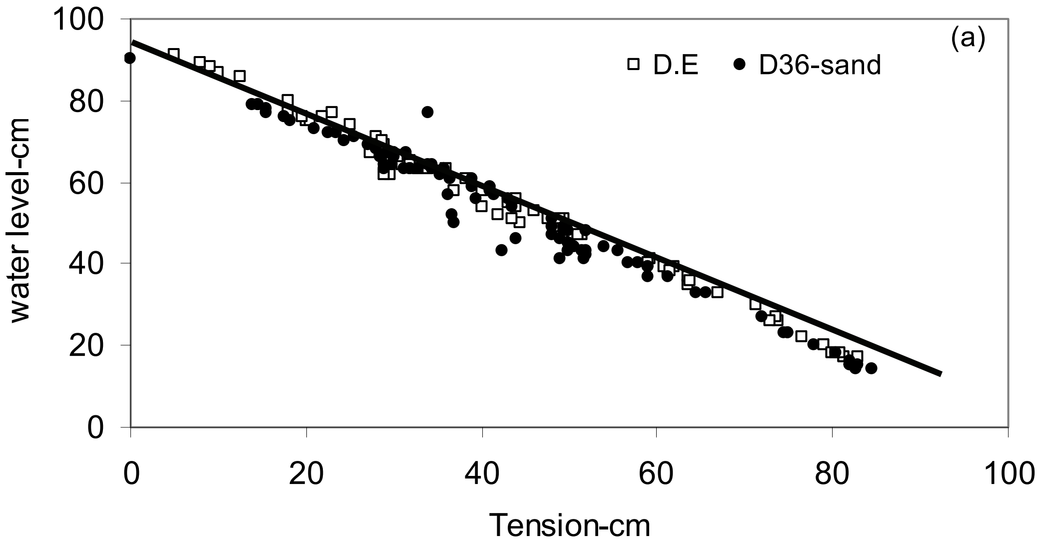

**Figure 2.12** Unsaturated hydraulic conductivity determined using the standard Bruce-Klute method (symbol) and Hydrus-2D simulated (lines) for (a) DE & D36 sand and (b) two soil samples

***Empirical results***

The data from the empirical test was used to validate the hydraulic characteristics of Diatomaceous Earth and very fine sand (D36) determined by using different methods. The empirical test was carried out to meet the following aims:

1) To show that the soil tension in the contact material at the mouth of the tube is related to the depth of water in the tube
2) To determine the effect of the wick material on the rate of water loss from the tube WFD, i.e. whether the water loss is energy or conductivity limited

Under equilibrium conditions, the slope of the regression line of wick tension regressed against water level in the tube should be -1, with a regression value close to one ($r^2 = 1$). A total of 6 drying cycles were monitored for each wick material and the slopes and regression values obtained under indoor conditions are presented in Appendix 2.4. The regression line for test no.1 was obtained by plotting measured tensions and water levels for several (about 10) drying cycles on a graph (Figure 13a) for both materials.



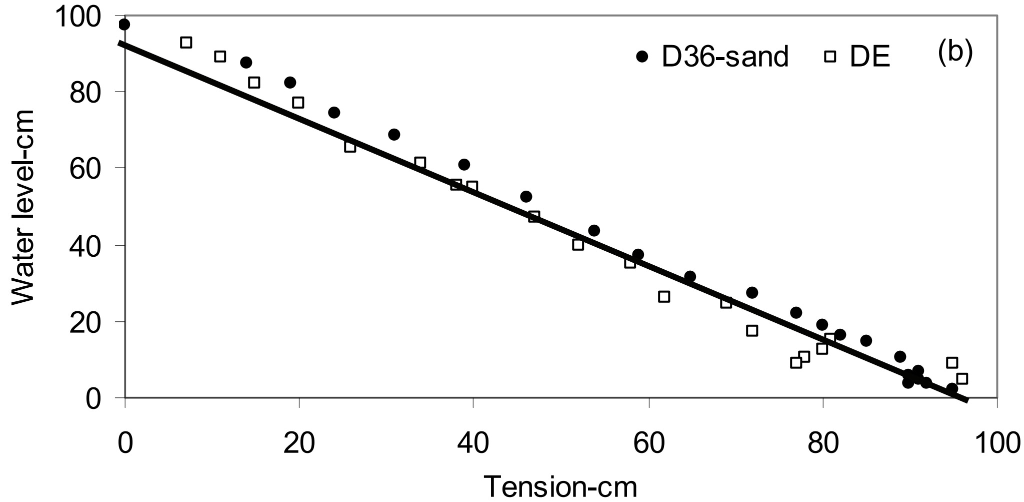




**Figure 2.13** Linear regressions between water level in the tube and wick tension for DE & D36-sand using a 90-cm tube detector with (a) 200 mm diameter opening, and (b) 50 mm diameter opening

Results from the empirical test showed that the water level in the tube was linearly related to the wick tension at the mouth of the tube with a good fit ($r^2 > 97\%$). The regression values were similar for both wick materials (Figure 2.13a and b).

The water level in the tube over time was analysed individually for some of the setups to determine the effect of different wick materials on the rate of water loss from the tube. Results of these analyses can be found in Appendix 2.4. It was observed that water loss from the tube was linearly related with time for DE (energy limited), but not for D36, which could be an indication that evaporation process of water from the tube filled with D36 sand involves two phases (energy and conductivity limited). The water level in the tube detector filled with D36 sand was observed to be 20-25 cm when the conductivity limited stage commenced, which is related to 65-70 cm tension at the mouth of the tube.

### 2.5.2 Field study results

***Tube wetting front detectors***

Field evaluations of the three lengths of tube detectors (TD45, TD60 & TD90) were carried out using two forms of water application, namely rainfall and sprinkler irrigation. The data include results on equilibrium between contact tension and bulk soil tension, linearity between wick tension and water level in the tube, and the correlation between wick tension and tube tension. Averages of three replicates of bulk soil tension, wick tension and water level measurements for each tube length taken over the measurement periods were used during all scenario analyses.

***Equilibrium between contact material and bulk soil tensions***

Results on equilibrium status between contact material tension and bulk soil tension (based on the averages of contact tension for each wick material and bulk soil tension measured at three depths) are presented in Table 2.3 (the reported tensions are averages of 15 observations replicated three times; rainfall data). A similar averaging method was used for the sprinkler irrigation data. An example of a graphical display of equilibrium conditions observed during the sprinkler evaluation period for 3 depths is shown in Figure 2.14.

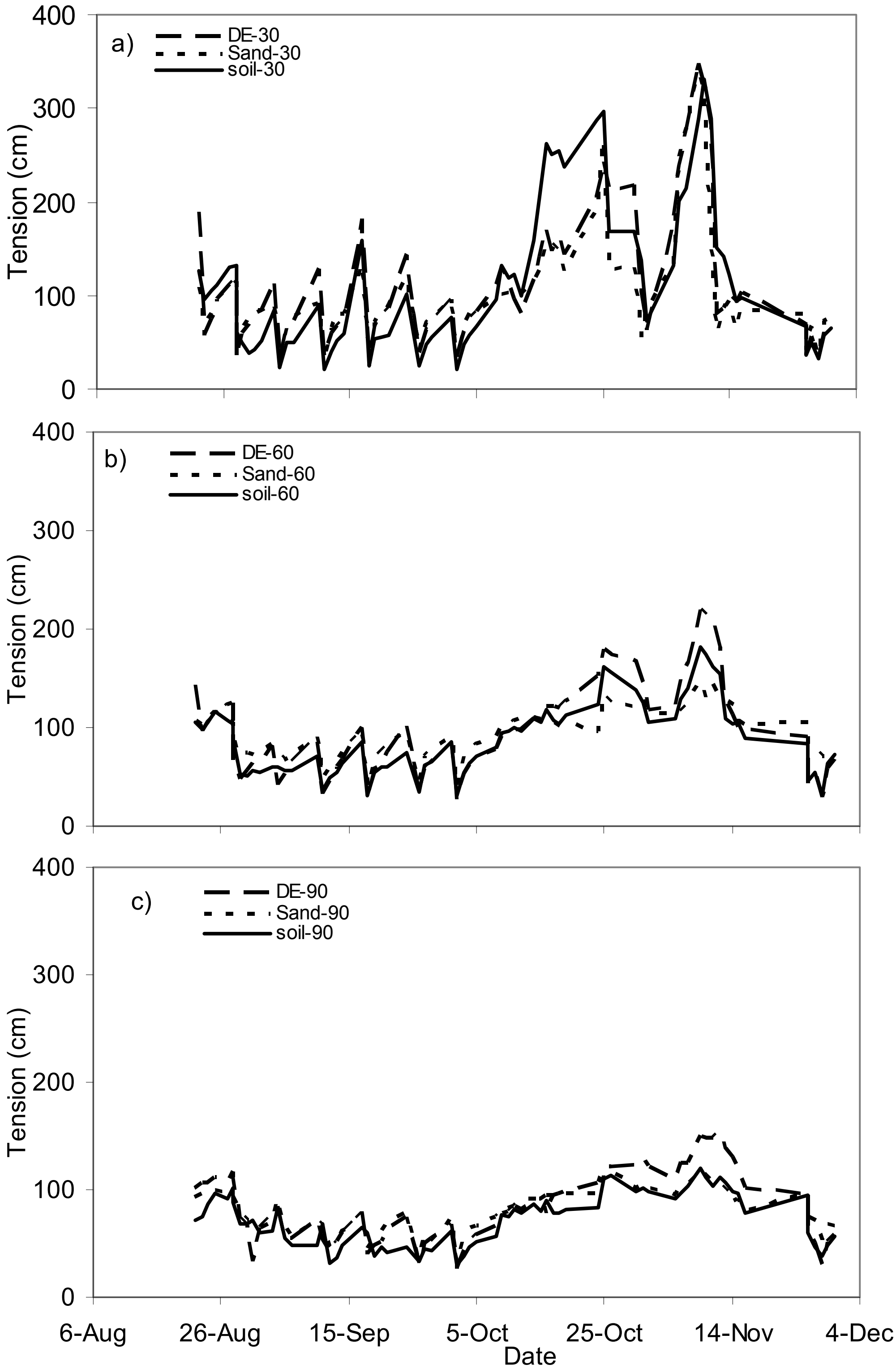



**Figure 2.14** Tension differences (equilibrium status) between the bulk soil and contact materials at (a) 30 cm (b) 60 cm and (c) 90 cm depths

A summarized analysis of the difference between contact and bulk soil tensions (equilibrium status) during the rainfall period is presented in Table 2.3. The table indicates that there was convergence towards the wick at 30 cm depth but divergence from the wick at 60 and 90 cm depths.

**Table 2.3** Contact and bulk soil tensions (rainfall)

| Soil depth (cm) | Tension (cm) | | | Tension difference(cm) | |
|---|---|---|---|---|---|
| | D36 | DE | Bulk soil | $\Delta h_{D36\text{-}soil}$ (cm) | $\Delta h_{DE\text{-}soil}$ (cm) |
| 30 | 71 | 83 | 64 | 7 | 19 |
| 60 | 112 | 124 | 142 | -30 | -18 |
| 90 | 129 | 169 | 179 | -50 | -10 |

Table 2.4 summarizes results for the paired t-test analysis results between contact and soil tensions (sprinkler irrigation). The results show that the observed mean differences between the DE and soil, as well as between D36 and soil, were highly significant at observation depths of 60 and 90 cm, but not at 30 cm depth. The scientific importance of this statistical significance, however, seems to be less important, as the observed mean differences fell within the accuracy range of the tensiometers used in water flow studies. The estimated lateral flux at the driest possible measurable tension for the tube detectors, possibly at 90 cm, was < 0.6 mm $d^{-1}$, which can be considered as a practically negligible water flux. These results, therefore, show that there was tension equilibrium between the wick materials and bulk soils at all depths. A similar trend was observed in the drier tensions, with some minor deviations (Figure 2.14).

**Table 2.4** Paired t-test analysis between contact and soil tensions (sprinkler irrigation)

| Soil depth (cm) | Mean | | t value | | Pr > / t / | |
|---|---|---|---|---|---|---|
| | DE-Soil | D36-Soil | DE-soil | D36-Soil | DE-Soil | D36-Soil |
| 30 | -8.26 | 9.28 | 0.22 | 1.78 | 0.83 | 0.08 |
| 60 | -8.38 | -5.9 | -4.98 | -3.09 | <0.0001** | 0.003** |
| 90 | -12.36 | -8.51 | -7.10 | -7.65 | <0.0001** | <0.0001** |

** Highly significantly different

***Wick tension at the mouth of a tube detector and water level in the detector***

The relationships between the wick tension at the mouth of a tube detector and water level in the detector were analysed using similar averaging techniques as applied for the equilibrium conditions for each rainfall and sprinkler irrigation data set. Data on the degree of linearity between water level in the tube and wick tension for rainfall and sprinkler data are presented in Tables 2.5 and 2.6, respectively. A graphical example of the change in water level and wick tension data over time for the TD90 detector under sprinkler irrigation is presented in Figure 2.15.

**Table 2.5** Summary of regression values for the relationship between water level and measured tension for 3 tube lengths (rainfall)

| Tube design | Wick material | Intercept | $r^2$ value |
|---|---|---|---|
| TD45 | DE | 41 | 0.93 |
| | D36 | - | - |
| TD60 | DE | 45 | 0.98 |
| | D36 | 42 | 0.77 |
| TD90 | DE | 79 | 0.92 |
| | D36 | 48 | 0.75 |

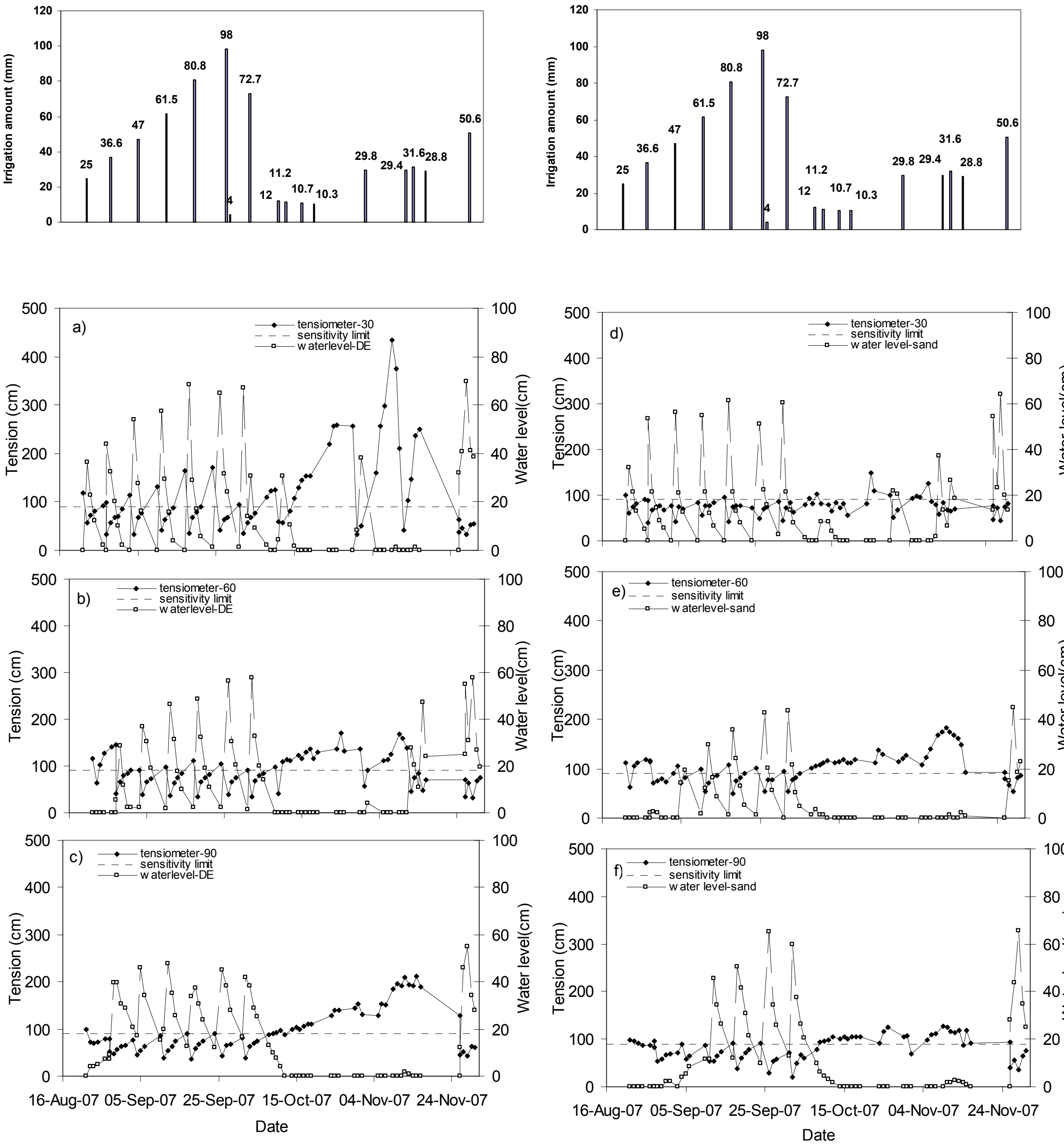



**Figure 2.15** Water level recorded in **TD90** filled with DE (left) and tensiometer readings at (a) 30 cm, (b) 60 cm and (c) 90 cm; or D36 sand **(**right**)** and tensiometer readings at depths of (d) 30 cm, (e) 60 cm and (f) 90 cm (sprinkler irrigation)

Results on rainfall data, water level and wick tension in a tube detector show that for a tube filled with DE, water level was linearly related to the contact tension, with $r^2$ values of 0.92 to 0.98. Similarly, for a TD filled with very fine sand, the water level was linearly related to contact tension, but with lower $r^2$ values of 0.75 to 0.77. The data for sprinkler irrigation (Table 2.6), showed that for a tube detector filled with DE, water level in the detector was linearly related to wick tension, with $r^2$ values of between 0.73 and 0.85. For a tube detector filled with very fine sand (D36), water level was linearly related to contact tension, with $r^2$ values of 0.69 to 0.84. The goodness of fit was generally higher for TDs filled with DE, when compared to D36.

**Table 2.6** Summary of regression values for the relationship between water level in the TD and measured tension for the three tube lengths (sprinkler irrigation)

| Tube design | Wick material | Intercept | $r^2$ value |
|---|---|---|---|
| TD45 | DE | 38 | 0.85 |
| | D36 | 54 | 0.84 |
| TD60 | DE | 50 | 0.60 |
| | D36 | 59 | 0.64 |
| TD90 | DE | 82 | 0.73 |
| | D36 | 85 | 0.69 |

The tube detectors filled with DE generally detected passing wetting fronts well: in a worst-case scenario, 73% of the fronts that fell within their sensitivity limits were detected (Table 2.6). The graphical display (Figure 2.15) also shows that whenever the tension at the mouth of a tube detector fell below its sensitivity limit (horizontal dotted line), water was collected by the detectors. On the other hand, as the tension rose out of the TD sensitivity limit, no water was collected by the detectors. A limited number of false responses (anomalies) were also observed.

***Wick tension vs. tube tension***

The measured difference in elevation between the static water level in the inner tube and the mouth of the tube detector can be converted to tension at the opening of the tube, using the hydrostatic pressure gradient of 9.8 kPa $m^{-1}$, which can hence be termed the tube tension. The wick tension is the tension measured in the wick at the mouth of the tube by a tensiometer.

The data from rainfall and sprinkler irrigation wetting events were used to determine the relationships between the wick tension and tube tension. The data were averaged in a similar way to the averaging techniques applied for describing the equilibrium conditions and the relationship between wick tension and water level in a tube detector. The paired t-test results between the tube tension and tensiometer readings for sprinkler data is presented in Table 2.7. A graphical representation of the data for tube tension vs. wick tension for sprinkler irrigation events, using the TD90 detector, is presented in Figure 2.16 as an example.

No statistical differences were recorded between the measured tube tensions and tensiometer readings (cm) for the TD60 and TD90 designs filled with DE. This confirms that the latter TD designs can accurately measure water tension at the mouth of the detector. However, significant differences between the mean measured tube tensions and tensiometer readings were recorded for the TD45s (Table 2.7). The graphical display of TD90 detector data (Fig. 2.16), for example, indicates that the measured tensions at the mouth of detectors and the calculated tensions (by converting the elevation difference between the static water level and mouth of a tube detector) matched very well. This confirms that tube detectors can also be used as tensiometers.

**Table 2.7** Paired t-test analyses between the tube tension and tensiometer readings (cm)

| **Tube design** | **Mean** | | **t value** | | **Pr > / t /** | |
|---|---|---|---|---|---|---|
| | **a-c** | **b-c** | **a-c** | **b-c** | **a-c** | **b-c** |
| TD45 | 9.0 | 6.0 | 4.63 | 3.81 | <0.0001* | <0.001* |
| TD60 | -1.0 | 3.0 | -0.85 | 3.77 | 0.398 | 0.0006* |
| TD90 | -1.0 | -2.0 | -0.82 | -1.69 | 0.413 | 0.094 |
| All pooled | 1.0 | 0.0 | 1.66 | 0.23 | 0.099 | 0.815 |

* Significantly different, a = tube filled with DE, b = tube filled with very fine sand and c = tensiometer readings

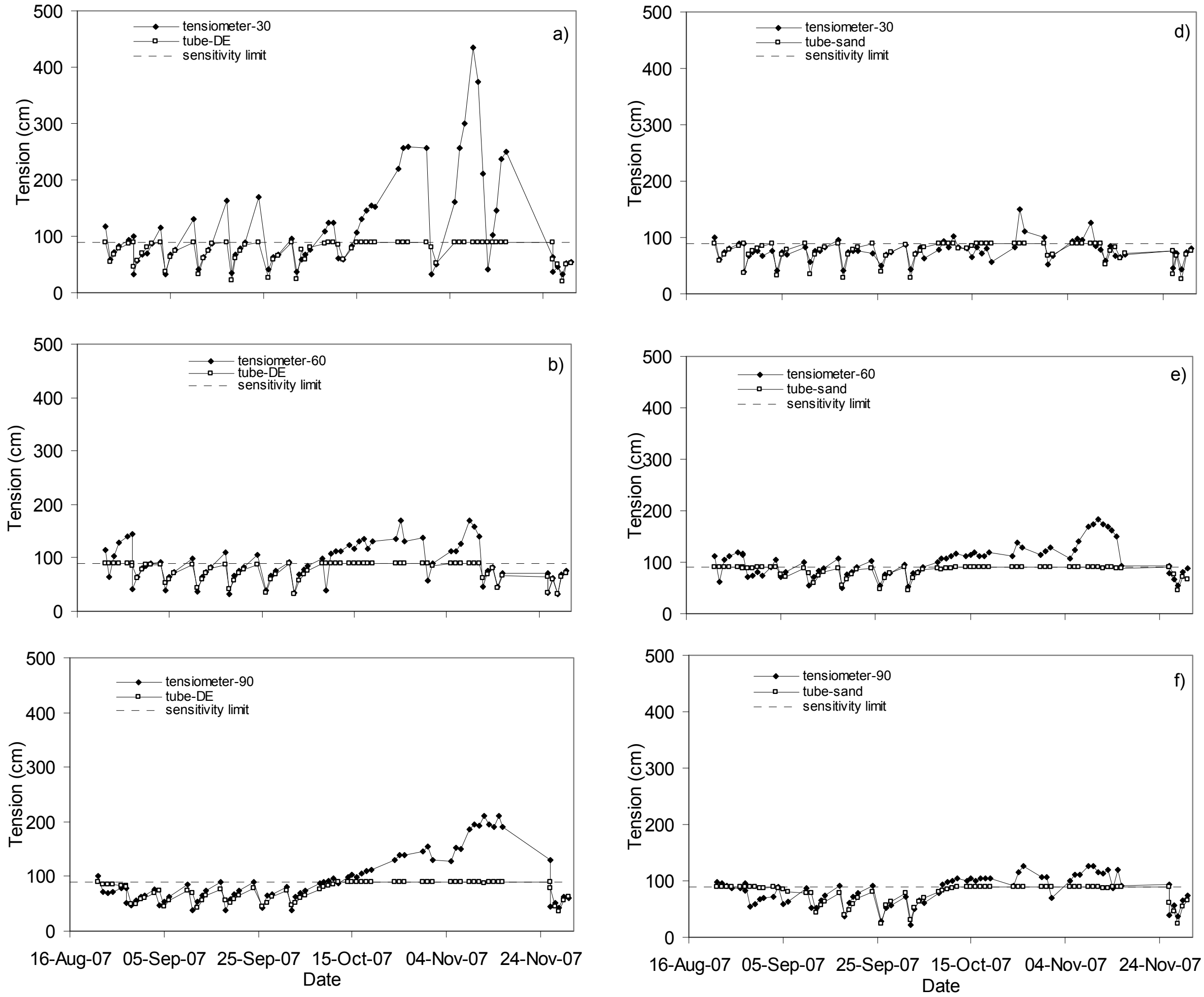



**Figure 2.16** Tube tension recorded with **TD90** filled with DE **(left)** and tensiometer reading at (a) 30 cm, (b) 60 cm and (c) 90 cm; or filled with very fine sand **(right)** and tensiometer readings at depths of (d) 30 cm, (e) 60 cm and (f) 90 cm

The mean tension difference between the TD45 and the tensiometer readings ranged from 6 to 9 cm and was found statistically significant at $P = 0.05$. Similarly, the tension offset between TD60 and tensiometer readings ranged from –1.0 to 3.0 cm; and between TD90 and tensiometer readings it ranged from –1.0 to –2.0 cm, but these differences were not statistically significant (Table 2.7). All the tensiometer and tube tensions of all three tube lengths were pooled together and subjected to a paired t-test analysis. The mean tension differences between all the tensiometer readings and tube tensions ranged between 0.0 and 1.0 cm and were not statistically significant.

***Comparisons of responses between tube detectors of different lengths***

Responses of the three TD lengths (TD45, TD60 and TD90) filled with either DE or very fine sand were assessed to compare the performance of each TD length under rainfall and sprinkler irrigation. The water levels recorded by the tubes in response to changes in contact material tension at the mouth of each tube detector were used to evaluate the performances of the tube lengths under the following two assumptions.

The first assumption was based on a 2 cm water level inside the inner tube and the maximum sensitivity limit of each tube length, which included three categories of responses: a correct positive response was considered if the water level in the inner tube exceeded 2 cm and the tension in the contact material fell within the maximum sensitivity limit of each length; a correct negative response was considered when the water level inside the inner tube was less than 2 cm, while the tension in the contact material exceeded the maximum sensitivity limit set for each length; a false response is the sum of responses when the tube collected > 2 cm water while the tension in the contact material exceeded the maximum sensitivity limit and when it collected < 2 cm water while tension in the contact material fell within the sensitivity limit of each length. The second assumption is based on a 4 cm water level in the TD inner tube, and the maximum sensitivity limit of each tube length. The maximum sensitivity limits were set based on the offset between tensiometer readings and tube tensions. Hence TD45, TD60 and TD90s were set to 50 cm, 60 cm and 90 cm contact material tensions respectively.

The response variations measured during the sprinkler irrigation period due to differences in contact materials and the lengths of the tubes, along with the means and standard errors, are presented in Tables 2.8 to 2.10. The number of responses for each TD length installed in the 9 plots, summed over the 15 measurements for rainfall and 68 measurements for sprinkler irrigation events, were tabulated according to the above two assumptions and are presented in Appendix 2.5.

**Table 2.8** Paired t-test analysis to discriminate between the tube lengths (evaluated on the basis of > 2 cm water level)

| Tube design | Mean | | Standard error | | Pr > / t / | |
|---|---|---|---|---|---|---|
| | **DE** | **D36** | **DE** | **D36** | **DE** | **D36** |
| TD1-TD2 | -1.7 | -10.3 | 9.2 | 6.7 | 0.87 | 0.265 |
| TD1-TD3 | -57 | -69.6 | 5.3 | 11.8 | 0.008** | 0.028* |
| TD2-TD3 | -55.3 | -59.3 | 3.9 | 7.8 | 0.005** | 0.016* |

* Significantly different (*P* = 0.05), ** highly significant (*P* = 0.01)

**Table 2.9** Paired t-test analyses to discriminate between the tube lengths (evaluated on the basis of > 4 cm water level)

| Tube design | Mean | | Standard error | | Pr > / t / | |
|---|---|---|---|---|---|---|
| | **DE** | **D36** | **DE** | **D36** | **DE** | **D36** |
| TD1-TD2 | -6.7 | -12.7 | 8.5 | 6.2 | 0.51[1] | 0.18[1] |
| TD1-TD3 | -61.3 | -65 | 3.3 | 11.5 | 0.003** | 0.029* |
| TD2-TD3 | -54.7 | -52.3 | 5.2 | 8.9 | 0.009** | 0.028* |

* Significantly different (*P* = 0.05), ** highly significant (*P* = 0.01) and [1] = not significantly different

**Table 2.10** Paired t-test analyses to determine the contribution of the wick materials used in the tubes to response differences (responses evaluated on the basis of > 2 cm and > 4 cm water level)

| Tube design | Mean | | | Standard error | | | Pr > / t / | | |
|---|---|---|---|---|---|---|---|---|---|
| | a | b | c | a | b | c | a | b | c |
| DE-D36[e] | 12.9 | -1.44 | -3.2 | 4.6 | 2.8 | 5.3 | 0.024* | 0.62[1] | 0.56[1] |
| DE-D36[f] | 13.1 | 0.11 | -3.9 | 4.8 | 4.0 | 5.5 | 0.024* | 0.97[1] | 0.50[1] |

[e]= evaluated according to the first assumption (> 2 cm water level), [f]= evaluated according to the second assumption (> 4 cm water level), a = correct positive responses, b = negative responses, and c = false responses, *= significantly different, [1]= not significantly different

The observed correct positive responses, correct negative responses, and false responses were not adequate to compare and discriminate performance between tube detector lengths. Therefore, SAS was used to determine if there were significant differences between tube lengths and wick materials (Tables 2.8 and 2.9). It was clear from Tables 2.8 and 2.9 that there was no significant difference in the means of positive responses between TD45s and TD60s. However, there were highly significant differences in the means of positive responses between TD45 and TD90s, as well as TD60 and TD90s filled with DE. Differences in the means of positive responses between TD45 and TD90s, as well as TD60 and TD90s filled with very fine sand were also significantly different. The results of comparisons between the three tube lengths showed that the correct positive responses for TD90s were consistently greater than that for TD45 and TD60 detectors (by 152 to 200%). Table 2.10 shows that differences in the wick material types used in the tube detectors resulted in significant differences between the mean differences of the correct positive responses. Hence the correct positive responses for tube detectors filled with DE exceeded that of detectors filled with very fine sand.

***Hybrid and FullStop wetting front detectors***

Fine sand (D33) and DE were tested under field conditions for their suitability as filter materials in funnel-shaped (FullStop) detectors. No laboratory tests related to the fine sand (D33) are reported in this chapter.

Field evaluations of the Hybrid and FullStop wetting front detectors were carried out under rainfall and sprinkler irrigation conditions. The data presented include establishment of equilibrium between contact tension and bulk soil tension; performance analyses and comparisons between design types and within designs (due to the effects of wick materials on hybrid detector performance and filter materials (sands) on the funnel-shaped detector). Averages over three replicates of bulk soil tension, wick tension and observed visual responses for each design were taken over the measurement periods and used during the various scenario analyses.

The analyses of equilibrium status between contact material tension and bulk soil tension for hybrid detectors; soil tension at the rim of the funnel and bulk soil at similar depths were based on average values obtained using a similar method of averaging as for the tube detectors. The response variations resulting during rainfall and sprinkler irrigation evaluation periods due to differences in contact materials, different filter materials, and designs (related to the diameter and length of both detectors) are presented in Tables 2.11 to 2.13, along with their means and standard errors. The number of responses for both designs installed in the 6 plots were summed and tabulated for rainfall and sprinkler irrigation. The basis of evaluation of the performances of each design was done by setting the maximum sensitivity limit on 55 and 30 cm for hybrid and funnel-shaped designs, respectively, and is presented in Appendix 2.6.

**Table 2.11** Paired t-test analysis responses between two wick materials (D36 sand and soil; hybrid detector)

| | **Mean** | **t value** | **Pr > / t /** |
|---|---|---|---|
| **Depth (cm)** | **a-b** | **a-b** | **a-b** |
| All pooled-irrigation | 2.1 | 2.62 | 0.031 |
| All pooled-rainfall | -0.11 | -0.32 | 0.076 |

a = hybrid filled with D36 sand, b = hybrid filled with soil

**Table 2.12** Paired t-test analysis responses between funnel-shaped detectors filled with D.E or fine sand (D33)

| Response | Mean | t value | Pr > / t / |
|---|---|---|---|
| | a-b | a-b | a-b |
| All pooled-irrigation | 1.08 | 1.86 | 0.09 |
| All pooled-rainfall | 1.0 | 1.0 | 0.391 |

a = funnel-shaped with D33 sand, b = funnel-shaped with D.E

**Table 2.13** Paired t-test analysis responses between two detector designs (hybrid and funnel-shaped)

| Type | Mean | | t value | | Pr > / t / | |
|---|---|---|---|---|---|---|
| | a-b | c-d | a-b | c-d | a-b | c-d |
| HD*FD-irrigation | -1.25 | -3.75 | -2.1 | -2.7 | 0.063 | 0.072 |
| HD*FD-rainfall | 0.67 | 1.67 | 0.55 | 1.39 | 0.64 | 0.30 |

a = hybrid (n = 12), b = funnel-shaped (n = 12), c = hybrid summed per depth (n = 4), and d = funnel-shaped summed per depth (n = 4), HD = hybrid design, FD = funnel-shaped design.

All the responses at the three depths were pooled together and subjected to a paired t-test analysis. The mean response difference between very fine sand (D36) and local soil used as wick materials in the hybrid detector was calculated as 2.1, which was statistically significant (P = 0.05) under irrigation. However, the paired t-test results for similar data types under rainfall conditions were not significant at (P = 0.05). The results related to the mean differences between very fine sand and local soil, therefore, seem to exhibit inconsistencies. The statistical results in Table 2.12 indicate that the mean response difference between the two filter materials (D.E or D33 fine sand) was not significant (P = 0.05). Table 2.13 shows that hybrid detector response was on average not superior to that of the funnel-shaped detector.

## 2.6 CONCLUSIONS AND RECOMMENDATIONS

Accurate measurement and prediction of water retention characteristics and unsaturated hydraulic conductivity are required for selecting a wick material that meets the criteria to ensure proper operation of a tube wetting front detector. A tube wetting front detector requires a wick material characterized by zero hydraulic capacity (high air-entry value) over the length of the tube. This helps the tube detector to rapidly establish a linear hydrostatic pressure profile. The wick material also should be highly conductive in most unsaturated soil types over the length of the tube in order to produce preferential water flow into the mouth of a detector and allow water to enter or exit quickly.

There was good agreement between van Genuchten retention model predictions and measured water retention data. Hence the agreement between fitted curves and measured data was very good ($r^2 > 0.97$). The water retention characteristics showed that DE is the best wick material in terms of its high entry potential (to a maximum tension of 100 cm). Therefore, it should be suitable for all tube detector lengths currently tested (longest prototype tube detector is 90 cm). This is useful to know as a wick material that loses zero or minimum water (DE, for example) over a selected length is essential to improve the response time of the detector.

The unsaturated hydraulic conductivity values estimated for the soil materials with the Hydrus-2D model (by simulating the Bruce-Klute test results) were over predicted in the wet range and under predicted in the dry range. However, the Bruce-Klute test showed that the conductivity of materials continued to conduct water at drier tensions than the simulated values. Bruce-Klute simulations with Hydrus-2D and the standard Bruce-Klute analyses results showed that very fine sand (D36) was the most conductive at tensions less than 80 cm, which suggests that it is a suitable wick material for tube lengths < 80 cm. However, as the tension got drier than 80 cm, DE was the most conductive material and met the requirement in terms of conductivity for longer tube detectors best.

Empirical results, using both DE and D36 sand, showed that water level in the tube detector was linearly related to the contact material tension at the mouth of a tube detector ($r^2 > 0.97$). Water loss from DE was energy limited over the length of the TD90 detector, but water loss from very fine sand had two phases of evaporation within the 0-90 cm tension range, showing that the material was both energy and conductivity limited.

Field studies generally indicated that there were equilibrium between contact materials and bulk soil tensions at all depths. For tubes filled with DE, the water level in the tube was linearly related to the contact material tension ($r^2$ = 0.73-0.98), and for D36 sand ($r^2$ = 0.69-0.84). The tube detectors filled with DE, for example, detected most wetting fronts that fell within the sensitivity limit of the tube detectors, with a worst case scenario success rate of 73%. The deviations from 100% could be attributed to disequilibrium conditions between contact material and bulk soil, errors in tensiometer readings and some other factors.

An assessment of the accuracy of tube detectors to measure soil tension was confirmed statistically ($P = 0.05$), with a mean tension difference of ± 3 cm between tensiometer and tube detector tension measurements, which was not significant. Hence it can be concluded that tube detectors can accurately measure soil tension.

The results of comparisons between three tube lengths (TD45, TD60 and TD90) showed that the TD90 detector gave the best "positive response" to passing wetting fronts, compared to the shorter TD lengths. Wick materials also differed significantly in mean "correct positive" responses, with DE-filled TDs giving the best results.

The mean response of hybrid detectors filled with very fine sand (evaluated under sprinkler irrigation) was significantly different ($P = 0.05$) from that of local soil used as wick material. However, under rainfall conditions the two wick materials did not give significantly different mean responses. The two filter materials (DE and D33 sand) used in the funnel-shaped detectors did not differ significantly different responses ($P = 0.05$). It was also found that the hybrid design detector did not perform significantly better than the funnel-shaped design.

# CHAPTER 3 – DETERMINING THE LOCATION OF FULLSTOP AND TUBE DETECTORS FOR FURROW IRRIGATION

## 3.1 INTRODUCTION TO SHORT FURROW IRRIGATION

Short furrow irrigation is an intergrade between traditional furrow irrigation and basin irrigation. Normally in this system, a long furrow is running across the slope, while at certain distances (10-30 m) water is led into cross-cutting canals, thus blocking the long furrows. As soon as enough water is taken into the short furrow, the inlet is closed and the water is allowed to infiltrate while the flow in the cross-cutting canal is led into the next short furrow. In short furrow irrigation, a common practice is that the irrigator cuts off the supply when the advance is completed. However, in some cases the irrigators may allow the water to pond in the short furrow for a while before cutting off the supply.

Short furrow irrigation is the most commonly used method of surface irrigation by the small-scale farmers in South Africa. The method is labour intensive as the flow must be changed frequently from one furrow to the next, but they can usually be irrigated more efficiently than long furrows as it is much easier to keep the percolation losses low (Brouwer et al., 1985). According to the ARC (2006), short furrow irrigation has the advantages of compensating for differences in flow and gradient, viz. flow rate, gradient and number of irrigations. The method is very difficult to mechanise - Figure 3.1 shows the dykes restricting the length of furrows to approximately 10 m and short furrows being constructed manually. In South Africa, the ARC (2006) has carried out research on 10 m and 30 m furrow lengths and with simulations and research, it was found that short furrows should have a zero gradient for the most uniform distribution of water.

**Figure 3.1** Short furrow irrigation system (after ARC, 2006)

Walker (1989) states that irrigation systems are often designed to maximize efficiencies and minimize labour and capital requirements. Since water flows over the soil in surface irrigation, application efficiency is strongly related to the water requirement depths (Reddy and Clyma, 1983).

In most types of surface irrigation, matching the flow rate, gradient, length and surface roughness is critical in achieving acceptable water distribution efficiency. However, according to PRAIS and CTA (2000), the short-furrow system overcomes most of the difficulties experienced by other surface irrigation systems, as it is relatively insensitive to variations in flow rate and soil type. Also, since the furrows are so short, it is relatively easy to adapt layouts to virtually follow natural gradients.

**Management of short furrow irrigation with wetting front detectors (WFDs)**

Most irrigation scheduling tools or techniques (tensiometry, neutron scattering, granular matrix, heat dissipation, time domain reflectometry, capacitance) have undergone many years of research and testing at multiple locations around the world before being released onto the market. The WFD is the product of a small team operating over a few years. As an irrigation scheduling tool, the WFD has been in use for a very short time and most research work has been carried out on drip, microjet, and sprinkler irrigation systems (Stirzaker et al., 2004b). In spite of this, most of the small-scale farmers – a key target audience – use furrow. There were, however, gaping holes in the understanding around how to deploy the WFD in furrow irrigation systems.

Furrow requires a reasonable amount of water to be applied at one time to attain uniform distribution. The water cannot simply be turned off when the wetting front reaches a set depth as it can be in the case of drip or sprinkler irrigation. Stirzaker et al. (2004b) provide conflicting evidence on the usefulness of detectors for furrow irrigation. A number of the problems that surfaced from a user survey were related to furrow irrigation, however, some case studies showed that small-scale farmers who used detectors in furrow irrigation saved water (or diesel), or produced higher yields and made greater profit (Stirzaker et al., 2004b).

For drip and sprinkler irrigation the source of irrigation water is directly above the detector. Water is supplied at rates lower than the saturated conductivity of the soil, so the velocity of the wetting front is influenced mostly by the initial water content of the soil and only weakly by any changes in soil structure that might have occurred during installation. In the case of furrow irrigation, water is ponded in the furrows, so infiltration may be higher in disturbed soil if the saturated conductivity is higher. Water then moves into the bed via capillary action, and the "strength" of the laterally moving fronts may be too weak to activate a WFD.

The strength of the front that a WFD can detect depends on its design. In order to "trip" (be activated), the WFD must collect water from an unsaturated soil. It does this by impeding the downward flow of water. The sensitivity of a WFD is determined by the balance between convergence of water films in the funnel (filling) and the effect of capillarity forces around the device (emptying). It follows that the sensitivity of the detector is determined by the diameter of the funnel (assisting convergence) and the depth from the rim of the funnel to the filter (restricting capillary emptying).

After irrigation or rain ceases, fronts get weaker as they move down through the soil, as each soil layer above retains some of the infiltrating water. In cases when the flux is low, and the background suction is around 3 kPa or drier, a funnel shape is not the best option for producing free water from the unsaturated soil. The low flux means that convergence is not effective, and the shallow depth of the funnel does not counter capillarity emptying. Thus, for flood irrigation we require a WFD that has a greater sensitivity so that it will capture weaker wetting fronts deeper in the soil. It should also be installed in such as way that it will not be activated by water moving through cracks or preferential pathways.

The Tube Detector (TD) may have several advantages over a FullStop under such conditions, as the Tube Detector dispenses with the funnel part (i.e. it has a narrow diameter) and the sensitivity is set by length alone. It can detect much weaker fronts, and it can be installed with less disturbance of soil because of its narrow diameter.

## 3.2 ASSESSMENT OF FULLSTOP AND TUBE DETECTOR PERFORMANCE UNDER FURROW IRRIGATION

The theoretical understanding of the Tube Detector is that its sensitivity should be proportional to its length (Stirzarker, 2005). Let us suppose that one places at a given depth in the soil a 60 cm TD and fills it with water. A column of 60 cm of water is equivalent to a hydrostatic pressure of 6 kPa. If the surrounding soil is dry, the soil will try to "wick" the water out of the TD. Let us assume that the suction (SP) of the surrounding soil is at 4 kPa. Consequently, since the surrounding soil has a SP of 4 kPa, (which is equivalent to 40 cm head of water), the soil can suck out from the TD opening all the free water up to a depth of 40 cm. The last 20 cm of the TD will remain filled with water. If the soil dries to 5 kPa, which is equivalent to a water head of 50 cm, then 10 cm more water will be sucked out of the TD, leaving the other 10 cm in the TD. When the soil dries to 6 kPa or 60 cm, it could suck all the water out. This implies that when the suction pressure of the surrounding soil (SSP) is equal to the equivalent suction pressure (ESP) of the TD, there should be no water in the TD. Therefore, the length of the TD determines its sensitivity. One objective of this study was to evaluate and compare the performance of FullStop and Tube wetting front detectors under field conditions.

Several field experiments were conducted to evaluate the sensitivities, placement position and performance of FullStop and Tube Detectors for short furrow irrigation.

### 3.2.1 Assessment of FullStop and Tube wetting front detector sensitivities

Field experiments were carried out at the University of Venda (UNIVEN) Research Farm to compare sensitivities of the two WFD versions at different placement depths in the soil profile. Detailed soil properties for the entire Dzindi scheme are presented in Appendix 3.1. FullStop and Tube Detectors (TDs) of different lengths (30, 60 and 90 cm; TD30, TD60 and TD90) were placed at three depths in the soil profile (TD mouth at 30, 60 or 90 cm soil depth). For each of the WFD placement depths (30, 60 and 90 cm) a tensiometer was also installed to measure the suction pressure (SP) or matric potential of the surrounding bulk soil (SSP). This enabled us to tell whether the adjacent surrounding bulk soil was in equilibrium with the wick material at a given depth. The strengths of wetting fronts were measured using SoilSpec tensiometers. In addition to natural rainfall, rainfall events were simulated by manually watering plots with watering cans. During the period of observation, 50 natural rainfall events and 24 irrigation events occurred. The depths of rainfall ranged from 0.3 to 75 mm, while those of irrigations ranged from 6 to 75 mm. The water volume (WV) collected in the TD was measured every time the tension readings were taken. The water in the TDs was extracted by means of a 4 mm diameter flexible tube and a syringe. In contrast to FS WFDs, the prototype TDs used in the study did not have reservoirs or indicators. Their response was measured by means of change of both WV in the TDs and the wick WSP.

Figure 3.2 gives an example of the typical results obtained for a TD90 (9 kPa sensitivity) placed at 90 cm soil depth. Generally the results indicated that nearly every time when the WSP fell below the sensitivity level of a TD (dotted horizontal line at 9 kPa suction; Figure 3.2), water entered the TD and in most cases set the TDs off, as indicated by the blue points on Figure 3.2. The opposite was also true, namely that when the wick suction pressure (WSP) rose to higher than the TD sensitivity level of 9 kPa, the detectors were emptied by capillarity action. Only in a few cases did the WSP fell below the sensitivity level of the TD, but the detectors were not activated. There were also a few incidences when the detectors were set off (collected water), even though the WSP was above the sensitivity line. Similar good results were recorded for TD60 and TD90 installed at all three depths (Figure 3.3).

The performance of the TD30 was very poor as compared to TD60 and TD90. The WSP hardly dipped into the activation range and even when it did, the detectors were hardly activated (Figure 3.4). In a number of cases the soil became saturated but even then water did not enter the TDs. This may imply that the capillary forces were much stronger than the SP of the detectors or these were transient fronts. Due to their poor response, the monitoring of the TD30 was later discontinued.

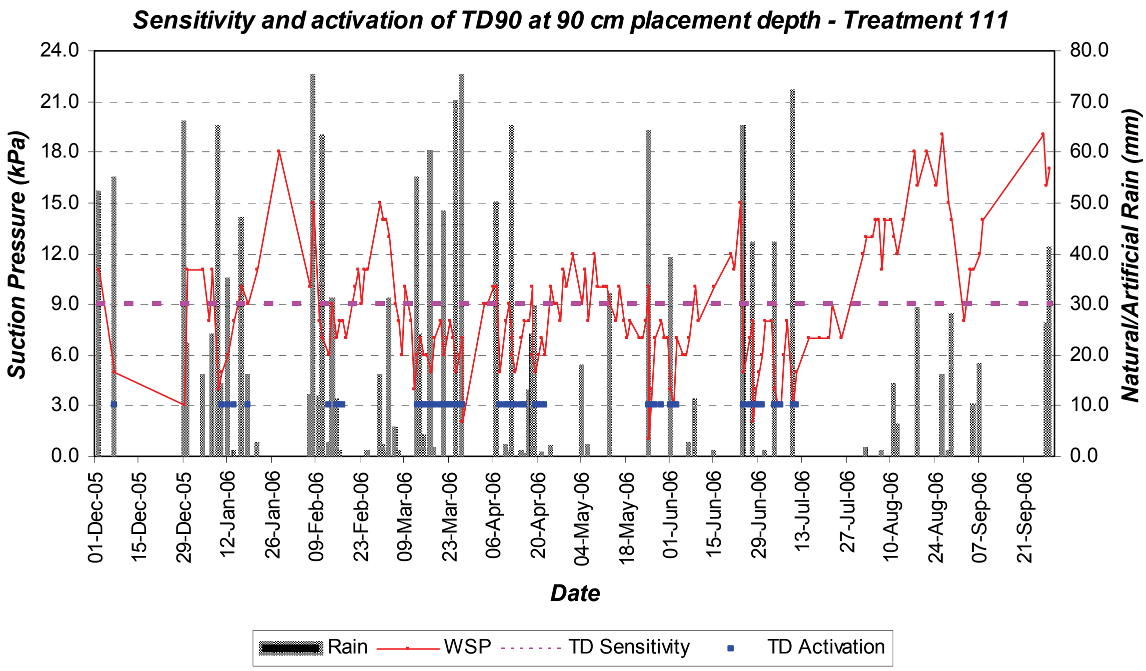



**Figure 3.2** Tube Detector activation (blue points) and wick suction pressures (WSP, kPa) recorded in response to rainfall for a TD 90 detector placed at 90 cm soil depth. Purple line indicates the TD sensitivity limit of 9 kPa

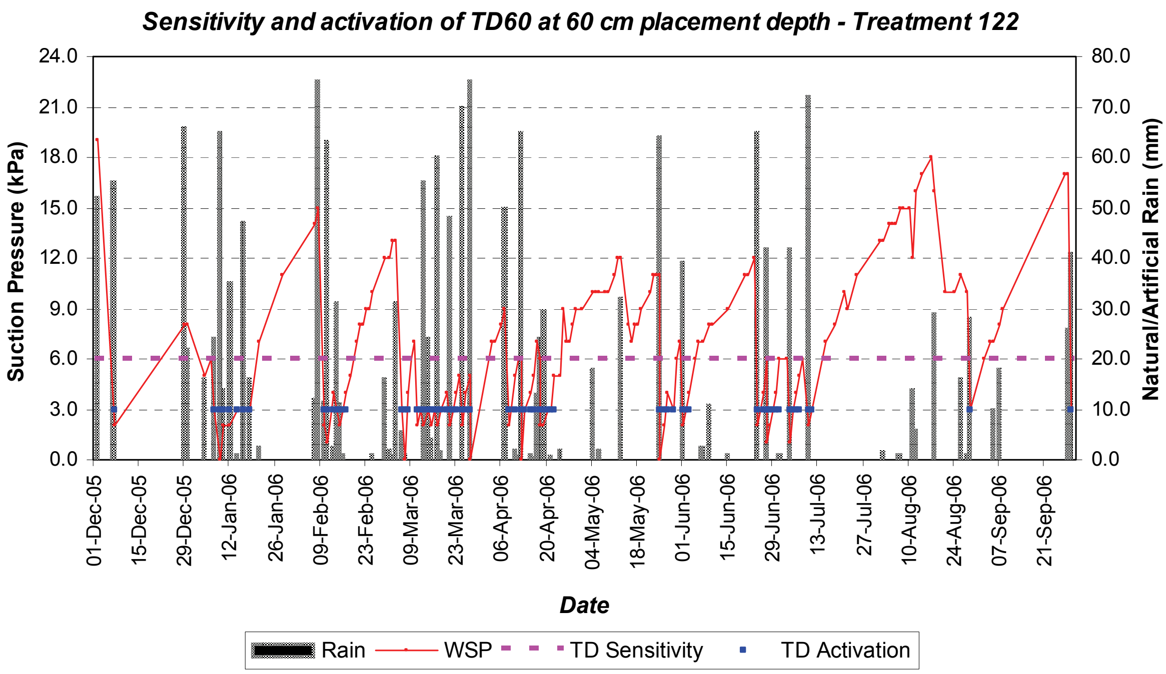



**Figure 3.3** Tube Detector activation (blue points) and wick suction pressures (WSP, kPa) recorded in response to rainfall for a TD60 detector placed at 60 cm soil depth. Purple line indicates the TD sensitivity limit of 6 kPa

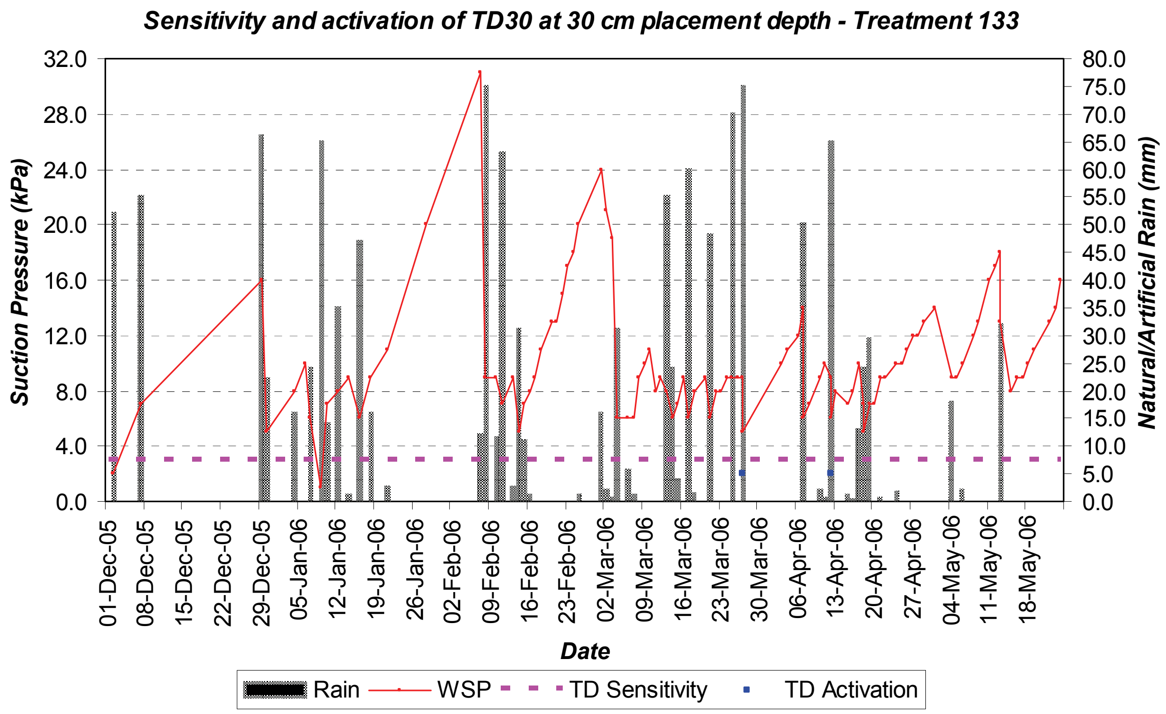



**Figure 3.4** Tube Detector activation (blue points) and wick suction pressures (WSP, kPa) recorded in response to rainfall for a TD30 detector placed at 30 cm soil depth. Purple line indicates the TD sensitivity limit of 3 kPa

Data on the total number of WFD activations recorded during the time of observation for the FSs and different TD versions that were installed at three depths is presented in Table 3.1. From this comparison it is evident that the TD60 and TD90 responded more frequently and thus performed much better compared to the FSs and TD30s. This shows that these two TD versions (TD60 and TD90) were able to detect much weaker fronts than the FS. It can therefore be concluded that TD detectors were more suitable to detect weak wetting fronts in the soil.

A comparison was also made between the water potentials measured in the TD wick material (WSP) and the surrounding soil (SSP) to establish if there was good agreement. As an example, the water potentials measured in the TD wick material (WSP) and the surrounding soil (SSP) for a TD60 installed at 60 cm depth are presented in Figure 3.5. These results showed that there was generally good agreement between the readings of tensiometers in the wick and those in the surrounding soil, indicating that TDs can act as good indicator of the water potential of the surrounding soil.

**Table 3.1** Average number of responses recorded for FullStop (FS) and three Tube Detector (TD) versions (TD30, TD60, TD90) installed at three soil placement depths (30, 60 or 90cm)

| Placement depth (cm) | Number of occasions when detectors in both replications were activated | | | | Number of occasions when detectors in one replication were activated | | | |
|---|---|---|---|---|---|---|---|---|
| | Tube Detector | | | FS | Tube Detector | | | FS |
| | TD30 | TD60 | TD90 | | TD30 | TD60 | TD90 | |
| 30 | 1 | 19 | 91 | 7 | 2 | 45 | 26 | 11 |
| 60 | 0 | 32 | 66 | 3 | 1 | 58 | 30 | 13 |
| 90 | 1 | 38 | 54 | 1 | 12 | 30 | 72 | 4 |

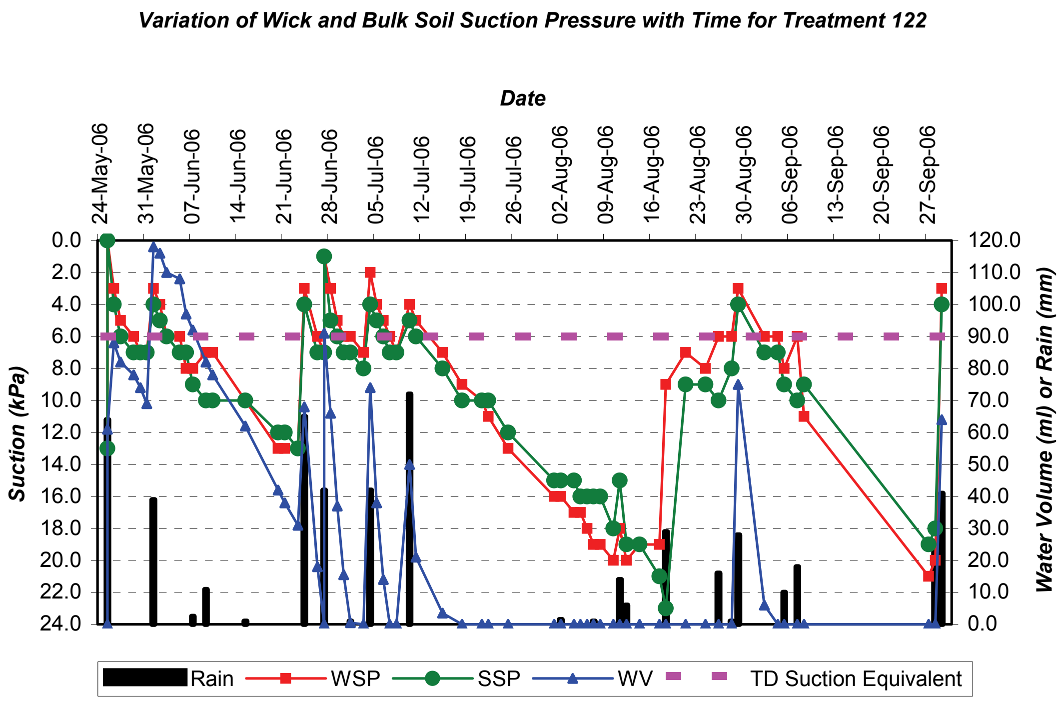



**Figure 3.5** Water potentials measured in the TD wick material (WSP) and surrounding soil (SSP) for a TD60 Tube Detector WFD installed at 60 cm soil depth

These sensitivity analysis experiments confirmed that Tube Detector sensitivity was proportional to its length, according to theory. The TD90 was found to be the most sensitive, while the TD30 was the least sensitive of the different TD versions. There was a time lag between tension development and filling of the TD with water, i.e. tension changed faster than water volume.

In general, the TDs performed much better than FSs at the same depths, except for the TD30, which performed worse than the FS at all depths. There seemed to be a fairly good agreement over time between the suction pressure measured in the TD wick and surrounding soil, except when the soil was very dry. From this data we are convinced that TD WFDs should be well suited for irrigation management under short furrow irrigation.

***Placement position of WFDs within the furrow***

Many soil, design and management factors affect the performance and uniformity of furrow irrigation systems, including the soil texture and structure, furrow length, spacing between wetted furrows, furrow slope, irrigation depth, discharge rate, cultivation practices and crop residue management (Brouwer et al., 1990; Solomon, 1993; Waskom et al., 1994; Cahoon, and Eisenhauer, 1995; Raine and Bakker, 1996; Van den Dries, 2002; Horst et al., 2005).

Figures 3.6a and 3.6b show how soil type and spacing of furrows can influence the lateral and downward infiltration of water into the soil in cases where every alternate furrow is irrigated. When the irrigated furrow spacing is too wide, there will be a dry area between the furrows and the crop may not get enough water (Figure 3.6a). The ideal is that ridge the shoulders of both ridges should be well wetted and the furrow in the “dry furrow” should remain dry (Figure 3.6b). In cases where every furrow is irrigated, the ideal furrow wetting pattern is illustrated in Figure 3.7

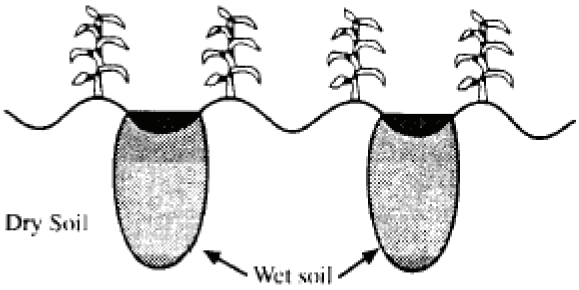



**Figure 3.6a** Soil A: Soil does not provide enough lateral movement for this wetted furrow spacing (after Yonts et al., 2003)

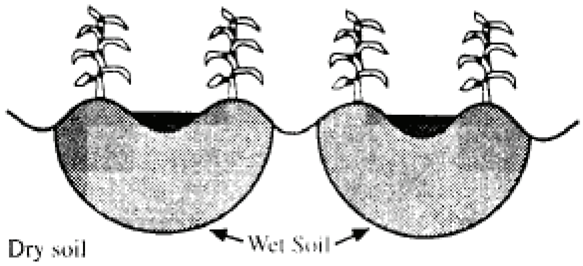



**Figure 3.6b** Soil B: Good lateral water movement for this wetted furrow spacing (after Yonts et al., 2003)

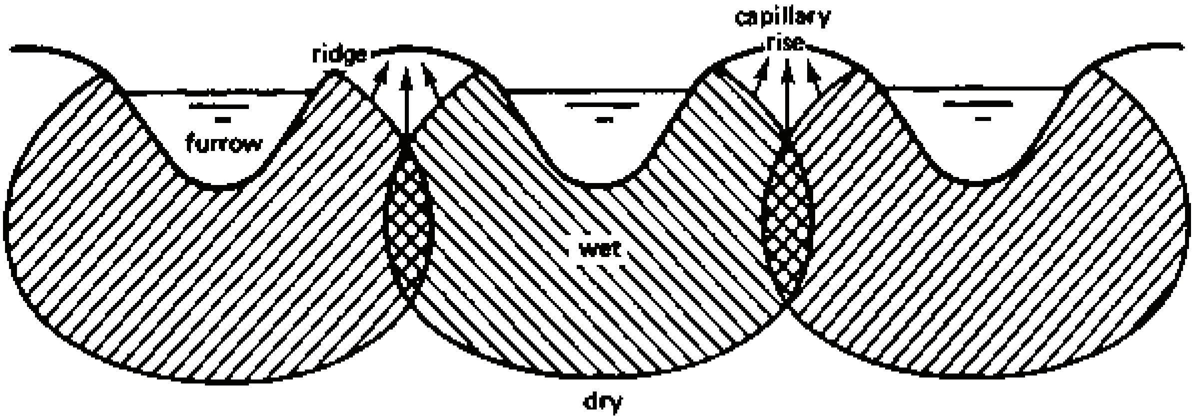



**Figure 3.7** A cross-section of an ideal furrow wetting pattern (after Yonts et al., 2003)

All these factors that influence uniformity of water distribution in and along furrows will also influence wetting patterns and, therefore, the ideal position for WFD placement within and along the furrow length. The obvious research questions are, therefore, where to locate the detector for furrow irrigation (under the bed, under the furrow or half way between them) and where to locate the detectors along the furrow length (beginning, middle or end) in order to ensure good WFD response. Next, there is the question of whether to use the detector in control or feedback mode. In control mode the water would be shut off when a strategically located shallow detector was activated. In feedback mode the date of the next irrigation and/or amount of irrigation would be adjusted, depending on the combination of deep and shallow detectors that responded during the previous irrigation event.

The questions of the positioning of TDs across the furrow, lengths of the TDs and placement depths were investigated in short furrow field experiments that were conducted on-station at the University of Venda.

Transects of TDs were installed at either of three placement depths (30, 60 and 90 cm below the soil surface) across the middle test furrows of plots. TD lengths of 60 and 90 cm were used in this study. Tensiometers were also installed to measure suction pressure of the bulk soil in positions corresponding to those of the TDs. In some transects, tensiometers were also installed in the TD wick materials.

Within a transect, TDs (and tensiometers) were positioned at three distances from the test furrow centre, namely on the furrow shoulder, (i.e. at 15 cm from the furrow centre), at 45 and 75 cm from the furrow centre. A cross-section of a TD transect installation is shown in Figure 3.8. The experiment was replicated three times. A graphical representation of the complete trial layout is given in Appendix 3.2. Maize was grown at a row spacing of 90 cm and in-row plant spacing of 50 cm.

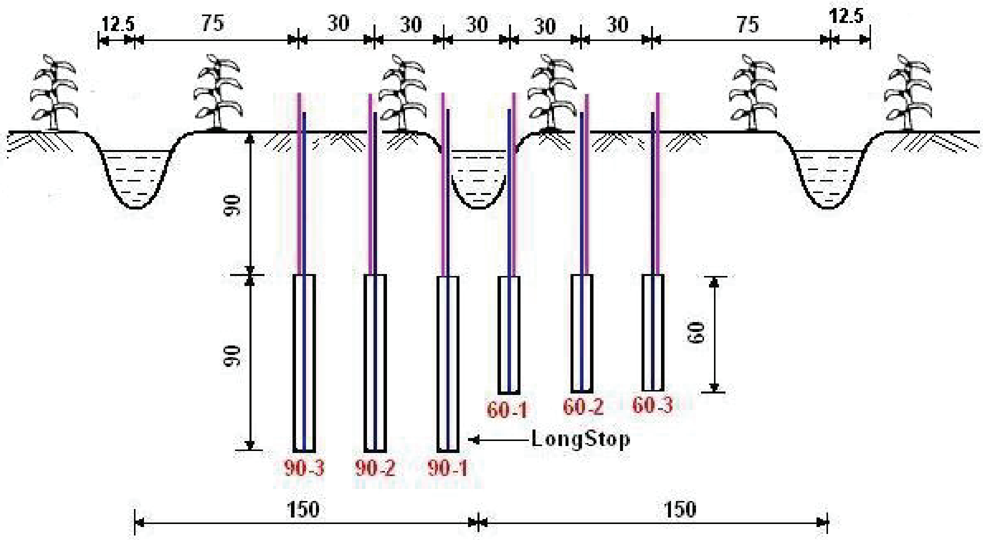



**Figure 3.8** A cross-section of a TD installation transect. Tube Detectors of 60 and 90 cm length (TD60 and TD90) were installed 30cm apart at distances of 15, 45 and 75 cm from the furrow centre

Sensitivity comparison between FSs and TDs was achieved by also installing three FullStops at placement depths of the 30, 45 and 60 cm on both shoulders of the test furrows in each replicate.

Irrigation was applied once every week according to farmer practice. Water was let into the furrow until it reached the tail end, whereafter some time was allowed for ponding, subsequent to which the water supply was cut off. Hence, the application time largely depended on the furrow length and the discretion of the operator to cut off the supply.

***Activation frequency***

A FullStop WFD requires about 15 ml to be activated (Stirzaker et al., 2004). In contrast to this, the prototype TDs is not used as a binary or on/off switch. Once a wetting front passes the Tube Detector “wick”, a certain amount of water accumulates in the TD inner tube. The amount of water collected is linearly proportional to the matric suction in the wick. In this study a TD was deemed to have ‘activated’ when it contained more than 10 ml of water.

In order to establish whether Tube Detectors are sensitive enough to give a signal that can be used for managing irrigation under furrow irrigation systems, we needed to determine whether the TDs filled with an amount of water equal to or greater than the minimum threshold value of 10 ml. To do this, the water volumes collected after a wetting event by the three TD replications per measurement position were averaged. In flood irrigation, large volumes of water are typically applied within a short period of time. Therefore, application depths (irrigation or rainfall) of less than 10 mm per event were ignored when TD performance under furrow irrigation was evaluated. During the observation period (between 9 December 2006 and 17 January 2007) 20 wetting events (irrigation or rainfall) occurred. Out of these 20 observations, nine wetting events had application depths greater than 10 mm. Table 3.2 presents the data recorded on the number of times when TD detectors were activated during the monitoring period, as well as the theoretical activation frequency (when calculated water volume ($WV_T$) from suction potential measured with tensiometers in the wick material exceeded 10 ml). The calculated activation frequencies (mean percentage response per measurement position) are also presented graphically in Figure 3.9.

Best response frequencies for both TD versions (TD90 and TD60) were observed at the closest distance from the furrow centre (15 cm) and lowest response frequency at 75 cm distance. The lowest variation in response frequency per measurement position was observed for the 60 and 90 cm placement depths. Studies have shown that there can be significant variability in measured soil water potential over short distances in the soil due to variation in soil physical and chemical properties (Beckett and Webster, 1971; Zacharias et al., 1997; Stirzaker, 2003). From Table 3.2 it is evident that most of the time the TDs collected sufficient water to set them off, especially at distances closer (15 and 45 cm) to the furrow centre and deeper in the soil profile (60 and 90 cm depths). If we adopt an activation frequency threshold of 70% as minimally acceptable, the TD90 cannot be installed further than about 50 cm away from the furrow center (Figure 3.9). For a wide furrow spacing of 150 cm, this worked out to be about one third (33%) of the furrow spacing on this heavy soil. For the TD60, the maximum distance for 70% activation frequency corresponded with a distance of approximately 60 cm from the furrow centre. This is about 40% of the furrow spacing. Soil properties will obviously influence the distance of lateral wetting in soils and the ideal positioning of WFDs should be investigated for each through experimentation. However, we expect that TD placement of not more than one third of the furrow spacing and 60 to 90 cm depth should ensure good TD response in most soils that are suitable for flood irrigation.

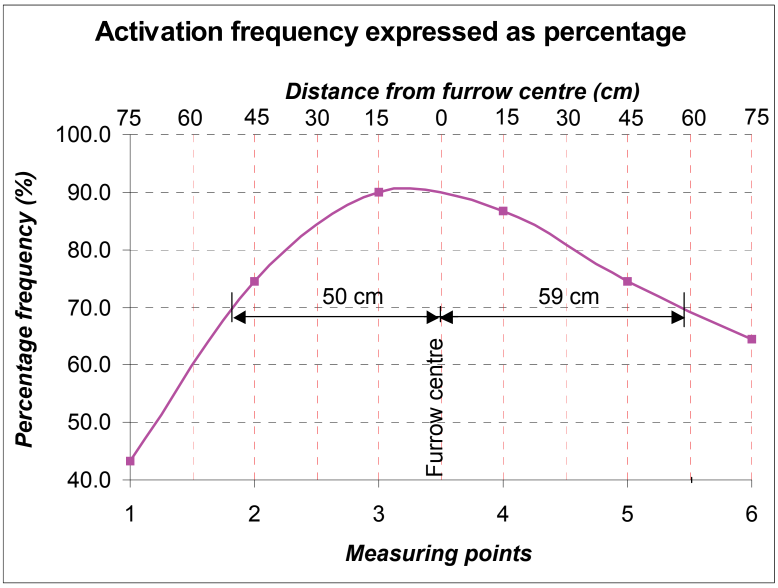



**Figure 3.9** Activation frequencies of the TD across the test furrow

**Table 3.2** Activation frequency of Tube Detectors (TD) placed at different lateral distances from the furrow centre (15, 45 or 75 cm) after wetting events of more than 10 mm

| **Transect position** | **Number of wetting events with water volume (WV) exceeding 10 ml (out of 9 potential events with application depths greater than 10 mm)** | | | | | |
|---|---|---|---|---|---|---|
| TD length and position | **$TD90_3$** | **$TD90_2$** | **$TD90_1$** | **$TD60_1$** | **$TD60_2$** | **$TD60_3$** |
| Distance from furrow centre (cm) | **75** | **45** | **15** | **15** | **45** | **75** |
| Frequency at 30 cm depth | 2 | 6 | 9 | 8 | 5 | 1 |
| Frequency at 60 cm depth | 2 | 8 | 9 | 9 | 9 | 8 |
| Frequency at 90 cm depth | 1 | 5 | 8 | 8 | 7 | 7 |
| Calc. frequency at 30 cm depth | 5 | 2 | 6 | 9 | 9 | 8 |
| Calc. frequency at 60 cm depth | 3 | 5 | 9 | 6 | 8 | 5 |
| Calc. frequency at 90 cm depth | 3 | 8 | 8 | 2 | 1 | 4 |
| **Mean occurrence frequency** | **4** | **7** | **8** | **8** | **7** | **6** |
| **Percentage frequency (%)** | **43** | **74** | **90** | **87** | **74** | **64** |

***Variation in suction pressure and water volume across the furrow***

The sensitivity of TDs is proportional to their length and therefore, a TD90 is more sensitive than a TD60. The volume of water collected by TDs is determined by the matric potential (or suction pressure; SP) of the surrounding soil. The strength of wetting fronts was measured with *SoilSpec* tensiometers and expressed as calculated water volume ($WV_T$). The average water volumes (WV) collected (by three replicates) and wetting front strengths ($WV_T$) recorded for each measuring point was computed and results are presented in Table 3.3. The mean suction pressures and water volumes recorded across the furrow are presented graphically in Figure 3.10. As expected, the strengths of wetting fronts decreased with distance from the furrow centre. In addition, as the SP values increased, WV values decreased and vice versa. SP averaged between 7.9 and 9.1 kPa for the TD60, while for the TD90, mean SP ranged between 7.7 and 9.9 kPa. This confirms that the TDs were able to detect a high proportion of weaker (>3 kPa) wetting fronts, compared to the sensitivity range of FullStop WFDs. The measured difference in suction pressure across the furrow (Figure 3.10) is due to the two dimensional wetting pattern under furrow irrigation. The occurrence of stronger fronts closer to the furrow centre explains why more frequent TD activations also occurred in this region.

The volume of water collected in the TDs is theoretically proportional to the suction pressure in the soil or wick material. When the measured SP values were plotted against the collected WVs, a very strong linear relationship ($R^2$ = 0.98) was indeed noted between these two variables (Figure 3.11). We can, therefore, conclude that the assumption, that TD sensitivity is proportional to TD length, is valid.

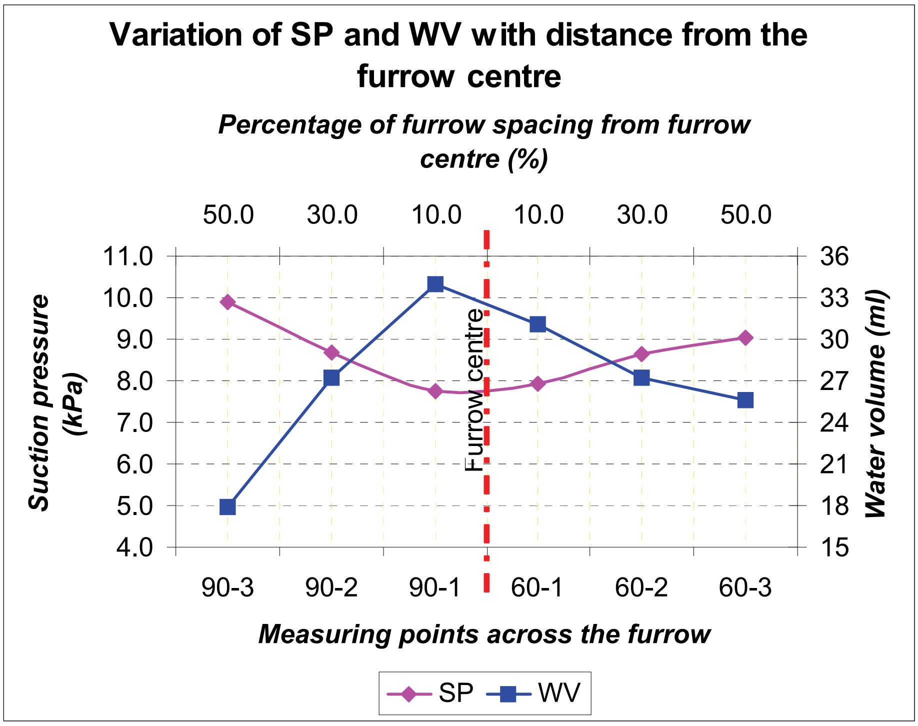



**Figure 3.10** Variation in suction pressure (SP; kPa) and water volume (WV; ml) collected in Tube Detectors placed across the test furrow

**Table 3.3** Suction pressures (SP) measured and water volumes (WV) collected from Tube Detectors (TD) placed at different lateral positions across the test furrow (distances of 15, 45 or 75 cm from the furrow centre)

| **(a) Variation in suction pressure (SP) across the furrow at various measuring points** | | | | | | |
|---|---|---|---|---|---|---|
| **Transect** | **SP (kPa) values at various measuring points (average of 20 events)** | | | | | |
| | **$TD90_3$** | **$TD90_2$** | **$TD90_1$** | **$TD60_1$** | **TD60** | **$TD60_3$** |
| Distance from furrow centre (cm) | 75 | 45 | 15 | 15 | 45 | 75 |
| SP at 30 cm placement depth | 11.5 | 9.5 | 8.0 | 7.2 | 8.1 | 9.6 |
| SP at 60 cm placement depth | 9.1 | 8.0 | 6.8 | 6.4 | 7.5 | 8.1 |
| SP at 90 cm placement depth | 9.1 | 9.1 | 7.9 | 8.3 | 8.7 | 9.2 |
| Calc. SP at 30 cm depth | 11.7 | 11.3 | 9.5 | 9.2 | 10.1 | 11.1 |
| Calc. at 60 cm depth | 10.2 | 9.5 | 7.1 | 6.9 | 6.8 | 7.3 |
| Calc. at 90 cm depth | 7.9 | 7.6 | 6.9 | 7.1 | 7.3 | 8.1 |
| **MEAN** | **9.9** | **8.7** | **7.7** | **7.9** | **8.6** | **9.1** |
| **(b) Variation in water volume (WV) across the furrow at various measuring points** | | | | | | |
| | **WV (ml) collected in TDs at various measuring points (average of 20 events)** | | | | | |
| WV at 30 cm placement depth | 10.3 | 23.2 | 43.1 | 20.9 | 8.9 | 5.5 |
| WV at 60 cm placement depth | 9.9 | 24.9 | 31.7 | 48.6 | 44.2 | 32.9 |
| WV at 90 cm placement depth | 7.6 | 19.2 | 14.7 | 23.5 | 21.0 | 22.9 |
| $WV_T$ at 30 cm placement depth | 15.8 | 7.7 | 21.2 | 61.7 | 48.7 | 46.6 |
| $WV_T$ at 60 cm placement depth | 34.9 | 25.3 | 61.6 | 12.7 | 20.9 | 20.3 |
| $WV_T$ at 90 cm placement depth | 19.1 | 33.6 | 31.6 | 9.8 | 5.8 | 24.0 |
| **MEAN** | **17.9** | **27.2** | **34.0** | **31.1** | **27.2** | **25.6** |
| **(c) Summary** | | | | | | |
| Mean suction pressure (kPa) | 9.9 | 8.7 | 7.7 | 7.9 | 8.6 | 9.1 |
| Mean water volume (ml) | 17.9 | 27.2 | 34 | 31.1 | 27.2 | 25.6 |
| Distance from the furrow centre to measuring point (cm) | 75 | 45 | 15 | 15 | 45 | 75 |
| Distance from furrow centre, expressed as % of furrow spacing | 50 | 30 | 10 | 10 | 30 | 50 |

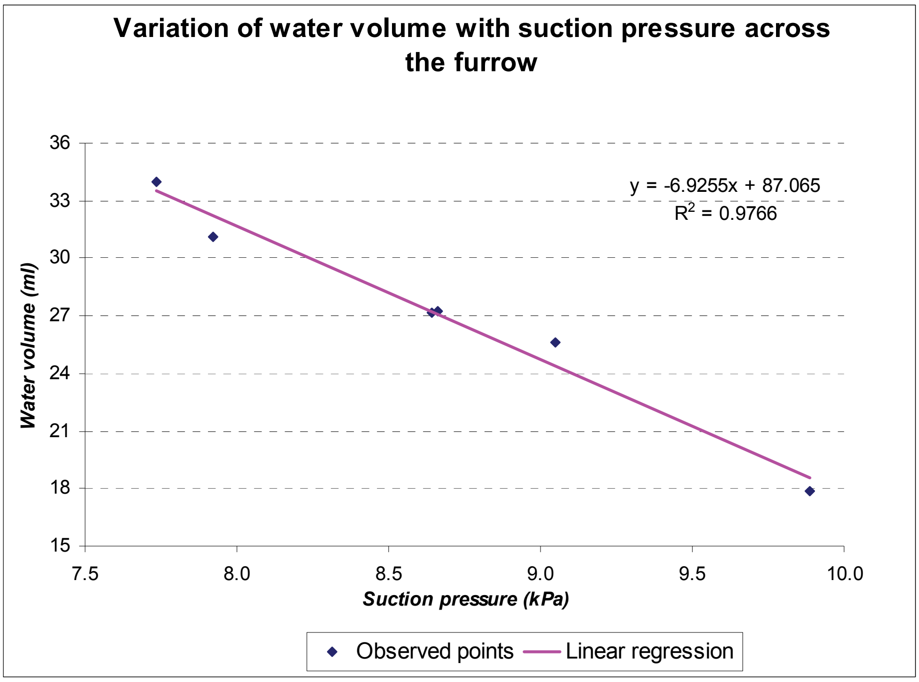



**Figure 3.11** Relationship between (WV; ml) collected in Tube Detectors and suction pressure (SP; kPa) measured across the test furrow

Ideal placement of the WFD along the furrow length will depend on uniformity of water application along the length of the furrow. Furrow slope, irrigation depth, discharge rate, cultivation practices and crop residue management will all influence the distribution uniformity along furrows. A longitudinal cross-section of a poorly wetted furrow is presented in Figure 3.12, while Figures 3.13 represents the ideal wetting pattern of an efficiently irrigated furrow.

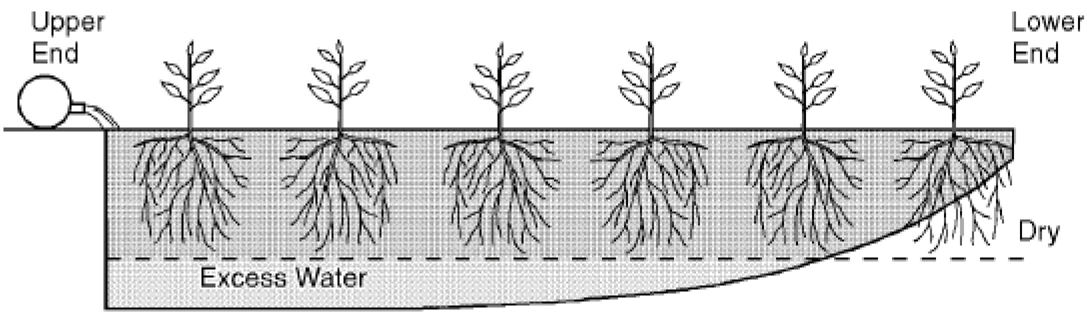



**Figure 3.12** Longitudinal section of a very slow furrow – advance stream too small (Waskom et al., 1994)

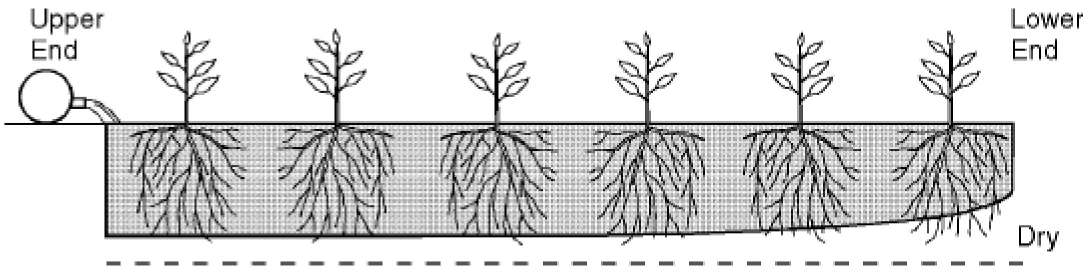



**Figure 3.13** Longitudinal section of an ideal infiltration pattern (Waskom et al., 1994)

Since short-furrow systems are relatively insensitive to variations in flow rate and soil type (PRAIS and CTA, 2000) due to the short distances (±10 m length), it is often assumed that water is distributed uniformly along the length of the furrow.

This research has confirmed that Tube Detectors can detect weaker wetting fronts than FullStops and, therefore, they can be placed deeper in the soil profile. Even with a wide furrow spacing of 1.5 m in clay soils, the TDs were sensitive enough to pick up weak fronts at 90 cm depth. However, TDs should not be placed too far from the furrow centre (less than 50 cm in these clay soils), as wetting front strengths may become too weak to activate TDs.

## 3.3 ON-FARM EVALUATION OF TUBE DETECTORS AND FULLSTOP WETTING FRONT DETECTORS

Under field conditions, low fluxes and weak wetting fronts are common. Since TD WFDs are more sensitive than the FullStop WFD, it is expected that the TD will be more useful as irrigation management tool under such conditions. Having demonstrated the good performance of TDs on the UNIVEN research site, trials were consequently started to evaluate them on farmer fields. This study tested the hypothesis that the TD will be a useful tool for irrigation management on smallholder farmer fields at the Dzindi Irrigation Scheme.

The Dzindi Irrigation Scheme consists of a total of 106 farmer plots. Farmers' plots are subdivided into a variable number of beds, which run along the contours. The numbers of beds per plot was found to range between 10 and 36. The length of the beds varied from 30 to 90 m, while the width varied from 4 to 10 m. Each bed is further subdivided into strips, which vary from 5 to 10 m in length. On average, a typical bed would have 7 to 12 strips. Furrow spacing varies from 50 to 90 cm, with 70 cm being the most common spacing.

For the on-farm evaluation of WFDs five farmers (spread over different blocks of the Dzindi Irrigation Scheme) were selected and in each farmer's plot, a representative bed was selected. The number of strips in the bed were determined and divided by three. A representative furrow in each strip (usually the middle furrow) was selected for installation of monitoring instruments (Figure 3.1) in the upper (start) and lower (end) third of the plot.

Both TD and FS WFDs were installed at different placement depths and positions (across the furrow beds). TD60s and TD90s were deployed at placement depths of 30, 60 and 90 cm. FSs were placed both in the shoulders of the furrows and in the centre of the beds at placement depths of 30 and 60 cm. All the farmers planted maize, except for one farmer, who planted cabbage.

The amounts of water collected in the TDs give an indication of their response to irrigations, and management of each field over the growing season. For example, if no TDs collected water throughout the season, then under-irrigation of that field is almost certain. If TDs only occasionally collect water, or only those in the shallowest depths collect water, we suspect periods of crop water stress. If TDs always contain water (especially the ones placed deeper in the soil profile), we know that the crop is being over-irrigated. Selections from the data are shown to demonstrate the continuum from under- irrigation to over-irrigation in different fields.

Since tensiometers were not installed in the wicks of TDs, the volume of water collected in the TD was to be correlated with the suction pressure measured by the Watermarks. Unfortunately no good data could be collected from these due to technical problems experienced (data loss due to cable theft and datalogger malfunctioning).

The response of FS WFDs varied from good to poor, depending on the field. In some cases (e.g. field of farmer Matshingane), the FSs performed much better than was expected (captured more than 80% of the events), but in other cases (farmer Kwinda) only 40 to 50% of irrigation and rainfall events were captured (Tables 3.4 to 3.5). FS placement in the furrow centre or shoulder did also not influence performance consistently, but in most cases placement in the shoulder of the furrow gave best results.

**Table 3.4** FullStop (FS) responses to irrigation or rain in Farmer Matshingane's field

| Events | Upper strip | | | | | | Lower strip | | | | | | Mean |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | FS response before irrigation | | | FS response after irrigation | | | FS response before irrigation | | | FS response after irrigation | | | |
| | F11 S* | F12 S | F13 S | F11 S | F12 S | F13 S | F21 C* | F22 C | F23 C | F21 C | F22 C | F23 C | |
| **Number of activations** | 7 | 6 | 5 | 3 | 3 | 3 | 3 | 5 | 5 | 2 | 3 | 3 | 4.0 |
| **Total number of events** | 12 | 7 | 7 | 3 | 3 | 3 | 7 | 7 | 7 | 3 | 3 | 3 | 5.4 |
| **Percentage frequency of activation (%)** | 71 | 86 | 71 | 100 | 100 | 100 | 43 | 71 | 71 | 67 | 100 | 100 | 81.7 |

*C = furrow centre; S = furrow shoulder

**Table 3.5** FullStop (FS) responses to irrigation and rain in Farmer Kwinda's field

| | Upper strip | | | | | | Lower strip | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Events** | **FS response before irrigation** | | | **FS response after irrigation** | | | **FS response before irrigation** | | | **FS response after irrigation** | | | **Mean** |
| | **F11 S** | **F12 S** | **F13 S** | **F11 S** | **F12 S** | **F13 S** | **F21 C** | **F22 C** | **F23 C** | **F21 C** | **F22 C** | **F23 C** | |
| **Number of activations** | 7 | 12 | 5 | 3 | 7 | 3 | 12 | 1 | 7 | 6 | 1 | 4 | 5.7 |
| **Total number of events** | 13 | 13 | 13 | 10 | 10 | 10 | 12 | 12 | 12 | 9 | 9 | 9 | 11.0 |
| **Percentage frequency of activation (%)** | 54 | 92 | 38 | 30 | 70 | 30 | 100 | 8 | 58 | 67 | 11 | 44 | 50.3 |

*C = furrow centre; S = furrow shoulder

With the exception of Farmer Kwinda's field, where the TDs responded very poorly, TDs generally performed fairly well, especially at the shallow 30cm placement depth, where they captured between 66 and 100% of all irrigation and rainfall events (Table 3.6).

**Table 3.6** Mean Tube Detector (TD) activation frequency to irrigation and rain in farmer fields

| **Farmer** | **Activation frequency of TD90 after irrigation (%)** | | | **Activation frequency of TD60 after irrigation (%)** | | |
|---|---|---|---|---|---|---|
| | **TD90 90cm depth** | **TD90 60cm depth** | **TD90 30cm depth** | **TD60 90cm depth** | **TD60 60cm depth** | **TD60 30cm depth** |
| Kwinda | 0.0 | 0.0 | 12.5 | 0.0 | 37.5 | 25.0 |
| Matshingane | 55.0 | 95.0 | 100.0 | 61.1 | 55.6 | 66.7 |
| Nethonzhe | 100.0 | 54.2 | 95.8 | 58.3 | 50.0 | 70.8 |
| Singo | 42.9 | 46.7 | 89.0 | 42.3 | 53.8 | 92.3 |
| Mean* | 65.9 | 65.3 | 94.9 | 53.9 | 53.1 | 76.6 |

* Excluding farmer Kwinda's field

For the TDs, there was a good correlation between placement depth and the response frequency of TDs (Table 3.6). The shallowest TDs (30 cm depth) mostly responded more often than the deep ones. The length of the TDs also influenced the frequency of response. In most cases the TD90s recorded more wetting fronts than the TD60s. This was expected, as the TD90 is more sensitive (9 kPa sensitivity) to weaker fronts than the TD60 (6 kPa sensitivity). Under controlled conditions of the UNIVEN experiment, the TD60 performed better than the TD90, which is opposite to the present results recorded for the farmers' fields. In general, TDs gave more consistent and reliable responses to wetting fronts than FSs under short furrow irrigation conditions.

Figure 3.14 gives a summary of the data recorded for only the TD90s placed at 60 cm depth at top and bottom of all four farmers' fields. The question here is whether farmers could improve on their irrigation management if they had only one or two Tube Detectors placed at two positions in their fields. For farmer Kwinda no wetting fronts were recorded after any of his irrigation events throughout the growing season. The irrigation amounts were most likely too small to rewet the profile, even at the top of the furrows. It can, therefore, be assumed that the crop was most probably under irrigated all the time and that crop water stress occurred throughout the season.

Farmer Matsingane recorded a number of strong fronts at both the top and bottom of the furrows. Early in the season the profile tended to stay wet (> -4 kPa) at both positions, which may suggest over irrigation, but later in the season the bottom of the furrow dried out more between irrigations. This indicates that the soil was not water logged and the irrigation was most likely well managed. The fact that the profile tended to be wetter at the top than the bottom of the furrow, may suggest uneven application depths along the length of the furrows.

The TD90s placed at 60 cm depth at the top of the furrow in Farmer Nethonzhe's field showed wet conditions early in the season, but continuous drying out as the season progressed. However, at the bottom of the furrow the TD90s recorded several strong wetting fronts, with drying out between irrigations. The absence of any response at the top of the furrow, while response were recorded at the bottom of the furrow (later in the season), is difficult to explain. It may suggest TD malfunctioning, or little water infiltration at the top of the furrow and ponding of water at the end of the furrow due to too steep slopes. However, the TD90s placed at 30 and 90 cm depths responded frequently (data not shown here), showing regular wetting and drying of the profile. This suggests malfunctioning of the specific TD90, probably due to installation or placement problems. In this instance incorrect conclusions may have been drawn if only one TD90 each was installed at the top and bottom of the furrow.

The TD90 installed at the top of farmer Singo's field showed regular wetting and drying cycles during the growing season, which suggests good irrigation management. However, the TD90 at the bottom of the furrow only collected water once during the growing season. This signals under irrigation at the bottom of the furrow, probably because the irrigation time was too short, resulting in too little water reaching the end of the furrow.

For all the farmer fields, with the exception of farmer Nethonzhe's field, two TDs gave sufficient information to make meaningful decisions on their irrigation management, and the conclusions drawn from this information agreed with the original conclusions made when the information from more TDs was available. Therefore, it can be concluded that in most cases a farmer could improve on his irrigation management if he had only one or two Tube Detectors placed at two positions in his field.

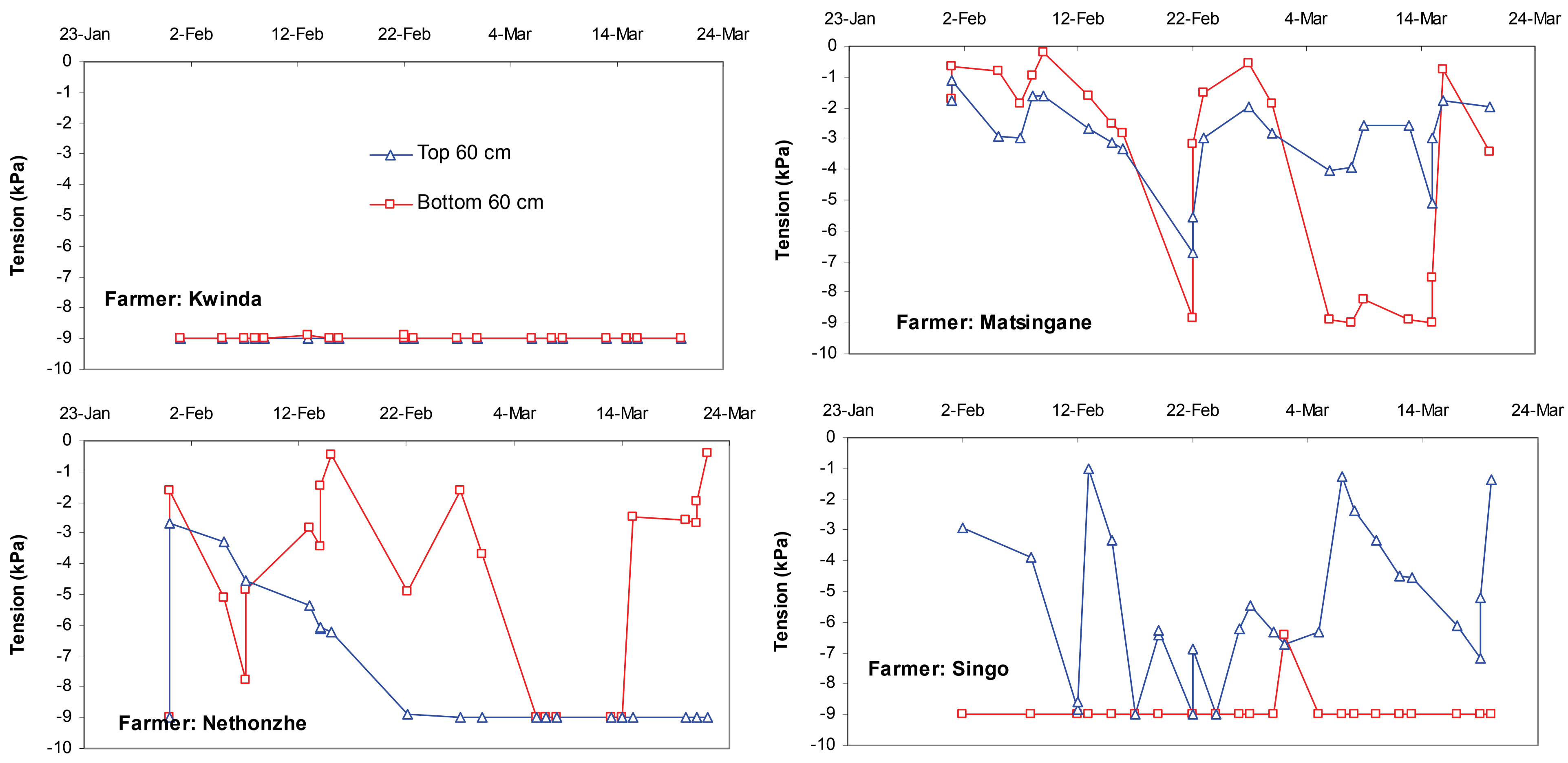



**Figure 3.14** Seasonal changes in suction (kPa) as calculated from water volumes collected by 90cm long Tube Wetting Front Detectors (TD90) installed at 60 cm soil depth at the top (triangles) and bottom (squares) of the beds in furrow-irrigated maize fields of farmers (a) Kwinda, (b) Matsingane (c) Nethonzhe and (d) Singo

## 3.4 DISCUSSION AND CONCLUSIONS

The response of FullStop WFDs in this study varied from very good to poor. In some fields the FSs performed much better than was expected, while in other fields only 40 to 50% of irrigation and rainfall events were captured. FS placement in the furrow centre or shoulder did not influence performance consistently, but in most cases placement in the shoulder of the furrow gave best results. The inconsistent FS response to irrigation events suggest that it may not be sensitive enough to be considered a reliable tool for irrigation management in short furrow irrigation. These results confirm the findings in the UNIVEN trials, which showed that the TD90 performed much better than FSs under short furrow conditions, probably because TDs are able to detect much weaker wetting fronts than FSs.

TDs generally performed well, especially when placed at the shallower depths (30cm). The length of the TDs also influenced the frequency of response. The more sensitive TD90 recorded more wetting fronts than the TD60. In the UNIVEN experiment that was conducted earlier, the TD60 performed better than the TD90.

Considering the question whether a farmer could improve irrigation management if they had installed one or two TDs in his field, the preliminary answer is 'yes'.  Under and over-irrigation in different fields looked fairly evident from the data. To be sure, the farmer's opinions would also be needed, although there could well be other factors that played a role.

Watermark granular matrix sensors were installed and data was logged at hourly intervals. Unfortunately no good data could be collected from these sensors due to technical problems experienced, such as data loss due to cable theft and datalogger malfunctioning. Earlier results showed that TD response could be confirmed with tensiometers. We believe that this would also have been the case if it was possible to retrieve and correlate the Watermark data with TD responses.

Our vision for the TD is that small scale farmers could read them using a 'dip stick'.  After irrigation they would lower a rod down the central tube of the TD.  If it comes up with a wet mark, they know that the irrigation reached the required depth. If not, they would apply more water next time or shorten the time interval to the next irrigation.

They would also ‘dip’ the TDs prior to irrigating. If a TD contained water, and the roots were at that depth, then no irrigation would be required. By combining this information with the local knowledge of the farmer, the condition of the crop, plus the involvement of extension staff, local ‘rules’ could be developed on what kind of TD response gave the best outcome.

# CHAPTER 4 – SOLUTE AND NUTRIENT MONITORING

## 4.1 INTRODUCTION

Predicting the movement of solutes in a profile is far more challenging than predicting water status (Flühler et al., 1996). Erratic flow patterns classified as preferential flow, fingering, and pulse splitting or stochastic-advective as opposed to advective-dispersive transport are common in unsaturated soils (Flühler et al., 1996). In most irrigated systems, the periodic leaching of salts from the soil profile is essential for sustainable crop production. These excess water applications will inevitably also lead to the loss of valuable nutrients from the soil. For this reason leaching fractions should be kept as small as possible. Electrical Conductivity (EC) is the simplest chemical measurement that can be made on a soil sample, and is highly correlated to the ion (fertilizer and salt) content of the soil water. The standard method for measuring EC is through a saturated extract. The soil sample is wetted up to near saturation, mixed and left for a set period of time. It is then filtered under vacuum and the EC is measured on the solution. This is a laboratory procedure, not suited to routine field use. The measuring of soil water EC (hereafter referred to as EC) has been a popular method to determine total solute concentration or salinity for decades (Corwin and Lesch, 2003). EC may also be useful to indicate total quantities of ions present and the potential for leaching losses of valuable nutrients such as $NO_3^-$ (Patriquin et al., 1993). High salinity can reduce crop growth through osmotic and/or toxic effects (Maas and Grattan, 1999; Pasternak, 1987), and through the reduction of root cell membrane permeability and nutrient uptake (Mansour, 1997; Hopmans and Bristow, 2002). Due to salt accumulations at the soil-root interface, salt concentrations in the rhizosphere can be much higher than in the bulk soil, but back diffusion can be expected to moderate this build-up (Hopmans and Bristow, 2002). Under conditions of stress, roots may modify their uptake patterns to reduce exposure to that stress, for example increase uptake from a region in the root zone not experiencing such stress (Hopmans and Bristow, 2002).

N and P fertilizer use efficiency is well known to be very low in most cropping systems. Total crop uptake for the two nutrients can be as low as 50% of applied N

(Smil, 1999) and 45% of applied P (Smil, 2000). Although plants are able to assimilate nitrogen in the form of $NO_3^-$, $NH_4^+$, urea and amino acids, generally crops will take up a higher proportion of $NH_4^+$ to $NO_3^-$ than present in the soil. Generally $NO_3^-$ uptake has been observed to be independent of transpiration, except in cases of low transpiration (Hopmans and Bristow, 2002). Shaner and Boyer (1976) observed that $NO_3^-$ uptake is mostly a function of metabolic rate rather than transpiration rate. Hopmans and Bristow (2002) point out that although unproven, active uptake is believed to dominate at low soil N concentrations, while passive uptake and diffusion is believed to be more important at higher soil N concentrations.

Differences in solute concentrations of soil water samples collected by active and passive samplers under temporally and spatially equivalent conditions can differ markedly (Litaor, 1988; Paramasivam et al., 1997). Identifying the causes of these differences can be a perplexing issue. As passive samplers only collect samples under very wet conditions (~3 kPa), they are more indicative of what is moving through the root zone, as opposed to suction cups which are more indicative of what plants are able to take up (Magid and Christensen, 1993; Simmons and Baker, 1993). As reviewed by Stirzaker and Hutchinson (1999), initial water content as well as four principle factors affects the composition of solute collected from an active sampler, namely: (1) the amount of suction applied to the cup, (2) length of suction period, (3) porous material used for the cup, and (4) the size of the cup. According to Corwin (1992), suction cups can influence soil solution chemistry through the adsorption of ions, the loss of volatile compounds, changes in redox dependent ions, and pH changes. The wetting front detector (WFD) is a funnel shaped device which is buried in the soil and is able to alert a user when a wetting front has passed a specific depth in the soil, thereby making it an effective irrigation scheduling tool (Stirzaker, 2005). The WFD is also able to collect and store a water sample from a wetting front at about 2 kPa. The funnel shape means that unsaturated flow lines are converged to towards a small area at its base, and after an irrigation/rainfall event water is withdrawn from the cavity by capillary action (Stirzaker and Hutchinson, 1999). An advantage of WFDs over SCs is that the high phosphorus (P) sorption characteristics of ceramic SCs often make these devices inadequate for sampling when studying compounds that can be adsorbed to the ceramic cup. Several studies have shown that only a fraction of phosphate was recovered after being passed through a ceramic suction cup (Tischner et al., 1998). A further advantage of WFDs over SCs for solute monitoring is that in annual cropping systems in which equipment must be removed between crops, it is easier to remove and re-install WFDs than SCs. Theoretically, samples collected from WFDs could also experience loss of volatile compounds as is the case with suction cups.

The were several objectives for this study. The first was to compare EC and $NO_3^-$ levels in soil water samples collected by means of active (SCs) or passive (WFDs) lysimetry and how these comparisons can be used to increase understanding of salt, $NO_3^-$ and $PO_4^{2-}$ mobility in mostly unsaturated flow.

## 4.2 MATERIALS AND METHODS

### 4.2.1 Lysimeter study

Three drainage lysimeters, each with a volume of 6.1 $m^3$, containing a sandy loam (12% clay) (SL) and sandy clay loam (18% clay) (SCL18) and a sandy clay loam (26% clay) (SCL26) were utilized in the trial. The three lysimeters are located on the University of Pretoria Experimental Farm (25°44'S 28°15'E, 1370 m above sea level). A gravel layer was used at the bottom of each lysimeter to facilitate drainage which was diverted into capture drums. The following instrumentation was installed into each lysimeter: logging tensiometers at depths of 15, 30, 45 and 60 cm depths; suction cups (SCs) at 15, 30, 45, 60, 80 and 100 cm depths; wetting front detectors (WFDs) at 15, 30, 45 and 60 cm depths, Decagon $ECH_2O$-TE sensors at 15, 30, 45, 60 and 80 cm depths (hereafter referred to as capacitance sensors); and two diviner access tubes. The vegetable crop swiss chard (*Beta vulgaris* ssp. *cicla*) was chosen for use in this trial due to its ease of cultivation, relatively deep root system (~ 80 cm) and because multiple harvests of the outer leaves can be made without having to replant the crop. The crop was planted at an effective spacing of 20 × 30 cm.

Suction was applied to the suction cups using a 60 ml syringe immediately following irrigation. This method allows for a total suction of +/-15 mBar Hg to be applied. Soil water samples were collected from both the WFDs and SCs the day following irrigation. Drainage was captured in large drums from which the quantity of drainage could be measured and a water sample taken for analysis. For each sample, EC was measured using a an ECScan-High EC meter (Eutech Instruments, Malaysia), $NO_3^-$ was analyzed using a Merck RQEasy Nitrate Reflectometer, and $PO_4^{2-}$ was analyzed using a C99 Multiparameter Bench Photometer (Hanna Instruments, Italy). $PO_4^{2-}$ was only determined for samples collected by WFDs as ceramic SCs are known to have sorption interactions with the P in soil water.

Irrigation water with and EC of 0.5 dS $m^{-1}$ was used. As the irrigation water from the farm had an EC of 0.3 dS $m^{-1}$, NaCl needed to be added to the water to achieve an EC of 0.5 dS $m^{-1}$.

***Management approach***

Irrigation was applied with the primary objective of not causing any water stress while minimizing percolation. Following planting small amounts of irrigation water were applied at regular intervals. Thereafter irrigation water was initially applied to set of the WFD placed at 15 cm, and as daily crop water demand increased, irrigation water was applied to trigger the WFD placed at 30 cm. Applications were made at weekly intervals, or more often if judged necessary.

Split-applications of N fertilizer are a widely used approach to reduce N leaching losses. Fewer, smaller N applications allow N concentrations in soil to remain low, reducing leaching loss risks. If an overall $NO_3^-$ concentration of less than 100 mg $l^{-1}$ was measured from WFD samples in the root zone, N fertilizer would be applied. If EC reached a value of 4 dS $m^{-1}$ or higher, additional irrigation would be applied. This would involve irrigating until the WFD below the WFD which normally responds, responds. If EC greater than 3 dS $m^{-1}$, N fertilization would be delayed if possible.

### 4.2.2 Commercial orchard study

All orchards were irrigated using drip irrigation. Cumulative irrigation was captured and measured using a suitably large container connected to a low output volume dripper in the irrigation line. The output volume of the dripper was 0.5 l $h^{-1}$. The orchard was fertilized using organic fertilizer underneath the drippers.

WFDs were installed in sets of three, each set in the same row (Figure 4.1). The instruments were installed at depths of 30, 45 and 60 cm. The installation distance between the WFDs at different depths was chosen to ensure no interference with one another, each directly underneath a dripper between two trees. Choosing the position of the instrument nests in the plum orchard was important because of soil variation. The most representative soil type was chosen in both orchards. Volumetric water content (VWC) was measured using a logging Enviroscan sensor. This consisted of a single probe in the plum and peach orchards and was used by the farmer to schedule his irrigation. Watermark sensors were later installed into selected sites, also at depths of 30, 45 and 60 cm.

**Figure 4.1** WFD installations in commercial orchards

Soil solution samples were collected daily after irrigation. Individual daily soil solutions samples were accumulated in the same sample container for each WFD over a period of one week, for example Friday to Friday. The accumulated samples were then analyzed for EC and nitrate, using a hand-held EUTECH ECScan and Merck semi-quantitative nitrate strips, respectively. The samples were kept at room temperature in dark sample bottles between sampling and analysis. For the second season, electrodes connected to HOBO loggers were inserted into the WFDs already installed in the field, allowing for continuous logging of the EC of the soil water sample collected by the WFD. In 2008, monitoring also began in a nectarine orchard using the automated EC logging system.

### 4.2.3 Municipal sludge trial

WFDs were used in a trial studying the feasibility of using very high municipal sludge applications in sod grass production. The study was conducted at the East Rand Water Care Works (ERWAT), Johannesburg, Gauteng, South Africa (26$^{o}$ 01' 01" S; 28$^{o}$ 16' 55" E, altitude 1577 m above sea level). The soil is a clay loam (Hutton, Soil Classification Working Group, 1991) or a loamy, kaolinitic, mesic, Typic Eutrustox with pH ($H_2O$) of 6 to 6.8 and an average soil profile depth greater than 1 m. The five treatments consisted of applications of 0, 8, 33, 67, and 100 Mg ha$^{-1}$ oven dry sludge per sod harvest. The value of 8 Mg ha$^{-1}$ represents the annual agricultural upper limit of the 1997 South African sludge guideline (WRC, 1997), which was recently increased to 10 Mg ha$^{-1}$ (Snyman and Herselman, 2006). Sludge was spread uniformly over the soil surface and was not incorporated. Adjustable nozzle micro-sprayers (Hunter, California, USA) at the four corners of each plot were used to irrigate the turfgrass using municipal drinking water. In the absence of rainfall, 10 mm of irrigation was applied every third day for the first 30 days after sludge application. During the rest of the growing season, until sod harvest, turf was irrigated twice a week (first irrigation 15 mm, followed three days later by irrigation sufficient to cause a WFD buried 0.3 m below the original pre-harvest soil surface to collect a water sample). Total irrigation and rainfall was 1438 mm (2005) and 1283 mm (2006), giving an approximate leaching fraction of 0.27 in 2005 and 0.3 in 2006.

Measurements were made of the EC and $NO_3^-$ concentration of the soil solution collected by the WFDs, using an ECScan-High EC meter (Eutech Instruments, Malaysia) and a C99 Multiparameter Bench Photometer (Hanna Instruments, Italy), respectively.

## 4.3 RESULTS

### 4.3.1 Lysimeter trial

***Volumetric water content***

The capacitance sensors clearly reflected the effects of irrigation and rainfall and plant water extraction on soil VWC (Figure 4.2). Some problems were experienced with the senor placed in the SCL26 soil lysimeter at 30 cm which led to the loss of some data. For the SL and SCL 26 soil, VWC was generally higher at 15 cm than at 30 and 45 cm, but his was not the case for the SCL18 soil. Some error in measuring VWC may therefore have occurred for one or more of these sensors in the SCL18 soil.

The use of WFDs to guide irrigation application amounts was judged to be successful as reasonable yields were achieved while drainage was totally limited until the onset of the rainy season. This was achieved while still keeping soil salt levels below the predefined threshold value.

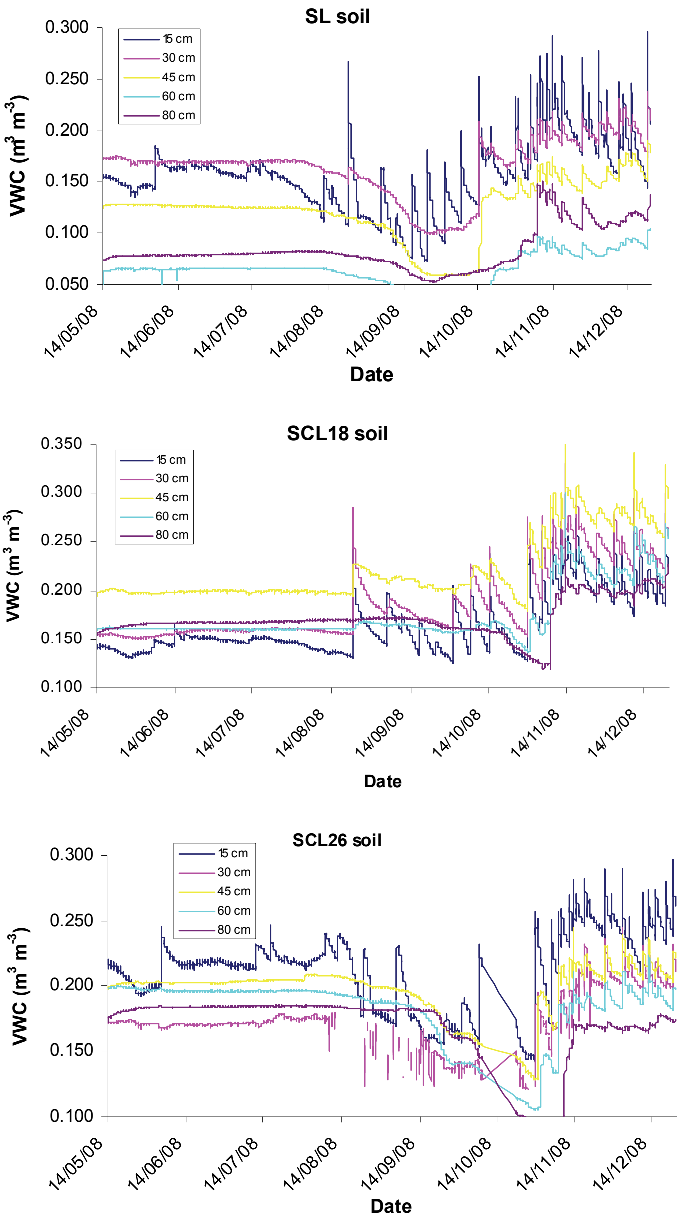



**Figure 4.2** Soil volumetric water content (VWC) as measured by the capacitance sensors at depths of 15, 30, 45, 60 and 80 cm for the three lysimeters

***EC measurement – WFDs, SCs, capacitance sensors***

As specified in the $ECH_2O$-TE sensor manual, measurement of EC becomes inaccurate under dry soil conditions when VWC is less than about 0.10 $m^3$ $m^{-3}$ (Anonymous, 2007). For this reason EC sensor data is not complete for the SL soil for depths 15, 30 and 45 cm, and no EC data was obtained for the depths 60 and 80 cm (Figure 4.3). As for the measurement of VWC for the SCL26 soil, the sensor buried at 30 cm measured erroneous EC values for a length of time.

For the three soils used in this trial, all of which can be judged to have relatively coarse textures, EC values measured by the sensors did not exceed 3 dS m$^{-1}$. Large EC spikes following fertilization were detected by SCs and to a lesser extent the WFDs, but were not detected by the automated sensors. The onset of the rainy season clearly caused EC levels to decline, and is most visible in the capacitance sensor data due to the high amount of measurements made.

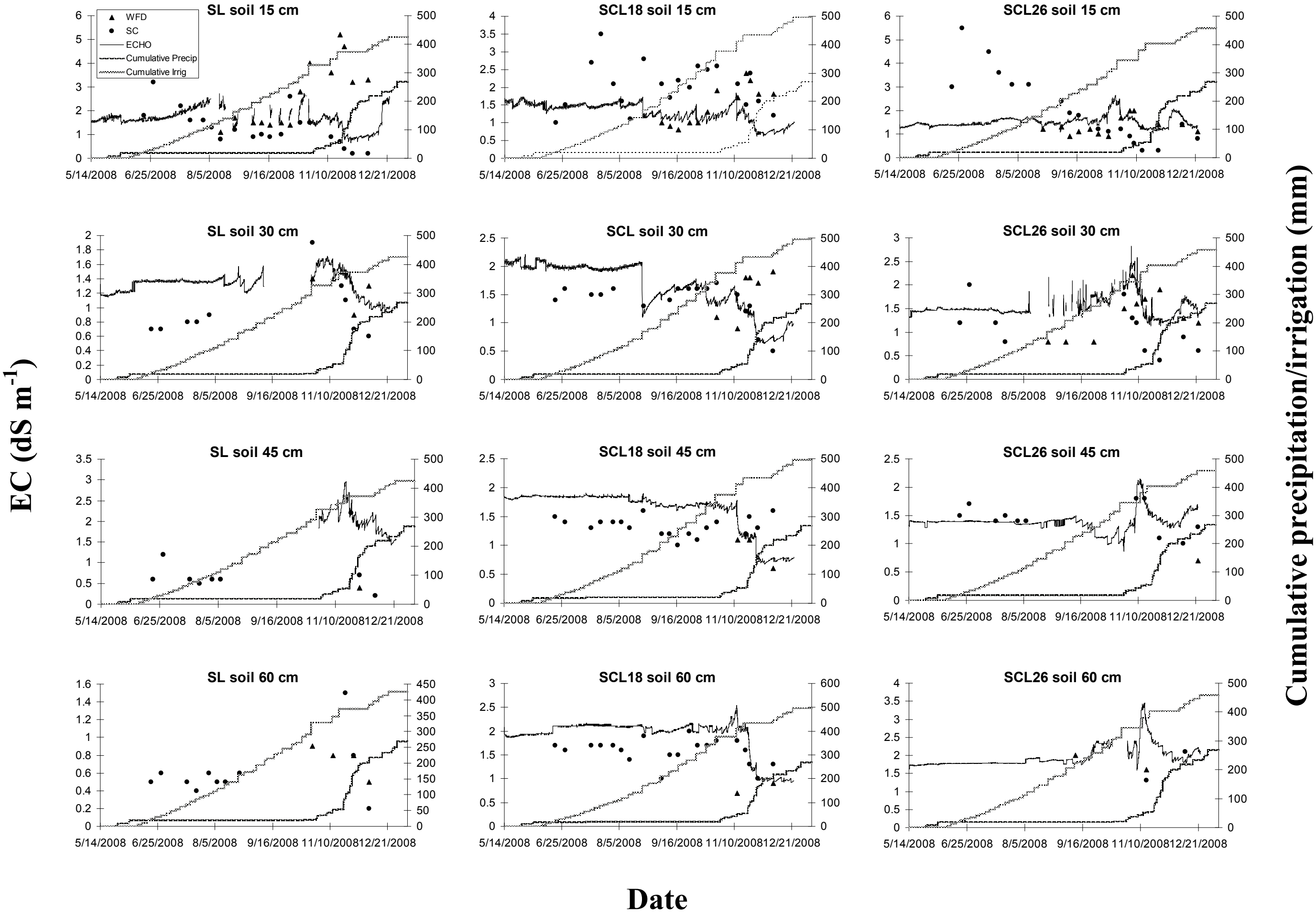



**Figure 4.3** Capacitance sensor, SC and WFD EC as well as cumulative irrigation and precipitation over the season

For the SL soil, higher EC values were consistently obtained for WFD than for SC samples at 15 cm. The same trend was observed for the SCL26 soil in the second half of the season at 15 and 30 cm, and for the SCL18 soil during the second half of the season at 30 cm. This trend was the opposite of what was expected and is in contrast to $NO_3^-$ concentrations which were normally lower in WFD samples than SC samples (see below).

Agreement between EC values measured by the capacitance sensors and those obtained from the SCs was generally better than agreement between capacitance sensors and WFD EC. After performing a simple linear regression analysis for EC values measured using the different methods, significant positive correlations ($r^2$ > 0.50) were only observed between SCs and the automated sensors in the SCL18 soil at 30 cm ($r^2$ = 0.60), and between WFDs and the automated sensors in the SL soil at 30 cm ($r^2$ = 0.51). Very little positive correlation was therefore observed between the methods and soil ranges used in this trial. Furthermore, between the SCs and WFDs, negative correlations often existed.

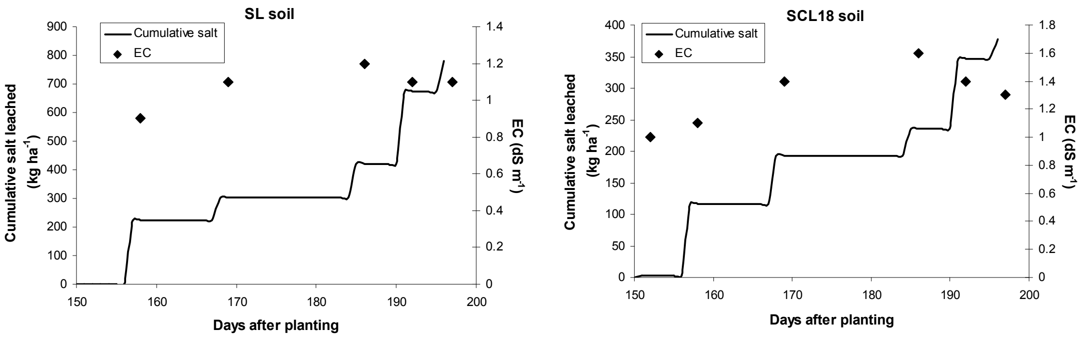



**Figure 4.4** Cumulative salt leaching and drainage water EC for the SL (left) and SCL18 (right) soils

Figure 4.4 contains cumulative salt leaching and measured EC values for the drainage water. For the SL and SCL18 soils, 781 and 377 kg $ha^{-1}$ of salt was calculated to have leached from the two soils, respectively. For the SL soil 122 mm of drainage was measured and for the SCL18 soil 45 mm of cumulative drainage was measured. For the SCL26 soil, 25 kg $ha^{-1}$ was calculated to have leached from the soil during a single drainage event of 6 mm (data not shown). A slight increase followed by a slight decrease in drainage water EC was observed for both the SL and SCL18 soils.

***$NO_3^-$ measurement – Active vs. passive sampling***

Relatively high soil solution $NO_3^-$ concentrations were observed for all three soils and at all depths at the onset of planting despite no fertilization having taken place since the previous season (Figure 4.5). These high $NO_3^-$ concentrations can be expected as a result of mineralization occurring over a four month period with very little drainage and no crop N uptake.

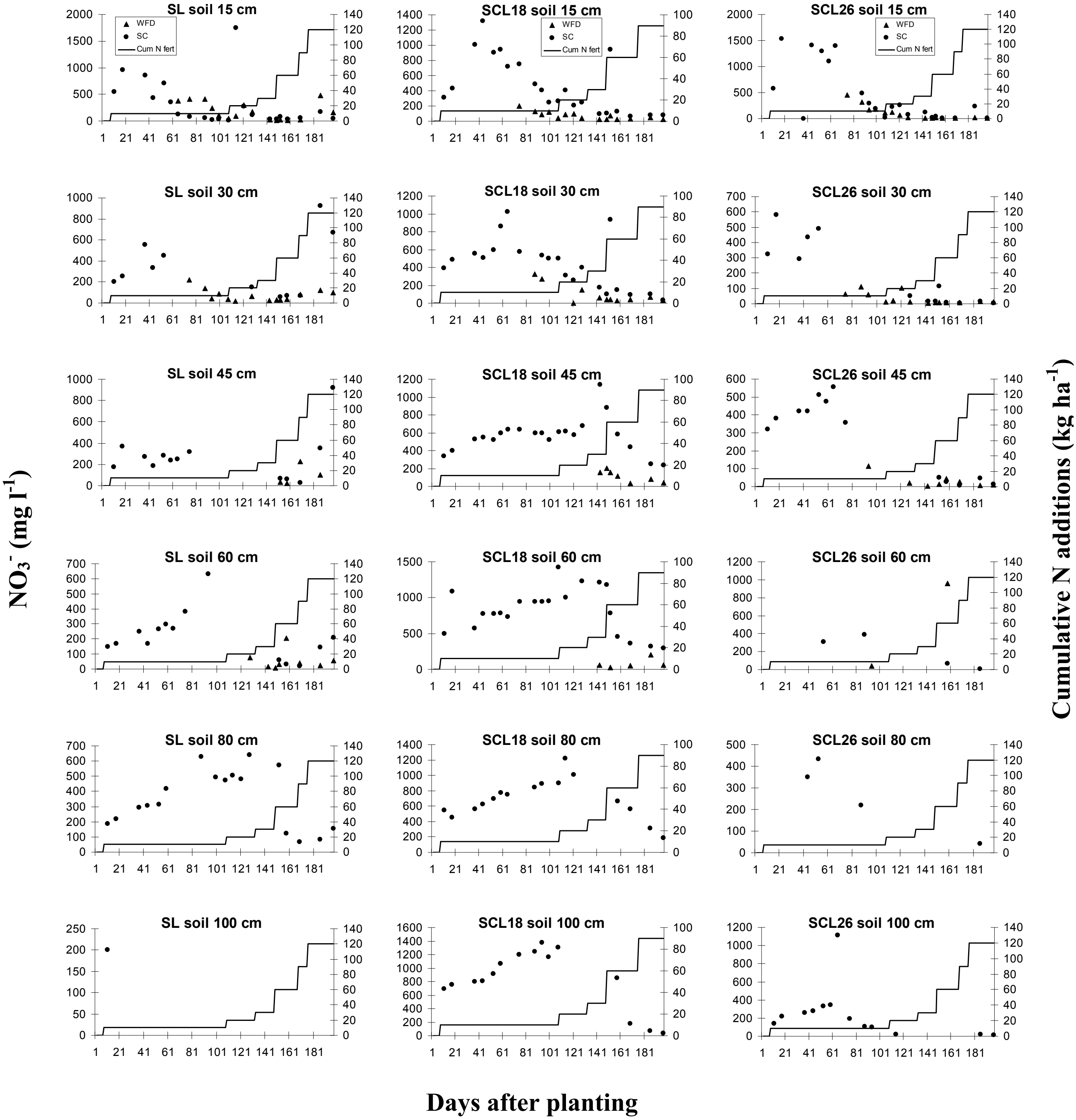



**Figure 4.5** $NO_3^-$ concentrations obtained from SCs and WFDs and cumulative N fertilizer additions over the growth season

After the planting of the crop, the removal of N from the system by an actively growing crop is clearly observable in the data. In most cases, $NO_3^-$ concentrations from WFDs were below those measured from SCs, especially for the SCL18 and SCL26 soils. This could correlate with lower solute concentrations expected in the mobile soil water phase due to bypass flow and has also been observed in other trials (Stirzaker and Hutchinson, 1999). However for the SL soil at 15 cm the opposite was often true. The SL soil has the coarsest texture of the three soils and it is therefore plausible that the least bypass flow takes place in this soil. SC and WFD $NO_3^-$ values correspond more closely than for EC. Significant positive correlations ($r^2 > 0.50$) between $NO_3^-$ concentrations measured in SCs and WFDs were observed for the SL soil at 30 cm ($r^2 = 0.76$), for the SCL18 soil at 45 cm ($r^2 = 0.66$), and for the SCL26 soil at 15 cm ($r^2 = 0.67$).

A migration of $NO_3^-$ down the soil profile is observable to some extent for all three soils, but is most apparent for the SCL18 soil. The addition of 10 kg N $ha^{-1}$ 7 DAP is observable for all three lysimeters with a concomitant increase in $NO_3^-$ concentration as detected by the SCs placed at 15, 30 and 45 cm. A second addition of 10 kg N $ha^{-1}$ 108 DAP is also observable for the SL and SCL18 soils at 15 cm. A third addition of 10 kg N $ha^{-1}$ 132 DAP does not result in a significant increase in SC $NO_3^-$ concentration for any of the soils. Similarly, the addition of 30 kg N $ha^{-1}$ 148 DAP did not cause a drastic increase in $NO_3^-$ concentration from SCs at 15 cm except for the SCL18 soil. Further N applications of 30 kg N $ha^{-1}$ 167 DAP (SL and SCL26 soils only) and 30 kg N $ha^{-1}$ 175 DAP (all lysimeters) did also not cause clearly observable increases in $NO_3^-$ concentration in either SCs or WFDs. As additions of fertilizer N were more clearly reflected at the beginning of the season when the crop did not yet have a developed root system, this N 'disappearance' is therefore mostly attributed to crop uptake.

In addition to crop N uptake, the onset of the rainy season clearly moved $NO_3^-$ down the soil profile. Figure 4.6 contains cumulative N leaching and drainage water $NO_3^-$ concentration data for the SL and SCL18 soils. $NO_3^-$ concentrations were observed to significantly increase over the growth season in the drainage water for the SCL18 soils, beginning at 330 and peaking at 1200 mg $l^{-1}$. The latter value is over 27 times greater than the effluent discharge standard dictated by DWAF for South Africa.

Cumulative N losses for the SL and SCL18 soils amounted to 65 and 86 kg ha$^{-1}$, respectively. Water from the single drainage event occurring for the SCL26 soil was measured to have a low $NO_3^-$ concentration of 7 mg l$^{-1}$ and only 0.09 kg N ha$^{-1}$ was calculated to have leached from this profile. As mentioned, the migration of $NO_3^-$ downwards through the profile in the SCL18 soil is clearly observable in the SC data. This is less clear from the WFD data, although small declines in $NO_3^-$ concentration are observed at all depths. Such relatively small fluctuations in WFD $NO_3^-$ concentrations, especially at the deeper depths, may therefore be highly representative of high $NO_3^-$ leaching in the profile as reflected by the SC data.

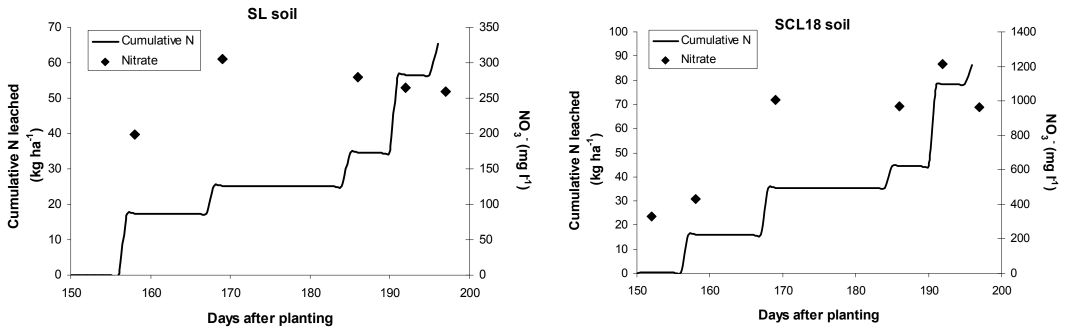



**Figure 4.6** Cumulative N leaching and $NO_3^-$ concentrations in the drainage water for the SL (left) and SCL18 (right) soils

### *EC and $NO_3^-$ correlations*

The simple and cheap measurement of EC has been proposed as a surrogate measurement to reflect the amount of specific ions, such as $NO_3^-$, present in the soil water. For example, Bhabani et al. (1999) demonstrated potential in using time domain reflectometry to predict $NO_3^-$ concentrations in soil.

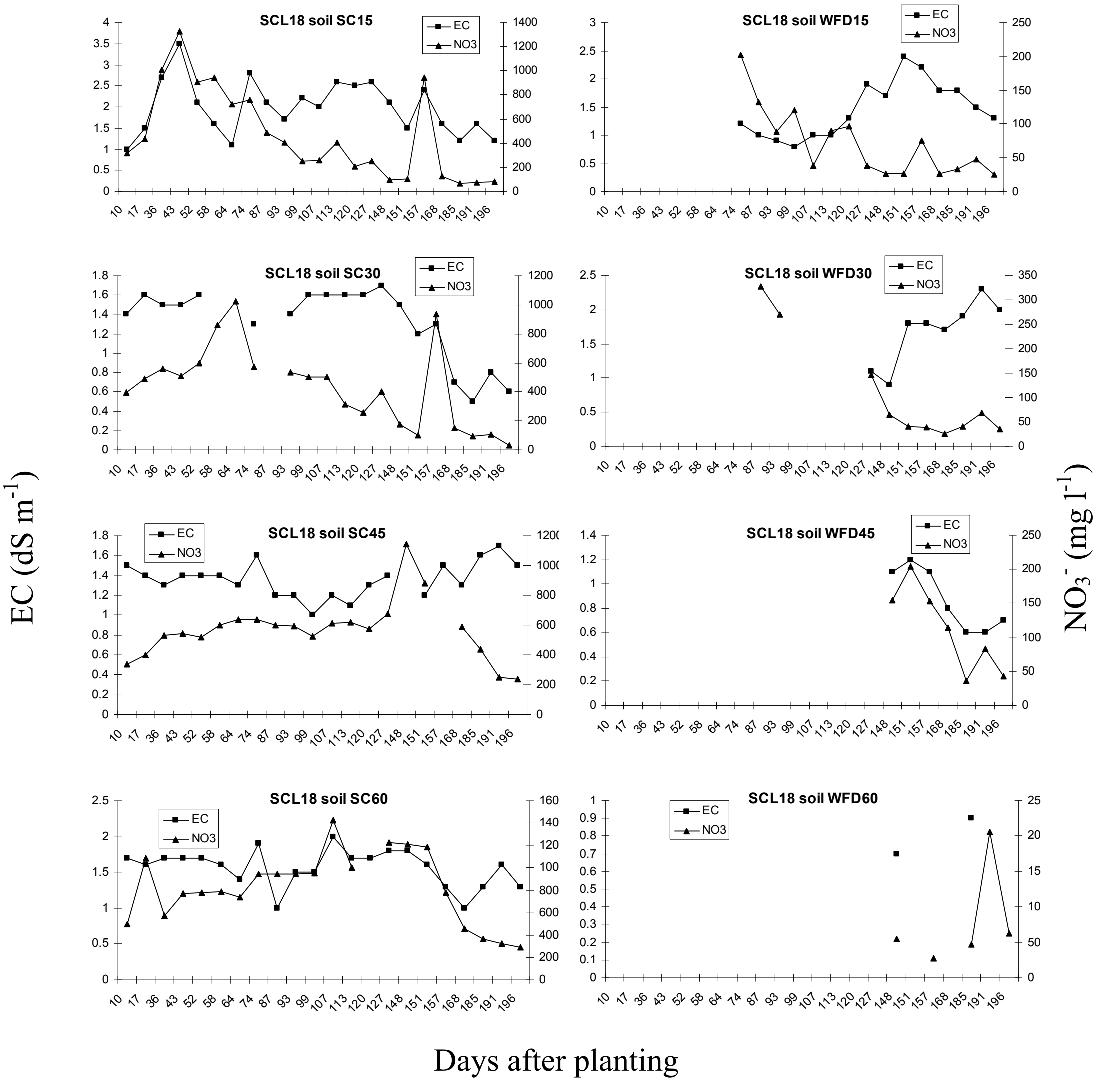



**Figure 4.7** SC EC and $NO_3^-$ values (left) and WFD EC and $NO_3^-$ values (right) for the SCL18 soil

The greatest overall positive correlation between measured EC and $NO_3^-$ concentrations were obtained for the SCs for all three lysimeters. The strongest correlations for the SCs of 0.69 and 0.83 were observed at 15 cm for the SL and SCL26 soils, respectively (Appendix 4.1 and 4.2). Positive correlations were also observed for the SCL18 soil between capacitance sensor EC and SC $NO_3^-$, and capacitance sensor EC and WFD $NO_3^-$, but not for the SL and SCL26 soils. High correlations could perhaps be expected in coarser textured soils as there is less influence from the cation exchange complex. Judging from the graphs, however, these data do show potential in using EC to reflect $NO_3^-$ content of a soil, especially in a controlled fertilization program where only N is added for certain periods of the growth season.

*Phosphate*

Water samples collected by WFDs could be successfully analyzed for inorganic P concentrations. In many cases P concentrations were observed to fluctuate between successive sampling events, especially for the SL and SCL26 soils at 15 cm (Figure 4.8). Despite this overall trends in increases/decreases of P could still be observed. At all depths, P concentrations ranged between 0.07-2.2, 0.4-8.7 and 0.2-4.2 mg P $l^{-1}$ for the SL, SCL18 and SCL26 soils, respectively. In all cases the highest concentrations were observed in the WFDs buried at 15 cm.

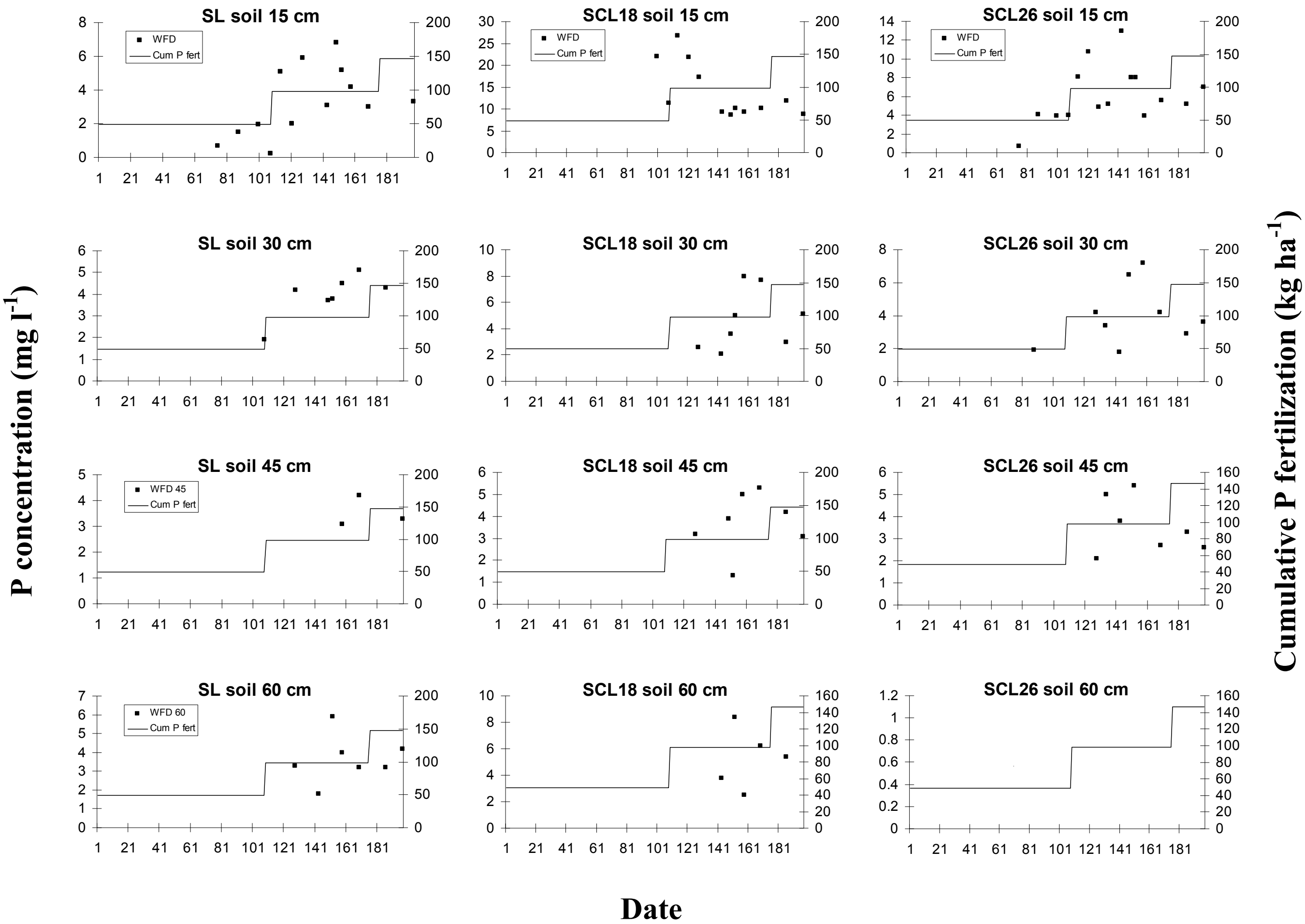



**Figure 4.8** Phosphate concentrations of water samples collected by WFDs throughout the season

The effect of the first P fertilizer addition of 49 kg $ha^{-1}$ at planting cannot be observed as WFDs did not collect soil water samples over this period. The second fertilizer addition of 49 kg $ha^{-1}$ 108 DAP can clearly be observed by a corresponding increase in P concentration at 15 cm for all three soils. Increases in P concentration can also be observed for the SL and SCL26 soils at 30 cm. A third application of 49 kg ha$^{-1}$ 175 DAP did not cause as drastic increases in P concentration measured at the WFDs at 15 cm. A similar phenomenon was observed for N. From these P concentrations in water samples collected by WFDs, an overall increase in the 'P status', most likely as a result of the fertilizer P applied, can be observed. In the case of the SL and SCL18 soils this increase in concentration can be seen right down to the 60 cm depth. This seems to indicate that fertilizer P is moving vertically down the profile, and may also be the case for the SCL26 soil, but unfortunately no samples from the WFD at 60 cm were available for analysis for this soil.

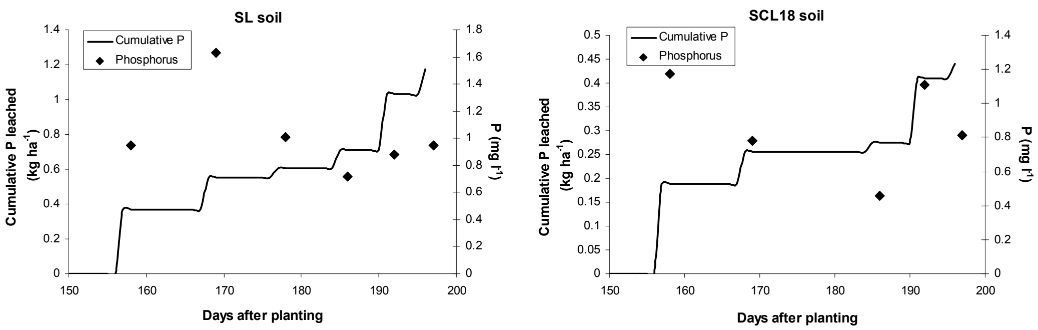



**Figure 4.9** Cumulative P leaching and P concentrations in the drainage water for the SL (left) and SCL18 (right) soils

For the SL soil, P concentrations in the drainage water ranged from 0.72 to 1.63 mg P l$^{-1}$, with a cumulative 1.17 kg P ha$^{-1}$ being leached over the growth season (Figure 4.9). In the SCL18 soil P concentrations ranged from 0.46 to 1.17 mg P l$^{-1}$ and cumulative P leached was 0.44 kg ha$^{-1}$. For the single percolation event for the SCL26 soil the P concentration was 0.88 mg l$^{-1}$ and 0.05 kg P ha$^{-1}$ was measured to have leached from the profile. Drainage water P concentrations were therefore generally lower than for the WFD but were observed to be higher than the DWAF effluent discharge limit of 1 mg P l$^{-1}$.

### 4.3.2 Commercial orchard trial

***Irrigation***

Figure 4.10 contains the cumulative rainfall and irrigation quantity application data for the peach and plum orchards. The quality of the irrigation water (~0.5 dS $m^{-1}$) was considered to be the baseline water quality as supplied from the source. In this case the source was a borehole.

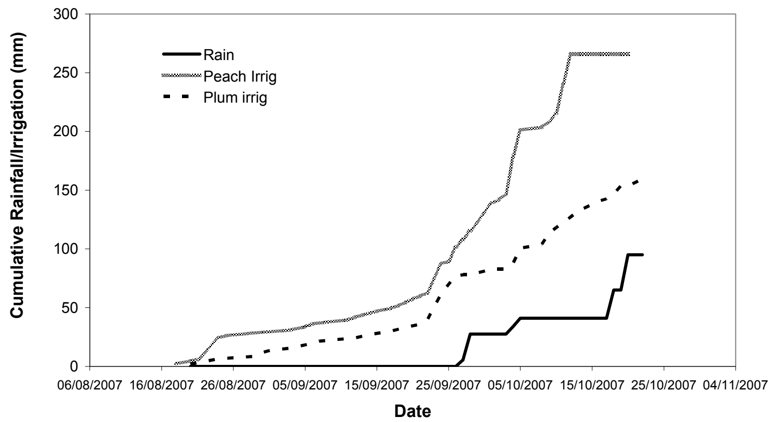



**Figure 4.10** Rainfall and irrigation quantities for the peach and plum orchards

Clearly more irrigation water was applied to the peach trees than to the plum trees, with the peach orchard receiving around 100 mm more irrigation water. This was due to the different soil types in the two orchards. The peach orchard soil contains less clay (23%) than the plum orchard (38%). The peach orchard can therefore be expected to hold less water and drain faster. Another reason is that a shallow clay layer exists in the plum orchard, preventing soil solution from easily percolating below the root zone.

***EC measurement – WFDs, SCs, capacitance sensors***

EC values for the SCs and WFDs were very similar at the three depths measured for the peach orchard. At 30 cm a sharp increase in EC is first measured in the SCs around the end of September, followed several days later by the WFD. This indicates an accumulation of salts at this depth which then moves past 30 cm.

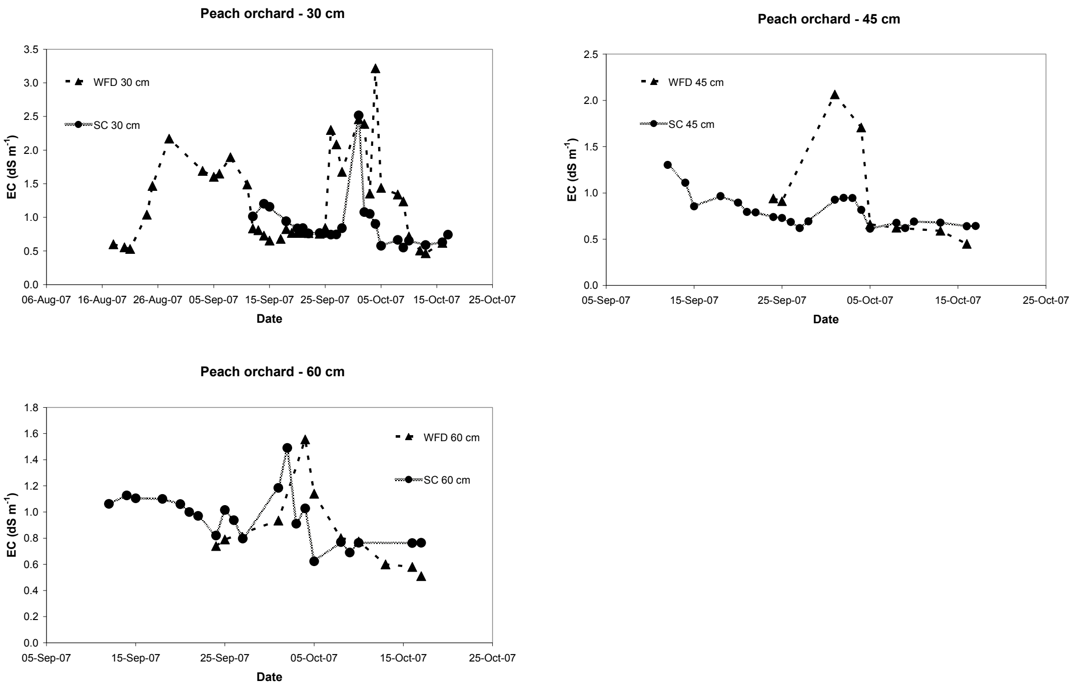



**Figure 4.11** Comparison of EC values measured in soil water samples collected by WFDs and SCs at depths of 30, 45 and 60 cm in the peach orchard

From late September to early October EC values are often observed to be significantly higher in the WFDs than in the SCs at 30 cm. At 45 cm, EC remains relatively constant, but an increase is observed in the WFD data towards the end of September. Thereafter EC values in WFDs and SCs are very similar. At 60 cm only small variations between WFD and SC EC were observed with both instruments displaying very similar trends. The highest EC for the season of around 3.2 dS $m^{-1}$ was measured in the WFD buried at 30 cm.

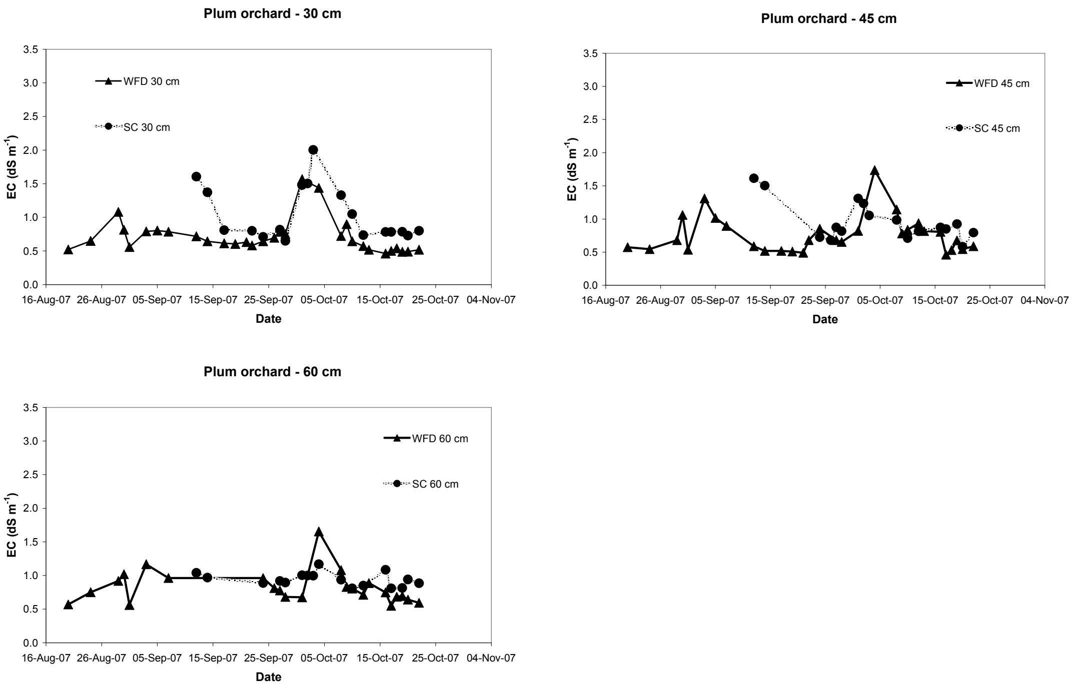
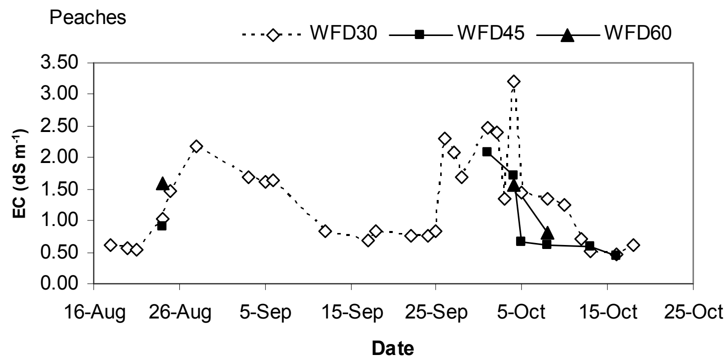



**Figure 4.12** Comparison of EC values measured in soil water samples collected by wetting front detectors (WFDs) and suction cups (SCs) at depths of 30, 45 and 60 cm in the plum orchard

EC values from WFDs and SCs were also very similar at all depths for the plum orchard (Figure 4.12). Unlike the peach orchard at 30 cm, SC EC values were almost always higher than the corresponding WFD EC values. In early October there is an EC spike at all three depths, followed by a rapid drop in EC. The WFDs placed at 45 and 60 cm generally responded more often than for the peach orchard.

***Interpretation of EC data to understand solute movement***

Figures 4.13 and 4.14 illustrate the change in measured EC of the leachate collected by the WFDs and SCs placed at different depths in the peach and plum orchards, respectively. According to Figure 4.13 the salt load in the upper part of the soil profile, as represented by the 30 cm WFD, decreases as the season progresses, settling at around 1 dS $m^{-1}$. The initial high salt signature is the result of the organic fertilizer placed under each dripper. The salt is released from the fertilizer mix and then moves with the irrigation water down the soil profile to be collected in the WFD sampler. Movement of the salt profile is also seen in the 45 and 60 cm WFDs, but later than in the case of the 30cm WFD due to the slow progress of the wetting front. Initially the similar moving salt signatures are sampled in both the 45 and 60 cm WFDs, both decreasing after initial high salt loads are released after application. Another spike in the salt load is seen on 20 October. This is due to the farmer supplying additional inorganic fertilizer into the system, also under the drippers, where after a decreasing trend is observed as the nutrients move down the soil profile. Measured EC values ranged 0.5 dS m$^{-1}$ to 5 dS m$^{-1}$ (only mean data presented).



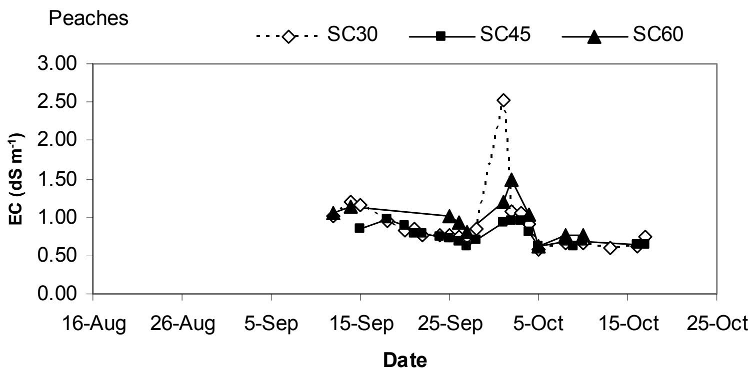
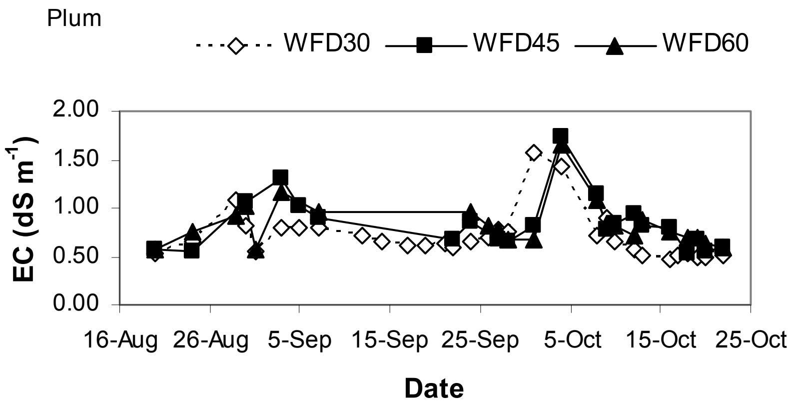




**Figure 4.13** EC data for 30, 45 and 60 cm WFDs (above) and SCs (below) in the peach orchard

Figure 4.14 indicates, as in the case of the peach orchard, a gradual decrease in EC over the weeks following high levels of fertigation through the dripper system. The 45 and 60 cm WFD showed higher salt loads than the 30 cm WFD. The farmer, as in the case of the peach orchard, also provided additional inorganic fertilizer under the drippers during late October. This fertilizer is easily soluble and moved quickly to the deeper soil layers with the irrigation water. The peak in EC was first picked up by the 30 cm detector at the end of October / beginning of November, followed by the 45 and 60 cm detectors, approximately one week apart. The EC then gradually decreased again as the fertilizer moved down the soil profile and was taken up by the trees. In the case of the plum orchard measured EC values ranged from just above 0.5 dS m$^{-1}$ to less than 2.5 dS m$^{-1}$, much lower than in the case of the peach trees where organic fertilizer was applied under the drippers.



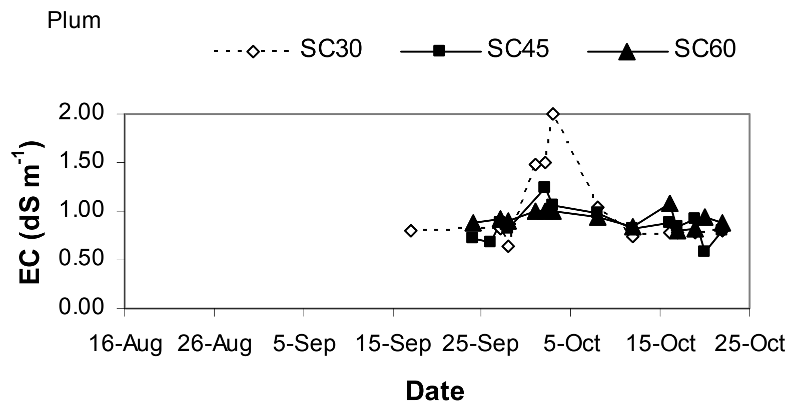




**Figure 4.14** EC data for 30, 45 and 60 cm WFD (above) and SCs (below) in the plum orchard

***Commercial orchard logged EC measurements***

EC values logged by the WFDs in the peach orchard placed at 30 and 45 cm were very similar and all indicated a similar trend. Initially there was a decline in EC at 30 and 45 cm while EC rose slightly at 60 cm. Thereafter as irrigation commenced in spring, as reflected by an increase in soil moisture by the Watermark sensors, a clear increase in EC can be observed at all three depths. While before 1 October the EC values at 45 cm were always above the EC values at 30 cm, this trend begins to change following 1 October where the opposite occurs. As for the previous season, this increase in EC at 30 cm followed later by 45 and 60 cm can be attributed to the dissolution of organic fertilizer placed under the drip lines. At around 20 October EC values at 30 cm and 45 cm again become very similar, while the EC value at 60 cm has increased but is still well below the EC values at 30 and 45 cm, indicating that the salt plume has not yet reached this depth and minimal fertilizer seems to be leaching. EC values clearly increase as the soil becomes drier.

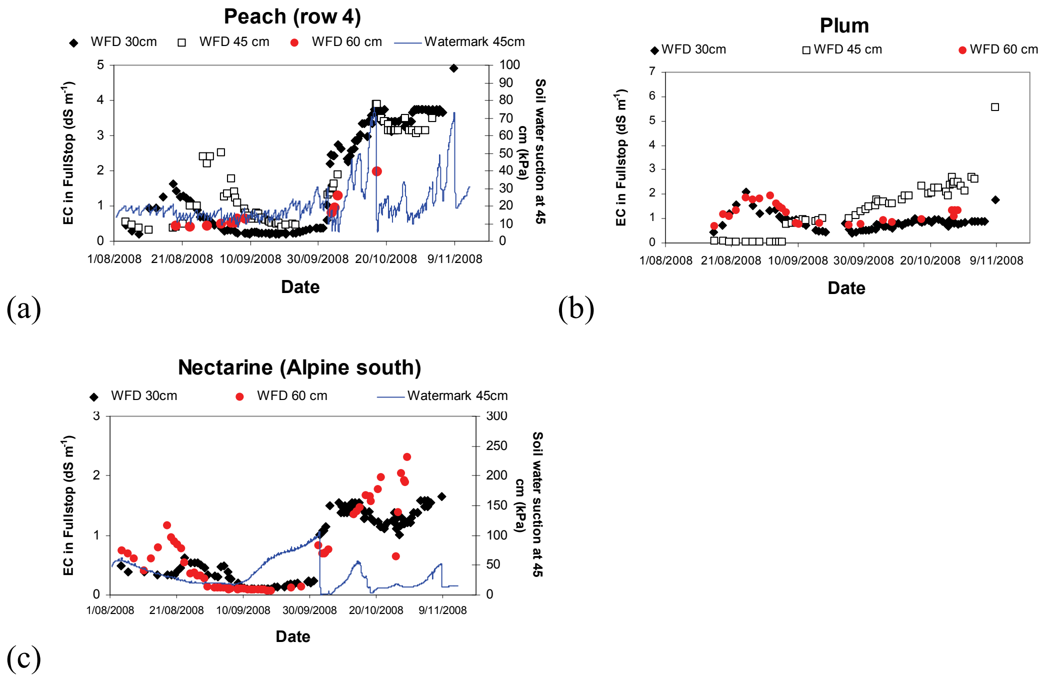


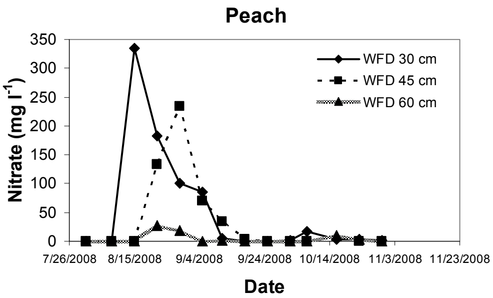

**Figure 4.15** Logged FullStop data for the peach (a), plum (b) and nectarine orchards for the 2008 growing season

For the plum orchard, a sharp increase in EC at 30 and 45 cm is not observed during September as for the peach orchard. Logged EC values were initially higher at 30 cm than at 45 cm, but the reverse is true later in the season. The increase in soil water EC as cumulative irrigation increases is seen at all three depths, but is most pronounced at 45 cm. This was also observed in the peach orchard. As with the previous season, the high EC values that manually measured in the peach orchard were not observed in the plum orchard over the growing season. The electrodes were therefore judged to have adequately reported this phenomenon therefore.

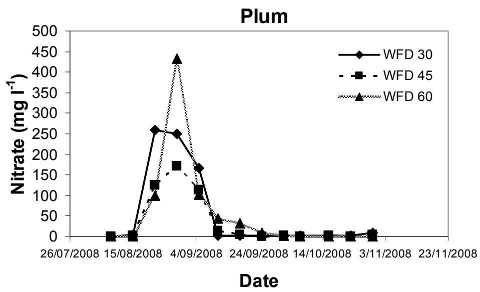
For the nectarine orchard, as with the peach orchard, there is a sharp increase in EC in September at 30 cm as a result of fertilization. EC values at 60 cm also increase at this stage, indicating a rapid movement of solutes to this depth, and possibly high leaching. Higher EC values are observed at 60 cm than at 30 cm for a stage after mid-October. Generally lower EC values were observed for the nectarine orchard than for the peach orchard.

***Nitrate measurements***

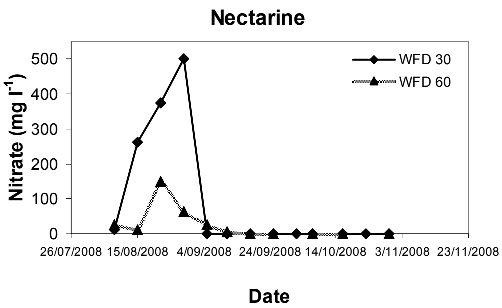
For all three orchards, a sharp increase in nitrate levels was observed at all three depths after mid-August. This increase is first observed at the shallowest WFD, followed by the deeper WFD(s). This would be attributed to a combination of organic matter mineralization and N fertilizer application. Thereafter nitrate concentrations drop quickly in early September and remain very low for the duration of the growing season. This may indicate that N fertilization and tree uptake were very well matched or even that N was under-applied. From this data, significant N leaching does not seem to have taken place over the monitoring period, except perhaps for the plum orchard.




(a)




(b)




(c)

**Figure 4.16** WFD nitrate data for the peach (a), plum (b) and nectarine (c) orchards for 2008 growth season

### 4.3.3 Municipal sludge trial

***EC measurement and salt leaching***

In the beginning of the season soil solution EC increased with sludge application rate. The EC of soil solution samples from the 100 Mg ha$^{-1}$ treatment collected 10 days after sludge application were only slightly higher than the threshold value with 10% yield reduction of 3 dS m$^{-1}$ for kikuyu (Yiasoumi et al., 2005).

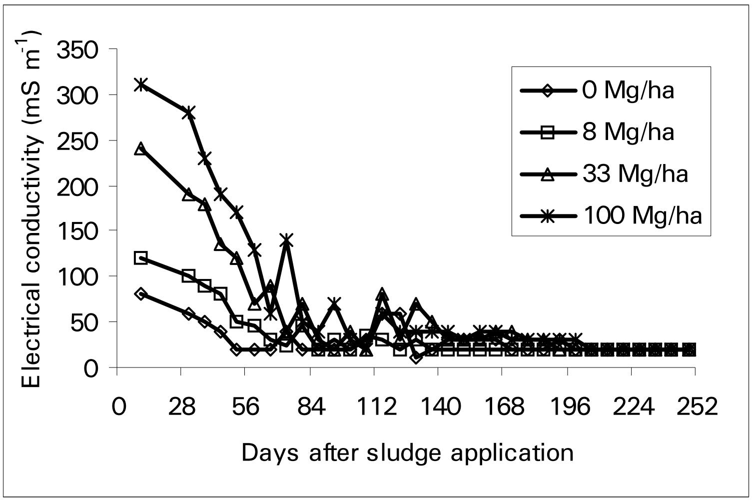



**Figure 4.17** EC of soil solution samples collected by the 0.3 m deep WFDs in a turfgrass sod field trial during the 2006 growing season

For soil solution samples from the 33 and 100 Mg ha$^{-1}$ treatments, the EC dropped very fast at the beginning of the season (similar results and trends were recorded during 2005: data not shown). This indicates that most of the salts added through the sludge were leached below the active root zone during the first 60 to 84 days after application. This was mainly because of the high leaching fraction (0.27 in 2005 and 0.3 in 2006) experienced during those periods from irrigation and rainfall.

The requirement to leach salts is the most difficult aspect of managing large volume sludge applications. Based on the EC of soil water and the growth studies, the leaching fraction could have been reduced. It may also be necessary to apply the sludge in two applications, and delay the second application until low nitrate is measured in the WFDs. This high leaching fraction, however, could simulate worst case scenarios.

*Nitrate measurement and leaching*

In the beginning of the season, soil solution nitrate concentration increased with sludge application rate. This is to be expected as nutrient supply far exceeds demand directly after sod harvest. Later during the season, the concentration of nitrate remained at low levels, presumably because the greater demand from the turf matched the mineralization rate from the sludge (Figure 4.18).

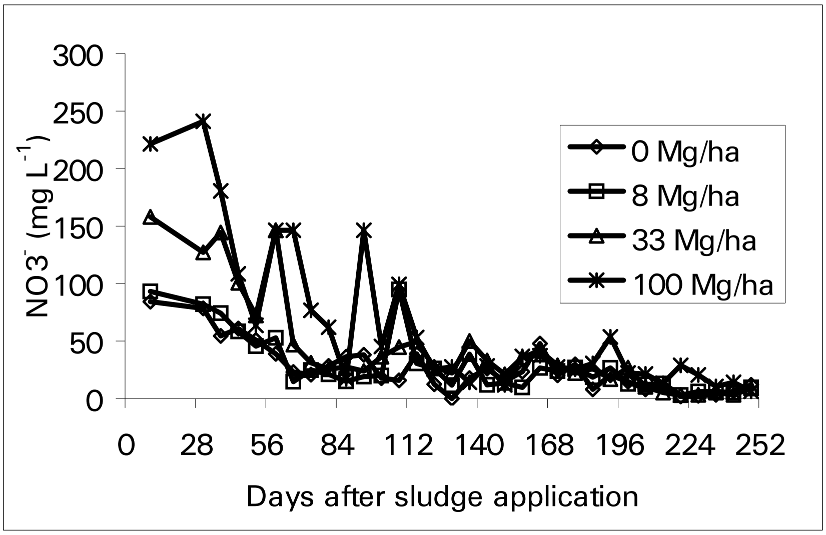



**Figure 4.18** $NO_3^-$ concentration of soil solution samples collected by the 0.3 m deep WFDs in a turfgrass sod field trial during the 2006 growing season

Similar results and trends were recorded during 2005 (data not shown). Generally, the concentrations of nitrate in the soil solution from all treatments were within the ranges reported by Biró et al. (2005) for leachate from organic and conventionally managed horticultural lands (0-255 mg $l^{-1}$ $NO_3^-$). It was also less than the maximum nitrate concentration in leachate from a simulated golf green (376 mg $l^{-1}$ $NO_3^-$) reported by Shuman (2001).The concentration of nitrate leachate from all treatments remained higher than South African drinking water standards (44 mg $NO_3^-$ $l^{-1}$) (Korentajer, 1991) for the first two to three months in the 100 Mg $ha^{-1}$ sludge treatment. The WFDs installed at 60 cm depth, however, did not collect soil solution samples from any of the treatments. Therefore, it was not clear whether the nitrate that passed the WFD at 30 cm, had leached below the WFD at 60 cm, perhaps in a weak front below the detection level of the WFD, or was stored between the two depths. The seasonal average nitrate leachate concentrations for the 0, 8, and 33 Mg $ha^{-1}$ sludge treatments

(26, 29, and 43 mg $NO_3^-$ $l^{-1}$ respectively) were less than the South African drinking water standard (44 mg $l^{-1}$) (Korentajer, 1991) and the EU nitrate concentration limit for groundwater (50 mg $NO_3^-$ $l^{-1}$) (Vlassak and Agenbag, 1999). The seasonal average nitrate concentration for the 100 Mg $ha^{-1}$ treatment (63 mg $NO_3^-$ $l^{-1}$), however, exceeded both limits. Compared with the zero sludge treatment, the addition of 8, 33, and 100 Mg $ha^{-1}$ sludge increased the average seasonal nitrate concentration of the leachate by 3, 17 and 36 mg $NO_3^-$ $l^{-1}$, respectively.

**4.4 DISCUSSION**

For the lysimeter and sludge application trials, using WFDs to guide irrigation management was judged to be successful as the crops were judged to be unstressed and drainage did not occur before the onset of the rainy season. Although not used to guide irrigation management in the commercial orchards, detectors placed at different depths did provide useful information on irrigation performance. In the same way regular measurement of EC at different depths in the soil profile also provided interesting insights into water management and salt movement in the different cropping systems. In many cases salt migration from one depth to another could clearly be observed, especially following fertilization. Decreases in EC after fertilization could also be as a result of crop uptake and soil adsorption.

It was hypothesized that lower EC values would be obtain in WFDs than in SCs for several reasons, including: (a) Bypass flow in macropores may be expected to have a lower concentration than the resident concentration across all pores, (b) SCs sample a smaller pore size volume that can be expected in most cases to have a higher EC after a strong wetting front has passed, and (c) Salts may further concentrate in the time between irrigation and sampling if there is a decrease in water content. Interestingly, this was not always the case. Several explanations for this could be possible. During drying out of soil water salts are concentrated. Then during a wetting event, the ‘front’ of the wetting front moves this high concentration down, especially in coarser textured soils, resulting in a relatively higher concentration entering the WFD reservoir. This could especially be the case if a salt plume is just above the depth of the WFD, and if the soil was relatively dry before the irrigation event as opposed to a wetter soil. It could also occur that salts are pushed past the depth in question by the wetting front (as detected by the WFD) resulting in a lower concentration than before (as detected by SCs when sampled later). This could be especially applicable in this case due to the slow rate of irrigation application used in order to achieve greater uniformity. In a subsequent sampling event the SC would be expected once again to be higher that the WFD EC, and this was not often the case. There could also have been an accumulation of salts in the funnel section of the funnel part of the WFD, which did not leave this area as the water did with diffusion as a driving force. Although the lysimeters have a relatively small volume (6.1 $m^3$), soil variability could also have contributed to differences between SCs and WFDs. Finally, the concentration of roots around WFDs, SCs or automated sensors could have contributed to surprising differences between EC or $NO_3^-$ values.

Poor correlation between SC and WFD EC values as assessed for the lysimeter trial does not mean that either is unsuitable for monitoring EC in soils. High correlation between SC and WFD EC values has been observed in similar trials. Furthermore, in this trial as well as in the aforementioned trails, both SCs and WFDs were able to clearly reflect trends of increases/decreases in soil salinity. For certain periods of the season, excellent correlation was often observed between the EC measured by the capacitance sensors and or EC values measured from the SCs and/or WFDs.

High increases in EC values were recorded following the application of fertilizer. For the lysimeter trial, EC values as high as 5.2, 3.5 and 5.2 were observed for the SL (WFD 15cm), SCL18 (SC 15 cm) and SCL26 (SC 15 cm) soils, respectively. For the commercial orchards, mean EC values were observed to rise to 3.2, 2.7 and 1.6 for the peach, plum and nectarine orchards, respectively, while in sludge application trial, a sludge application of 100 Mg $ha^{-1}$ led to an EC of 3.1 $dSm^{-1}$. Generally, higher ECs should therefore be expected in systems receiving inorganic as opposed to organic fertilizers. Kaledhonkar and Keshari (2006) pointed out the importance of maintaining low salinity levels at the time of germination as to not negatively affect the seedling emergence rate. Although seedlings were transplanted into the lysimeters for this trial and most likely not affected by the high EC values, the data does suggest that high fertilizer applications at planting can cause increases in EC which could potentially reduce seedling emergence rate.

At planting, especially when the land has lain fallow for a significant period, soil $NO_3^-$ levels may be significantly high enough as a result of mineralization not to warrant immediate N fertilizer application. The same may also apply for plant available P levels, especially if little significant rainfall has occurred over this period. This strategy might be of particular benefit when high rainfall is expected at the commencement of the growing season.

For all trials and treatments, an actively growing crop led to very low NO3- concentrations in the root zone. For the lysimeter trial, N fertilizer applications of either 10 or 30 kg $ha^{-1}$ did not always cause drastic increases in $NO_3^-$ concentrations as detected by either SCs or WFDs. This was also observed in the commercial orchard trial, and indicates a fertilizer 'disappearance' phenomenon, and has also been observed for other scenarios (Groot and De Willigen, 1991). According to Benbi and Richter (2002), high fertilizer disappearances in early spring may be due to initial N immobilization by dormant microbial biomass. Assuming 30 kg N $ha^{-1}$ of fertilizer is applied as soluble N, the increase in $NO_3^-$ concentration in a surface layer 15 cm deep at 0.24 VWC can theoretically be expected to increase by 370 mg $l^{-1}$. Absence of this increase is most likely due to very rapid active uptake by the crop. Higher $NO_3^-$ concentrations were observed in water samples collected by SCs than WFDs. This must be considered when using WFDs to guide management decisions as crop roots may therefore actually be exposed to higher $NO_3^-$ concentrations than detected by the WFDs.

Although positive correlations between EC and $NO_3^-$ were not always very high, trends for EC and $NO_3^-$ were observed to be similar in many cases, especially for the SCs. It therefore does seem plausible that monitoring EC can not only be useful to manage salinity build-up, but also as a surrogate for estimating the 'N status' a soil. Overall, correlations were observed to be much higher for the SCL18 soil than for the SL and SCL26 soils. This indicates that this approach may be more applicable in soils with a specific texture. Such a management approach will require further research, however.

$PO_4^{2-}$ concentrations were observed to fluctuate far more than for EC and $NO_3^-$ values. This may have been due to soil P sorption processes taking place between sampling events. Such fluctuations may need to be taken into account when interpreting P concentrations obtained from WFDs. The effect of added fertilizer P on increasing P concentrations in samples collected by WFDs does seem apparent. A better understanding of this will require further research, including establishing datasets spanning over a longer term. Establishing P concentration thresholds that can inform fertilization management also requires further studies.

## 4.5 CONCLUSIONS

A large body of work has now been done on the use of WFDs to monitor soil water EC and $NO_3^-$ concentrations, and to a lesser extent P concentrations. In almost all scenarios, the WFDs responded well to irrigation events, and the detectors showed good reliability in obtaining samples under a wide range of cropping systems. In many cases EC and $NO_3^-$ values obtained from SCs and from WFDs were highly similar and clearly displayed the same trends occurring in the soil. A better match between SC and WFD EC for the commercial orchard trial than for the lysimeter trial may have been due to the daily, drip irrigation system used in the orchards, compared to the sprinkler type irrigation used in the lysimeter trial, mostly on a weekly basis.

For the commercial trial in 2008, when automated EC sensors were installed into the WFDs, high EC values were observed in the second half of the growing season in all cases. Although a build-up of salts in the profile can be expected due to addition with irrigation, we are uncertain that the sensors continued to measure EC accurately. Nonetheless the automated sensors show great potential as a cheap, effective method of measuring soil water EC.

WFDs were successfully used to improve understanding of the leaching of salts and $NO_3^-$ in a system to which high rates of municipal sludge had been applied. The use of WFDs as an important management tool in these types of disposal systems therefore shows great potential in driving both irrigation and sludge application strategies.
The use of threshold EC and $NO_3^-$ values, as detected in WFDs, shows great potential but is still in its infancy. This could lead to a 'reactive management strategy' that may lead to more efficient farming, both economically and environmentally. Much work

has been done on determining the effect of increases in soil EC (determined by the saturated paste method) and decline in crop yield. This work and new research must be adapted to establish crop-specific EC thresholds as measured in WFDs. Less work has been done on establishing $NO_3^-$ thresholds at which no crop N stress will take place. This should also be a priority for new research on WFDs.

# CHAPTER 5 – TRAINING PACKAGE

## 5.1 OVERVIEW

The WFD certainly captured the imagination of irrigators. Although we could not hope to sustain the sales of the first few couple of years, we are concerned about a decline in annual sales over the past several years.

It is probable that the WFD did not deliver on all of its perceived promises. Yet our accumulating research experience tells us that when deployed and interpreted correctly, the WFD continues to provide valuable information. We know a lot more about WFDs than we did when the product was released, and believe this understanding needs to be communicated to users; hence the development of this training package.

We see the training package as different from the usual marketing that takes place in the private sector. This is because the WFD is a general learning and teaching tool. For example it can be used to help organise the existing knowledge of irrigators and provide a framework for understanding data from other tools.

The training package is laid out as a PowerPoint presentation containing 10 modules each with five slides. Each module is a concise summary of principles, complemented by real on-farm case studies. The package is not stand alone – it requires a trained facilitator to lead a group of irrigators. We hope to be able to start rolling out this training over the next 12 months.

The ten parts of the training package are laid out below and the content presented on the following pages as two slides to a page.

Part 1: Wetting front detectors (WFD)
Part 2: Using a WFD
Part 3: Irrigation scheduling with a WFD

Part 4:  Soil solution monitoring

Part 5:  Electrical conductivity monitoring

Part 6:  Salt leaching case studies

Part 7:  Irrigation / salt case study

Part 8:  Managing nitrogen

Part 9:  Nitrate case study

Part 10: Solute Signatures

These PowerPoint slides are presented in Appendix 5.1.

We acknowledge the "Solute Signatures Master Class" developed through the CRC for Irrigation Futures, from which some of the material was drawn.

# CHAPTER 6 – CONCLUSIONS AND RECOMMENDATIONS

The revised objectives of this project have, to a large extent, been reached, and are discussed separately below.

## 6.1 TUBE DETECTOR DESIGN AND FILL MATERIALS

The accurate determination of water retention characteristics and unsaturated hydraulic conductivity are required for selecting a wick material for the proper operation of a Tube Detector (TD). After testing various wicking materials, diatomaceous earth was identified as the best wick material in terms of its high entry potential at least over a tension of 100 cm. Very fine sand was identified to be the most conductive for tensions less than 80 cm and implies a suitable wick material for tube lengths < 80 cm.

Field studies indicated there was equilibrium between contact material and bulk soil tensions although wick materials were slightly wetter than bulk soil at 60 and 90 cm depths, and drier than bulk soil at 30 cm depth. For tubes filled with DE, the water level in the tube was linearly related to the contact material tension ($r^2$ = 0.73-0.98), and for Tube Detectors filled with very fine sand ($r^2$ = 0.69-0.84).The assessment of the accuracy of TD60 and TD90 tube lengths to measure soil tension has been confirmed statistically, ($P$ = 0.05) with a mean tension difference of ± 3 cm, which was not significant. Hence, tube detectors can be used as tensiometers.

## 6.2 WFD POSITIONING IN FURROW IRRIGATION

The on-station sensitivity analysis experiments confirmed that Tube Detector sensitivity is proportional to its length, according to theory. The TD of 90 cm length (TD90) was the most sensitive, while the TD30 was the least sensitive and is not a viable option.  There was a good agreement over time between the suction pressure measured in the TD wick and the surrounding soil, within the measurement range of the Tube Detector.  As expected, the 60 and 90 cm Tube Detectors collected water from fronts not detected by the FullStop WFDs placed at the same depths in the soil profile.

Tube Detector placement depth and positioning (in the furrow, on the ridge or shoulder), were investigated in on-station experiments at the University of Venda. Transects of TDs were installed at different placement depths (30, 60 and 90 cm below the soil surface) and distances from the furrow centre, using TD60s and TD90s. FullStops were installed on the test furrows shoulders for sensitivity comparison with TDs.

Best response frequencies for both TD versions (TD90 and TD60) were observed at the closest distance to the furrow centre (15 and 45 cm) and 60 to 90 cm placement depths. Soil properties may influence the ideal positioning of WFDs across the furrow. However, we suggest for most soils that the TD be placed not more than one third the furrow spacing away from furrow centre, and 60 to 90 cm deep.

A very strong linear relationship ($R^2$ = 0.98) was noted between measured suction pressures and the volume of water collected. This confirms that the theory that the volume of water collected in a TDs is proportional to the suction pressure in the soil or wick material.

The on-farm evaluation of Tube Detectors was conducted on the Dzindi Irrigation Scheme. The results showed highly variable responses. At one extreme the Tube Detectors were full of water at all depths for the entire season. At the other the shallow Tube Detectors barely collected any water at all. This strongly suggests that haphazard irrigation practices would be compromising yields – both too much and too little water.

Our vision for the TD is that small scale farmers could use them using in a 'dip stick' mode. After irrigation they would lower a rod down the central tube of the TD. If it comes up with a wet mark, they know that the irrigation reached the required depth. If not, they would apply more water next time or shorten the time interval to the next irrigation. They would also 'dip' the TDs prior to irrigating. If a TD contained water, and the roots were at that depth, then no irrigation would be required. By combining this information with the local knowledge of the farmer, the condition of the crop, plus the involvement of extension staff, local 'rules' could be developed on what kind of TD response gave the best outcome.

## 6.3 SOLUTE MONITORING

FullStop WFDs have been observed to function very well as solute monitoring tools under a variety of different types of irrigation systems. The consistency under which samples are collected, no requirement for the application of any force before samples are collected, ease of sample extraction, and sampling of the wetting front adds several pluses to the use of FullStops over conventional methods. In many cases, good general correlations between solute concentrations in FullStops and in suction cups installed at the same depth were observed. In some cases correlation was not good, even negative for certain periods of the growth season. This can be attributed to the different mechanisms used to collect samples. Installing FullStops at different depths in a soil profile often produced excellent data on the vertical movement of solutes in the soil. The presence of solutes at different depths in the soil profile, termed solute signatures, can provided valuable information on whether over- or under-irrigation is taking place. High potential has been observed in developing an N fertilization management strategy based on N levels measured in FullStop water samples. For an actively growing crop, the addition of N fertilizer was often not reflected in the FullStops, even when placed at 15 and 30 cm depths.

From the knowledge gained from research conducted during this project and other prior research, a comprehensive training package in the form of PowerPoint slides has been prepared. It is envisaged that this training will provide great insight to farmers on water, salt and nutrient management and lead to better management practices.

## 6.4 FUTURE RESEARCH NEEDS

Although originally promoted as a stand-alone irrigation scheduling tool, the WFD has essentially become more of a learning tool, useful in reflecting the consequences of a current management approach. It can function to involve the interplay between experienced farmers and objective feedback to determine the outcome of adjusting certain management practices. These learnings can then be built into management rules, such as irrigate until a specific detector responds once a week, or do not allow a deep detector to respond when nitrate levels are high. WFDs can also be used in an integrated approach, in which various irrigation scheduling 'tools' can revolve around objective WFD responses. These 'tools' include farmer experience, atmospheric scheduling (requires weather station input), soil moisture monitoring and soil water EC and nutrient status monitoring. Such a multi-level, integrated approach can then reduce the complexity of getting irrigation scheduling right.

Further research activities should definitely involve training farmers in the use of WFDs as learning tools. Feedback that is collected can be used to further improve training. It is believed that such activities conducted will also facilitate dialogue between scientist and consultants with farmers and lead to better overall management practices.

The FullStop has been observed to perform very well as a passive lysimeter under many different irrigation scenarios, and can be highly useful to farmers and researchers alike in monitoring soil solute levels. It is believed that further work on determining soil water salt and nutrient concentration thresholds for optimal crop production will be highly beneficial to farmers.

# REFERENCES


ARC (AGRICULTURAL RESEARCH COUNCIL) (2006) Flood irrigation systems: Furrow irrigation. Available online: http://www.arc.agric.za/institutes/ili/main/publications/articles/floodfurrow.htm

BENBI DK and RICHTER J (2002) A critical review of some approaches of modelling nitrogen mineralization. *Biol. Fert. Soils* 35 168-183.

BHABANI SD WRAITH JM and INSKEEP WP (1999) Nitrate concentrations in the root zone estimated using time domain reflectometry. *Soil Sci. Soc. Am. J.* 63 1561-1570.

BIGELOW C BOWMAN DC and CASSEL DK (2004) Physical properties of three sand size classes amended with inorganic materials or sphagnum peat moss for putting green root zones. *Crop Sci. Soc. Am. J.* 44 900-907.

BIRÓ B, VARGA G, HARTL W and NÉMETH T (2005) Soil quality and nitrate percolation as affected by the horticultural and arable field conditions of organic and conventional agriculture. *Acta. Agr. Scand. B-S P.* 55 111-119.

BROUWER C, GOFFEAU A and HEIBLOEM M (1985) Irrigation Water Management: Training Manual No. 1 - Introduction to Irrigation. Food and Agriculture Organization of the United Nations, (FAO), Rome, Italy. Available online: http://www.fao.org/docrep/R4082E/r4082e00.htm#Contents

CAHOON, J, and EISENHAUER, D., (1995). Fine tuning furrow irrigation systems. Nebraska Cooperative Extension NF93-118. Available online: http://ianrpubs.unl.edu/irrigation/nf118.htm

CORWIN DL and LESCH SM (2003) Application of soil electrical conductivity to precision agriculture: Theory, principles and guidelines. *Agron. J.* 95 455-471.

DEPARTMENT OF SOIL and CROP SCIENCES (2005) Land judging in Colorado. Colorado State University Available online: http://www.agsci.colostate.edu/pdf/land_judging_2005.doc

DEPARTMENT OF WATER AFFAIRS and FORESTRY (1997) Overview of Water Resources Availability and Utilisation in South Africa. CTP Book Printers (Pty) Ltd: Cape Town.

FLÜHLER H, DURNER W and FLURY M (1996) Lateral solute mixing processes - A key for understanding field-scale transport of water and solutes. *Geoderma* 70 165-183.

GROOT JJR and DE WILLIGEN P (1991) Simulation of the nitrogen balance in the soil and a winter wheat crop. *Fert. Res.* 27 261-272.

HOPMANS JW and BRISTOW KL (2002) Current capabilities and future needs of root water and nutrient uptake modelling. *Adv. in Agron.* 103 103-183.

HORST MG, SHAMUTALOV SS, PEREIRA LS and GONCALVES JM (2005) Field assessment of the water saving potential with furrow irrigation in Fergana, Aral Sea basin. *Agric. Water Manag.* 77 210-231.

ICID (INTERNATIONAL COMMISSION ON IRRIGATION and DRAINAGE) (1997) The Watsave Scenario. Available online: http://www.icid.org/ws_scenario.pdf

KALEDHONKAR MJ and KESHARI AK (2006) Modelling the effects of saline water use in agriculture. *Irrig. and Drain.* 55 177-190.

KORENTAJER L (1991) A review of the agricultural use of sewage sludge: Benefits and potential hazards. *Water SA* 17 189-196.

LITAOR MI (1988) Review of soil solution samplers. *Water Resour. Res.* 24 727.

LORENTZ S, GOBA P and PRETORIUS J (2001) Hydrological Processes Research: Experiments and Measurements of Soil Hydraulic Characteristics. WRC Report no: K5/744, Pretoria, South Africa.

MAAS EV and GRATTAN SR (1999) Crop yields as affected by Salinity. I: R.W. Skaggs and J. van Schilfgaarde, (Eds) Drainage of Agricultural Lands. Agronomy Monographno. 38. American Society of Agronomy. 677 S. Segoe Rd. Madison, WI 53711.

MAEKO TC, ANNANDALE JG, STEYN JM, and STIRZAKER RJ (2003) Wetting front detectors: an innovative way to manage irrigations. SASCP, SAWSS, SSSSA Joint Congress. 20-23 January, Stellenbosch, South Africa.

MAEKO TC, STIRZAKER RJ, ANNANDALE JG and STEYN JM (2004) Irrigation management with wetting front detectors. SASCP Congress. 22-25 January, Bloemfontein, South Africa.

MAGID J and CHRISTENSEN N (1993) Soil solution samples with and without tension in arable and heathland soils. *Soil Sci. Soc. Am. J.* 57 1463-1469.

MANSOUR MMF (1997) Ceel permeability under salt stress. In: Jaiwal PK, Singh RP and Gulati A (eds). Strategies for improving salt tolerance in higher plants. P. K. Jaiwal, R.P. Singh, and A. Gulati, Eds. Science Publ., Inc. Enfield, NH 03748. 87-110 pp.

MPUISANG T, ANNANDALE JG, STIRZAKER RJ and STEYN JM (2004) Sensitivity analysis of a wetting front detector. SASCP Congress. 22-25 January, Bloemfontein, South Africa.

MUALEM Y (1976) A new model for predicting the hydraulic conductivity of unsaturated porous media. *Water Resource. Res.* 12 513-522.

NICHOL CF, ROWLETT DK and BARBOUR SL (2008) A new standpipe lysimeter design for measurement of soil matric Suction. *J. Vadose Zone* 7 919-929.

NIEDERHOLZER F and LONG L (1998) Simple irrigation scheduling using the "look and feel" method. Oregon State University Extension Service.

NKGAPELE RJ, ANNANDALE JG, JOVANOVIC NZ, STEYN JM and STIRZAKER RJ (2003) Simple irrigation scheduling using the Soil Water Balance model (SWB) and wetting front detectors (WFD). SASCP, SAWSS,

PARAMASIVAM S, ALVA AK and FARES A (1997) Vadose zone soil solution sampling techniques to investigate pollutant transport in soils. *Trend. Soil Sci.* 2 115.

PASTERNAK D (1987) Salt tolerance and crop production – a comprehensive approach. *Ann. Rev. Phytopath.* 25 271-291.

PATRIQUIN DG, BLAIKIE H, PATRIQUIN MJ and YANG C (1993) On-farm measurements of pH, electrical conductivity and nitrate in soil extracts for monitoring coupling and decoupling of nutrient cycles. *Biol. Agric. Hort.* 9 231-272.

PRAIS (PROGRAMME FOR AGRICULTURAL INFORMATION SERVICES) AND CTA (TECHNICAL CENTRE FOR AGRICULTURAL and RURAL CO-OPERATION) (2000): Modern design techniques to improve traditional irrigation methods. Agri-Outreach Vol. 3, No 3. University of the Free State, Bloemfontein, South Africa. Available online: http://www.uovs.ac.za/support/library/prais/News15.php

RAGHUWANSHI NS and WALLENDER WW (1998) Optimal Furrow Irrigation Scheduling Under Heterogeneous Conditions. Elsevier Science. September 1998, vol. 58, no. 1, pp. 39-55(17). Available online: http://www.ingentaconnect.com/content/els/0308521x/1998/00000058/00000001/art00030

RAINE SR and BAKKER DM (1996) Better design and management of irrigated canefields. Australia. Available online: http://www.usq.edu.au/users/raine/BS90S.htm

REDDY JM and CLYMA W (1983) Choosing optimal design depth for surface irrigation systems. *Agric. Water Manag.* 6 335-349.

SAS INSTITUTE (1999-2001) SAS user's guide: Statistics.8$^{th}$ ed. SAS Ins., Cary, NC.

SHANER DL and BOYER JS (1976) Nitrate reductase activity in maize (Zea mays L.) leaves. I. Regulation by nitrate flux. *Plant Phys.* 58 499-504.

SHUMAN LM (2001) Phosphate and nitrate movement through simulated golf greens. *Water Air Soil Poll.* 129 305-318.

SIMMONS KE and BAKER DE (1993) A zero-tension sampler for the collection of soil water in macropore systems. *J. Environ. Qual.* 22 207-212.

SMIL V (1999) Nitrogen in crop production: an account for global flows. *Global Biogeochem. Cycl*. 13 647-662.

SMIL V (2000) Phosphorus in the environment: natural flows and human interferences. *Annu. Rev. Energy Environ.* 25 53-88.

SNYMAN HG and JE HERSELMAN (2006) Guidelines for the utilization and disposal of wastewater sludge, Volume 2: Requirements for the agricultural use of wastewater sludge. WRC Rep. TT 262/06.Water Research Commission, South Africa.

SOIL CLASSIFICATION WORKING GROUP (1991) Soil classification. A taxonomic system for South Africa. Dept. of Agric. Development, Pretoria, South Africa.

SOLOMON KH (1993) Irrigation systems and water application efficiencies. Irrigation Australia, Autumn. 6-11 pp.

SOUTH AFRICAN CONSULATE GENERAL (2003) Water affairs and forestry. Available online: http://www.southafrica-newyork.net/consulate/wateraffairs.htm

SOUTH AFRICAN INSTITUTE FOR AGRICULTURAL ENGINEERING (2003) Irrigation design manual. Agricultural Research Council, Pretoria, South Africa

SOUTH AUSTRALIAN RESEARCH AND DEVELOPMENT INSTITUTE – SARDI, (2001). Scheduling. South Australia. Available online: http://www.sardi.sa.gov.au/pages/horticulture/apricot/hort_apri_scheduling.htm:sectID=141&tempID=83

STEYN JM, ANNANDALE JG, STIRZAKER RJ, and NKGAPELE J (2004) SWB generated calendars for irrigation management by resource-poor farmers. SASCP Congress. 22-25 January 2004, Bloemfontein, South Africa.

STEYN JM, STIRZAKER RJ, ANNANDALE JG, JOVANOVIC NZ and MAEKO TC (2002) Irrigation management with cheap and simple wetting front detectors. SASCP and SASHS Combined Congress. Cedara, South Africa.

STIRZAKER RJ (2003) When to turn the water off: scheduling micro-irrigation with a wetting front detector. Irrig. Sci. 22 177-185.

STIRZAKER RJ (2005a) Managing irrigation with a Wetting Front Detector. UK Irrig. 33 22-24.

STIRZAKER RJ (2005b) Report Deliverable 3: Report on LongStop detector tests: Unpublished progress report of WRC project K5/1574//4: Adopting the WFD to furrow irrigation.

STIRZAKER RJ (2005b). Working report No.2: Unpublished working report of the WFD project - adopting the WFD to furrow irrigation.

STIRZAKER RJ and HUTCHINSON P (1999) A new method for benchmarking salt and nitrate leaching. Final Report, National Program for Sustainable Irrigation, CSIRO, Australia.

STIRZAKER RJ and HUTCHINSON PA (2005) Irrigation controlled by a wetting front detector: field evaluation under sprinkler irrigation. Aust. J. Soil Research 43 935-943.

STIRZAKER RJ HUTCHINSON PA and MOSENA ML (2000) A new way for small farm irrigators to save water. In: Proceedings of the 6th International Micro-irrigation congress, 23-26 October, 2000, Cape Town. South African National Association of Irrigation and Drainage, Cape Town. 1-10 pp.

STIRZAKER RJ, ANNANDALE JG, STEVENS JB, STEYN JM and MAEKO TC (2004a) The Fullstop wetting front detector. SASCP Congress. 22-25 January, Bloemfontein, South Africa.

STIRZAKER RJ, STEVENS J, ANNANDALE J, MAEKO T, STEYN M, MPANDELI S, MAUROBANE W, NKGAPELE J and JOVANOVIC N (2004b) Building Capacity in Irrigation Management with Wetting Front Detectors. WRC Report No. TT 230/04.

STIRZAKER RJ, STEVENS JB, ANNANDALE JG and STEYN JM (2009) Stages in the adoption of a wetting front detector. www.interscience.wiley.com DOI: 10.1002/ird.472

STIRZAKER RJ, STEVENS JB, ANNANDALE JG, MAEKO TC, STEYN JM and JOVANOVIC NZ (2003b) The wetting front detector – from research to practice. ICID congress, Montpellier, France, September.

STIRZAKER RJ, STEVENS JB, ANNANDALE JG, MAEKO TC, STEYN JM and JOVANOVIC NZ (2003a) The wetting front detector – finding the balance between simplicity, accuracy and cost. SABI national congress. 6-8 May 2003. Goudini Spa, South Africa.

STIRZAKER RJ, STEVENS JB, ANNANDALE JG, MAEKO TC, STEYN JM, MPANDELI S, MAUROBANE J, NKGAPELE J and JOVANOVIC NZ (2004b) Building capacity in irrigation management with wetting front detectors. WRC Report No. TT 230/04. Pretoria, South Africa.

STIRZAKER RJ, SUNASSEE S and WILKIE J (2004c) Monitoring water, nitrate and salt on-farm: a comparison of methods. Irrigation Association of Australia 2004 conference, Adelaide.

STIRZAKER RJ and WILKIE J (2002) Four lessons from a wetting front detector. Irrigation Association of Australia 2002 conference, Sydney.

TISCHNER T, NÜTZMANN G and PÖTHIG R (1998) Determination of soil water phosphorus with a new nylon suction cup. *Bull. Environ. Contam. Toxicol.* 61 325-332.

TYNER JS and BROWN GO (2004) Improvements to estimating unsaturated soil properties from horizontal infiltration. *Soil Sci. Soc. Am. J.* 68 1-6.

USDA (1997) SRFR v3. US Department of Agriculture. US Water Conservation Laboratory, Phoenix. AZ.

VAN DEN DRIES ALJ (2002) The Art of Irrigation: The Development, Stagnation, and Redesign of Farmer-Managed Irrigation Systems in Northern Portugal. Wageningen University Dissertation.

VAN GENUCHTEN MTH (1980) A Closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Sci. Soc. Am. J.* 44 892-898.

VLASSAK K and AGENBAG GA (1999) Nitrogen dynamics in intensive and extensive agriculture. In: Vlassak K (ed.) Nitrogen dynamics in intensive and extensive agriculture proc. Bilateral workshop Flanders- RSA (Republic of South Africa) jointly organized by K.U. Leuven (Katholieke Universiteit Leuven) and RUG (Ghent University). 30 Aug - 20 Sep. Leuven, Belgium. 7-25 pp.

WALKER WR (1989) Guidelines for designing and evaluating surface irrigation systems. FAO, Rome.

WASKOM RM (1994) Best management practices for irrigation management. Colorado Department of Agriculture, and Agricultural Chemicals and Groundwater Protection Advisory Committee. Bulletin #XCM – 173. University Cooperative Extension, Colorado State University.

WATER RESEARCH COMMISSION (1996) Policy Proposal for Irrigated Agriculture in South Africa. Discussion paper prepared by Backeberg GR, Bembridge TJ, Bennie ATP, Groenewald JA, Hammes PS, Pullen RA and Thompson H. WRC Report No KV 96/96: Pretoria.

WATER RESEARCH COMMISSION (1999) Agrimarket Survey. Market Surveys and Statistical Analysis Consultants: Pretoria.

WESTERMANN DT, BJORNEBERG DL, AASE JK, and ROBBINS CW (2001) Phosphorus Losses in Furrow Irrigation Runoff. *J. Environ. Qual.* 30 1009-1015.

WRC (1997) Permissible utilization and disposal of sewage sludge. 1st ed. Water Research Commission, South Africa.

YIASOUMI W, EVANS L and ROGERS L (2005) AGFACT AC. 2, 9th ed. NSW Department of Primary Industries, Australia.

YONTS CD, EISENHAUER DE and VARNER D (2003) Managing furrow irrigation systems. Nebraska Cooperative Extension, Institute of Agriculture and Natural Resources University of Nebraska-Lincoln, USA. Available online http://ianrpubs.unl.edu/irrigation/g1338.htm

# APPENDICES

## APPENDIX 1.1 CAPACITY BUILDING AND KNOWLEDGE DISSEMINATION ACTIONS

1) Students: Degree studied – whether black or white/male or female student, whether degree is complete or on course to be completed

| Name | Black / White | Male / female | Degree | Completed | Graduation date / comments |
|---|---|---|---|---|---|
| Goitom Adhanom | Black | Male | PhD | No | Expected Sep 2010 |
| Eyob Tesfamariam | Black | Male | PhD | Yes | April 2010 |
| Michael van der Laan | White | Male | PhD | Yes | April 2010 |
| Hendrik Smith | White | Male | PhD | No | Studies aborted |
| Charles M'Marete | Black | Male | PhD | No | Not certain |

2) Knowledge dissemination outcomes ( include additional information):

| Medium | Number to date | Anticipated additional number |
|---|---|---|
| Refereed publications | 3 | 2 |
| Popular articles | 3 | 1 |
| Conference presentations | 13 | 1 |
| Workshops | 1 | |
| Other | | Several (see below) |

3) Knowledge application: Where has the knowledge generated in the project been applied and by whom. Where do you anticipate the knowledge will be applied in future?

Knowledge generated with regard to the use of Tube Wetting Front Detectors has only been applied by team members to date. It is foreseen that this will change if tube detectors get to the point of commercialization, as there is huge potential for the device as a tool to guide irrigation management in furrow irrigation systems.

A training package has been produced around the WFD as a learning tool. It will help to organise irrigator's existing knowledge, help them to make sense of new information, and helps them to develop management strategies that will improve water, salt and nitrate management. A range of training sessions ("master classes") is planned as a follow-up action.

**APPENDIX 2.1** Theory of standard Bruce-Klute test evaluation

The soil-water diffusivity curve, D (θ) can be estimated from measured imbibition curve, λ (θ), by using a Bruce-Klute test. This method assumes horizontal, semi-infinite and one-dimensional flow (Tyner and Brown, 2004). The time rate of change of water content in a horizontal column of soil during imbibition of water is expressed in the mass balance equation (Lorentz et al., 2001) as:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left( K(\theta)\frac{\partial h}{\partial x} \right) \qquad [1]$$

Due to the difficulty of solving water content and matric suction functions, a term diffusivity D (θ) is substituted in the mass balance Eq [1] to yield:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left( D(\theta)\frac{\partial \theta}{\partial x} \right) \qquad [2]$$

Where D (θ) is given as a product of $K(\theta)\left|\frac{dh}{d\theta}\right|$, and $\left|\frac{dh}{d\theta}\right|$ is the slope of water retention characteristics, x is the horizontal distance from the inlet, t is the elapsed time, θ is the volumetric water content, K (θ) is the unsaturated hydraulic conductivity, and h is the matric suction.

The initial and boundary conditions for this test are:

$\theta = \theta_i$ for $x > 0$ and $t = 0$,
$\theta = \theta_o$ for $x = 0$ and $t > 0$,
$\theta = \theta_i$ for $x = \infty$ and $t > 0$, [3]

where $\theta_i$ is the antecedent water content and $\theta_o$ is the inlet water content. A Boltzmann variable, λ, given by $\frac{x}{\sqrt{t}}$ is used to transform Eq. [2] and [3] into ordinary differential equation as:

$$\frac{\lambda}{2}\left( \frac{d\theta}{dh} \right) = \frac{d}{d\lambda}\left[ D(\theta)\frac{d\theta}{d\lambda} \right] \qquad [4]$$

Moreover, Eq. [4] becomes true when the following conditions are fulfilled,

$\theta = \theta_i$ for $\lambda = \infty$

$\theta = \theta_o$ for $\lambda = 0$ [5]

The Boltzmann variable, λ, given by $\frac{x}{\sqrt{t}}$ integrates Eq. [4] to yield,

$$D(\theta) = -\frac{1}{2}\frac{d\lambda}{d\theta}\int_{\theta i}^{\theta}\lambda d\theta \quad [6]$$

The diffusivity function can be determined from the plot of water content versus Boltzmann variable obtained from the measured data but requires integration of the curve fitted to the data. A more convenient method suggested by Lorentz et al. (2001) where a suitable analytical function is fitted to the original data as,

$$\lambda(\theta) = \left(\frac{p+1}{\theta s - \theta r}\right) S \left(\frac{1-(\theta s - \theta r)}{\theta s - \theta r}\right)^{p} \quad [7]$$

Where S is the sorptivity, p is a curve fit parameter, $\theta_s$ is saturated water content and $\theta_r$ is the residual water content.

The inlet flux, $q_0$, in the Bruce-Klute test is given by

$$q_0 = \frac{1}{2} S (\theta_i, \theta_0) t^{-1/2} \quad [8]$$

Where $q_0$ is the water flux at the inlet (x = 0) and S (θi, $\theta_0$) defined as the sorptivity which is computed as,

$$S (\theta i, \theta_0) = \int_{\theta i}^{\theta} \lambda d\theta \quad [9]$$

Substituting Eq [7] into Eq [6] that was suggested by (Lorentz et al., 2001) to compute D (θ) as:

$$\frac{\left[p (p+1) S^2 (1-\theta)^{p-1} - (1-\theta)^{2p}\right]}{2(\theta_s - \theta_r)^2} \quad [10]$$

The slope of water retention curve is then evaluated for each material in order to determine the unsaturated hydraulic conductivity. The slope is determined first by fitting a curve using the van Genucthen equation into the measured retention data, which relates water content to soil tension:

$$\theta = \left[ \frac{1}{1+(\alpha h)^{n}} \right]^{\frac{n-1}{n}} \qquad [11]$$

Then, the slope of the retention curve can then be determined with:

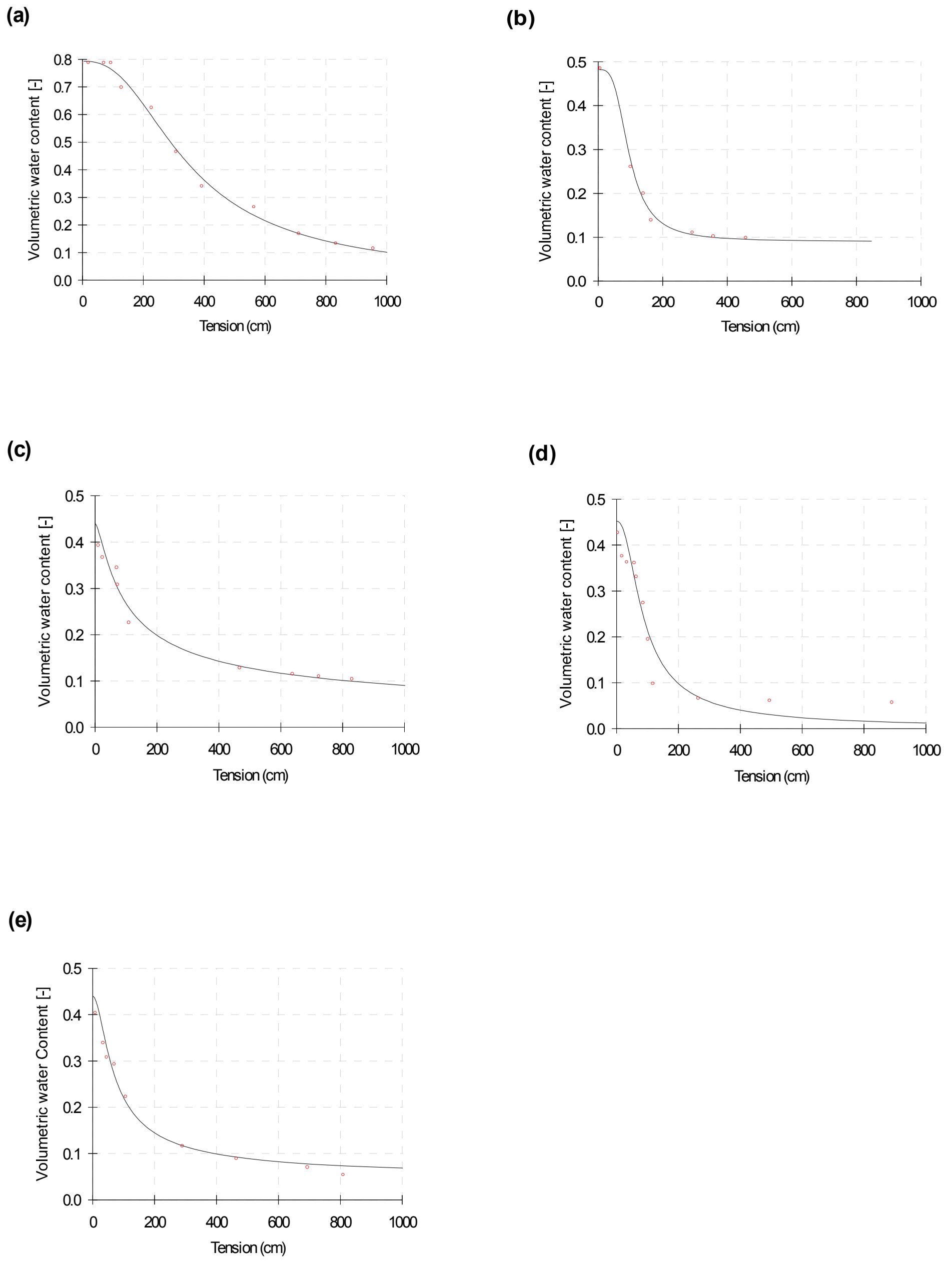
$$\frac{dh}{d\theta} = \frac{1}{\alpha(1-n)(\theta_s - \theta)} * \left[ \left( \frac{\theta - \theta_r}{\theta_s - \theta_r} \right)^{\frac{1-n}{n}} - 1 \right]^{\frac{1-n}{n}} * \left( \frac{\theta - \theta_r}{\theta_s - \theta_r} \right)^{\frac{2n-1}{1-n}} \qquad [12]$$

Where $\alpha$ and n are curve fit parameters, h = soil tension, $\theta_r$ and $\theta_s$ are residual and saturation water contents respectively.

Finally the unsaturated hydraulic conductivity was determined as

$$K(\theta) = \frac{D(\theta)}{\frac{dh}{d\theta}} \qquad [13]$$

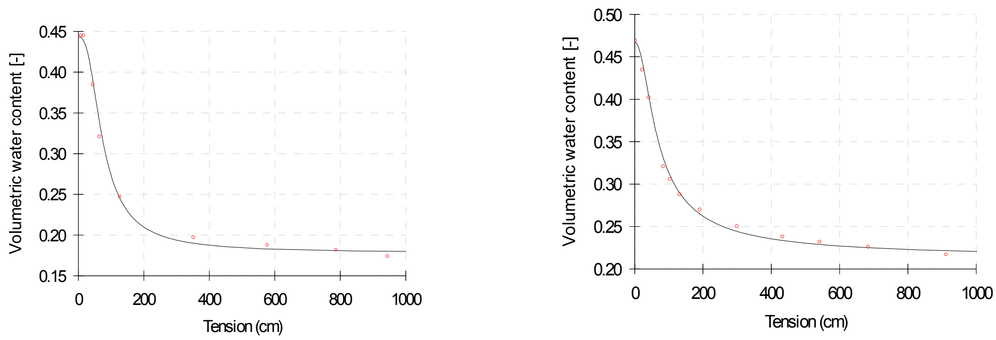
**APPENDIX 2.2** Water retention curves fitted with RETentionCurve (RETC)




method

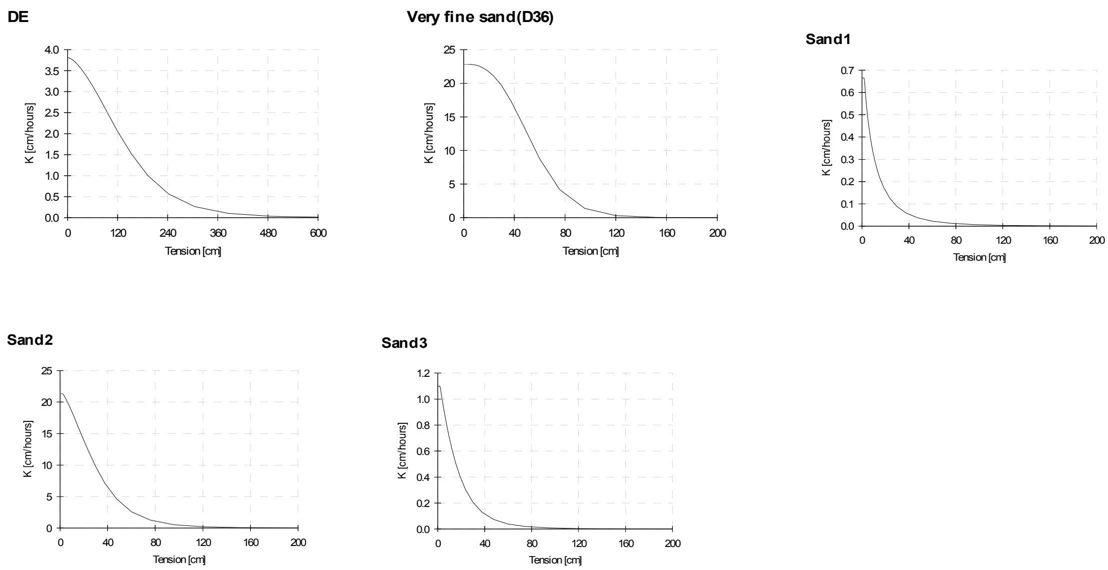
Measured retention data (dots) and corresponding best fit van Genucthen model (solid line) for the five wick materials: Diatomaceous Earth (a), very fine sand-D36 (b), Sand1 (c), sand2 (d), and Sand3 (e).

(f) (g)

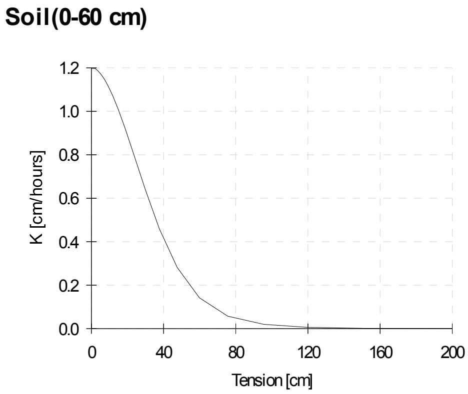


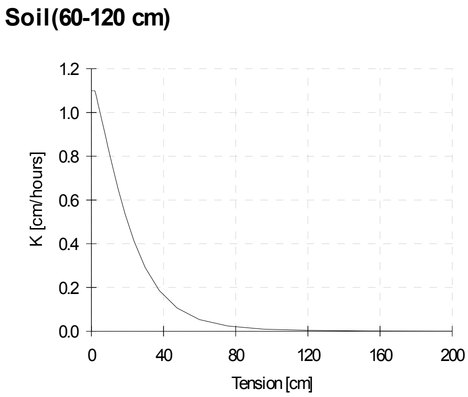

Measured retention data (red dots) and corresponding best fit van Genucthen model (solid line) for the two soil materials: 0-60 cm soil depth (f) and 60-120 cm soil depths (g)

**APPENDIX 2.3** Hydraulic conductivity curves obtained by simulating Bruce-Klute test using Hydrus-2D model




Predicted unsaturated hydraulic conductivity curves for five wick materials using Hydrus-2D model which implemented van Genuchten retention characteristics into Mualem conductivity Model



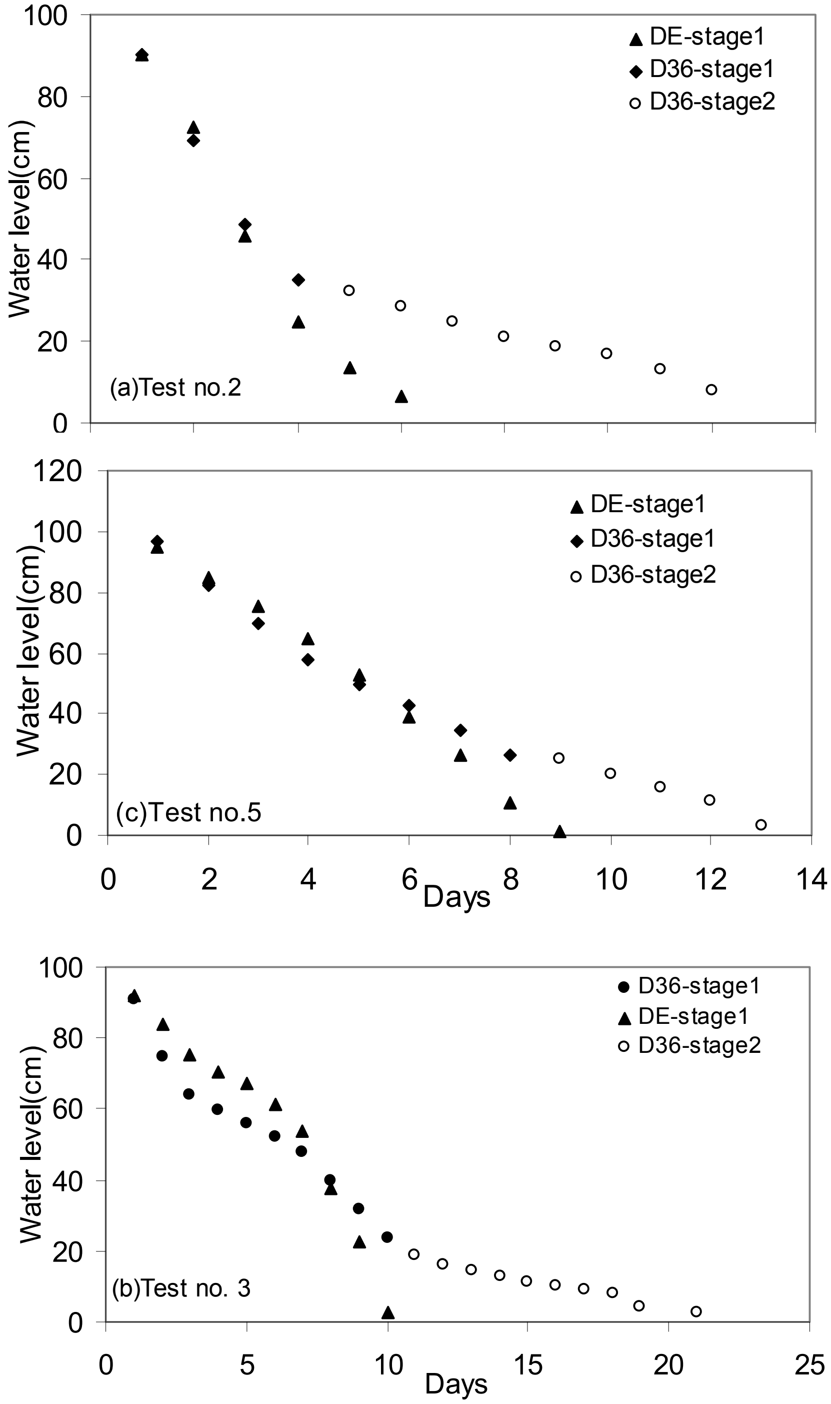

Predicted unsaturated hydraulic conductivity curves for two soil materials using Hydrus-2D model, which used van Genuchten retention characteristics into Mualem conductivity Model.

**APPENDIX 2.4** Empirical observations and correlation values

| Test no. | ***Indoor drying test (90-cm-LS)*** | | | | | | |
|---|---|---|---|---|---|---|---|
| | LS-DE | | | LS-D36 | | | |
| | Slope | $R^2$ | I-1 | Slope | $R^2$ | I-2 | *Experimentation dates* |
| 1 | -0.98 | 0.98 | 97 | -0.94 | 0.97 | 94 | *11/02/2006-12/05/2006*** |
| 2 | -1.12 | 0.95 | 96 | -1.18 | 0.92 | 105 | *30/11/2007-11/12/2007*** |
| 3 | -1.03 | 0.99 | 96 | -1.16 | 0.97 | 100 | *08/01/2008-28/01/2008*** |
| 4 | FE | FE | FE | -1.00 | 0.98 | 99 | *05/02/2008-17/02/2008*** |
| 5 | -1.03 | 0.99 | 100 | -1.03 | 0.99 | 97 | *01/03/2008-10/03/2008*** |
| *6* | *-1.07* | *0.97* | *98* | *-1.03* | *0.99* | *100* | *01/03/2008-22/03/2008** |

FE= failed to empty; ** = setup with 200 mm diameter wick placed on top of the tube opening; * = setup with 50 mm diameter wick on the tube opening; I-1 & I-2 are intercepts for D.E and very fine sand respectively.

**Water level vs. time**




Water level inside the tube regressed against time for both wick materials using 90 cm long tube (Tests no. 2, 3 and 5 as indicated in Table 2.2)

**APPENDIX 2.5** Number of responses at different soil depths for all TD designs filled with DE and very fine sand summarized on the basis of the water level > 2 cm (rainfall)

| Type | Depth (cm) | DE | | | *Very fine sand* | | |
|---|---|---|---|---|---|---|---|
| | | *Number of responses* | | | | | |
| | | Correct positive | Correct negative | False response | Correct positive | Correct negative | *False response* |
| TD45 | 30 | 9 | 25 | 8 | 4 | 35 | *3* |
| TD60 | 30 | 14 | 14 | 15 | 10 | 29 | *3* |
| TD90 | 30 | 17 | 17 | 8 | 11 | 20 | *11* |
| TD45 | 60 | 2 | 37 | 3 | 0 | 38 | *4* |
| TD60 | 60 | 3 | 34 | 5 | 0 | 37 | *5* |
| TD90 | 60 | 6 | 28 | 8 | 7 | 24 | *11* |
| TD45 | 90 | 0 | 35 | 7 | 0 | 41 | *1* |
| TD60 | 90 | 4 | 32 | 6 | 2 | 37 | *3* |
| *TD90* | *90* | *4* | *32* | *6* | *7* | *27* | *8* |

Number of responses at different soil depths for all TD designs filled with D.E and very fine sand summarized on the basis of the water level > 2 cm (sprinkler irrigation)

| | Depth (cm) | DE | | | *Very fine sand* | | |
|---|---|---|---|---|---|---|---|
| | | *Number of responses* | | | | | |
| | | Correct positive | Correct negative | False response | Correct positive | Correct negative | *False response* |
| TD45 | 30 | 43 | 127 | 34 | 23 | 145 | *36* |
| TD60 | 30 | 27 | 125 | 52 | 31 | 135 | *38* |
| TD90 | 30 | 90 | 71 | 43 | 104 | 70 | *30* |
| TD45 | 60 | 36 | 137 | 31 | 21 | 153 | *30* |
| TD60 | 60 | 42 | 124 | 38 | 21 | 148 | *35* |
| TD90 | 60 | 95 | 91 | 18 | 67 | 68 | *69* |
| TD45 | 90 | 41 | 132 | 31 | 16 | 156 | *32* |
| TD60 | 90 | 56 | 122 | 26 | 39 | 140 | *25* |
| *TD90* | *90* | *106* | *79* | *19* | *98* | *57* | *49* |

**APPENDIX 2.6 Performance evaluations by design**

Number of correct positive responses at different soil depths for Hybrid design

| Soil depth (cm) | *Number of positive responses* | | | | | |
|---|---|---|---|---|---|---|
| | D36 sand | | | *Soil* | | |
| | Rep1 | Rep2 | Rep3 | Rep1 | Rep2 | *Rep3* |
| 30 | 6 | 6 | 8 | 0 | 7 | *0* |
| 60 | 2 | 3 | 5 | 0 | 2 | *0* |
| *90* | *0* | *2* | *1* | *0* | *0* | *1* |

Number of responses at different soil depths for funnel-shaped design

| Soil depth (cm) | *Number of positive responses* | | | | | |
|---|---|---|---|---|---|---|
| | Fine sand | | | *DE* | | |
| | Rep1 | Rep2 | Rep3 | Rep1 | Rep2 | *Rep3* |
| 15 | 13 | 9 | 13 | 9 | 13 | *11* |
| 30 | 8 | 8 | 6 | 5 | 6 | *5* |
| 45 | 5 | 6 | 5 | 5 | 4 | *4* |
| *60* | *3* | *5* | *3* | *3* | *3* | *3* |

**APPENDIX 3.1:** ***Physical and chemical properties of the soil at the UNIVEN study site***

| ***A. Textural analysis*** | | | | | | | |
|---|---|---|---|---|---|---|---|
| Type of Particle | | **Particle size distribution (in %) for each soil layer** | | | | | **Texture** |
| | | **Coarse sand** | **Medium sand** | **Fine sand** | **Silt** | **Clay** | |
| Diameter of particles (mm) | | 2-0.5 | 0.5-0.25 | 0.25-0.05 | 0.05-0.002 | <0.002 | |
| **Depth of soil layer (cm)** | **0-30** | 1.7 | 2.2 | 8.3 | 31.9 | 57.5 | Clay |
| | **30-60** | 1.5 | 1.5 | 6.0 | 28.7 | 60.9 | Clay |
| | **60-150** | 1.8 | 1.5 | 6.7 | 29.9 | 59.2 | Clay |

| ***B. Bulk density*** | | | | | | |
|---|---|---|---|---|---|---|
| **Soil layer (cm)** | **0-30** | **30-60** | **60-90** | **90-120** | **120-150** | **Mean** |
| **Bulk density (kg $m^{-3}$)** | 1110 | 1140 | 1100 | 1130 | 1200 | 1136 |

| ***C. Minerology clay and chemical analysis*** | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Depth of soil layer (cm)** | **Percentages of various minerals (%)** | | | | | **Chemical analysis** | |
| | **Quartz (Qz)** | **Kaolinite (Kt)** | **Smectite (St)** | **Feldspar (Fs)** | **Hematite (Hm)** | **Carbon (%)** | **pH $H_2O$** |
| **0-30** | 0 | 99 | 1 | 0 | 0 | 1.71 | 5.44 |
| **30-60** | 0 | 80 | 20 | 0 | 0 | 0.72 | 5.37 |
| **60-150** | 0 | 64 | 29 | 0 | 7 | 0.52 | 5.54 |

| ***D. Exchangeable extractable cations*** | | | | | | |
|---|---|---|---|---|---|---|
| **Depth of soil layer (cm)** | ***Exchangeable extractable cations (me/100g soil)*** | | | | | |
| | **Na** | **K** | **Ca** | **Mg** | **S value** | **T value (CEC)** |
| **0-30** | 0.12 | 0.09 | 2.12 | 1.24 | 3.57 | 19.11 |
| **30-60** | 0.10 | 0.04 | 1.48 | 0.95 | 2.56 | 13.97 |
| **60-150** | 0.12 | 0.03 | 1.01 | 0.78 | 1.93 | 15.62 |

**APPENDIX 3.2 DESCRIPTION OF THE DZINDI IRRIGATION SCHEME**

## 3.2.1 Location of the study area

Dzindi Irrigation Scheme is one of the smallholder irrigation schemes in Limpopo Province of South Africa. According to Arcus Gibb (2004), smallholder irrigation schemes in South Africa are irrigation projects that are larger than 5 ha in size and that were either established in the former homelands or initiated in resource-poor areas by previously disadvantaged or black farmers or agencies assisting the development.

Dzindi Irrigation Scheme is located in the village of Itsani, which is situated about 12 km from Thohoyandou Town. The other adjacent villages to the scheme include Shayandima, Tshisaulu, Lwamondo and Manamani. Figure 3.2.1 shows the location of Itsani Village in which the scheme is situated.

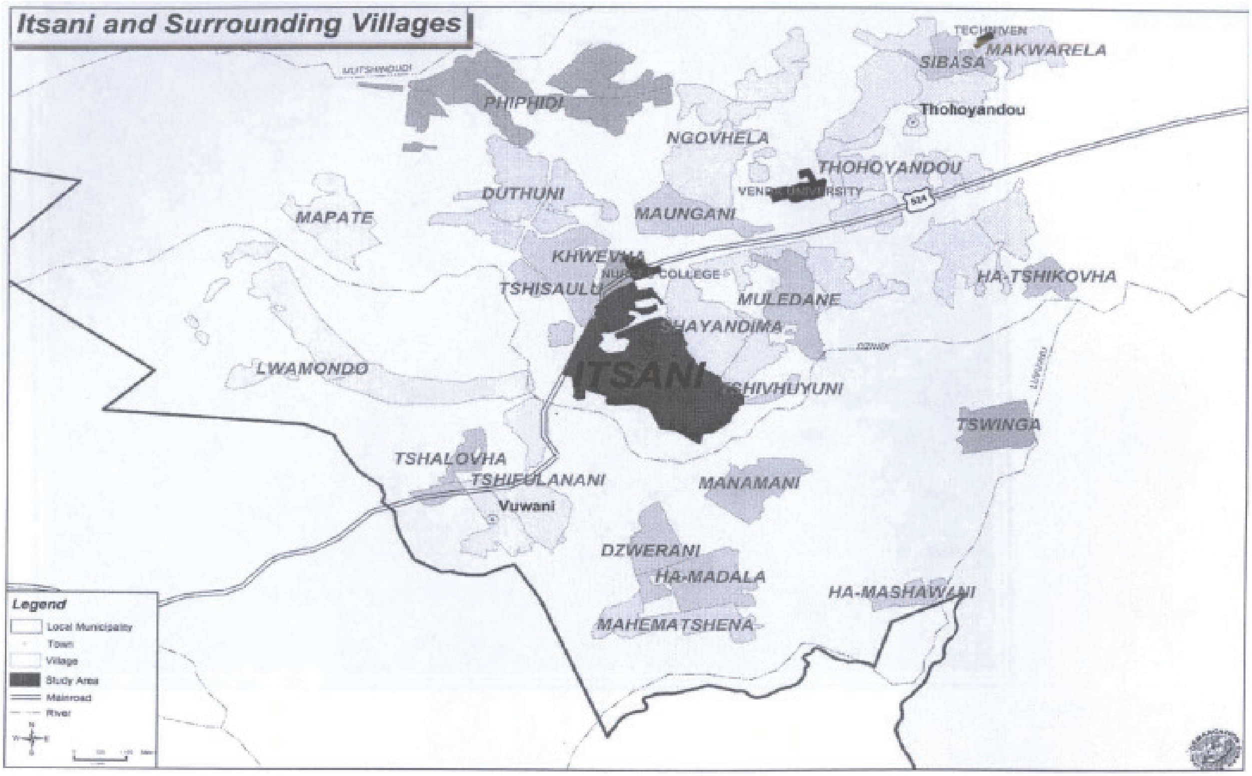



***Figure 3.2.1**: The location of Dzindi Irrigation Scheme (after Wim van Averbeke et al., 2004).*

The irrigation scheme consists of four (4) irrigation blocks with 106 plots. The distribution of plots per irrigation block is shown in Table 3.2.1. The average size of a plot is 1.28 ha bringing the total irrigated land to about 136 ha. One plot in Block 1 is used as a demonstration site. Out of the 102 farmers in the scheme, 99 own one plot each while three farmers own two plots each. The plots are subdivided into variable number of strips (beds). The numbers of strips or beds per plot ranges between 10 and 36.

*Table 3.2.1: Distribution of Plots per Irrigation Blocks in the Dzindi Irrigation Scheme*

| Irrigation Blocks | Block 1 | Block 2 | Block 3 | Block 4 | Total |
|---|---|---|---|---|---|
| Number of plots | 25 | 35 | 13 | 33 | 106 |

Plot holders practice short furrow irrigation. De Lange (1994) describes short furrow irrigation as a form of surface irrigation whereby a field is subdivided into small narrow basins separated from each other by earth ridges.

### 3.1.2 Historical background of the scheme

Dzindi Irrigation Scheme is one of the many irrigation schemes that were developed by the South African Government for small-holder black farmers. The philosophy of developing these schemes was the same all over the country. Most of these schemes did not even document historical facts of their development and Dzindi Irrigation Scheme is no exception.

In a timeline format, the historical background of the Dzindi Irrigation Scheme was reconstructed from the community's oral narration by Van Averbeke et al. (2004). Van Averbeke et al. (2004) describes "timeline" as a group activity in which participants share their recollection of important events and processes that occurred in their community. A summary of the main events leading to the establishment of the scheme and the running of the scheme is presented chronologically in Table 3.2.2.

*Table 3.2.2: Timeline of the Dzindi Irrigation Scheme*

| **Year** | **Important events** |
|---|---|
| 1940s | Talks on the establishment of the Dzindi Irrigation Scheme commenced. |
| 1951 | The personnel of the Department of Agriculture prevailed upon Chief Tshivhase who was reluctant in allowing the establishment of the scheme to embrace the idea of the scheme. |
| 1952 | Chief Tshivhase and the headmen Tshikororo and Mawasane endorsed the establishment of the scheme in a meeting. |
| 1953 | Construction of the scheme begun in Block 1 while clearing vegetation for Blocks 2&3 started |
| 1954 | Allocation of plots commenced |
| 1962 | Farmers started planting *ndodzi* (pigeon peas) instead of maize, bambara groundnuts and vegetables. |
| 1963 | A white pastor introduced hybrid maize seed to farmers. |
| 1964 | Farmers plant tomatoes for the first time. |
| 1966 - 1968 | Wheat and cotton were introduced but due to marketing problems, this farming system did not succeed. |
| 1969 - 1974 | There was reallocation of vacant plots to farmers as Venda is prepared for self-governing. The Shangaan speaking plot holders were forced to vacate their plots as they were moved to Gazankulu. |
| 1970 | Farmers not utilizing their plots were expelled from the scheme and at the same time, a diary project was started at Dzindi |

| Year | Important events |
|---|---|
| 1971 | Commencement of the era of the Venda homelands administration. |
| 1972 | Farmers were given the green lights to plant crops of their choice |
| 1976 | There was drought that resulted in low yields. |
| 1977 | There were floods that prevented people from cultivating their fields from February to June. |
| 1980 | There arose a conflict between headmen Makumbane and Tshikororo due to allocation of residential sites by Headman Tshikororo close to the main canal resulting in pollution of the canal. |
| 1981 | The dairy project that was started in 1970 collapsed. |
| 1983 | Drought, which killed livestock, continued to be a threat to farmers. |
| 1985 | The existing farmers' association was transformed into a registered cooperative. |
| 1986 | Agriven (ARDC) arranged a tomato production contract for farmers with a processing company based at Tzaneen. Large quantities of tomatoes were produced but the company purchased very little leaving farmers in debts. |
| 1989 | Scheme Management Committee (SMC) allowed progressive farmers to utilize non-irrigated land. |
| 1990 | Political uprising, which engulfed the whole country, affected activities at the Scheme as result of the youth's revolt against SMC over their parents work. |
| 1991 | The dairy project was restarted on individual farmer's basis |
| 1995 | In order to reduce the amount of water entering the main canal, people lowered the weir as a result of low flow in the Dzindi River. |
| 1998 | The government withdrew tractors from the scheme. |
| 1999 | Plot holders of Dzindi collectively purchased a tractor. |
| 2000 | The 2000 floods destroyed fences and the pipe that conveys water to the dam in Block 1. At the same time, Dzindi Co-operative ceased to exist and the dairy project collapsed again. |
| 2004 | The plot holders collectively obtained a "Permission To Occupy" certificate for the scheme as a whole. |

*Source: Van Averbeke, et al., 2004*

### 3.2.3 Topography

Dzindi Irrigation Scheme is bordered to the North by the Soutpansberg Mountains, with steep slopes and peaks that rise up to 2 000 m in some places. The scheme itself lies at about 550 m above sea level in a plateau with gently to moderately undulating landscape that is found south of the Soutpansberg Mountains.

### 3.1.4 Vegetation

According to Acocks (1988), Dzindi is located in a vegetation unit called the North-eastern Mountain Sourveld which is found along the southern edge of the Soutpansberg Mountain range. The dominant species according to van Averbeke (2004) are *Themeda triandra, Londetia simplex* and *Rendlia altera*.

### 3.2.5 The climate of the area

Dzindi Irrigation Scheme experiences semi-arid and subtropical climate (Van Averbeke et al., 2004). During summer the area tends to be quite hot becoming mild during the winter season. It receives an annual rainfall of 980 mm, which is likely the same as that of the long-term mean rainfall of Lwamondo. Most of the rain falls during the summer months from October to April as shown in Table 3.2.3. The month of February is the rainiest month.

The rainfall received in four months from November to February amounts to 669 mm accounting for 68% of the annual rainfall. From Table 3.2.3, it can also be seen that the annual evaporation standing at 1848 mm by far exceeds annual rainfall. The lowest monthly mean temperatures of about 10.2$^{o}$C are experienced in July while the monthly maximum temperatures (of 29.5$^{o}$C) are experienced in January.

### 3.1.6 Source of water and its management

In the Dzindi Irrigation Scheme, irrigation water is obtained from the perennial Dzindi River, which drains the entire project area. The river originates from the slopes of the Soutspansberg Mountains. Water is diverted from the river by means of a weir after which a conveyance concrete lined open channel (4 km in length) delivers water from the river to the project area where the water is distributed via a network of concrete parabolic secondary and tertiary canals. In Block 1, the furthest from the water source, there is a balancing earthen dam from which water is transferred to the distribution canals and the plots in that block. In all the other irrigation blocks, the main canal directly supplies water to the secondary and tertiary canals distribution canals, which brings the irrigation water to plot edge.

*Table 3.2.3: Climatic Data for Lwamondo (1990-2004)*

| | | | | | |
|---|---|---|---|---|---|
| Station number | = | 07236646 | Station name Venda | = | Lwamondo |
| Latitude | = | 23.0700° S | Longitude | = | 30.3800° E |
| Height | = | 614 m | Magisterial District | = | Vuwani |

| **Month** | **Rain-fall (mm)** | **Temperature (°C)** | | | **Pan Evapo-ration (mm)** | **Humidity (%)** | | | **Sun-shine Hours (hrs)** |
|---|---|---|---|---|---|---|---|---|---|
| | | Min. | Max. | Mean | | Min. | Max. | Mean | |
| **Jan** | 172.1 | 19.8 | 29.5 | 24.6 | 182.9 | 44.7 | 87.2 | 66.0 | 6.7 |
| **Feb** | 236.8 | 19.8 | 28.8 | 24.3 | 135.1 | 46.0 | 88.6 | 67.3 | 6.4 |
| **Mar** | 95.4 | 18.7 | 28.3 | 23.5 | 145.0 | 46.4 | 89.8 | 68.1 | 6.6 |
| **Apr** | 54.5 | 16.0 | 26.8 | 21.4 | 133.6 | 42.9 | 88.4 | 65.7 | 7.0 |
| **May** | 19.2 | 12.9 | 25.1 | 19.0 | 130.0 | 39.2 | 84.9 | 62.1 | 7.6 |
| **Jun** | 16.1 | 10.5 | 23.2 | 16.9 | 120.1 | 36.6 | 81.1 | 58.8 | 7.4 |
| **Jul** | 13.2 | 10.2 | 22.8 | 16.5 | 122.0 | 37.5 | 83.5 | 60.0 | 7.4 |
| **Aug** | 10.4 | 11.6 | 24.7 | 18.2 | 149.0 | 35.0 | 80.1 | 57.5 | 7.6 |
| **Sep** | 24.6 | 14.2 | 26.8 | 20.5 | 184.0 | 36.7 | 79.3 | 58.0 | 7.4 |
| **Oct** | 71.5 | 16.3 | 27.6 | 22.0 | 196.0 | 40.3 | 81.9 | 61.1 | 6.7 |
| **Nov** | 112.2 | 17.9 | 28.1 | 23.0 | 171.6 | 43.7 | 83.6 | 63.6 | 6.1 |
| **Dec** | 148.3 | 19.2 | 29.1 | 24.2 | 178.4 | 44.4 | 85.4 | 64.9 | 6.3 |
| **Total/ Mean** | 980.1 | 15.6 | 26.7 | 21.2 | 1847.7 | 41.1 | 85.4 | 62.8 | 6.9 |

*Source: Agricultural Geo-referenced Information System (AGIS), 2004*

A study evaluating the water distribution system of the Dzindi Irrigation Scheme was carried out by Van der Stoep and Nthai (2005). Figure 3.2.2 shows the main canal and the measuring during the above study. In their study, Van der Stoep and Nthai (2005) arrived at a number of conclusions some of which are presented below. Among others, the study:

a) showed that only 18% of the water diverted at the weir was required at field level by the actual planted crops based on climatic requirements;
b) suggests that approximately 85% of the water diverted at the weir reached the secondary canals leading to the irrigated areas (therefore the losses were 15% of the inflow)
c) states that of the 15% losses, 5.8% can be directly linked to evaporation and seepage losses, leaving 9.2% unaccounted for;
d) shows that the losses that occur in the system are mainly at block level and largely due to high return flows (including losses in the secondary canals)
e) estimated that between 50 and 70% of the water that reached the secondary canals, is return flow and not used for irrigation

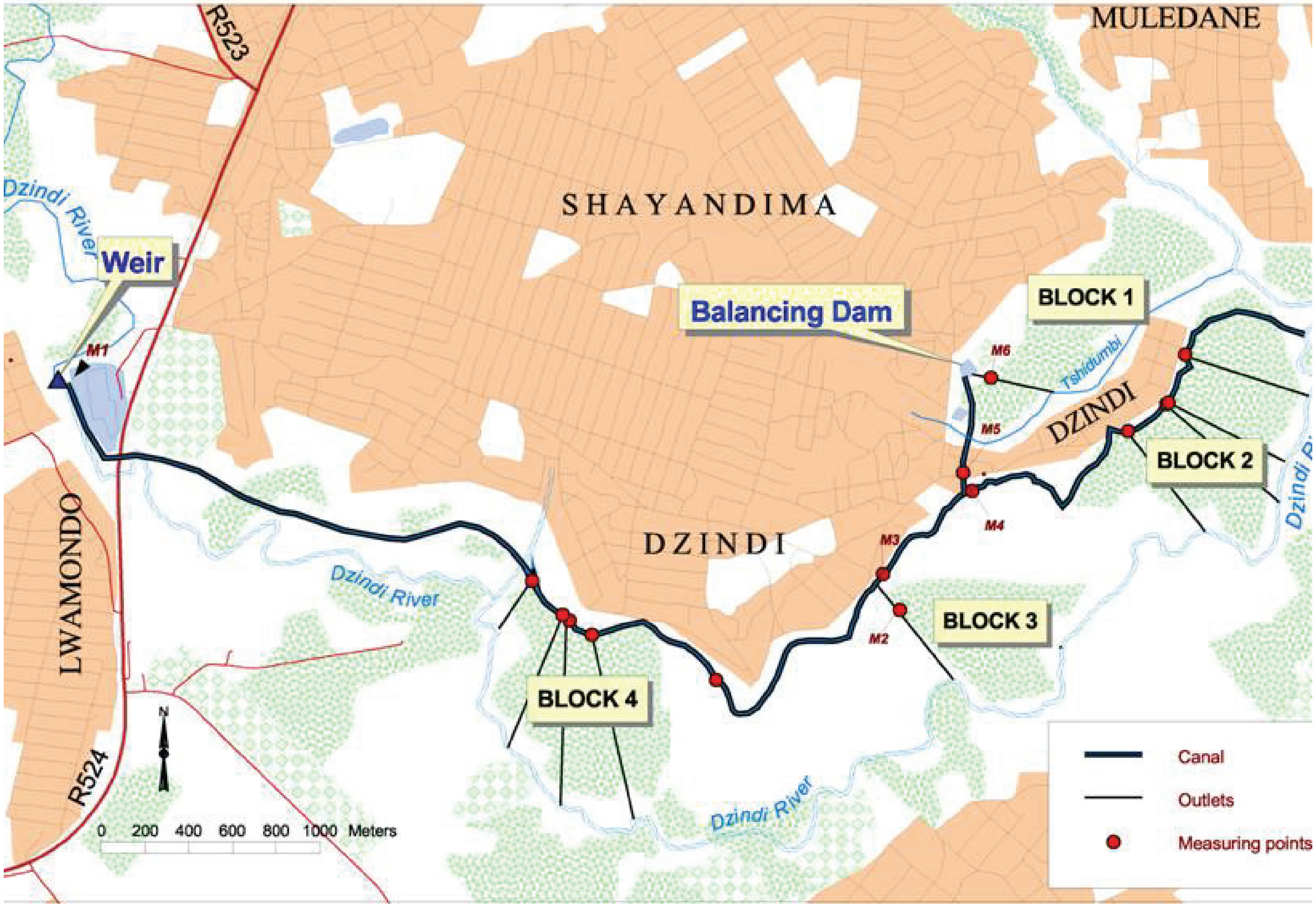



***Figure 3.2.2***: *The main canal and the irrigation blocks of the Dzindi Irrigation Scheme (after Van der Stoep & Nthai, 2005).*

Van der Stoep and Nthai (2005) stated that the biggest immediate need is to improve the management of the infrastructure. The authors also found that the application efficiency in the scheme is fairly good. Farmers have a fixed irrigation timetable of irrigating once per week. Time to irrigate at Dzindi is of crucial importance as water allocation is subject to limitations (Letsoalo et al., 2003). Even though Letsoalo et al. (2003) state that the amount of water entering the scheme is sufficient only to allow each farmer to irrigate his or her field once per week, Van der Stoep and Nthai (2005) through measurements found that 50 to 70% of the water that reaches secondary canals is actually return flow.

According to Letsoalo et al. (2003), in each day, two farmers per irrigation block or section of block have the right to draw water from the canal that serves their section. One farmer irrigates in the morning while the other draws water during the afternoon. This rule applies only during day time. At night, those who are willing to work or irrigate may use water as they wish. The water flows continuously through the main canal. All water that is not used returns to Dzindi River (Letsoalo et al., 2003).

### 3.2.7 Land use

The area is mainly used for agriculture, and settlement. However, farmers do not live in the scheme itself but in the adjacent villages surrounding the scheme. They travel to the scheme to carry out various farm operations from their homes in the villages.

Farmers at Dzindi grow vegetables and field crops like maize. They practice both commercial and subsistence farming. Several crops are grown in the study area depending on which types of crops are suitable and in which season of the year. Some crops are grown in summer, while others are grown in winter.

In winter, farmers mainly grow vegetable crops while in summer they grow both vegetable and field crops. Crops grown in winter include cabbages (*Brassica oleracea*), Swiss chard (*Spinacia oleracea*), Chinese cabbage (*Brassica rapa L ssp. Chininensis*), Muxe (*Solanum retroflexum*), and Onions (*Allium Ceppa*). Crop grown in summer include, tomatoes (*Lycopersicon lycopersicum*), green peppers (*Capsicum annum*), maize (*Zea mays*), pumpkins (*Cucurbita maxima*), groundnuts (*Arachis hypogaea*) and bambara groundnuts (*Vigna subterranean*) are grown.

### 3.2.8 The geology and soils of the study area

#### 3.2.8a The geology of the study area

The Goudplaats Gneiss unit is the oldest unit in the region and Dzindi Irrigation Scheme is situated near the North-western edge of the unit (Brandi, 1987). The rock in this unit consists of light and dark grey biotite gneiss and migmatite. Mineralogically, the rocks in this unit consist of Oligoclase, quartz, biotite and hornblende.

The Department of Mineral and Energy Affairs (1985) shows that, before the Dzindi River reaches the scheme, it flows through the rocks of the Sibasa Formation, which form part of the Soutpansberg Group and the rocks occur west of Dzindi River.

The Sibasa Formation is a volcanic succession with sparse intercalations of quartzite, shale and tuff. Its thickness is estimated to be around 2000m. The lavas are blackish or greenish black in colour and consist of altered pyroxene and plagioclase with minor amounts of olivine and opaque minerals. The ground mass is often intensely epidotised and chloritised (Brandi, 1987).

#### 3.2.8b Soils of the study area

The soil survey conducted by Murray (1951) after the establishment of the Dzindi Irrigation Scheme over a period of two weeks gave rise to four main soil types in the area commanded by the weir in Dzindi River that supply the water to the scheme. The soils were reddish brown clays, grey sands, grey clays and alluvium. However, Barnabé Adriaens (2005) identifies 5 soil units at Dzindi. The soil maps of the 4 irrigation blocks at DIS are presented in Figures 3.2.3. to 3.2.7 respectively. These figures also show the plot boundaries, the farmers' fields numbers.

The five soil units identified and described by Barnabé Adriaens, (2005) at Dzindi include:

- deep red well-drained soils of the Hutton form (Soil Classification Working Group, 1991:138), indicated as **A1** and **A2** on the soil map (Figure 3.2.4). Barnabé Adriaens, (2005), states that the Hutton form correlates well with the Ferralsols of FAO and WRB and that:
    - soils designated as mapping unit **A1** have a A-horizon clay content that was estimated to range between 30 and 40%. The clay content is increasing with depth;

    - soils designated as mapping unit **A2** are very clayey throughout, i.e. with a clay content in excess of 40% clay content at the soil surface. Again the clay content was increasing with depth. This soil was extremely laborious to auger;
- deep soils with impeded drainage of the Westleigh form (Soil Classification Working Group, 1991:110) designated as soil unit **B** on the soil map (Figure 3.2.3). This soil correlates with Acrisols or Luvisols in FAO or WRB. The morphology of the B-horizon (distinct high-chroma mottles embedded in a grey-coloured matrix) indicates that root development is subject to restrictions as a result of occasional water logging;
- shallow sandy often stony soils, designated as **C1** and **C2** on the soil map (Figure 3.2.4). Those soils are associated with a quartz vein that runs through the landscape. Depending on soil depth they are classified as:
    - soil unit C2: Mispah form soils (Soil Classification Working Group, 1991:186), very stony shallow sandy soils with an effective rooting depth of less than 300 mm. This soil correlates with Leptosols or Regosols in FAO or WRB.
    - soil unit C1: Glenrosa form soils (Soil Classification Working Group, 1991: 184), deeper sandy soils with an effective rooting depth of at least 300 mm. This soil correlates with Cambisols or Regosols in FAO or WRB.

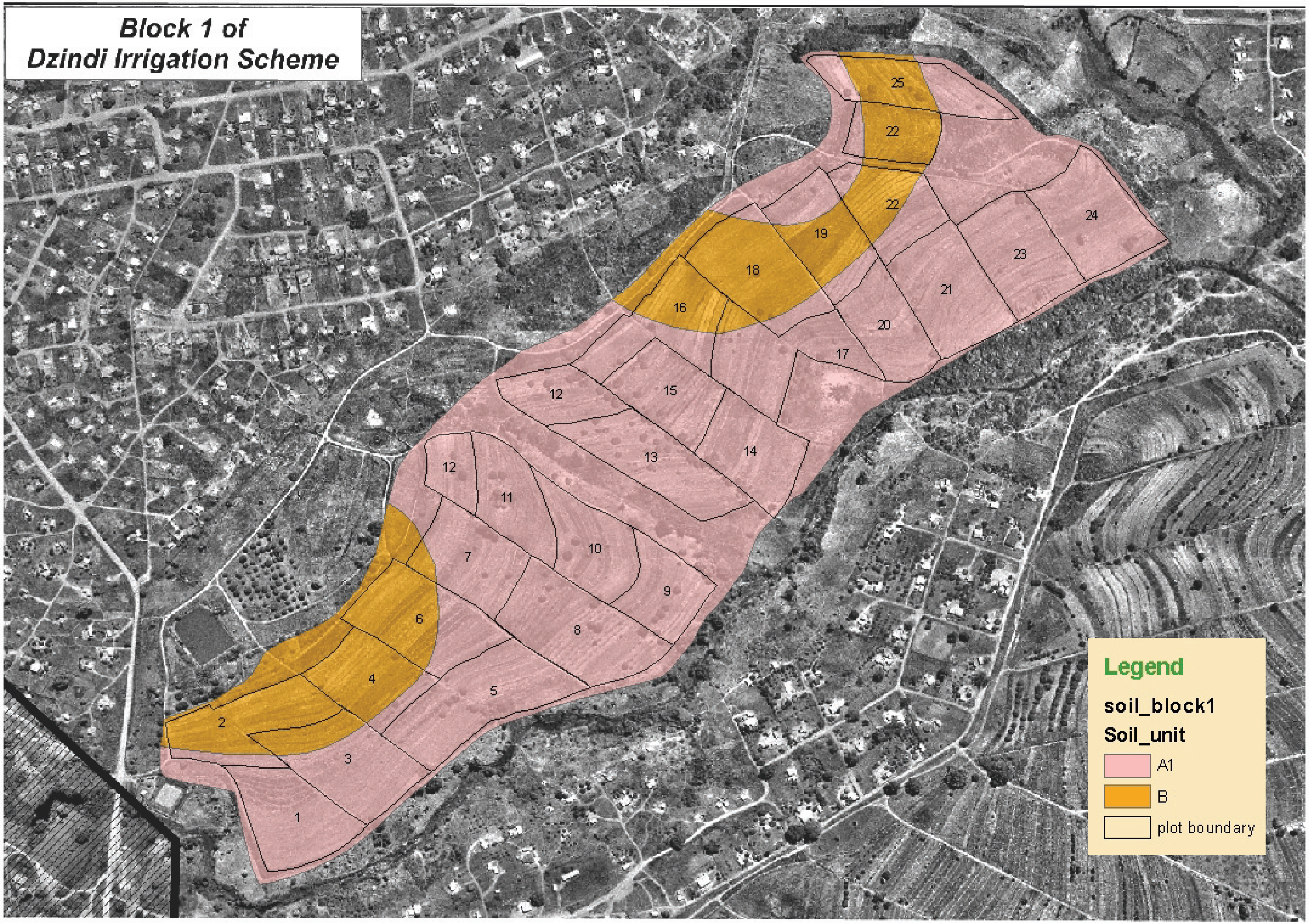



*Figure 3.2.3: The soil map of Block 1 of Dzindi Irrigation Scheme (After Barnabé Adriaens, 2005).*

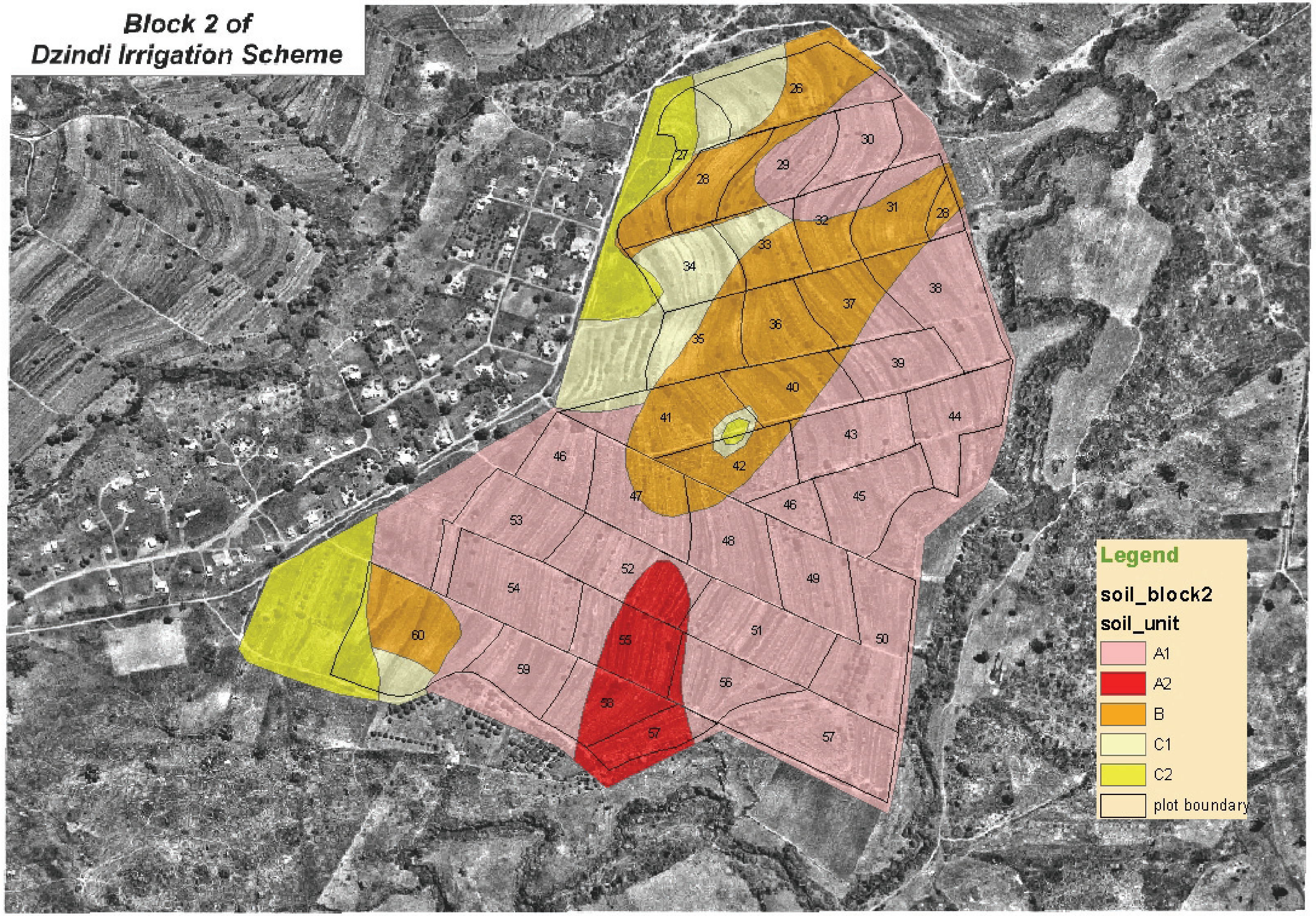



***Figure 3.2.4***: *The soil map of Block 2 of Dzindi Irrigation Scheme (After Barnabé Adriaens, 2005).*

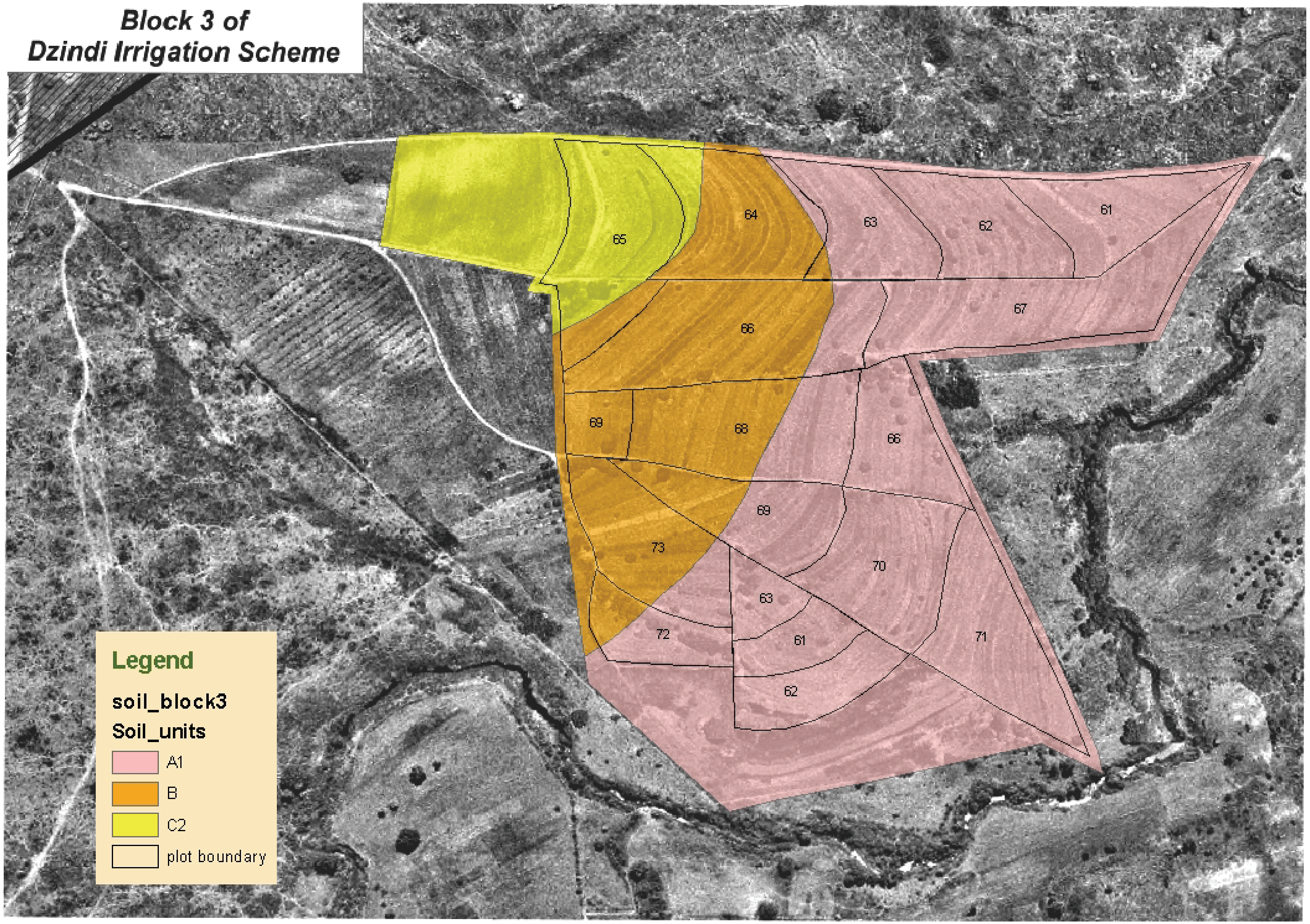



***Figure 3.2.5***: *The soil map of Block 3 of Dzindi Irrigation Scheme (After Barnabé Adriaens, 2005).*

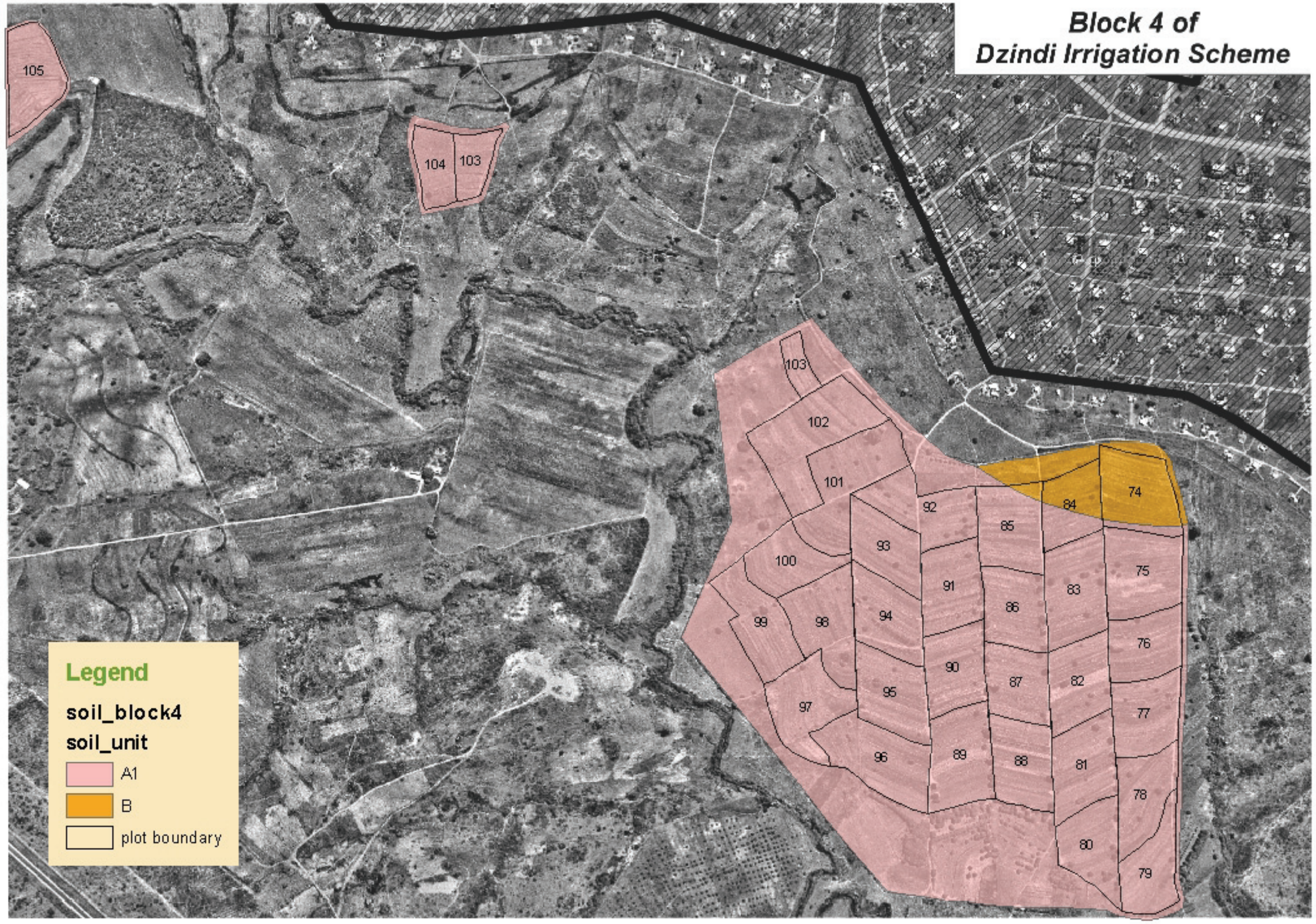
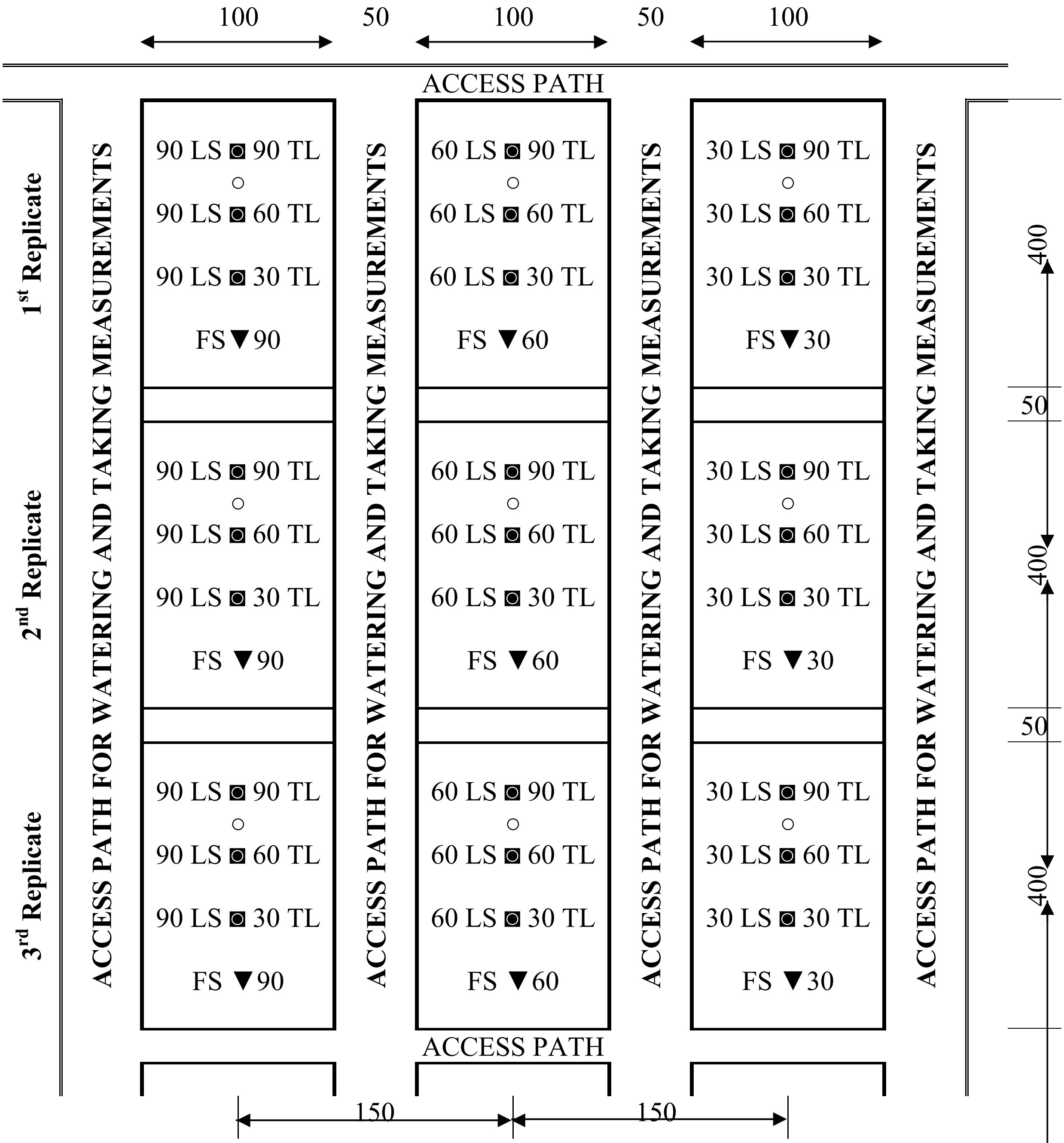



***Figure 3.2.6**: The soil map of Block 4 of Dzindi Irrigation Scheme (After Barnabé Adriaens, 2005).*

## APPENDIX 3.3

***Western End***




**Legend**

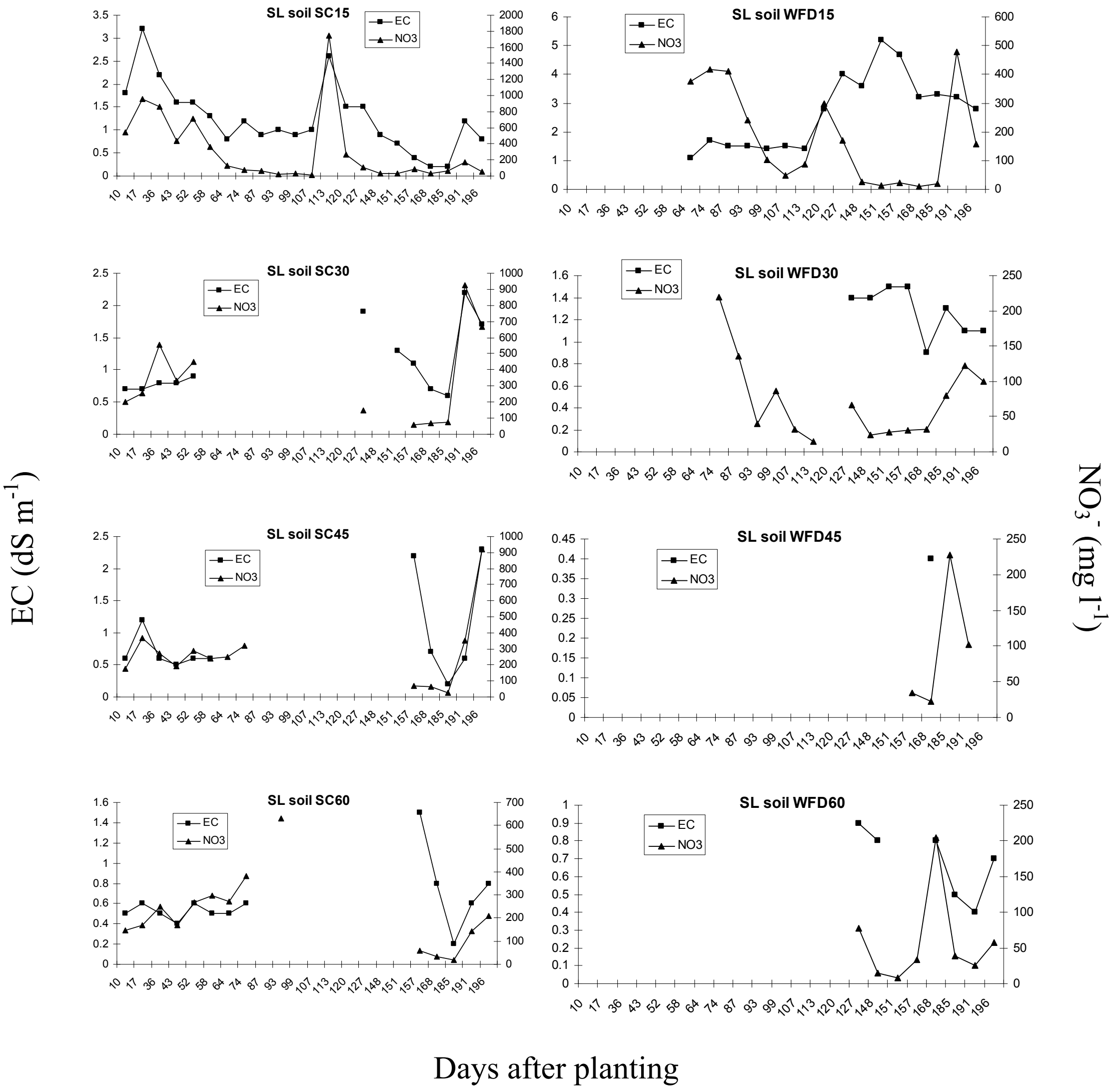
| | | | |
|---|---|---|---|
| ◙ | LongStops (LS) together with tensiometer in the "wick" | ▼ | FullStops (FS) showing depth from soil surface to the mouth |
| ○ | Tensiometer 50 cm from LS | TL | Tensiometer length |
| FS | FullStop | 60 | Depth or length in cm |

All measurements are in centimetres

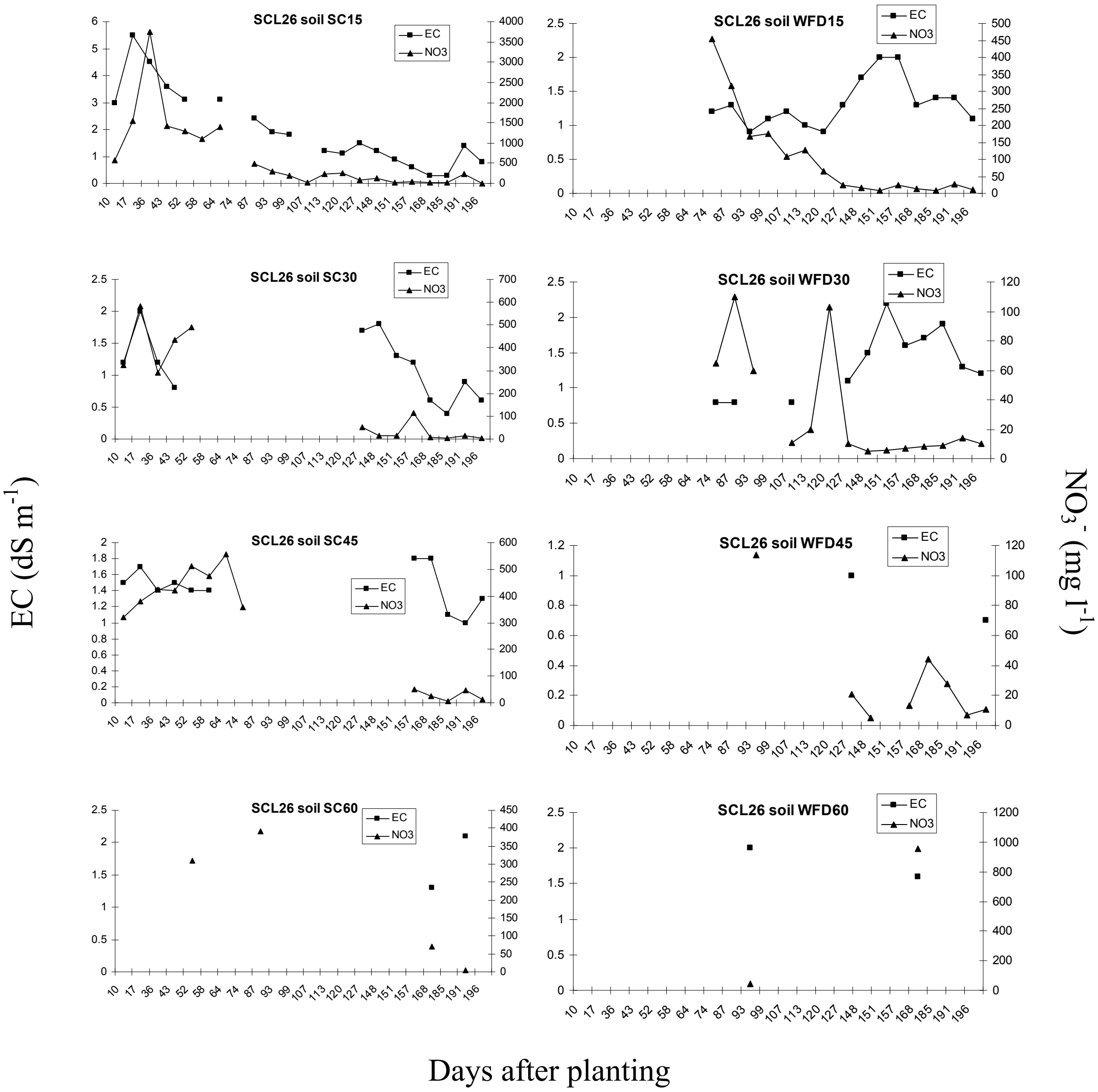
***Eastern End***

***Figure 3.3.1**: Schematic presentation of the experimental site layout at Univen.*

**APPENDIX 4.1** SC EC and $NO_3^-$ values (left) and WFD EC and $NO_3^-$ values (right) for the SL soil



**APPENDIX 4.2** SC EC and $NO_3^-$ values (left) and WFD EC and $NO_3^-$ values (right) for the SCL26 soil



**APPENDIX 5.1** PowerPoint slides making up the WFD training package

Slide 1

# Learning about Water, Salt and Nitrate Management using Wetting Front Detectors

A training package developed for the
Water Research Commission

(Section 1)

Slide 2

## Contents

Part 1: Wetting front detectors (WFD)

Part 2: Using a WFD

Part 3: Irrigation scheduling with a WFD

Part 4: Soil solution monitoring

Part 5: Electrical conductivity monitoring

Slide 3

## Part 1- Introduction to Wetting Front Detectors

1.1. What is a wetting front?

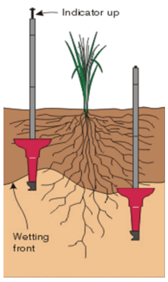
1.2 How does a Wetting Front Detector work?

1.3 Relationship to other tools

1.4 Measuring vs Learning

1.5 Salt and nutrients

Slide 4




## 1.1. What is a wetting front?

Every time we irrigate we set up a wetting front which moves down into the soil.

The front moves slowly in dry soil and quickly in wet soil.

A wetting front marks the boundary between the wet soil above and the drier soil below.

A Wetting Front Detector (WFD) records when a wetting front goes past. This information can be used to help irrigation management.

Frequent light irrigations only wet the topsoil, and much of the water is lost as evaporation from the soil surface.

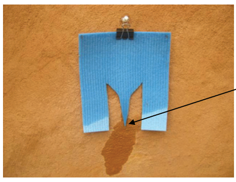
Very large irrigations can move water below the root zone and leach nutrients out of the soil.

Slide 5

## 1.2 How does a WFD work?

A WFD collects some of the downwards flow of water. Water enters the wide end of the funnel and the soil inside the funnel gets wetter and wetter as the cross-sectional areas reduces.

At the base of the funnel is a mesh filter. When the soil at the base of the funnel becomes saturated, some water moves through the filter into reservoir. This water activates a float and indicator mechanism.



We can visualise the concentration of water in the funnel by watching a wetting front move down a sponge. The water is dripping off the end of the point (representing the base of the WFD), even though the wetting front has not reached the bottom of the sponge.

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## 1.3 Relationship to other tools

There are two basic groups of soil water monitoring devices. The first group measure the soil tension (or the suction that the plant must exert to extract water from the soil). These devices can be used without calibration to tell you how dry the soil is (e.g. tensiometers).

The second group of devices tell you the amount of water in the soil (e.g. neutron and capacitance probes). The data requires some interpretation – such as full points and refill points on a graph.

A WFD is different from both the above groups. It does not give a continuous reading from wet to dry – just indicator up or indicator down to show if a 'strong' wetting front has gone past the depth it is buried.

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## 1.4 Measuring or Learning

The devices that measure suction or amount of water in the soil give you a number – and then you decide what to do.

A WFD is different. Normally we place them at two depths in the root zone. The aim is to get a visual impression of your current strategy i.e. how deep the water is going.

Then you to adjust your strategy (more or less water at time during the season) to get the desired response. The strategy may be to get neither, one or both detectors to respond.

Finding the 'desired response' takes a bit of experience – which we deal with in more detail later.

WFDs are learning tools that help bring together farmer experience with simple measurements.

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## 1.5 Salt and nutrients

WFDs also measure what the water is carrying with it, as it moves down into the soil.

The detector needs about 20 ml of water to set off the indicator. Most of this water is 'wicked' out of the detectors as the soil dries after irrigation, leaving a 5 ml sample.

This sample is sufficient for measuring the electrical conductivity (EC) and the nitrate content of the soil water.

Monitoring the soil solution is important. In the absence of rainfall, the root zone requires some leaching, otherwise the salt may build up and damage the plants. But if leaching is done at the wrong time, nitrate will be washed out of the soil.

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## Part 2- Using a Wetting Front Detector

2.1. Types of Wetting Front Detector

2.2 Weak and Strong fronts

2.3 Placement depth

2.4 Soil disturbance?

2.5 Tube Wetting Front Detector

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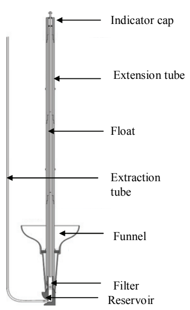
## 2.1 Types of WFDs

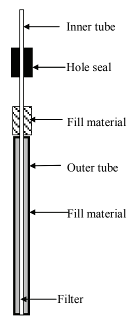



The funnel version of the WFD is called a FullStop. This is a commercial version which was released in 2004.

There is a second prototype version which is shaped like a tube. The tube is 50 mm in diameter and 600 to 900 mm long (right).

The FullStop WFD is best for drip irrigation. Drip irrigation produces ‘strong’ wetting fronts which are generally easy to detect in the top 0.5 m of soil.

The tube version is probably best for flood irrigation. They can work at much deeper depths, respond to ‘weaker’ fronts and cause less soil disturbance on installation.



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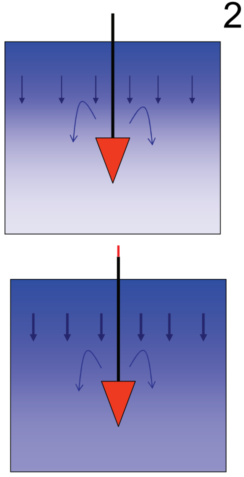

## 2.2 Weak and Strong fronts

Water is 'pulled' downwards into the root zone by gravity and capillary action of the drier soil below. Water is also 'pulled' from wetter areas to drier areas – e.g. water is pulled sideways from a drip emitter.

Gravity pulls water down into the funnel, but when the front is weak, only a few drops of water may go through the filter. In this case the float will not be activated, even though some water will go past the detector. This is because the soil outside the funnel is drier than the soil inside, and pulls water out as fast as the funnel collects water.

Weak fronts tend to occur deeper in the root zone, because the soil above has absorbed much of the water. For this reason, the placement depth is important. The soil needs to be at 3 kPa of suction or wetter for the FullStop WFD to collect water.

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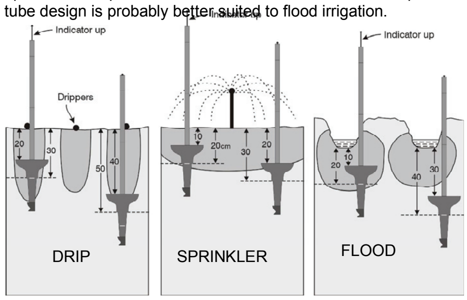
## 2.3 Placement depth

It is very important that the FullStop detector is placed at depths appropriate for the irrigation system, and for the amount of water applied at one time. For example, wetting fronts from drip tend to go quite deep, especially for widely-spaced drippers in orchards. The deepest placement recommended for a WFD in this case would be 60 cm.

Strong wetting fronts do not go as deep from sprinkler irrigation – we recommend a maximum placement depth of 400 mm. We have used the FullStop WFD for flood, but think the tube design is probably better suited to flood irrigation.



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## 2.4 Soil disturbance?

The 200 mm diameter funnel of the FullStop means there is quite a lot of soil disturbance during installation.

Water may preferentially move through the softer soil above a WFD and give a wrong reading. This can happen if the soil is flooded.

Under drip and sprinklers the soil surface is usually not flooded. If we irrigate at 5 mm per hour, then the water sinks it at 5 mm/h over the FullStop and over the non-disturbed surrounding soil. The amount of water it takes to get the FullStop to respond depends mostly on how dry the soil is – rather than the soil structure.

The drier the soil, the more water that will be required to get a FullStop to respond.

When roots are disturbed in perennial crops, it can take several weeks for them to re-grow into the disturbed soil zone above the detector.

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## 2.5 Tube WFD

The tube shaped WFD is more sensitive than the FullStop. This means it can be placed deeper in the soil and will collect a water sample from weak fronts.

When fronts are weak, the water is draining very slowly through the soil. This slow drainage can occur over quite long periods, so can add up to significant amounts of water.

When the drainage is very slow, water still enters the tube, but the high walls (600 to 900 mm) prevent the water from getting out again.

The tube detector can be installed with less disturbance. We can then seal the hole with clay or cement and the tube WFD will still collect water. This means the tube detector is better for flood irrigation.

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# Part 3 – Irrigation scheduling with a WFD

3.1. The standard method

3.2 WFD basics

3.3 Automatic shut off

3.4 Simple lessons

3.5 Depth placement and detector response

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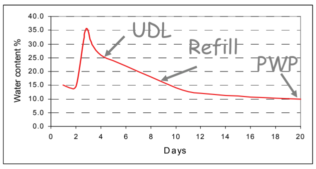
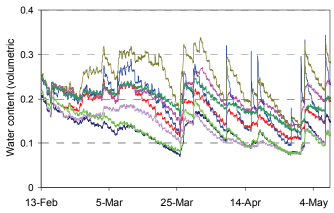
# 3.1 The standard method




The standard method of irrigation scheduling is to define three ‘soil wetness’ points on a graph.

Immediately after irrigation the soil drains under gravity and a day or two later the soil reaches field capacity or the upper drained limit (UDL).

For a few days the plants can remove water from the soil at the rate they need to. Then, as the soil gets drier, the plants experience some water stress. The Refill point marks the water content below which the plants experience water stress.

When the plants have used all the available water, we have reached the Permanent Wilting Point (PWP). In practice there is a lot of variability in soil, so its hard to pick absolute UDL and refill points from water content measurements.

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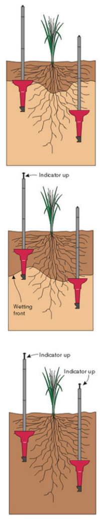

# 3.2 WFD basics

Shallow DOWN Deep DOWN

If neither indicator is triggered, then watering is shallow. This is the desired outcome for young crops and after fertiliser application. It is also the usual result for centre pivot irrigation.

Shallow UP Deep DOWN

Water has moved past the shallow detector to the lower part of the root zone. The usual case for drip irrigation. We would not necessarily want to activate the shallow detector at each sprinkler irrigation event.

Shallow UP Deep UP

Both detectors should respond when it is necessary to fill the whole root zone – for example during very hot weather, sensitive growth stages or when the profiles is being leached of salt.

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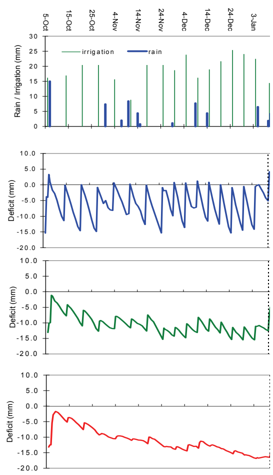


# 3.3 Automatic shutoff

In the early research phase we used electronic detectors to shut off solenoid valves as soon as the water reached the detector.

This method can be very accurate, as the figure shows for sprinkler irrigated turf. The water was turned on automatically every fourth day and shut off when the wetting front reached a detector buried at 15 cm.

In this case the top layer of soil was always brought back to the full point, while the water content in the lower layers slowly declined, showing there was no over-irrigation.

Automatic irrigation is only possible if you match the detector placement depth and the irrigation interval with the potential transpiration rates for different times of the year.

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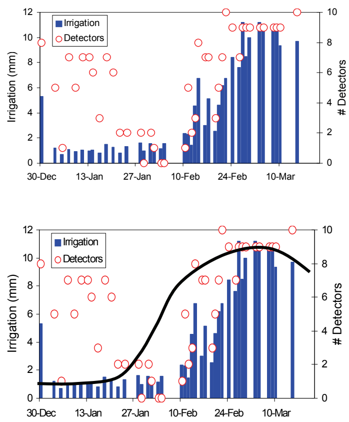


## 3.4 Simple lessons

This example shows 12 detectors in a drip irrigated pumpkin crop. Early in the season, very small amounts of water were applied, but 6 to 10 detectors responded each day.

During the middle of the season, 0 to 4 detectors responded, even when more water was applied.

Towards the end of the season, 10 or more responded.

Ideally we want few responses at the start of the season, because this is when nitrate leaching occurs (lesson #1).

Then, as the pumpkins enter the exponential growth phase and set fruit, we want most of the detectors to respond because the crop is at a sensitive stage (lesson #2).

The example shows how the irrigation did not match the growth curve of the pumpkins

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## 3.5 Recommended depth placements

Below are recommended placement depths for drip and sprinkler irrigation.

| Type of irrigation | Water applied at each event | Shallow Detector | Deep Detector |
|---|---|---|---|
| Drip | Amount applied per dripper usually less than 6 litres at one time (eg row crops or pulsing) | 300 mm | 450 to 500 mm |
| Drip | Amount applied per dripper usually more than 6 litres at one time | 300 mm | 500 to 600 mm |
| Sprinkler | Irrigation usually less than 20 mm at one time | 150 mm | 300 mm |
| Sprinkler | Irrigation usually more than 20 mm at one time | 200 mm | 300 mm |

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# Part 4 – Soil solution monitoring

4.1. Why measure solutes?

4.2 Active and passive solutes

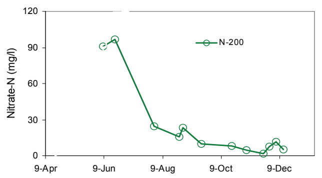
4.3 Measurement tools

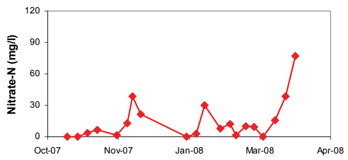
4.4 Adding Salt

4.5 Losing Nitrate

Slide 22

# 4.1 Why measure solutes?




Irrigation is not just about water.

All water contains some salt. When we add water to the soil we always add some salt as well. It can be hundreds of kilos per hectare per year – even tons.

We also add fertiliser to soil, and fertiliser dissolves in the water. Some fertilisers are relatively insoluble or are strongly attracted to soil particles. Others are highly soluble and go where the water goes.

Quite a number of irrigators measure how much water is stored in their soil, but very few measure how much fertiliser such as nitrogen is available to their crop.

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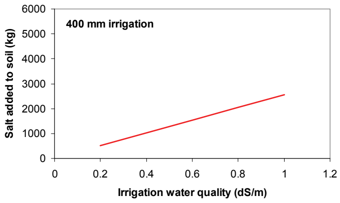
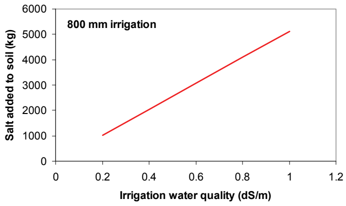
# 4.2 Active and passive solutes




There are two 'solutes' that are important to monitor, particularly for high value irrigated crops

Nitrate is an 'active' solute. Nitrate arrives in the soil solution from fertiliser applications and decomposition of organic matter. Nitrate is removed by crop uptake, leaching, and gaseous loss. Nitrate is 'active' because there are a number of 'sources and sinks'.

The other 'solute' which is important to monitor is made up of the unwanted salts, usually dominated by sodium chloride.

We call the unwanted salts 'passive' solutes. They are mostly added via the irrigation water. They are not taken up by plants. They accumulate in the soil unless leached out of the root zone.

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# 4.3 Measurement tools

Soil can hold many years supply of nutrients such as Phosphorus and Potassium. Soil tests provide a reasonable indication of how much there is.

Nitrogen is usually the most limiting nutrient. Most available nitrogen is in the soil as nitrate and the levels of nitrate in the soil change quickly. Regular monitoring throughout the growing season is necessary for good management.

The easiest way to measure nitrate is to take a sample of the soil solution. This can be captured in a WFD, or sucked out of the soil using a suction cup.

Some capacitance type instruments can give a reasonable estimate of the 'bulk' conductivity of the soil i.e. all the ions in the soil.

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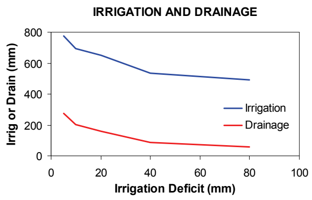
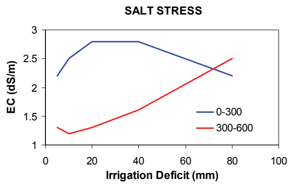
# 4.4 Adding salt




If we irrigate frequently, and keep the soil near the full point, then water will drain below the root zone during wet weather. This leaching of water will carry salt out of the root zone.

If we allow the soil to dry out between irrigation events, and irrigate accurately, there will be less leaching, but more salt in the soil.




Frequent small irrigations add salt to the top half of the root zone.

Fewer large irrigations, will move salt towards the lower parts of the root zone.

Monitoring where the salt is can tell us a lot about how well we are irrigating.

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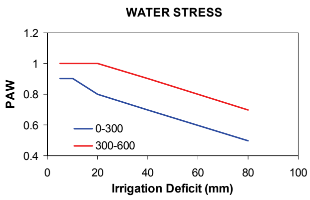
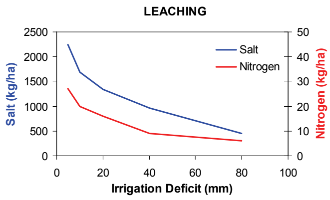
# 4.5 Losing nitrate




Frequent irrigations keep the soil wet and so the crops will experience very low water stress.

Crop stress increases as the irrigations become further apart.

But frequent irrigation also means the soil profile is kept near the full point. So when it rains, water will leach below the root zone.




This water will leach salt from the root zone. It will also leach nitrate.

Irrigation is a compromise. Frequent irrigation keeps the soil wet (good for plants) but which results in more leaching and loss of nitrate.

But without leaching salt builds up in the soil.

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# Section 5 – Electrical Conductivity

5.1. World scene

5.2 Salt and irrigation

5.3 Matric and osmotic potential

5.4 Measuring EC

5.5 Salt thresholds

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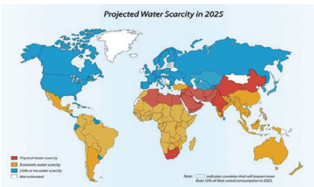
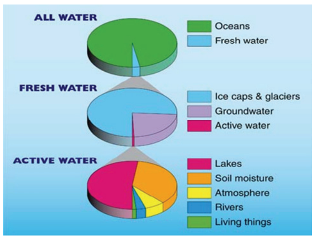
## 5.1 World scene




Over one third of the world's food is produced under irrigation, consuming 70% of all diverted water, on 15% of the arable land

Two thirds of the world population will live in water scare areas by 2025

Between 15 to 40 % of irrigated land is seriously affected by salinity, sodicity and waterlogging

Only 3% of the water on earth is fresh, of which 2/3 is frozen.

Of the remaining 1%, only a tiny fraction forms part of the freshwater hydrological cycle

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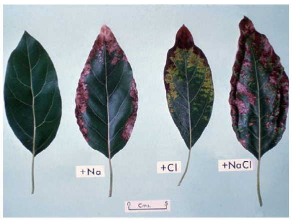
## 5.2 Salt and irrigation




All irrigation water contains some salt, and most of this salt is excluded at the root surface during transpiration. Salt will accumulate in the soil, unless leached, and eventually damage plant growth. Salt is always pushed to the edges of the wetting pattern.

A small amount of salt gets into the plant. Leaves turn brown and die as salt accumulates, seen first in the oldest leaves. Most of the salt remains in the soil until it is leached beyond the root zone by irrigation and / or rain.

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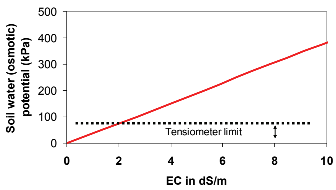
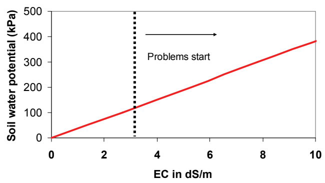
## 5.3 Matric and osmotic potential




Plants must suck water away from soil particles – we call this this matric suction, as measured by a tensiometer.

Plant must also suck water away from salt across membranes in the root. We call this osmotic suction, and it can be estimated from the EC.

The plant experiences a combination of matric and osmotic suction. An EC of 2 dS/m exerts a reasonable osmotic force against which the roots must pull to extract water (equivalent to a tensiometer at full range). However most plants are not usually affected by salt until the EC rises to over 3 dS/m (as measured in a WFD)

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## 5.4 Measuring EC

The Electrical Conductivity (EC) is the easiest measurement to make on soil solution. It is a measurement of all the ions in the solution - both good salts (fertiliser) and bad (usually dominated by sodium chloride).

Hand held conductivity meters are easy to use in the field, have good accuracy and a relatively inexpensive.

Unfortunately people use different units for EC and this can be confusing.

Many field EC meters in the conductivity unit deciSiemens/metre (dS/m)
1 dS/m = 100 mS/m
= 1000 µS/cm
= 1000 mmhos/cm
Which is approx 640 milligrams salt/litre

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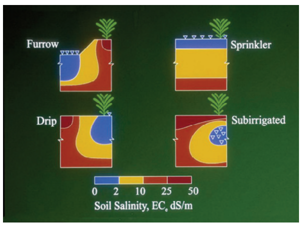


## 5.5 Salt thresholds

There are charts which give the threshold EC above which plant growth will be affected.

These charts are based on the EC from a saturated paste. The EC of saturated paste is lower than the EC of the soil water, because distilled water is added to a soil sample to make a saturated paste.

As a rough guide the soil solution EC from a suction cup or WFD is double the saturated paste.

Salt thresholds are very approximate - the sensitivity of the crop varies with cultivar, rootstock, stage of growth, duration of stress and the soil moisture regime and salt distribution is very variable in the profile.

Slide 1

# Learning about Water, Salt and Nitrate Management using Wetting Front Detectors

A training package developed for the Water Research Commission

(Section 2)

Slide 2

## Contents

Part 6: Salt leaching case studies

Part 7: Irrigation / salt case study

Part 8: Managing nitrogen

Part 9: Nitrate case study

Part 10: Soil solution summary

Slide 3

## Section 6 – Salt management case studies

6.1. Case studies

6.2. Scheduling by salt

6.3 Salt build up

6.4 Salt leaching

6.5 Salt distribution

Slide 4

## 6.1 Case studies

Case study 1: Turf irrigation with low-salt recycled water (0.3 dS/m). During the drought the managers had to prove that they were not using too much water.

Case study 2: Wine grapes irrigated with marginal quality water in a winter rainfall area (0.8 dS/m).

In both the low salt and higher salt case studies, the accumulation and distribution of salt can show us how well irrigation is being carried out.

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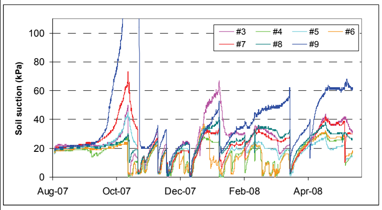
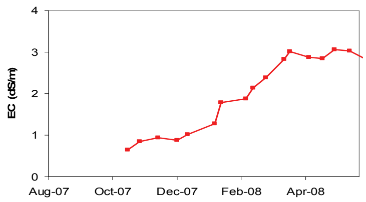
## 6.2 Scheduling by salt




Case Study 1

Seven watermark sensors are measuring the soil tension at 25 cm depth under a turf playing field.

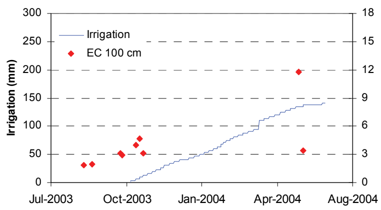
Its difficult (impossible) to prove that water is not being wasted from soil water measurements alone.

The EC of the irrigation water is 0.3 dS/m and the EC in the WFD at 25 cm increases to over 3 dS/m over the summer.

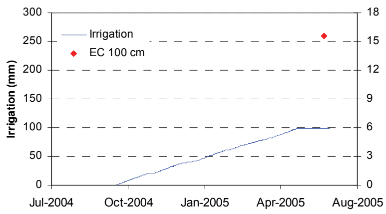
This shows that only a small amount of water was leached through the root zone (about 1/10th). If there was significant leaching, the EC would not build up.

Slide 6

## 6.3 Salt build up




6.1




Case study 2

Grape growers use small amounts of water to grow premium quality grapes.

Year: 2003

Rain: 436 mm

Irrig: 141 mm

EC at 100 cm depth around 3 dS/m at start of season and 11.8 dS/m at end of season

Year: 2004

Rain: 332 mm

Irrig: 99 mm

Less rain and less water applied.

WFD does not collect at 100 cm during irrigation season but collects one sample at 15.6 dS/m at end of season (rain).

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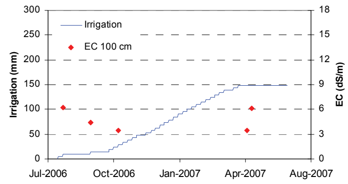
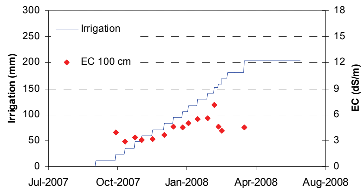
## 6.4 Salt leaching




Year: 2006
Rain: 253 mm
Irrig: 148 mm
Irrigator tries adding more water at each event, but still does not collect at 100 cm water during the irrigation season. Samples 6.1 dS/m at end of season.




Year: 2007
Rain: 323 mm
Irrig: 204 mm
Irrigator gives slightly more water over the season and a lot more water at one time. Able to collect at 100 cm during the irrigation season. Maximum EC is 7.1 dS/m

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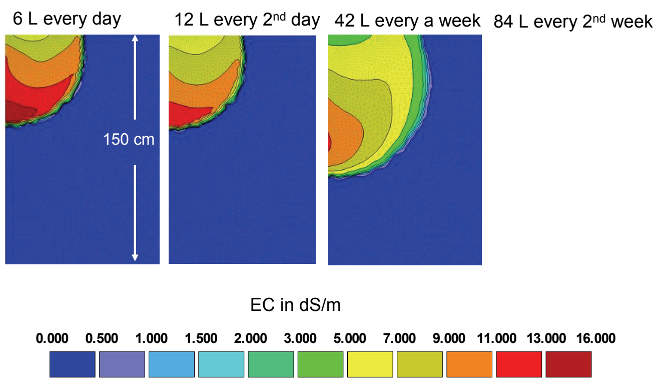
## 6.5 Salt distribution



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## Part 7 – Putting it together

7.1. Case study

7.2 Et and soil moisture

7.3 Logging WFD with electrode

7.4 Depth and EC

7.5 All together

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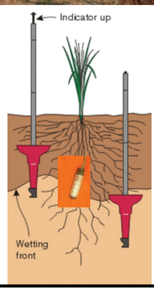
## 7.1 Case study




Early season stone fruit in summer rainfall region.

History of irrigation management using tensiometers, capacitance and WFDs

Farmer monitors WFDs manually and collected solution for EC and nitrate measurement in the field

Case study evaluates logged WFDs measuring EC

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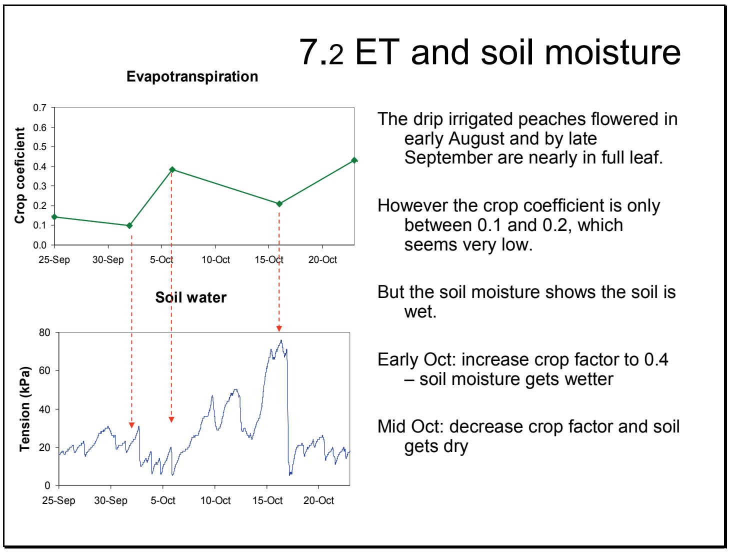


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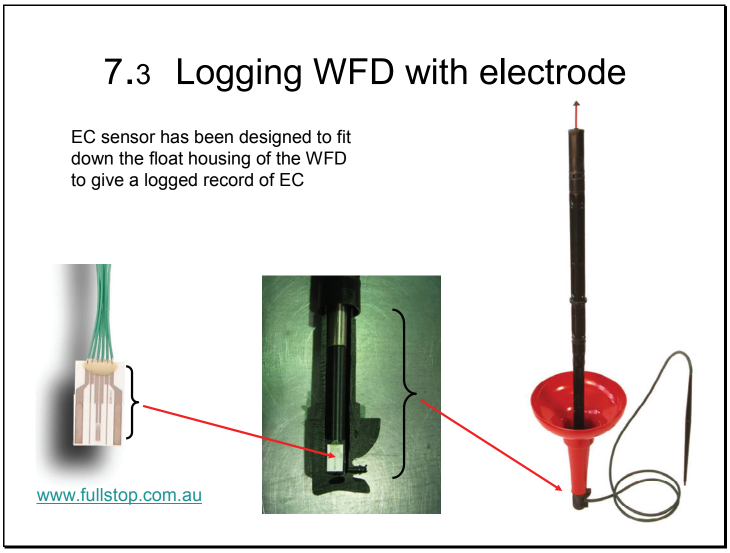

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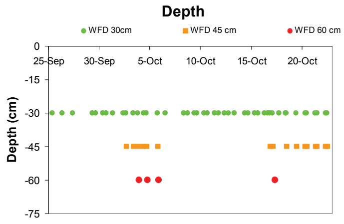
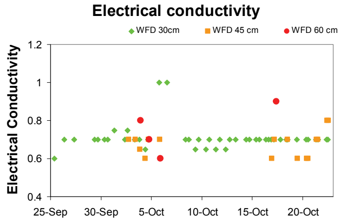
## 7.4 Depth and EC




The peaches are drip irrigated every day. Almost every day the water reaches 30 cm (green dot).

About half the time it reaches 45 cm (Brown dot)

Occasionally the water reaches 60 cm (red dot)

The same depth data can be viewed as EC of the water captured by the WFD

In this case the EC is fairly constant at all three depths

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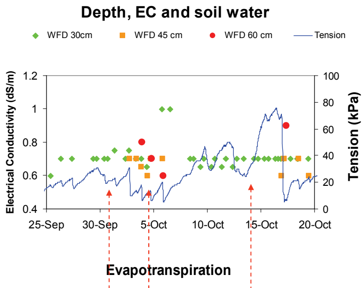
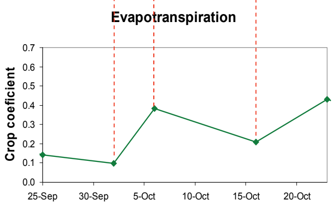
## 7.5 All together




Evaporation, depth, moisture content and EC

Late Sep: crop coefficient low, only 30 cm WFD responding, EC low

Early Oct: crop coefficient increased, deep WFDs responding – some leaching?

Mid Oct: crop coefficient decreased, only shallow WFDs responding

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# Part 8 – Nitrogen in agriculture

8.1. World snapshot

8.2 Monitoring N

8.3 What's in the water?

8.4 Mineralisation of organic matter

8.5 Fertiliser transformations

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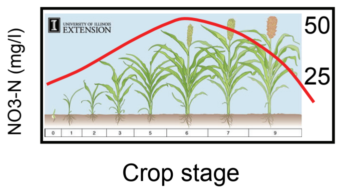
# 8.1 World snapshot

The population of the world doubled between 1960 and 2000

The total food energy intake of the whole world has gone up by 10% in the last 25 years.

The use of nitrogen fertilizer increased 8 times during the same period.

The greatest single energy input into agriculture is through the factories that make nitrogen fertilizer.



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# 8.2 Monitoring N

Some irrigators have sophisticated fertiliser injection systems with on-line monitoring of EC and pH

Very few irrigators routinely monitor fertiliser levels in the root zone, even though its not hard to do.

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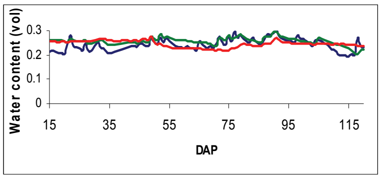
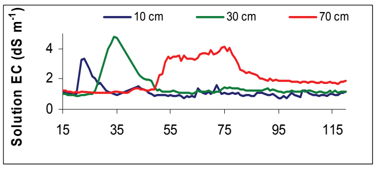
# 8.3 What's in the water?




If we were just measuring water, then the irrigation strategy looks OK. The soil stays between 0.2 and 0.3 m³/m³




The same probes measuring 'bulk' EC gives us a very different picture.

The bulk EC shows us what is in the water. There is a 'bulge' of nutrients moving down the profile

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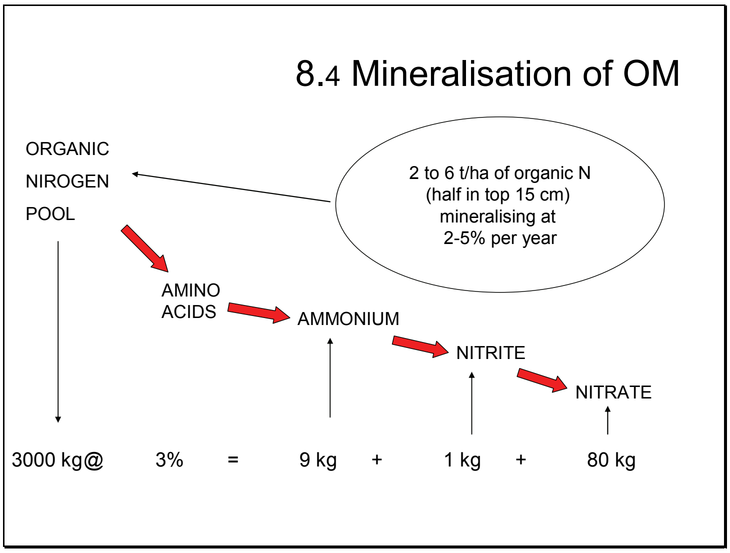


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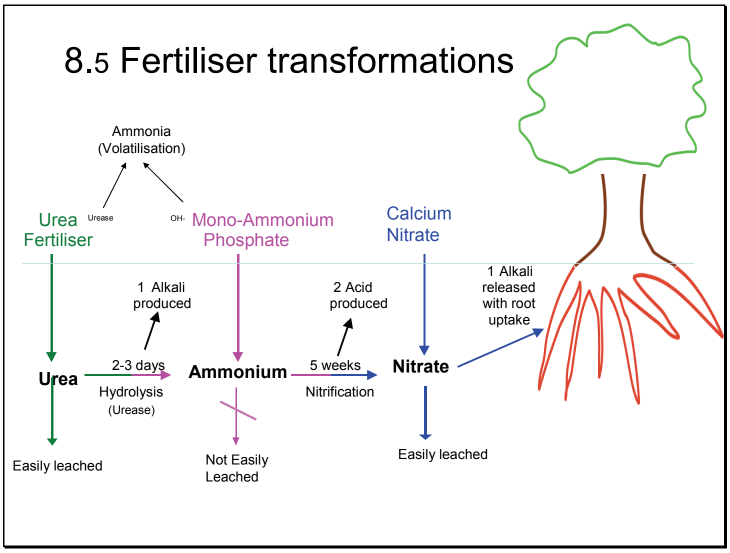

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## Part 9 – Managing nitrate

9.1. Empirical studies

9.2 Mass balance

9.3 Nitrate Dynamics

9.4 Leaf nitrogen

9.5 Soil nitrate

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## 9.1 Empirical studies

Uptake efficiency for selected vegetable crops

| Crop | N % | P % | K % |
|---|---|---|---|
| Broccoli | 30 | 8 | 30 |
| Capsicum | 22 | 7 | 156 |
| Lettuce | 34 | 6 | 120 |
| Tomato | 74 | 26 | 139 |
| Potato | 191 | 10 | 388 |

Fertiliser recommendations are usually made from empirical studies (field trials).

By comparing the recommended applications with the nutrient removal in a good crop, we can see the efficiency of nutrient use

Uptake efficiency (%) =

$$\frac{\text{Removal in a good crop}}{\text{Recommended Application}}$$

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# 9.2 Mass balance

Another method is to calculate the nutrient demand of the crop on a monthly basis. The expected water use for each month is calculated. The nutrient supplied divided by the volume of water gives the concentration of nitrogen fertiliser in the water. The example below is for citrus.

| Month | ETo (mm) | Rainfall (mm) | ETc (mm) | Nitrogen applie (kg/ha) | N conc mg/l | Nitrate ppm |
|---|---|---|---|---|---|---|
| Jan | 190 | 3 | 155 | 20 | 13 | 57 |
| Feb | 175 | 1 | 145 | 17 | 12 | 52 |
| Mar | 156 | 0 | 133 | 14 | 11 | 47 |
| Apr | 108 | 0 | 95 | 6 | 6 | 28 |
| May | 66 | 7 | 59 | 4 | 7 | 30 |
| Jun | 45 | 32 | 42 | 3 | 7 | 32 |
| Jul | 50 | 22 | 45 | 3 | 7 | 30 |
| Aug | 84 | 25 | 75 | 10 | 13 | 59 |
| Sep | 97 | 9 | 83 | 16 | 19 | 85 |
| Oct | 165 | 4 | 136 | 23 | 17 | 75 |
| Nov | 160 | 42 | 132 | 20 | 15 | 67 |
| Dec | 179 | 28 | 145 | 24 | 17 | 73 |
| **Tot** | **1475** | **173** | **1245** | **160** | **13** | **57** |

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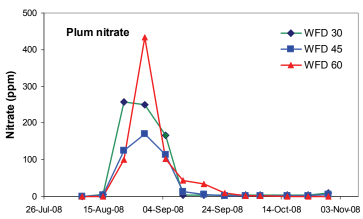
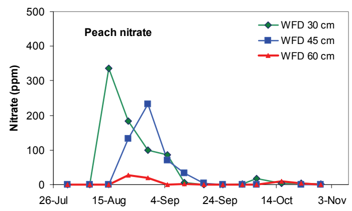
# 9.3 Nitrate Dynamics




Fertiliser was applied to the plum crop on 15 August. One week later nitrate is recorded in WFDs at 30, 45 and 60 cm. A week later high levels are seen at 60 cm – We assume nitrate being washed out of the root zone

In the case of the peach crop, the nitrate is first seen at 30 cm, then peaks two weeks later at 45 cm.

Very little nitrate is observed at 60 cm. We assume most of the nitrate was taken up by the crop.

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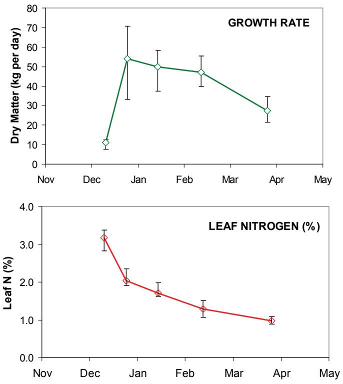
# 9.4 Leaf Nitrogen




This case study is from a silver beet crop that was harvested on five occasions over a five month growing season.

When the crop was young, the leaf N was high (>3%).

The growth rate remained constant as the leaf N fell from above 2% to below 1.5%.

The correlation between growth rate and N% in the leaf is not always very good. This is because nitrate gets 'diluted' by extra growth.

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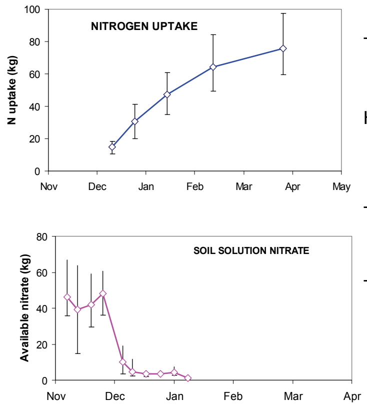
# 9.5 Soil Nitrate




The total amount of N taken up over the five harvests was 80 kg/ha.

However almost no nitrate was recorded in the WFDs after December.

The crop continued to grow well through January and February

This is because the crop was growing from nitrogen mineralising from organic matter.

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## Section 10 – Summary

10.1. Managing water

10.2 Managing salt

10.3 Managing nitrate

10.4 Solute Signatures - EC

10.5 Solute Signatures - Nitrate

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## 10.1. Managing water

- The FullStop is a tool for learning-by-doing
- The FullStop needs other information built around it - like practical experience and information from other soil water monitoring tools
- We can generate simple rules around the use of the FullStop which are useful in a management context (e.g. once a week the deep detector should respond or do not let the detector respond after applying fertiliser)
- We can evaluate our consistency in management (e.g. at the start of the season they responded frequently, but in the middle of the season they did not)

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## 10.2 Managing salt

- Good irrigation requires us to measure water AND what is in the water (the salt and nitrate).
- We don't mind seeing salt rising near the bottom of the root zone because that tells us we are not using too much water.
- But we do not want the salt to get too high because that will damage our crops.
- Published salt thresholds should be used with care. It is important to look at the salt trend (increasing / decreasing) and its where build up is occurring (top soil / sub soil).
- EC from a suction cup or WFD is around double that of a saturated paste

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## 10.3 Managing nitrate

- Monitoring nitrate helps to show when N fertiliser could be applied and when the soil is susceptible to N leaching
- Nitrate and irrigation have to be monitored together. The best way to save on fertiliser costs can be to adjust the irrigation strategy
- There are few guidelines as to what the soil nitrate level should be. Low soil nitrate is not necessarily a bad thing. The plant may able to get nitrate as soon as it is mineralised from organic matter – or the crop may have all the N it needs.
- The nitrate monitoring should be interpreted together with the EC monitoring

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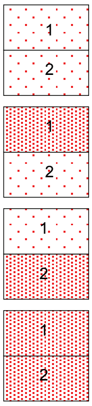
## 10.4 Solute Signatures - EC




1. Salt does not accumulate in the root zone
   Possibly wasting water and nitrate

2. Salt IS rising in the upper part (1) of the root zone
   Try to push salt into lower part of root zone

3. Salt IS rising in the lower part (2) of the root zone
   OK – its what we expect

4. Salt is high in whole profile after harvest
   Leach - but delay until the efficacy of natural rainfall in the off-season has been fully realised

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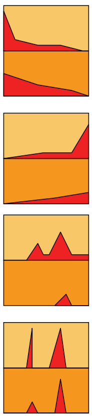
## 10.5 Solute signatures - nitrate



1: Asynchrony: Lots of nitrate at start of season when crop demand is low
   Do not irrigate heavily and withhold fertiliser

2: Gradual oversupply: May occur when for continuously fertigated crops
   Monitor nitrate and adjust dose

3: Discrete fertiliser applications: but they do not go out the bottom of the root zone
   This is what we want to see

4: Too much applied at one time: nitrate spikes seen at both depths
   Apply less fertiliser more often and reduce irrigation around fertigation times