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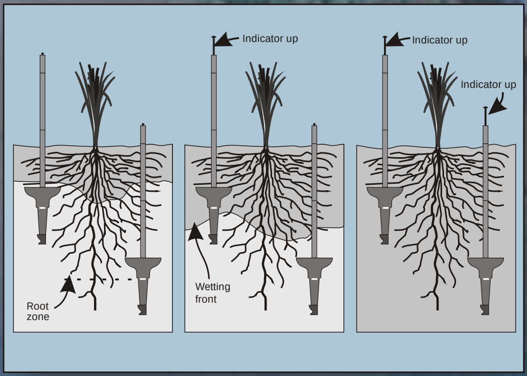
TT 230/04

Water Research Commission



BUILDING CAPACITY IN IRRIGATION MANAGEMENT WITH WETTING FRONT DETECTORS

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Report to the
Water Research Commission

March 2004

WRC Report No. TT 230/04

Obtainable from:

Water Research Commission
Private Bag X03
Gezina
0031

The publication of this report emanates from a project entitled: *Cheap and simple irrigation scheduling using wetting front detectors* **(WRC Project No. 1135)**

ISBN No. 1-77005-138-4
Printed in the Republic of South Africa

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Executive summary

Introduction

Efficient use of water in the agricultural sector is an issue of national importance in South Africa and the science required to achieve this goal is relatively mature. However, a recent survey among commercial farmers showed that they ranked irrigation scheduling as priority number four or five amongst their major concerns. Most farmers are prepared to admit that their system is not perfect, but at least it works. After a period of trial and error they have settled on management system that satisfied them and they need a good reason to re-evaluate it. Small-scale farmers were preoccupied with issues such as their access to land, water, credit and markets and showed little awareness of the importance of water use efficiency.

This project introduced a Wetting Front Detector to farmers with the purpose of stimulating a re-think about irrigation management on their farms. The Wetting Front Detector (WFD) was designed to be the simplest tool that could assist farmers to improve their understanding of irrigation. To achieve this aim, the wetting front detector must pass two tests. First, the device itself and how it works must make intuitive sense to farmers. It should be relatively easy to install and give "believable" results that challenge the farmer's perceptions. Second it must pass the accuracy test. We have to demonstrate that crops irrigated according to the principles of the Wetting Front Detector perform adequately against standard scientific procedures. A combination of research and extension was employed to satisfy these objectives.

Project objectives

Five objectives were set out in the original proposal.

Introduce farmers to the Wetting Front Detector concept of irrigation management
Evaluate the acceptability by small scale and commercial farmers
Determine from users their perceived benefit from using WFDs
Research the best methods for using the WFDs
Develop guidelines for different crops, soil and irrigation systems

Methodology

The overall rationale for meeting the objectives is summarized in Figure 1. The WFD is a very new device, that has undergone minimal on-farm testing, yet the decision was made to introduce it to farmers and put the simplicity and "user-friendly" claims to the test (step 1). Over 200 WFD were distributed to farmers, some of whom had no further contact with the research team and others who were visited by the project team on a regular basis. After a one to two year period, 54 of these collaborators, representing commercial, small scale, teaching institutions and extension agencies, were interviewed. The experience of these users formed the basis of the "acceptability" test (step 2). Irrigators who had persevered with the technology were also asked what they liked about the detectors, its problems and the lessons they had learnt from their experiences (step 3).

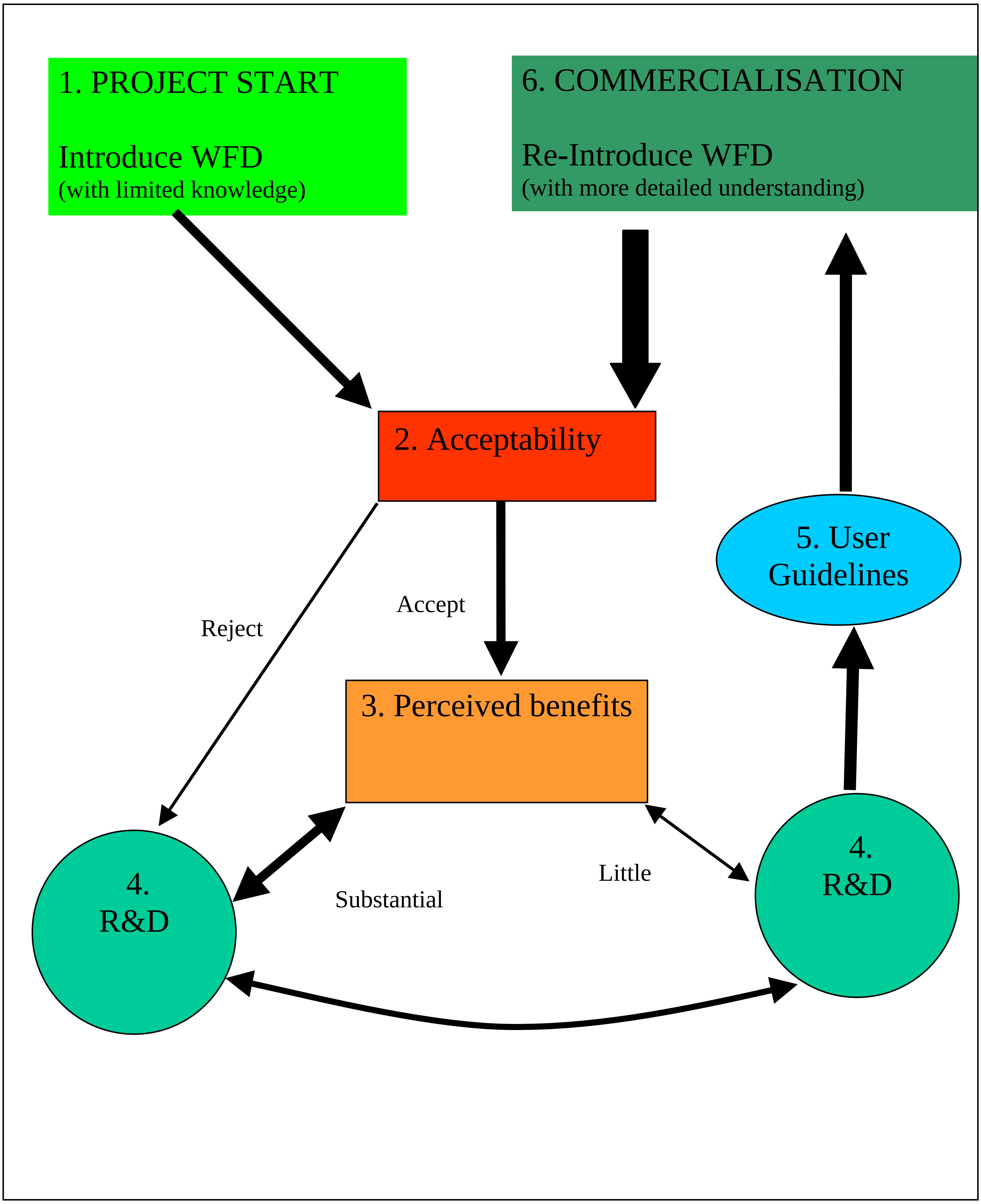


Figure 1 The steps in the development from the idea to a commercial product. Steps 2 to 6 were carried out concurrently with iteration between scientists, extension workers, farmers and industry.

While the extension work was being carried out a series of experiments were conducted at the Hatfield research station to compare different ways of using the WFD with standard irrigation scheduling practices. This formed the basis of the accuracy test (step 4).

As new data was produced from the trials, and successes and failures relayed back to the project team from the farmers, the instructions for using WFDs were considerably modified (step 5). New experiments were carried out to test design modifications to overcome specific problems. By combining the findings from the scientific tests, the experience of the farmers, the insights from the extension workers, and the skills of an irrigation product company, a commercial version of the Wetting Front Detector was designed and manufactured.

Results

Part One of this report describes how the wetting front detector works, the status of research prior to this project and steps leading up to commercialisation. The three strands of the project, namely quantitative research, intensive monitoring of leading farmers and on-farm experience are then discussed separately in Parts Two, Three and Four respectively.

The trials at the Hatfield experiments showed that the electronic WFD used in automatic mode produced the best results, even better than the standard neutron probe method. Two other ways of using WFDs were less successful, with one over-irrigating and one under irrigating the crop. In all cases the detectors clearly showed where under-irrigation was occurring, but over-irrigation was not always as obvious. The new insight from the trials was that their needs to be a strong management response to the activation of deeply placed detectors.

Pilot trials were also conducted to test modifications to the detector that would make it more sensitive and a version specifically tailored to furrow irrigation was designed and built. These modified versions performed well and require evaluation by farmers.

The acceptability and accuracy of the WFD was evaluated by monitoring its performance on the properties of three leading table grape farmers in different districts (Part Three). These leading farmers had already invested in scheduling technology, so if simple information from detectors provided them with further insights on how to improve their management, we assume that the method would be acceptable and sufficiently accurate to help many other farmers.

The study revealed that these farmers had very different irrigation strategies and used very different amounts of water. In each case the wetting front detectors highlighted areas where management could be improved. Wherever possible a dialogue was maintained with the farmers and their changing perceptions and management response recorded. The on-farm trials showed that the detectors were sufficiently accurate and useful to challenge expert farmers. There was no substantial evidence that the detectors were not sensitive enough.

The experience of working with farmers provided a whole new frame of reference that was in contrast to traditional scientific thinking. In the scientific trials we sought mathematical algorithms that related the detector response to the management e.g. if 4 out of 5 deep detectors are activated then reduce the next irrigation by 30%.

These rigid rules had no capacity to "learn" from past experience, so irrigation management was as good as the rule that governed it. In contrast, the farmers looked at patterns of detector response and compared this against their own experience and intuition. Farmers were more interested in managing risk, rather than the scientific obsession with accuracy. The subjective ways in which farmers used detector information may turn out to be more powerful than the "objective" methods evaluated in the controlled experiments.

Semi-structured interviews were held with 54 irrigators, teachers or consultants, all of whom had had practical experience with the wetting front detector. The skill level of respondents ranged from those who were experienced consultants to small-scale farmers with little formal education. 48% of respondents felt that the value of the detector lay in its role as a learning tool, while 32% were interested in additional or alternative scheduling methods to what they were using and 20% wanted a device that could sample soil solution for nutrient analysis. One hundred percent of respondents reported that the WFD concept was easy to understand, but 28% encountered some difficulty when it came to using the detector. Ultimately 82% of users had a positive perception towards the detector, whereas the remaining 18% felt it was not compatible with their needs or irrigation system.

Much of the incompatibility reported above was traced back to problems experienced with centre pivot and furrow irrigation. The original instructions had provided no information on how to use detectors for these applications because very little research work had been conducted. Pilot trials were therefore carried out to see if these problems could be resolved, and the indications are that the detector in its current form can be successfully used for these applications. However, modifications to the original model will make the use of the detector better for some applications.

Conclusions and Recommendations

The Wetting Front Detector achieved the aim of creating a dialogue between researchers and farmers, challenged the perceptions of both parties, and stimulated changes to irrigation practice. Based on this user survey and the scientific evaluation, a detector, which blended the strong points of the electronic and mechanical version, was designed and is being produced commercially.

One of the most valuable insights from the project was the role the WFD can play as a learning tool among farmers of very different skill levels. During the project the focus shifted from delivering a tool that will solve irrigator's problems, to a tool that encourages a journey of learning and discovery. The learning based approach developed during this project required researchers and extension workers to play new roles which do not always fit well with institutional cultures. Experiential learning processes need to be facilitated and managed well, and the necessary facilitating skills are very important.

The project started with a prototype detector distributed to farmers with brief general instructions. It ends at Step 6 of Figure 1 with a commercial product and a much fuller understanding of how a Wetting Front Detector should be used. Success from this point will depend on how well we can facilitate the learning process of irrigators. There is a clear need for educational material, both written and web based and training for farmers and extension workers.

Acknowledgements

The research in this report emanated from a project funded by the Water Research Commission entitled:

CHEAP AND SIMPLE IRRIGATION SCHEDULING USING WETTING FRONT DETECTORS

The Steering committee responsible for this project, was made up of the following persons:

Dr S Mkhize	:	Water Research Commission (Chairperson)
Dr GR Backeberg	:	Water Research Commission
Dr KK Ayisi	:	University of the North
Mr CK M'Marete	:	University of Venda
Mr M Shaker	:	Limpopo Department of Agriculture
Dr RJ Rutherfoord	:	Golder Associates
Dr LD van Rensburg	:	ARC-ISCW, Glen
Mr FB Reinders	:	ARC-IAE, Silverton
Mr J Taljaard	:	Water Research Commission (Secretary)

The financing of the project by the Water Research Commission and the contribution of the members of the Steering Committee is gratefully acknowledged.

This project was only possible with the co-operation of many individuals and institutions. The authors therefore wish to record their sincere thanks to the following:

1. Dr Gerhard Backeberg: Not only did Gerhard maintain the vision of producing a simple device throughout the duration of the project, he also challenged us to move way out of our comfort zone. It was Gerhard who insisted we do the science and the extension side by side and thereby bring people and technology together. He encouraged us to be bold and was prepared to share the risk that entailed.

2. Agriplas: Agriplas, especially Bertus Kruger and Etienne Erasmus, also caught the vision early on and were prepared to share the long and sometimes difficult road of turning a piece of science into a product. We thank them for their dedication and open communication throughout.

3. The farmers, both commercial and emerging, that co-operated so enthusiastically with us on this project.

4. Rilette Luus, for her efficient and friendly assistance with getting the report together for us in the correct format.

PART ONE: An introduction to the Wetting Front Detector

Bridging the gap between science and practice

The science of irrigation scheduling has a long and illustrious pedigree. Field monitoring of soil suction began in the 1930's with the development of the tensiometer (Richards and Neal 1936), followed by water content measurement using neutron scattering (Gardner and Kirkham 1952). More recently the development of a range of capacitance or reflectometry probes that measure the dielectric property of soil (Topp and Davis 1985, White and Zegelin 1995), has reinvigorated interest in soil water monitoring.

Other methods for improving irrigation have proceeded in parallel with soil water monitoring. The simplest is the pan evaporation - crop factor method, which in recent years has been greatly enhanced by availability of automated weather data acquisition and crop simulation models (Allen et al. 1998, Annandale et al. 1999). Lastly there are several methods to monitor the water status of the plant itself, the simplest field-based method being canopy temperature (Jackson et al. 1977).

Studies have shown that farmers who use any of the above methods invariably save water and/or increase yields. Yet surveys also show that most farmers do not make use of these scientific tools. A national census of irrigators carried out in Australia in 1999 revealed that less than 15% used science-based tools, whereas over 90% relied heavily on "local knowledge".

The above gap between the science and practice of irrigation scheduling is traditionally seen as a failure in adoption that should be addressed by extension i.e. the problem has been solved so we must get the target audience to implement it. The trouble with this view is that it makes the assumption that the problem is lack of awareness of solutions on the part of the target audience. However, it is possible that research and extension programs have been based on the worldviews of the problem solvers, rather than their clients (Blacket 1996). For example, scientists take it for granted that irrigation farmers want to spend time and money on saving water, yet farmer surveys show that this aim is not near the top of their priority list.

When the technology transfer approach is struggling, Blacket (1996) recommends that we pursue 'learning based' approaches. The WFD project follows this model. Starting from the simplest requirement of the user, it gives a yes/no answer to the question: "did the irrigation water penetrate to the desired depth?" The assumption is that farmers want to replenish the water in the root zone that had been used by the plants. Detectors are placed in a pair, a shallow one about half way down the managed root zone and a deeper one towards the bottom of the managed root zone. If detectors are rarely activated the crop is likely to be under-irrigated. If shallow and deep detector regularly respond to irrigation, the crop is likely to be over-irrigated. Ideally we want most of the irrigations to fall between these extremes.

The learning based approach means that we take as our starting point the farmer's current practice, implicitly valuing their existing skill level. The farmer is asked to watch the response of the detectors and decide what it means for them. Since we already know that farmers rely heavily on local knowledge, we make the assumption that this knowledge has to some extent been tested and refined over the years. We also know that it is very difficult for farmers to know if they are over-irrigating on well-drained soils without the aid of a scientific tool (Stirzaker 1999). However, change incurs risk of under-irrigation, and so there needs to be a process during which information reduces the risk to the point that the farmer is willing to alter practices. In other words the value of the information to the farmer resides in its success in reducing risk to the point that the farmer is willing to change (Pannell and Glenn 2000).

How the wetting front detector works

The detector works on the principle of flow line convergence. Irrigation water or rain moving downwards through the soil is concentrated when the water molecules enter the wide end of the funnel. The soil in the funnel becomes wetter as the funnel narrows and the funnel shape has been designed so that the soil at its base reaches saturation when the wetting front outside is at a similar depth. Once saturation has occurred free water flows through a filter into a small reservoir and activates a float (Stirzaker et al. 2000, Stirzaker 2003). The wetting front detector was developed and patented by CSIRO Land and Water, Australia, in 1997.

The wetting front detector can be used to schedule irrigation, because the time it takes for water to reach a certain depth depends on the initial water content of the particular soil (Philip 1969). If the soil is dry before irrigation, the wetting front moves slowly because the water must fill the soil pores on its way down. Therefore a lot of water is needed before the detector will respond. If the soil is quite wet before irrigation, then the wetting front will move quickly through the soil. This is because the soil pores are already mostly filled with water so there is little space for additional water to be stored. Thus a short irrigation will cause the detector to respond.

The float in the detector is activated when free water is produced at the base of the funnel. Water is withdrawn from the funnel by capillary action after the wetting front dissipates. Depending on the version used, capillary action can be used to “reset” the detector automatically, or water can be removed via a syringe. The water sample can be used for routine salt and fertilizer monitoring.

Status of the research prior to this project

An electronic version of the detector was used for all research work in Australia prior to 2000. At first we were unsure how much “free” water was produced by convergence in the funnel, since an electronic float switch only needed to be displaced about 1 cm for activation and this did not require much water. Further investigation showed that over 20 ml of water was produced by convergence in the funnel in the vast majority of situations. This was sufficient to operate a mechanical float, which required slightly more water than the electronic version because the float needed to be lifted at least 5 cm to give a visible signal.

The development of the mechanical version brought two changes. First it dispensed with all electronics, which meant that the detector would be suitable for a wide cross section of farmers. Second we needed to change the way in which the detector was used from “control” to “feedback” mode. The electronic version was connected in series with an irrigation controller and a solenoid valve. When the detector was activated by a wetting front it interrupted the power to the solenoid valve, thus overriding the controller. A mechanical detector could not be used in control mode. The farmer would have to evaluate the detector response after irrigation and use this feedback to decide what to do next time.

The mechanical prototype was built in 1999 and its performance compared with the electronic version under laboratory conditions prior to the commencement of the WRC project (Figure 1.1). The accuracy of mechanical and electronic versions proved to be similar under laboratory conditions and both versions were used in the WRC project. Development and testing of the mechanical version was essential to fulfill the aims of the project relating to small–scale farmers.

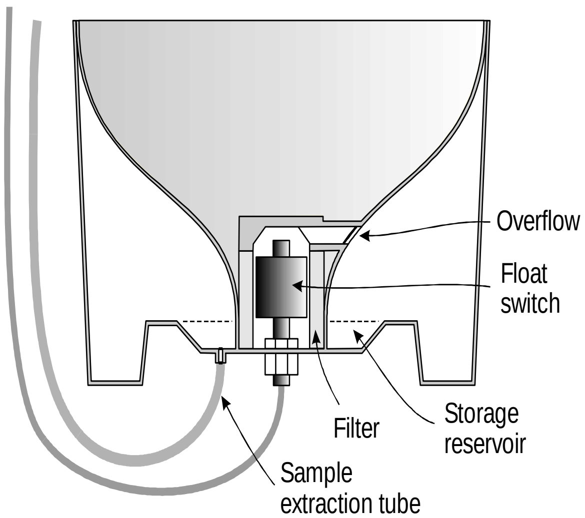
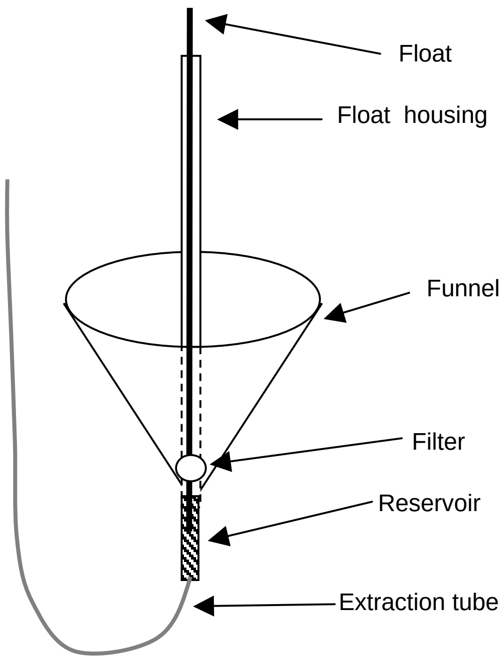


Figure 1.1 a) The electronic prototype contains a float switch behind the filter. If the cell containing the float fills completely, water overflows into a storage reservoir and this sample can be extracted for nutrient or salt monitoring. Water around the float switch is withdrawn back through the filter by capillary action as the soil dries, thus resetting the detector



b) The mechanical prototype has a narrow reservoir below the filter which houses a styrofoam float. As the reservoir is filled the float moves up the float housing and protrudes above the soil surface. The reservoir is emptied by syringe through an extraction tube

Commercialisation

Prior to signing the WRC contract in March 2000, CSIRO disclosed that it was negotiating with an Australian company to manufacture the electronic version of the detector. The commercial partner informed CSIRO in December 2000 that although they believed the product would be a “success” they were not the right company to exploit it. Thus six months into this project there was no strategy for commercialisation. In March 2001 the South African company, Agriplas Pty Ltd, expressed their interest in developing a hybrid version of the electronic and mechanical versions.

Negotiations continued through 2001 and a license agreement was signed between CSIRO and Agriplas in March 2002. Following this there was a period of design and testing of prototypes, and both parties agreed on the final design in October 2002. Changes to Agriplas management structure delayed progress until May 2003, when tooling for production began. The first version of the production model was produced in September 2003.

The fact that the research, extension and commercialisation proceeded concurrently focused the project more sharply than any set of milestones or objectives. Handing technology over to users is the fastest way to find the problems, both in the design and the instructions. Entering into partnership with the private sector is the fastest way to find out if you have a potentially commercial product. We had two years to identify the weak points of both prototypes and work out how to combine the best of both versions. We had a similar time to do the research, dialogue with farmers, fine-tune the instructions and come up with a realistic picture of what the wetting front detector can and can’t do. This report tells the story.

PART TWO: Accuracy of the detector: Research at the Hatfield Experimental Station

The research team at the University of Pretoria had no prior experience with the wetting front detector, so the project started with a quantitative evaluation of the technology. Furthermore, there had been no in-field testing of the mechanical version and therefore no evaluation of using detectors in “feedback” mode. Thus the research component had four goals:

- evaluation of the mechanical version
- demonstration to the senior members of the research team the capability of wetting front detectors
- platform for postgraduate studies and capacity building
- develop skill base amongst the research group to support the extension effort, respond to farmer queries and produce instructions for users

The wetting front detector is both a method and a device for irrigation scheduling. The normal method for determining how much water to apply requires four pieces of information, namely, the current or initial water content or θ_i, the water content at the upper drained limit or field capacity θ_{udl}, the refill point θ_{rf} or minimum allowed water content and the depth of soil that needs to be filled to field capacity. If a soil water-monitoring tool such as a neutron probe is used, the initial water content (θ_i) is measured, the refill point is at the discretion of the irrigator and the upper drained limit and root zone depths can be determined by observing the measurements over time. The wetting front detector method attempts to avoid the complexity of measuring θ_i, in favour of the simpler measurement of depth of infiltration. However, the information of whether the water reached a certain depth or not can only be determined after an irrigation event.

From the perspective of the farmer, the depth to which water infiltrates makes intuitive sense, because most have some idea how deep the active rootzone is. From a scientific perspective, it is necessary to establish the relationship between the amount of water applied, depth of infiltration and initial water content (see Appendix 1).

Once we have shown that the method of irrigation scheduling to a fixed depth is sound on a theoretical basis, we need to choose a device that can tell us the depth of water infiltration. Any device that can measure the change in water content would be suitable, but the aim is to do it as simply and cheaply as possible. This is the rationale for the wetting front detector – to find the easiest way to monitor depth of infiltration.

There is, however, one confounding factor. The wetting front does not stop once the irrigation is turned off. The front continues to move downwards (and outwards in the case of drip) under the forces of gravity and capillarity for many hours after irrigation ceases. This is called redistribution. The concept of field capacity (or the soil’s upper

drained limit) embodies the idea that redistribution (or drainage) is not an important term in the water balance of an irrigated field 48 hours after rain or irrigation.
During redistribution the front gets weaker and weaker and therefore harder to detect with a simple detector described here. Our prototype wetting front detectors have a switch point of around 2 kPa suction. That means if the soil is wetter than 2 kPa, the detector will be activated. If it is drier than 2 kPa, water will be able to move past the detector without activating it.

The rationale underpinning the entire wetting front detector project is finding a balance between simplicity, accuracy and cost. This section deals with the accuracy component. Four experiments conducted at the Hatfield Experimental site are described.

Hatfield experiment 1 – Sunflowers

All the experiments were conducted in the rain shelter facility at the University of Pretoria Experimental Farm at Hatfield. The facility had 60 hydraulically isolated plots. The 30 outer plots were used as a border and the six irrigation treatments were randomly assigned to 30 inner plots in five blocks. The treatments were:

1. Neutron Probe (NProbe): prior to the experiment, all plots were irrigated to excess and allowed to drain for 48 hours. The water content was summed over 1200 mm depth and this value taken as field capacity. The total water stored over 1200 mm was measured just prior to irrigation at 100 mm intervals. The difference between the current water content and field capacity was computed for each replicate and the average deficit applied to the treatment. The required amount of irrigation was converted to a run time and programmed into an irrigation controller.

2. SWB Model (SWB): the Soil Water Balance model was used to compute the crop water use, using pre-determined growth parameters for sunflowers and weather data from a station 50 m away from the site.

3. Automatic control by wetting front detector (Auto): An irrigation run time was programmed into the controller that would be well in excess of crop requirements (>50 mm per irrigation). When the wetting front had penetrated to a depth of 300 mm, the electronic detector cut the power between the solenoid valve and the controller, thus stopping irrigation.

4. Automatic control by wetting front detector with feedback (Auto-FB): This treatment was the same as the above but factored in redistribution. If sufficient water redistributed past 300 mm to activate a second electronic detector at 600 mm depth, then the next irrigation to that plot was cancelled.

5. Building a crop factor with a wetting front detector (Crop Factor): The treatment had mechanical wetting front detectors installed at 300 and 600 mm depths. Potential evaporation was computed from the weather station and multiplied by an estimated initial crop factor. This crop factor was subsequently adjusted up or down based on the number of detectors at a depth of 600 mm that were activated by the previous irrigation (Table 2.1).

6. Feedback control using wetting front detectors: The treatment had mechanical wetting front detectors installed at 300 and 600 mm depths. The first irrigation amount was estimated and subsequently adjusted up or down depending on the number of detectors at a depth of 600 mm that were activated by the previous irrigation (Table 2.1).

Table 2.1 The algorithms used to increase or decrease irrigation in the Crop Factor and Feedback treatments

	Treatment	
Deep detectors activated	**Crop Factor Change factor by**	**Feedback Change irrigation by**
0	+ 0.1	+30%
1	+ 0.05	+30%
2	0	0
3	0	0
4	-0.05	-30%
5	-0.1	-30%

Each plot measured 2 x 2.5 m and contained three rows of drip tape with a spacing of 300 mm and emitter rate of 2 l/h. There were 34 emitters per plot giving an application rate of 13.6 mm/h (Photos 2.1 - 2.3). The automatic and mechanical wetting front detectors were installed by augering a hole to the required depth and backfilling the soil in the order it was removed (Photo 2.1). Detectors were placed directly beneath an emitter. Each of the 30 plots already had a neutron probe access tube, so treatments 2 to 6 were evaluated by measuring the change in soil water content on a weekly basis. Irrigation was at first carried out twice weekly, and then once per week toward the end of the season as the weather cooled.

Experimental protocol

The first crop of sunflower (Photo 2.6) was a test run of the equipment and electronics. Prior to irrigation the following tasks were carried out:

- Take Neutron Probe measurements in the NProbe treatment and compute average deficit
- Download weather station and input data into SWB model for the SWB treatment
- Compute ETo and multiply by crop factor for Crop Factor treatment
- Determine irrigation run time on controller for each treatment, apart from those under automatic control, which received a 3 hour run time (Photo 2.4).

After irrigation the following tasks were carried out:

- Count the number of detectors that were activated in the Crop Factor treatment and compute new crop factor
- Count the number of detectors that were activated in the Feedback treatment and compute next irrigation quantity
- Download loggers to find out when electronic detectors shut off irrigation for the Auto and Auto-FB treatments (Photo 2.5)
- Check if 600 mm detectors were activated in the Auto-FB treatment. Skip next irrigation to plot where deep detector was activated.

Photo 2.1 (left)
The rainout shelter at the Hatfield experimental site. A hole is being augered for an electronic detector (foreground)

Photo 2.2 (right)
Some of the 30 inner plots, all hydraulically isolated to a depth of 1 metre, surrounded by the border plots. Each plot was 2 m x 2.5 m

Photo 2.3 (left)
Each plot had three rows of drip tape with a spacing of 30 cm and emitter rate of 2 l/h. There were 34 emitters per plot giving an application rate of 13.6 mm/h. The aluminium can on the left covers the neutron probe access tube and the wires from the automatic detectors can be seen

Photo 2.4 (right)
The irrigation amount was calculated for treatments 1, 2, 5 and 6 and the run time programmed into the controller. The WFD Auto treatments were given a run time of 3 hours, which would be shortened if a detector was activated before this time

Photo 2.5 (left)
Each treatment was controlled via a solenoid valve. In the case of the WFD Auto treatments, each plot had its own valve controlled independently by its own detector. The time that the water was automatically shut down was logged

Photo 2.6 (left)
The sunflower crop under the rainout shelter prior to flowering

Results

The electronic detectors were activated by irrigation and the time was logged, but due to an electronic fault they did not shut down the solenoid valve and override the controller. The Crop Factor treatment also experienced a problem, so the remaining three treatments are discussed below.

All treatments were irrigated the same during February when the crop was establishing. By harvest in May, the NProbe treatment had received 225 mm, SWB 301 mm and the Feedback treatment 337 mm (Figure 2.1a), producing seed yields of 2.05, 2.29 and 2.51 t/ha respectively. Although the yield appears correlated with increasing amounts of irrigation, the yields were not significantly different.

The profile did not get appreciably wetter or drier in any treatment (Figure 2.1b and 2.1c). Our preliminary conclusion, therefore, was that the NProbe treatment was not under irrigated (storage did not decline), and therefore the SWB and Feedback treatments were over-irrigated. However, the neutron probe data proved to be extremely variable, with total water use in different replicates varying from 146 to 297 mm. There are two possible reasons for this. First the field capacity values may have been inadequately measured. Second the distance between the closest dripper and the neutron probe access tube was not consistent.

Figure 2.1d shows that four of the five deep detectors of the WFD Feedback treatment responded when irrigation exceeded 30 mm, or two irrigations occurred close together. The detector response was greatest between 10 and 30 March, at the time the cumulative irrigation between the Neutron Probe and WFD Feedback treatments was diverging. Of the 11 irrigations, there were three occasions when the algorithm in Table 2.1 called for an increase in irrigation (0 – 1 detectors responded), four occasions when irrigation stayed the same and four occasions when the algorithm reduced irrigation (4-5 detectors responded). All five detectors at 300 mm responded to each irrigation. Given that one deep detector never responded (Block 4, possibly due to poor installation or blocked dripper) it seems the algorithm was not sufficient to prevent over-irrigation.

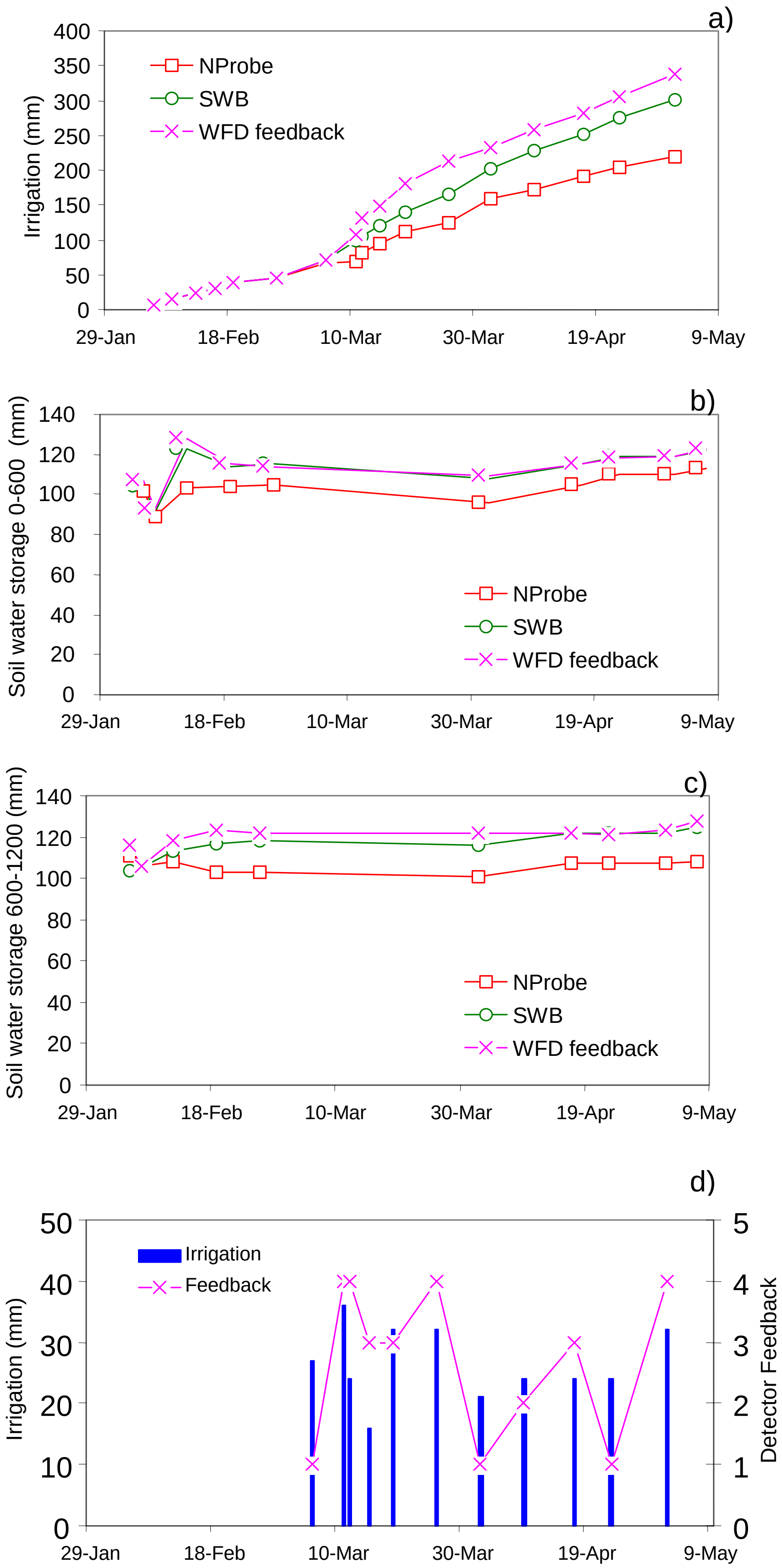


Figure 2.1

a) Cumulative irrigation

b) Soil water storage over 0-600 mm

c) Soil water storage over 600-1200 mm

d) Amount of irrigation applied to the WFD Feedback treatment on each irrigation day (left axis) and the number of 600 mm depth detectors that responded (right axis)

Hatfield experiments 2 – 4

Lucerne was planted in October 2001 and the same treatments applied as described for the sunflower experiment above. More detail on agronomic practices can be found in the dissertation of Maeko (2003). Since lucerne can be cut, the experiment was repeated three times as follows:

Summer	12 January to 14 February
Autumn	14 March to 11 April
Winter	25 April to 30 May

Problems experienced in the sunflower test run were rectified. The wiring for the electronic detectors was fixed so the solenoid valve in each plot was closed when the detector was activated. Field capacity was redetermined for each plot and the neutron probe calibrated against gravimetric samples taken from the site.

For each cycle of the experiment the total amount of water and the lucerne dry matter yield was measured. The change in soil water storage between the start and end of the cycle is computed from neutron probe data. The soil water balance equation below was used to calculate water use by each treatment.

$$ET = I + P - D - R - \Delta S$$

Where ET = evapotranspiration, I = irrigation, P = precipitation, D = drainage below 120 cm, R = runoff and ΔS is the change in soil water storage between 0 and 1200 mm.

Since there was no runoff or precipitation (rain-out shelter and plots had raised borders), the above equation can be reduced to,

$$ET + D = I - \Delta S$$

Evapotranspiration and drainage are combined, because it is not possible to separate these terms with our experimental setup.

Hatfield experiment 2: Summer (12 January to 14 February)

Prior to this cycle the wires between the controller and solenoids of the Feedback and Crop Factor treatments were inadvertently switched. These treatments were therefore irrigated incorrectly and omitted from the analysis.

The NProbe treatment required the most water and there was no significant difference among lucerne yields (Table 2.1). Three treatments ended the cycle around 20 mm wetter, with the soil water storage remaining the same in the Auto-FB treatment. The 300 mm deep electronic detectors in both automatic control treatments shut off irrigation in each plot every time, and on no occasion was there sufficient redistribution of water to set off the deeper detectors at 600 mm in the Auto-FB treatment.

Table 2.1 Total irrigation, change in soil water storage (∆S) over the 0-1200 mm depth, crop water use including drainage (ET+D) and dry matter of lucerne harvested during for cycle 1. Positive ∆S means the soil got wetter and negative ∆S that the soil got drier

Treatment	Irrigation (mm)	∆S (mm)	ET + D (mm)	Dry matter (t ha^{-1})
NProbe	196	19	177	4.0
SWB	154	21	133	4.2
Auto	137(120)[1]	22	115	4.2
Auto-FB	140(132) [1]	-2	142	3.7

[1] Additional irrigation was received when detectors reset before the run-time on the controller had elapsed. See text for details.

Table 2.1 gives a value for the water applied to the Auto treatments and a second lower number in parenthesis, which is what the treatment actually required. The difference is due to the fact that the detector "reset" before the 3 hour run-time on the controller had elapsed. After irrigation was shut down by the detector, the soil surrounding the detector was able to suck water out of it before the time on the controller had expired. The float in the detector returned to the rest position, thus reactivating the circuit between the controller and the solenoid. Irrigation recommenced until it was either shut down by the detector again or the 3-hour run-time had elapsed. The end result was that the automatic control treatments received slightly more water than intended.

When the neutron probe data was plotted as a deficit from field capacity it became clear that redistribution was still occurring in the profile at the time the original field capacity determination was made. Thus the top soil (0-600 mm) showed much lower deficits than expected and the subsoil (600-1200 mm) higher deficits than expected. Thus one day was picked (26 April 02) which appeared to best represent field capacity for each treatment, and this was taken to be the full point.

The NProbe treatment required 35 to 62 mm more water than the other treatments (Fig 2.2a). Since the yield was similar among treatments, we expect much of this extra water to be contained in the drainage (D) term. The neutron probe measurements in the subsoil support this observation (Figure 2.2c) as readings were close to field capacity and taken just prior to irrigation at the driest point in the cycle.

Both automatic control treatments ended with a topsoil deficit of 18 mm three days after the last irrigation, demonstrating that the wetting front detector method could keep the top soil well irrigated. The subsoil of the Auto treatment started with a subsoil deficit of 25 mm and this increased slightly to 35 mm over the cycle. The Auto-FB treatment started with a subsoil deficit of 43 mm and this was reduced slightly to 36 mm. Although the water content of the subsoil in this treatment did increase during the latter part of the cycle, this was not sufficient to activate any of the deep detectors.

Since the NProbe treatment used more water than the other treatments, and this extra water was not stored in the soil nor resulted in more growth, our conclusion from the summer cycle is that the NProbe treatment was over-irrigated. The SWB treatment and the automatic control treatments with wetting front detectors were able to keep the top soil sufficiently wet without causing drainage past the 1200 mm depth.

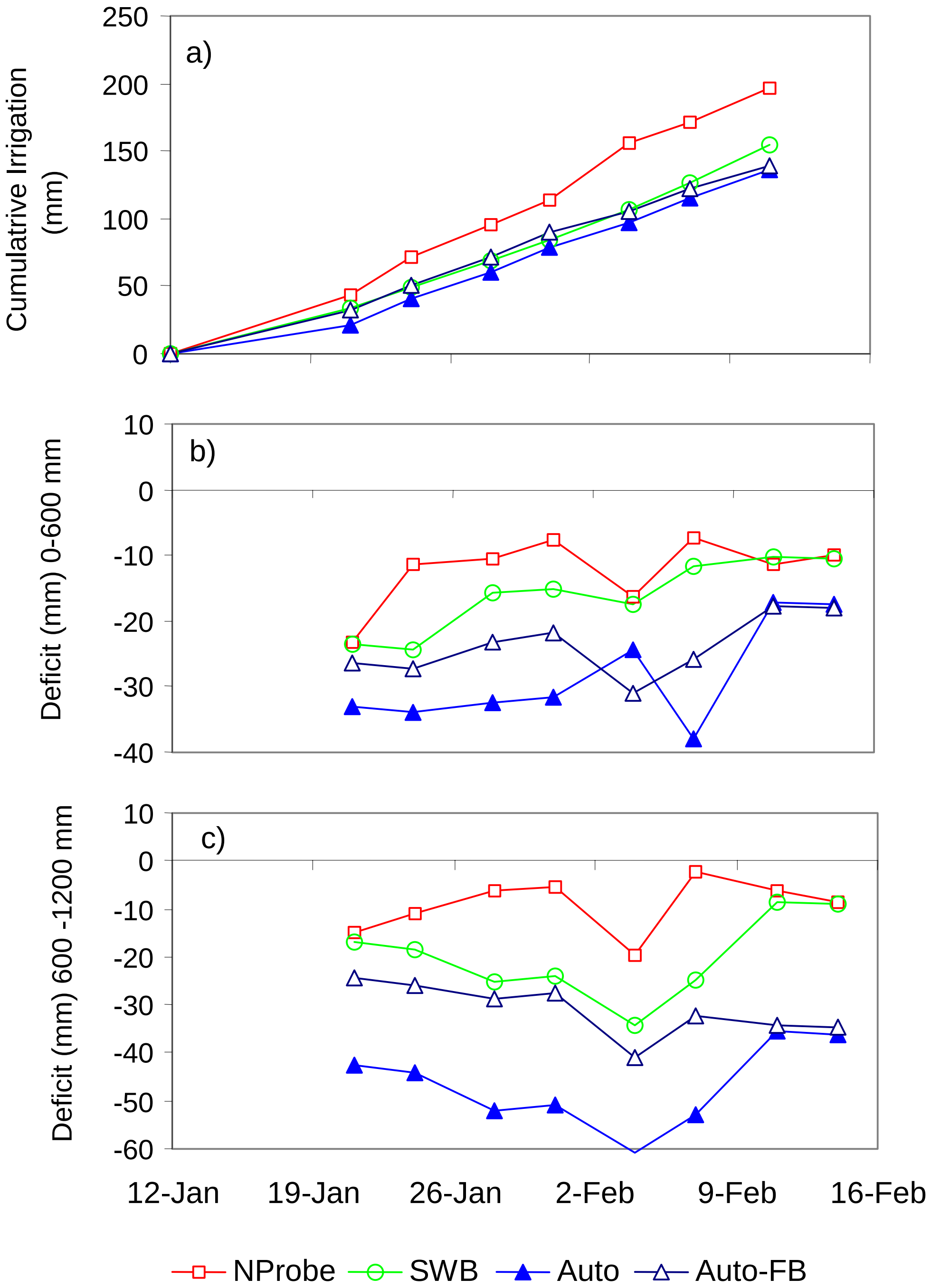


Figure 2.2
a) Cumulative irrigation
b) Soil water deficit (mm) over 0-600 mm
c) Soil water deficit (mm) over 600-1200 mm

Hatfield experiment 3: Autumn (14 March to 11 April)

The treatments ended the summer cycle at different water contents (Fig 2.2). Therefore the entire experiment was given 64 mm of sprinkler irrigation prior to the commencement of the autumn cycle to bring all treatments back to the same starting point. The original drip line was replaced with pressure compensating drip to ensure better uniformity and the change meant the irrigation rate changed from 13.4 to 18.4 mm/h. For this cycle the irrigation input variable in SWB was incorrectly updated, so this treatment was removed from the analysis.

Four of the five treatments required from 143 to 183 mm of irrigation (Table 2.2), with the Feedback treatment requiring considerably more. The irrigation record was not easy to reconcile with the neutron probe record, given that there was no significant difference in biomass production among treatments. The NProbe treatment, which received only 149 mm, did not mine the soil store, whereas the Auto-FB treatment required 21 mm more irrigation and mined the soil stored by 17 mm.

All treatments maintained a soil water deficit of less than 23 mm throughout the cycle in the top soil. The Crop Factor and Auto-FB treatments both displayed a drying trend in the subsoil. The deeper detector responded several times in the Auto-FB treatment, meaning that sufficient water moved below 300 mm, after the solenoid valve was closed, to activate the detector at 600 mm. When a deep detector responded, the relevant plot was omitted for the next irrigation, resulting in Auto-FB treatment requiring slightly less water than the automatic control treatment without feedback. The Feedback treatment was clearly over-irrigated.

Table 2.2 Total irrigation, change in soil storage (ΔS) over the 0-1200 m depth over the cycle, crop water use including drainage (ET+D) and dry matter of lucerne harvested for cycle 2. Positive ΔS means the soil got wetter and negative ΔS that the soil got drier

Treatment	Irrigation (mm)	ΔS (mm)	ET + D (mm)	Dry matter (t ha^{-1})
NProbe	149	4	145	2.8
Auto	183 (173) [1]	15	168	2.8
Auto-FB	170 (170) [1]	-17	187	2.8
Crop Factor	143	-10	153	3.4
Feedback	255	20	235	2.8

[1] Additional irrigation was received when detectors reset. See text for details.

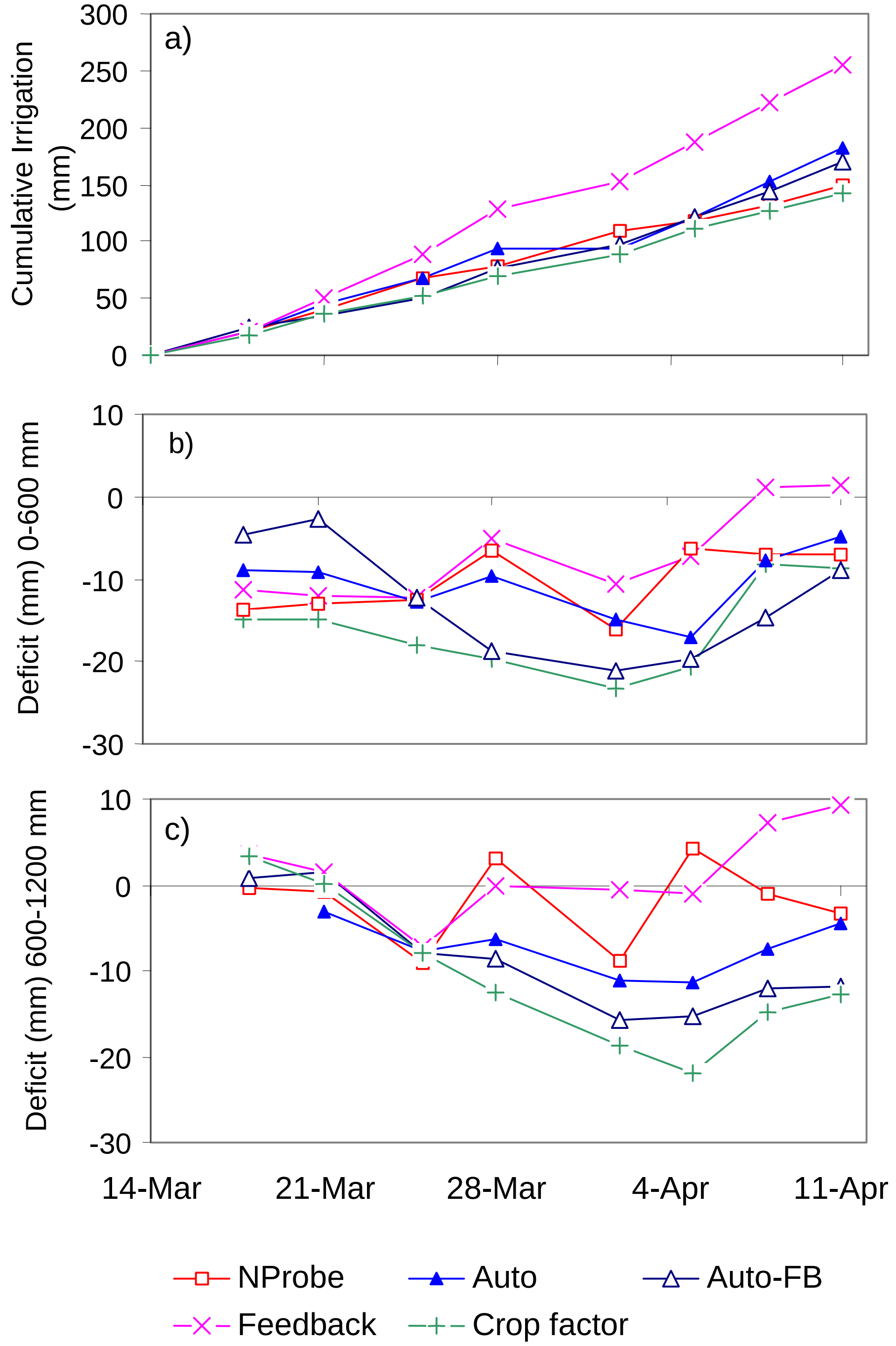


Figure 2.3

a) Cumulative irrigation

b) Soil water deficit (mm) over 0-600 mm

c) Soil water deficit (mm) over 600-1200 mm

Hatfield experiment 4: Winter (25 April to 30 May)

The experiment was sprinkler irrigated to remove difference in water storage among treatments from the previous cycle. All treatments were executed according to plan. One detector in the Auto treatment and one solenoid in the Auto-FB treatment malfunctioned, so the affected replicates were removed from the analysis.

This cycle had the largest range in water applications (Fig 2.4), but again there was no significant treatment effect on lucerne yield. Since the soil has a high water holding capacity and was well drained, and the lucerne had deep roots, short periods of under or over-irrigation were unlikely to affect yields.

Again all treatments kept the deficit under 20 mm in the topsoil. The SWB and Crop Factor treatments, which required the lowest amounts of water, mined the store of subsoil water and thus were under-irrigated. The Auto and Feedback treatments were over-irrigated because they required more water than the other treatments that could not be stored in the root zone and did not produce more biomass.

Table 2.3 Total irrigation, change in soil storage (∆S) over the 0-1200 mm depth, crop water use including drainage (ET+D) and dry matter of lucerne harvested for the winter cycle. Positive ∆S means the soil got wetter and negative ∆S that the soil got drier

Treatment	Irrigation (mm)	∆S (mm)	ET + D (mm)	Dry matter ($t\ ha^{-1}$)
NProbe	196	-3	199	2.5
SWB	113	-21	134	2.5
Auto	230 (196)	-8	238	2.5
Auto FB	173 (157)	-5	178	2.4
Crop Factor	92	-37	129	2.6
Feedback	260	0	260	2.7

[1] Additional irrigation was received when detectors reset. See text for details.

This cycle highlighted the difference between the two automatic control treatments. On 9 occasions the deep detector in Auto-FB treatment was activated, resulting in the affected plot missing the next irrigation. This had the effect of lengthening the irrigation cycle where subsoils were wet and presumably reducing drainage. The end result was a saving of 57 mm compared to shutting the water off at 300 mm with no feedback (Auto treatment).

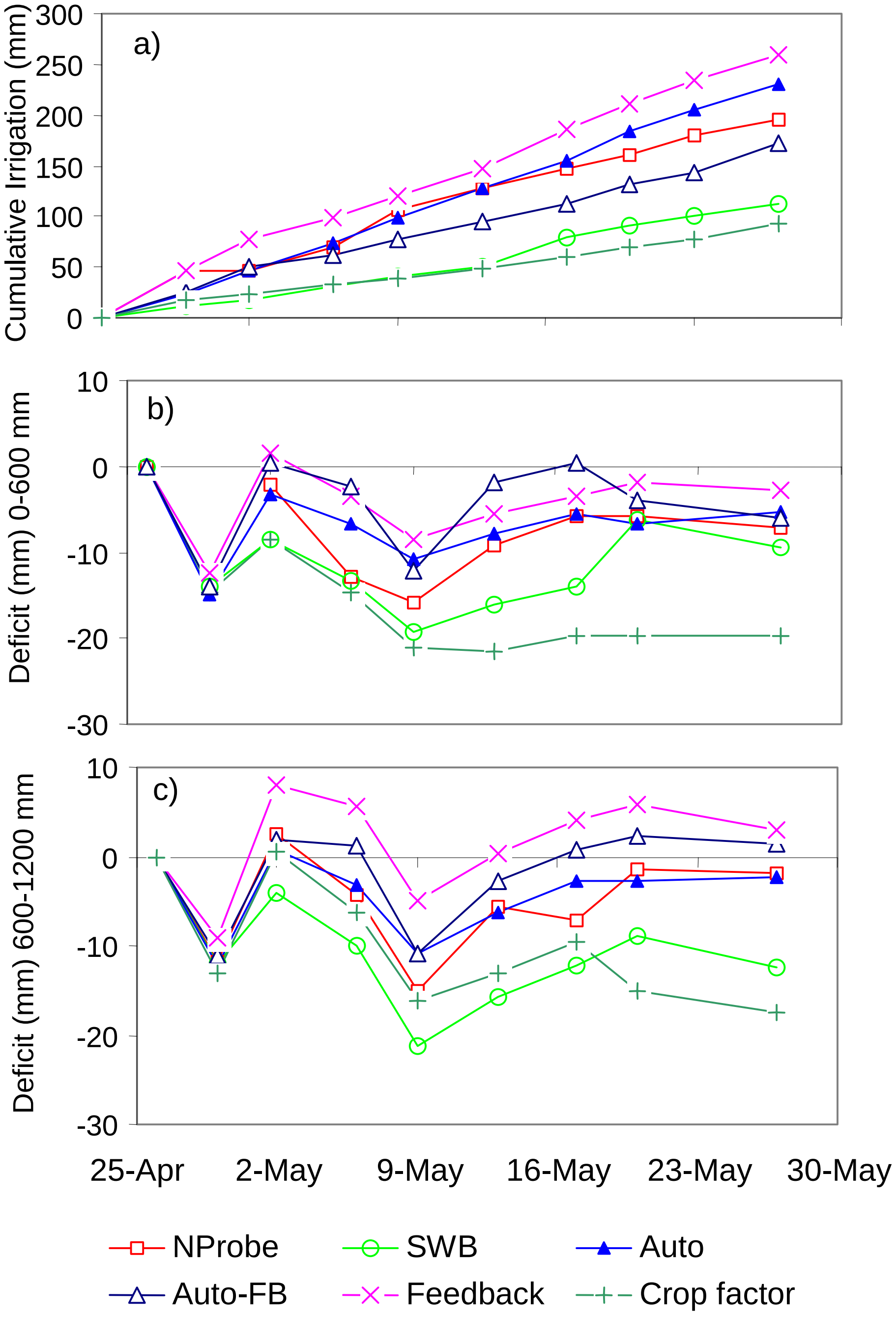


Figure 2.4

a) Cumulative irrigation

b) Soil water deficit (mm) over 0-600 mm

c) Soil water deficit (mm) over 600-1200 mm

Table 2.4 describes how the Auto-FB treatment was managed. The irrigation "wanted" is the amount of water applied up to the time that the electronic detectors shut down the solenoid. The irrigation "applied" includes any additional water received after the float had reset, but before the run-time on the controller had expired. Note that there were only 4 replicates for this cycle. If two deep detectors responded after an irrigation event, then only two plots would be irrigated next time, so only two shallow detectors would respond.

Table 2.4 Results from the WFD auto2 treatment during the winter cycle

Date	Irrigation 'wanted' (mm)	Irrigation 'applied' (mm)	Number of shallow detectors responding	Number of deep detectors responding	Replicate(s) skipped
29-Apr	25	25	4	0	None
2-May	21	24	4	2	1 & 2
6-May	11	12	2	0	None
9-May	10	16	4	1	2
13-May	17	17	3	2	1 & 3
17-May	18	18	Lost data file, all replicates were irrigated		
20-May	16	19	4	2	1 & 3
23-May	11	12	2	0	None
27-May	29	30	4	1	3
30-May	19	20	3	1	1

Lessons learnt from the Summer/Autumn/Winter lucerne cycles

The lucerne yield was not significantly different among treatments for any of the cycles despite large difference in irrigation amounts. However, the soil was very well drained and would have allowed root exploration well below the 1200 mm monitored in this trial. Thus short periods of over or under-irrigation would be unlikely to affect yields, and since treatments were watered between cycles, there was not sufficient time for serious deficits to develop. Therefore, the best scheduling treatments are those that used the least water, without forcing the lucerne to mine the soil storage.

The lessons learnt were as follows:

1. The best outcome came from using the wetting front detectors in automatic mode. The cumulative water required over the three cycles was 541 mm for NProbe, 489 mm for the Auto treatment and 469 mm for Auto-FB treatment (calculated as water "wanted" not "applied"). Even using the water "applied" data (which includes water applied after the detector had shut down the solenoid the first time), the Auto-FB treatment required 58 mm less water than the NProbe treatment.

2. The detector in automatic mode saved more water when there was a deeper feedback detector. As the season cools down (moving from summer to winter cycle), ET falls and there is less water used by the plants on the day of irrigation. Thus there is more water available for redistribution. Moreover, with the irrigation interval staying the same, the soil is wetter before irrigation at the cooler time of year, so the redistributing water will go deeper. Thus, when scheduling automatically with a WFD, the deeper feedback detector becomes more necessary as ET falls or the irrigation interval shortens. This is described in detail in Appendix 2.

3. The detectors clearly identified under-irrigation in the Crop Factor treatment but did not prevent over-irrigation in the Feedback treatment. The weaknesses in the Crop Factor and Feedback treatments were in part due to the algorithms used. Under-irrigation occurred in the Crop Factor treatment because the algorithm could not increase the crop factor fast enough, and over-irrigation in the Feedback treatment because too many deep detectors had to be activated before the irrigation was reduced.

No scheduling method is perfect. The Neutron probe method appeared to provide too much water in the first cycle and the Soil Water Balance model too little water in the third cycle. Since both methods are sound on a scientific basis, the aberrations are due to variability and calibration. The performance of the Wetting Front Detector depended on how the data was interpreted and implemented.

Although the Auto-FB treatment proved best, this does not in itself demonstrate the superiority of the detector method of irrigation scheduling. The experiment examined three different ways of using a detector, one of which proved to be very accurate, but one provided too much and one too little water. We did not know in advance which of the three methods would be best. We conclude therefore that it is difficult to prescribe exactly how a wetting front detector should be used with no prior knowledge of the crop and site. However, the detectors do provide a general overview of what is happening and the pattern of response should point the irrigator in the right direction, as illustrated below for cycle 2 (Fig 2.5) and cycle 3 (Fig 2.6).

In both cycles the Feedback treatment was over-irrigated and the Crop Factor treatment was under-irrigated. Total water applied to the Feedback treatment over the first five irrigations was 153 mm, during which time the soil profile remained full (Fig. 2.5a). All five shallow and five deep detectors were activated by the 38 mm irrigation on 28 March (Fig 2.5 b). In contrast the total water applied to the Crop Factor treatment over the same period was 88 mm, the soil dried by 42 mm (Fig 2.5c). On just one occasion, two shallow detectors were activated, and no deep detectors at any time. Towards the end of the cycle the soil water store did increase and this was reflected in the response of shallow detectors (Fig 2.5d).

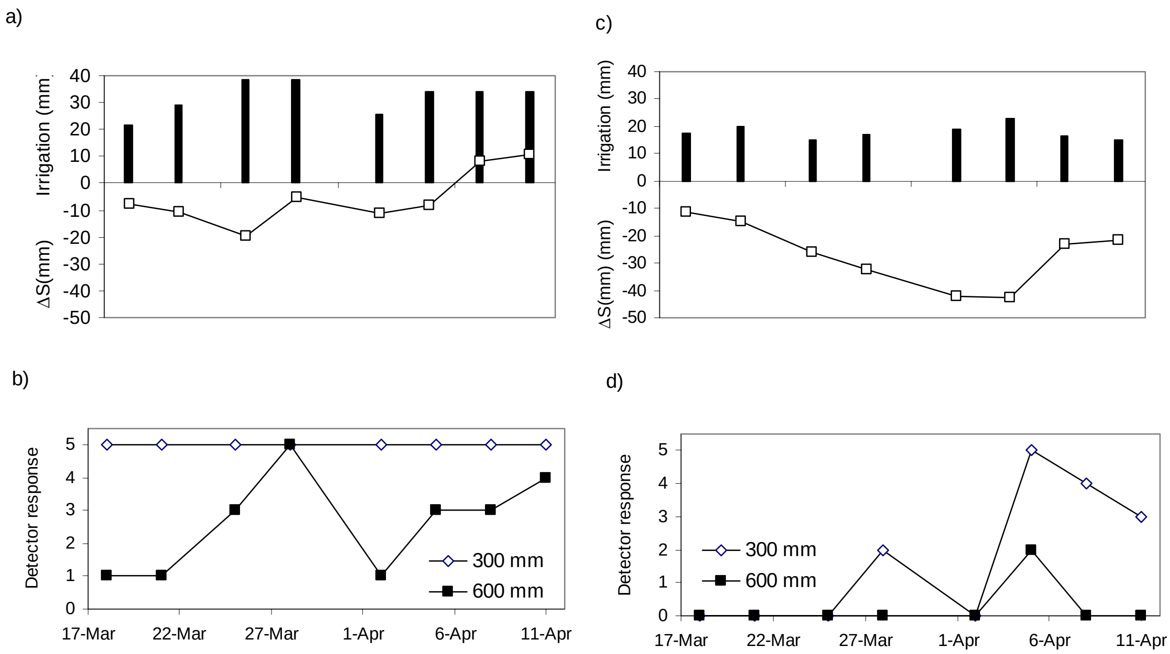


Figure 2.5

a) The amount of irrigation applied (bars) and the change in soil water content over the 0 -1200 mm depth (ΔS - open squares) for the Feedback treatment in cycle 2

b) The response of the shallow (300 mm) and deep (600 mm) detectors in the Feedback treatment.

c) The amount of irrigation applied (bars) and the change in soil water content over the 0 -1200 mm depth (ΔS - open squares) for the Crop Factor treatment in cycle 2

d) The response of the shallow (300 mm) and deep (600 mm) detectors in the Crop Factor treatment.

A similar picture is seen for cycle three. The Feedback treatment was over irrigated, and on three occasions this was reflected by the response of 4 of the 5 deep detectors (Fig 2.6a,b). There was no detector response in the Crop Factor treatment, while the total soil water deficit remained between 30 and 40 mm (Fig 2.6c,d).

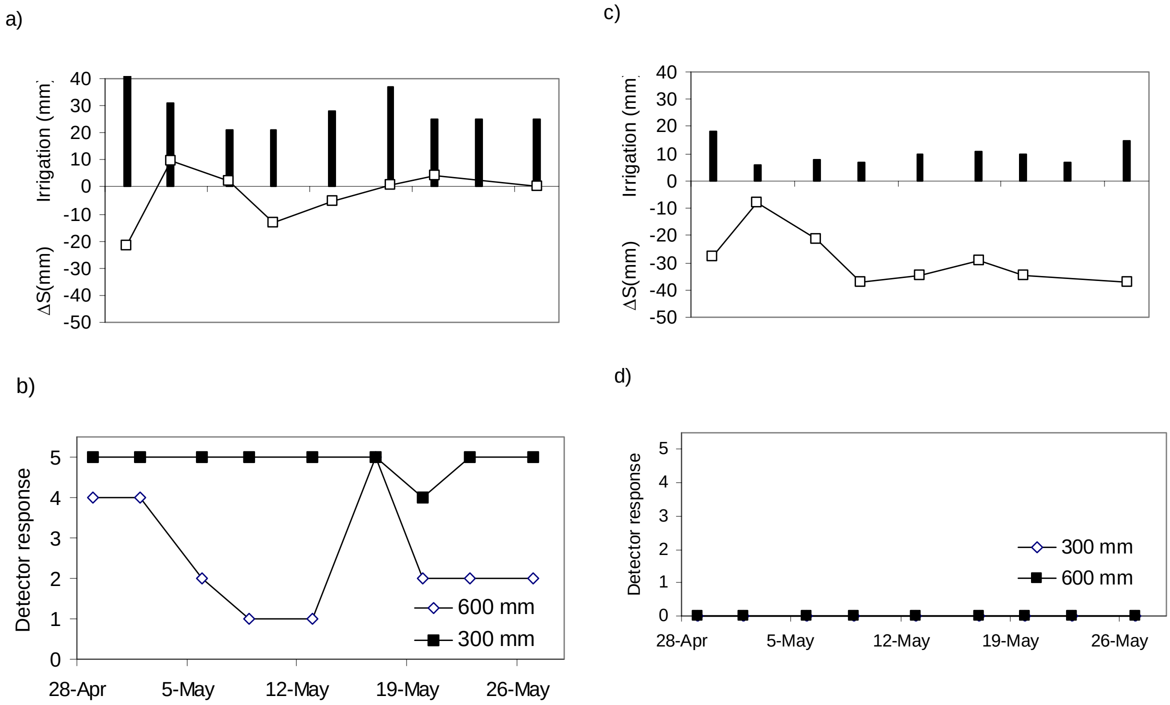


Figure 2.6

a) The amount of irrigation applied (bars) and the change in soil water content ΔS (open squares) for the Feedback treatment in cycle 3

b) The response of the shallow (300 mm) and deep (600 mm) detectors in the Feedback treatment.

c) The amount of irrigation applied (bars) and the change in soil water content ΔS (line) for the Crop Factor treatment in cycle 3

d) The response of the shallow (300 mm) and deep (600 mm) detectors in the Crop Factor treatment.

The most obvious lesson from the above is that if few or no shallow detectors are responding, then the crop is being under-irrigated. Where shallow detectors were consistently activated the crop is not under-irrigated.

The new insight provided by this experiment is that there needs to be a strong management response to the activation of deep detectors. The Auto-FB treatment always doubled the irrigation interval when a deep detector was activated, but the Feedback treatment required 80% of deep detectors to respond before there was any reduction in irrigation.

Clearly better algorithms would have led to a better outcome, but this is not the whole story. The Feedback treatment was over-irrigated for the last three irrigation events of both cycles, with only 6 of a possible 15 deep detectors responding in cycle 3 and 10 of a possible 15 responding in cycle 2. This may be a consequence of variability in irrigation or plant growth, resulting in some replicates being over irrigated and some not. It is more likely, however, that redistributing fronts were moving past the detectors at a strength that could not be detected. This issue of sensitivity is discussed in the following section.

Sensitivity of the Wetting Front Detector

As stated in Part One, the core of the Wetting Front Detector project is to find a balance between simplicity, accuracy and cost. The Hatfield experiments indicated that it might be advantageous to increase the sensitivity of a deep detector for certain situations.

Tests under laboratory conditions have shown that the funnel-shaped prototypes used in the Hatfield experiment have a "trip" point at around 2 kPa or 20 cm of suction. This corresponded to a flux of 0.2 to 0.4 mm/h across a range of soil types (Stirzaker 2003 and unpublished data). Since application rates by irrigation exceed 2 mm/h, we conclude that wetting fronts produced by irrigation will fall within the detection limits. However, water may move below the detector once the irrigation is turned off. Redistributing water can move at suctions below the detection limit and result in significant quantities of water moving below the detector.

The sensitivity of a detector is determined by the balance of two processes. Convergence in the funnel concentrates the water at the base of the funnel. Capillarity moves water from wetter to drier zones in the soil, and thus counteracts the convergences by "sucking" water out of the funnel. If convergence brings more water to the base of the funnel than capillarity can remove, then the water potential will rise to zero and liquid or free flowing water will be produced in the funnel and the float will be activated. Thus the sensitivity of the detector is determined by the diameter of the funnel and the depth from the rim of the funnel to the filter.

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. When the flux is low, and the background suction around 2 kPa or drier, then a funnel shape is not the best option for producing free water from the unsaturated soil. The low flux means that convergence is not powerful, and the shallow depth of the funnel does not counter capillarity. A narrow, long wetting front detector that we call a LongStop may be a more suitable design for deep placements.

Photo 2.7
The LongStops installed at Hatfield Research Station

Hutchinson and Bond (2000) describe a "tube tensiometer" that consists of a buried tube, 100 cm long, filled with diatomaceous earth and with a pressure transducer behind a filter at the base. The tube fills with water as water infiltrates into the open end. The tube is emptied by capillarity. By definition, the suction in the soil at the top of the tube at equilibrium is equal to the distance from the top of the tube to the water table within the tube. The height of the water table in the tube, if present, is measured by the pressure transducer at it base.

The LongStop uses the same principle, although the degree of accuracy provided by the pressure transducer is not required. Following the FullStop philosophy described in Part One, we seek the simplest information that could help a farmer make an improvement to their irrigation management. Thus we set the tube length to the sensitivity required for a particular situation and then by means of the float, provide a yes/no response as to whether a front of a given strength has reached a given depth.

Two LongStops, one 70 cm long and the other 100 cm long, were evaluated against an accurate pressure transducer tensiometer (Figure 2.7). Times of irrigation are shown by the filled diamond. The horizontal bars show when the float first rose and ends when the float reset in response to the change in soil water tension. The dotted lines mark matric potentials of -100 and -70 cm, so whenever the soil was wetter than the length of the tube (above the dotted line), the float should be up. Apart from one occasion when the 70 cm detector responded to an irrigation event when the matric potential was drier than 70 cm, the agreement between the LongStops and the tensiometer was extremely close.

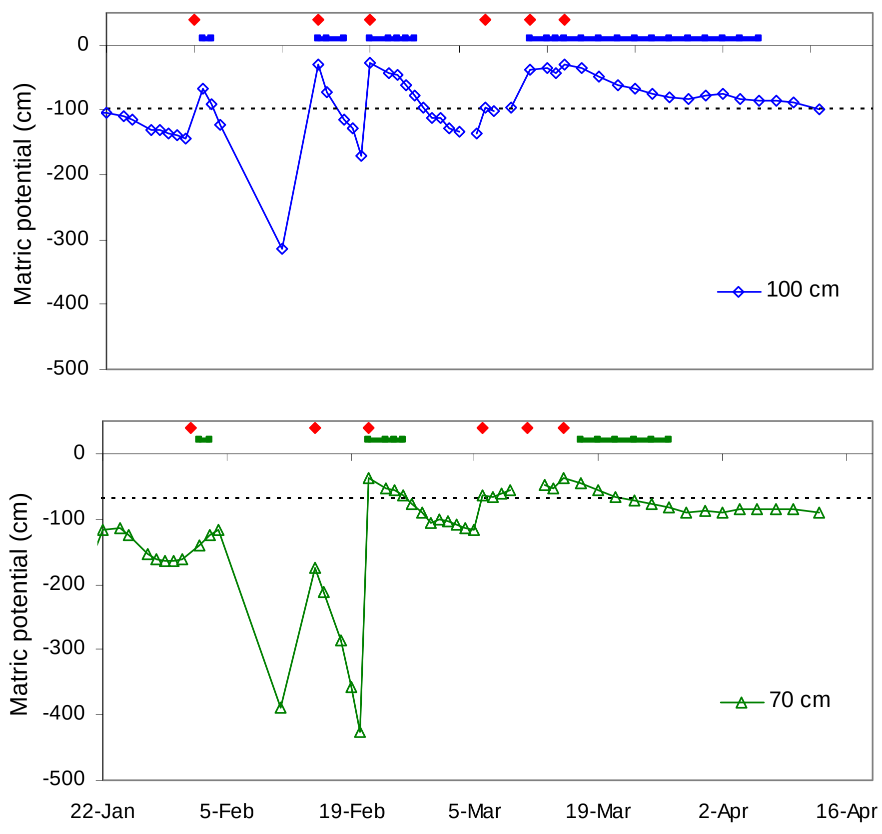


Figure 2.7 The period the float was raised (horizontal bars) for a 100 cm (top) and 70 cm (bottom) LongStop with the tube opening at a depth of 50 cm. The matric suction at 50 cm depth is shown as well as the time of irrigation (diamonds)

Twenty LongStops, containing diatomaceous earth and with a tube length of 65 cm, were installed at the Hatfield Experimental Farm beneath drippers on the adjacent dripper line to where the original funnel version was installed. A hole was augured to a depth of 95 cm and the LongStop inserted so that the open end was 30 cm from the soil surface. A further 10 cm of diatomaceous earth was packed above the LongStop to act as a wick. The next 10 cm was filled with original soil, but heavily compacted, so that disturbed soil would not provide a preferential path for infiltrating water. The deeper LongStop was installed in a similar way with the open end of the tube at 60 cm, so that both versions of the detector were measuring wetting fronts at the same depth. Installation was completed in August, allowing 10 weeks for the lucerne roots to re-establish before monitoring began.

The performance of the two versions of different sensitivity was compared over 4 lucerne growth cycles between 5 December and 27 March 03. During this period there were 21 rainfall or irrigation events, giving a possible total of 210 detector responses at each depth, should every detector be activated at each irrigation. At the 30 cm depth, FullStops were activated 133 times and LongStops 117 times, or a response of 63% and 57% respectively. At 60 cm, FullStops were activated 56 times and LongStops 50 times, or a response of 27% and 24% respectively (Figure 2.8).

Apart from one event in each of the first and second cycles, the response was very similar. From this data it appears that the failure of the FullStop to detect weak redistributing fronts was not an issue. The fact that both detectors responded in a similar fashion suggests that wetting fronts were stronger than 2 kPa, or weaker than 6 kPa. Fronts weaker than 6 kPa would be carrying very small amounts of water.

It is important to note that the comparison was not carried out during a period of low evapotranspiration, when the treatment using the deep FullStop in feedback mode performed most poorly. It remains possible that weak redistributing fronts were more common during this time of year, because the subsoil was wetter before each irrigation event.

Photo 2.8
Installation of the LongStop at Hatfield. The hole above the detector can be sealed, so the response is not affected by soil disturbance

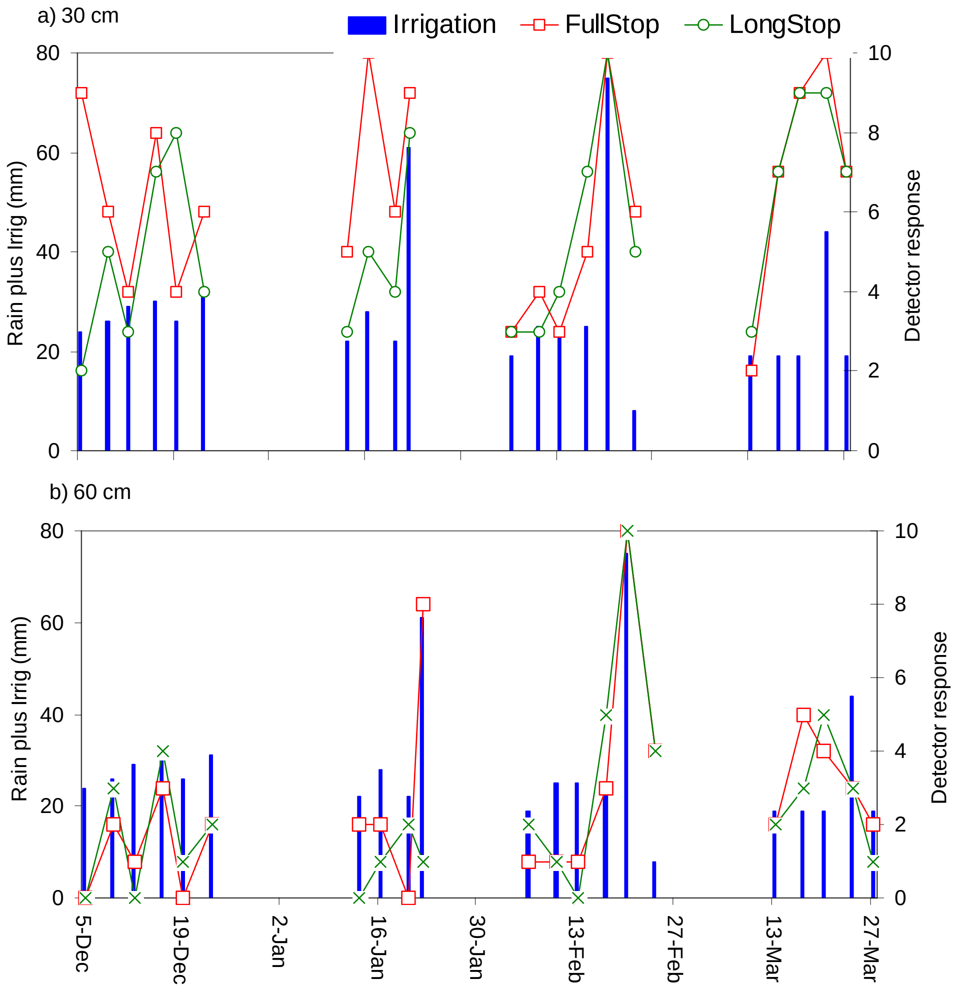


Figure 2.8 The amount of irrigation applied the number of FullStops and LongStops that responded at a) 30 cm and b) 60 cm

Further evaluation of the LongStop is required. It is slightly more complex than the FullStop, because it must be packed with a medium that has a high conductivity at a suction of 5 to 10 kPa. This is because the LongStop self-empties by capillary action, and it is important that the material in the LongStop remains in equilibrium with the soil at the mouth of the tube. The LongStop also requires a deeper hole to be dug for installation, to accommodate its length. However, it can be installed with less soil disturbance than the FullStop (Photo 2.8), which is an advantage for deeper placements. The "wick" of diatomaceous earth above the LongStop also sucks water into the detector from all directions, so the installation hole itself can be sealed, thus overcoming the problem of soil disturbance.

A second potential advantage of the LongStop is that it resets when the soil has dried to 6 kPa. During the first 3 cycles, the LongStops that had collected water after an irrigation were empty before the next irrigation. However, it was noted during the fourth cycle in March 03, that a number of deep LongStops had not self-emptied before the next scheduled irrigation. This indicates that the subsoil was wetter prior to irrigation, consistent with the lower evaporative demand. Thus the LongStops could be used to delay irrigation, a feature that might be very useful for flood irrigation, as described in the next section.

PART THREE: On-Farm Monitoring

The aim of this part of the project was to intensively monitor detector performance on the properties of leading farmers. From this we could evaluate the detector performance under real management conditions and what the farmers learnt from the experience. Our assumption was that if a leading farmer found the simple information provided by the detector to be useful, then many other farmers would too. We confined detailed monitoring to one crop, grown in different regions, using different irrigation management systems.

Drip irrigation of grapes in Mpumalanga

Table grapes were grown under drip irrigation with the aim of reaching the early season export market. Vine rows were 3.5 m apart with 2 lines of drip tape per row. Emitters were spaced 1 m apart and had a flow rate of 1.5 l/h, giving an application rate of 0.86 mm/h. Four electronic detectors were logged at a depth of 60 cm. They were all in the same row, two emitters apart. The amount of irrigation was measured by logging a pressure transducer connected to the drip line, which recorded when the line was pressurised. Rain was measured with a tipping bucket rain gauge, which was located on the ground under the netting that covered the vineyard (Photo 3.1).

Photo 3.1
Rain gauge and logger box

The detectors were installed in September 2000. The vine roots were disturbed during installation, so we did not expect meaningful data until the root system had re-established. Fewer roots above the detector would mean that the soil would tend to be wetter, causing wetting fronts to move faster through the soil.

The wetting front detectors were used to evaluate the irrigation strategy over the 00/01 and 01/02 seasons. For the purposes of this evaluation we made a rule that sufficient water had been applied when two of the three reliable detectors had responded to the wetting front (intermittent data was obtained from the fourth detector due to logging problems). The time irrigation continued after two detectors had responded was considered to be excess to vine requirements. The justification for this was that, in the absence of rain, irrigation was generally carried out daily or every second day, so the 60 cm depth from the emitter to the detector would be very wet nearly every day. Below 60 cm the gravel content increased sharply and fewer roots were observed. Our estimate of excess irrigation is subjective. On the one hand water would redistribute well below 60 cm after the irrigation was turned off, but we expect the vines could extract a little water from below 60 cm.

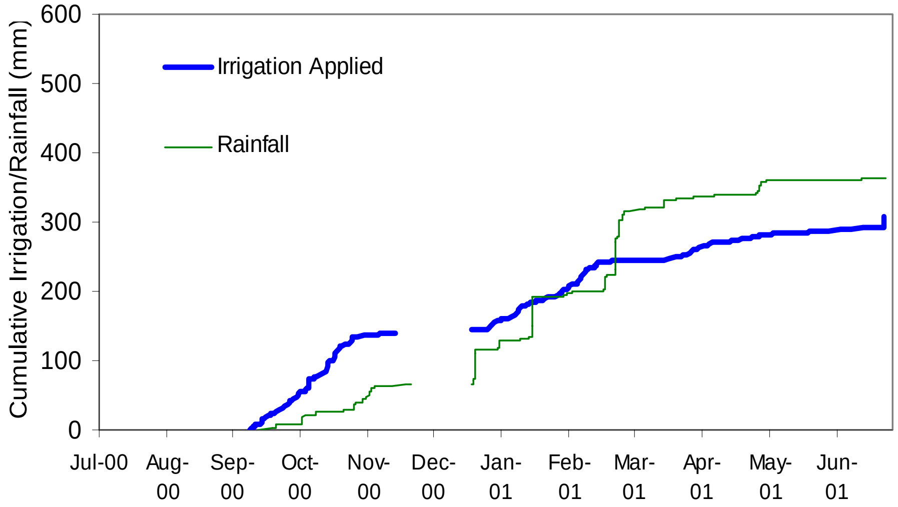


Figure 3.1
Cumulative rain and irrigation for the 00/01 season. Data is missing during November and December

Installation occurred after the irrigation season had started, and the data was lost from the logger during November and December 2000. Over the monitored period (10 September to 31 October and 1 January to 30 June) irrigation totalled 308 mm and rainfall 364 mm (Figure 3.1). Figure 3.2 shows the daily amounts of irrigation applied (closed bars) and the amount of irrigation applied after two of the three detectors were activated (open bars). Note that when both bars show the same amount, two detectors were still activated from the previous irrigation. According to our rule above, most of the time irrigation carried out in September and October was excess to vine requirements, although this was the re-establishment period after soil disturbance. After January it was rare for two detectors to respond before the irrigation was switched off.

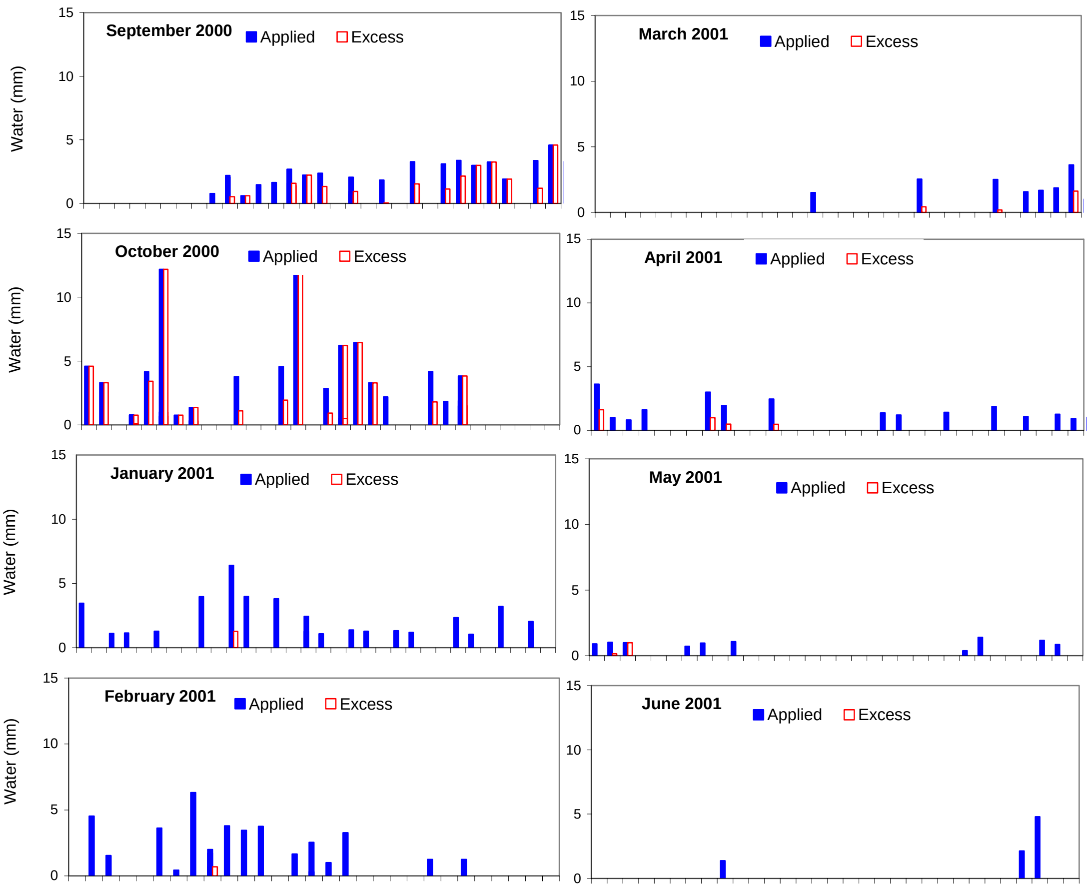


Figure 3.2 The amount of irrigation applied (closed bar) and the amount of water applied while two of the three detectors were activated (open bar) for the 00/01 season. Rainfall has been omitted

The data for the 01/02 season is more complete, from 1 Jul to 20 April, during which there was 456 mm of irrigation and 513 mm of rainfall (Fig 3.3). In July, 3 to 5 mm were applied around every third day. This was changed to 1.5 to 3 mm every second day during August and 2 mm per day in September. From late September to mid October there was a huge increase in irrigation, coinciding with the time the berries are sizing, after which it drops back down to around 2 mm per day in the absence of rainfall. Substantial rain during November and December meant that almost no irrigation was required. Irrigation resumed in January at 2.5 to 5 mm per day (Fig 3.4).

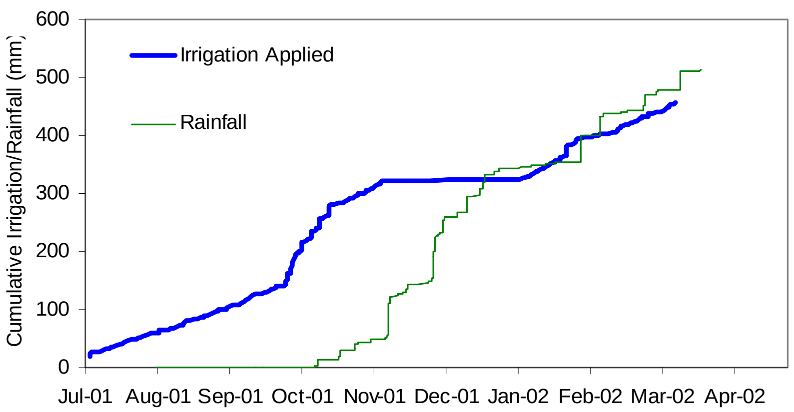


Figure3.3
Cumulative rain and irrigation for the 01/02 season

A large proportion of the irrigation up to mid August was unnecessary, according to our rule. After this date, irrigation appeared to be better matched to vine requirement until late September. During the period of high irrigation lasting to mid October, the detectors recorded the soil as being almost continuously wet. In other words the soil at 60 cm was wetter than 2 kPa whilst almost all the irrigation was taking place. Irrigation, drainage and transpiration were all taking place simultaneously, so the soil never had a chance to dry to field capacity, which is usually between 4 and 8 kPa. This was very similar to the previous season. There was more rain and more irrigation in Jan/Feb 02 compared to the previous year, and a significant proportion of the irrigation was excess to crop requirement.

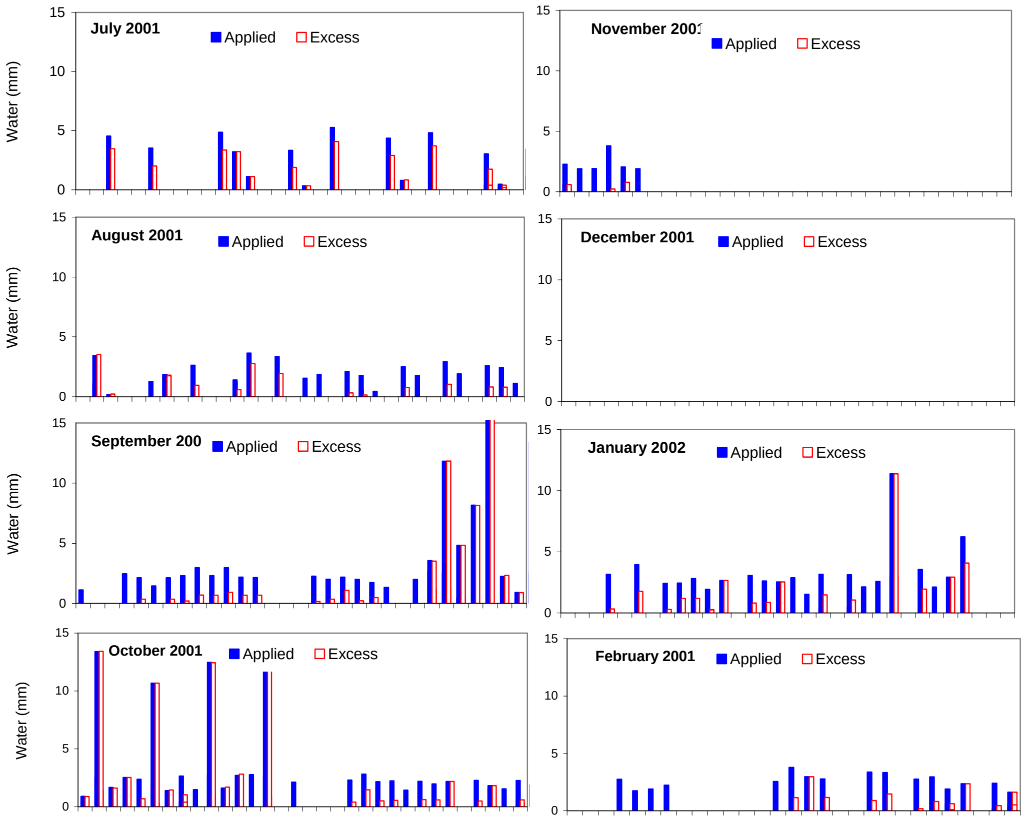


Figure 3.4 The amount of irrigation applied (closed bar) and the amount of water applied while two of the three detectors were activated (open bar) for the 01/02 season. Rainfall has been omitted

Lessons from the WFD response

The WFD gives some clear indications of where irrigation management should be reviewed:

1. For the first part of the season (till mid September) when the crop demand is low, the maximum amount of irrigation at one time should be around 2 mm or two to two and half hours duration. Irrigating more than this will cause a substantial amount of water to move past 60 cm.

2. Low applications at one time (2 mm) means that irrigation should be carried out at least daily once the vines are in leaf. Fewer applications per week are required in July/early August.

3. The long irrigations (12 hours or more) given during the critical growth period through September and October are wasteful. It would be better to pulse irrigation several times in a day for a much shorter duration.

4. When the irrigation interval stretches out to 3 or 4 days in mid summer, then 4 to 7 mm (4 ½ to 8 hours) can be applied at one time before activating detectors.

Two key lessons stand out. Water can be saved during July - early August and mid September – mid October, by shortening the duration of irrigation at one time to 2 to 3 hours, and cutting out the long “insurance” irrigations. Second, the wetting patterns appear to be very narrow, because two hours of irrigation (3 litres of water) regularly reaches 60 cm.

The latter point seems hard to believe even for a sandy soil (Photo 3.2), so we need some confidence that this is realistic, and not a result of our installation. Two pieces of evidence are provided:

1. Around 3 litres of water per emitter was sufficient to activate a detector when irrigation was carried out on a daily basis, but this increased to around 10 litres of water when the irrigation interval was lengthened to 3 to 4 days. This is in agreement with the theory that says the duration of irrigation is related to the initial water content of the soil and suggests that the roots had re-established in the disturbed zone and substantially dried the soil.

2. It required at least 20 mm and up to 50 mm rainfall to get the detectors to respond. If we assume the wetting patterns from the emitters cover 10% of the surface, this equates to 2 to 5 mm of irrigation by drip, which is the amount of irrigation that elicited a respond from the detectors.

Photo 3.2
The soils are very sandy, which is contributing to the rapid downward movement of wetting fronts

Learning with the farmer

We were initially invited onto the farm by the owners to discuss irrigation in general. The owners employed an irrigation consultant using a neutron probe, but felt the information provided did not fully satisfy their requirements. They subsequently discontinued the service, calling on it occasionally if they felt “very unsure”.

The owners were intrigued by the wetting front detectors and agreed to have the mechanical version installed in a pumpkin crop (4 mechanical detectors) and in the grapes (2 mechanical detectors). We received no feedback from the installation in pumpkins and the general response from the installation in the grapes was that the detectors were “popping up all the time”.

Members of the project team visited the farm every 2 to 3 months and discussed progress with the farm worker responsible for the block and whenever possible with the owners. Initially there was some skepticism about the detectors, because the mechanical version always appeared to be activated. After a few months the farm worker requested more detectors to try out in other areas. First detectors were installed between drip emitters, to see if that would reduce the number of responses. However, the detectors never responded to irrigation in this position (as expected). Then detectors were installed higher up in the block, and it was reported that they responded less than the original detectors in a lower position that were near the logged electronic version. Subsequently it was discovered that the water pressure at the top of the block, and hence application rate was lower, which corresponded with the detector response.

After the second season we discussed the logged data record in detail with the owner, who clearly identified the periods of over irrigation and attributed them to either:

- a time when fertigation was carried out and the water was needed to get the fertiliser on (early in the season) and
- the time when it was essential not to stress the crop and extra “insurance” irrigation was applied.

A visit after the third season revealed that large changes had taken place. Apparently the insurance irrigations of September and October had been dispensed with, and towards the end of the season the inter-row dripper lines were removed, thus halving the application rate. The owner asked us specifically not to remove the mechanical detectors (which we had come to do) because “we use them for our management”. They had also purchased more sophisticated soil monitoring equipment.

This story unfolding over three years reveals what we expect will become a fairly common experience. First, the farmers had used existing irrigation scheduling methods (neutron probe and tensiometer), and although they had been helpful they had not completely “solved” the problem. Second, the detector was greeted with some enthusiasm, but during its first year of operation was viewed with considerable skepticism. Third, over time a pattern emerged that made sense to the farmer and gave them a focus for action. Lastly the farmers reached a point where they implemented change and found that their crop had not suffered. Interestingly the farmer remarked that the neutron probe, tensiometer and wetting front detector had been “pointing in the same direction”, and this had given them confidence to make changes.

Removing half the irrigation system (from two lines per vine row to one) is a drastic change, and means that our four recommendations based on row and inter-row drip lines cannot be directly implemented. It is up to the farmer to continue to watch the irrigation, crop and detector response to fine-tune their new system.

Grapes under micro-sprinklers in the Northern Cape

Logged detectors were placed at depths of 30 and 50 cm, shallower than the previous example because micro jet irrigation wets up the entire soil surface and wetting fronts typically do not move as deep. Irrigation and rainfall were recorded using a tipping bucket rain gauge and irrigation was separated from rainfall using the data from a pressure transducer inserted into the irrigation line. Unfortunately some of the loggers/detectors malfunctioned so only part of the season is shown below. Our contact person who had been trained in the installation and maintenance then moved to another farm.

From August to October the irrigation interval varied between 1 and 12 days, and the quantity was always less than 20 mm. No detectors responded during this period (Fig 3.5).

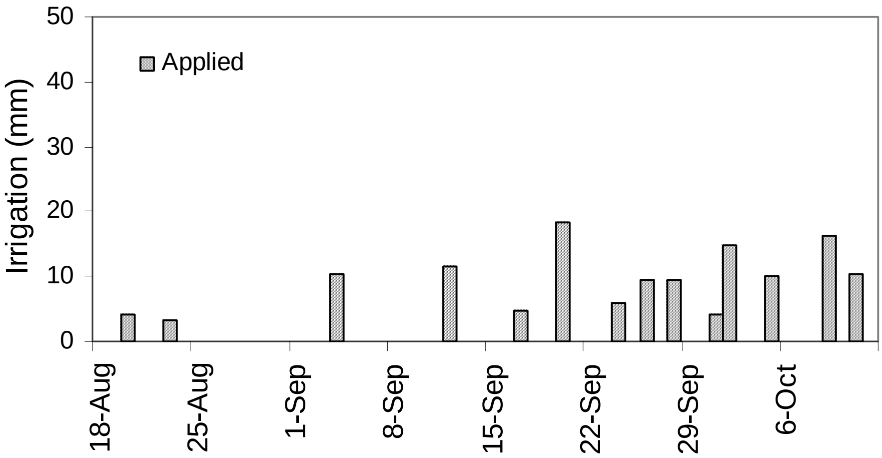


Figure 3.5
The time and amount of irrigation from mid August to mid October

From mid November through to late January irrigation was carried out every second day, generally for 3 to 5 hours and usually during the day. Figure 3.6 shows the amounts of water applied (hatched bars) and the amount of water that had been applied at the time the 30 cm detector tripped (open circle). Between 18 Nov and 1 Jan, 11 to 43 mm was applied per irrigation, totalling 445 mm or 10.1 mm/d. The 30 cm deep detector responded after 15-25 mm had been applied, requiring a total of 366 mm or 8.3 mm/d. This number appears reasonable, as the entire soil surface was wetted, so evaporation would have proceeded at near potential rates.

Four consecutive irrigation events from 4 December were all below 20 mm and failed to set off the detector. We presume the wetting fronts did not penetrate to 30 cm. When the irrigation quantity exceeds 20 mm in mid December the detectors responded again, and clearly irrigation amounts greater than 30 mm push wetting fronts well below a depth of 30 cm.

After Jan 2 the picture becomes less clear. Much less water is given and as expected the detectors do not respond. However there are three occasions in mid January when detectors do respond to low applications.

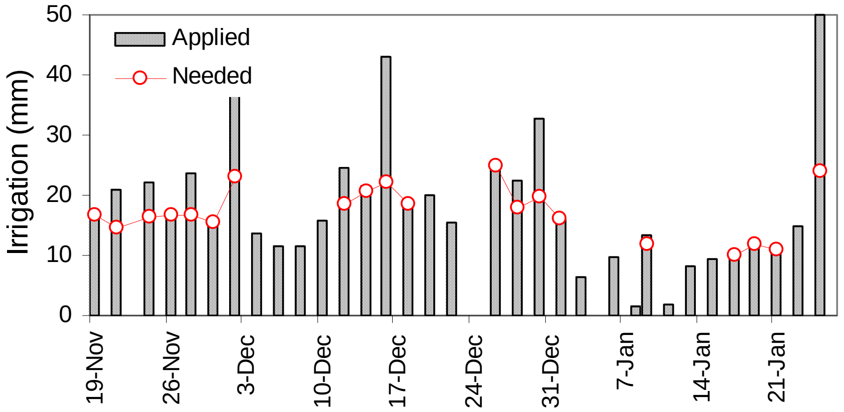


Figure 3.6
The total amount of water applied (bars), and the amount of water applied at the time the 30 cm detector tripped (circles) at Upington

The irrigation application rate was calculated by dividing the amount of water captured in the rain gauge by the time the irrigation was on as logged by the pressure transducer. We see that the irrigation rate varies from 1 mm/h to 8 mm/h (Fig. 3.7). Furthermore the periods when the detectors did not respond coincide with times when the application rate was low. It turned out that the water is pumped from the river into a holding dam and gravity fed into the irrigation system. Fluctuations in the water level of the holding dam caused changes in pressure in the system, hence application rate. Thus the detectors were responding to the level in the holding dam, and the irrigation manager, who was giving similar time of irrigation throughout, was unaware of the problem.

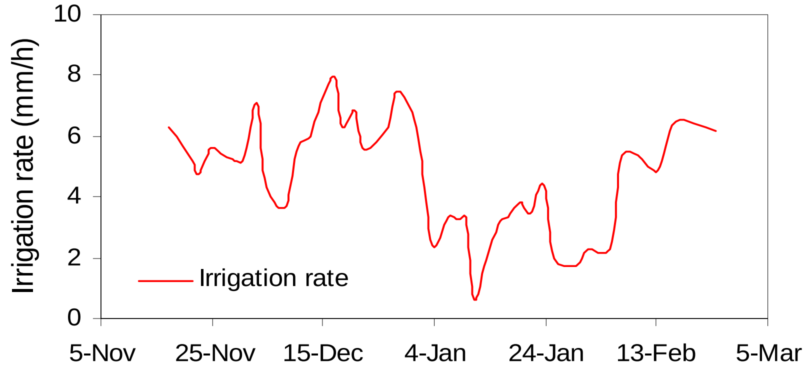


Figure 3.7
The irrigation rate calculated as the water measured in the rain gauge divided by the length of time the pipes were pressuresed

Unfortunately the loggers recording data from the 50 cm detector malfunctioned. This was a setback as this site had been chosen specifically to test the sensitivity requirement of a deep detector. The combination of low application rates common to micro-sprinklers and sandy soils produces fronts that may be near the detection limit of the instrument. Deep placement of detectors often means that the irrigation is turned off before the front reaches the detector. However, the water continues to move downward under gravity, and as it does the strength of the front weakens. If the soil suction at the detector increases above 2 kPa, the detector will not respond.

The shallow detector did provide useful information. Water use would have been cut by nearly 20% had the detector been allowed to shut off irrigation during the period 19 Nov to 1 Jan. It also alerted the manager to the importance of system pressure on application rate. Unfortunately, the irrigation manager moved to another farm, so we did not have the opportunity of a long period of learning as experienced in the previous study.

Grapes under open hydroponics in the Western Cape

This farm was under micro-sprinklers, but the owner changed over to drip several years ago when he switched to open hydroponics. Water is the critical issue on this farm, and limits the area that can be planted. The farmer has put enormous effort into saving water. He uses tensiometers, schedules according to weather data, is a member of an irrigation study group and keeps records to benchmark his own performance over the years.

Each vine receives 2.4 l/h, which averages out at 0.53 mm/h, and this is applied in pulses of 20 minutes separated by 1 to 2 hours. The farmer is perfecting a rather complex method of predicting daily water use. The season is broken into five stages that coincide with plant growth stages. Each plant growth stage will get a certain number of pulses per day (0.5 to 4.5 pulses), regardless of the weather. This one pulse 'cycle' results in a minimum application of 0.1 to 0.8 mm/day, depending on growth stage. This minimum application is then added to during the day according to real time atmospheric conditions, according to a formula that is the intellectual property of the farmer. In short, the "cycle" can be repeated up to 3 times, giving a maximum application of 2.4 mm/d

The method has two benefits for the farmer. First, he knows from his own historical weather data approximately how much water each stage will get. Since he is applying nutrients in the water he knows in advance the concentrations to use. His system simply fine-tunes how much water is received on a particular day. Second, he has shallow rocky soils, so he feels more comfortable with prediction than feedback, which might provide information too late for him to do anything about. By comparing water use and yield across blocks and seasons, the farmer refines his system and has been able to cut his water and nutrient use in half since first converting to open hydroponics.

Detectors were buried at 30 and 55 cm and the rainfall measured with a tipping bucket gauge. Placement was shallower than the previous example of drip irrigation because the farmer wanted to know that the short pulses of irrigation were penetrating to around 30 cm, but that there was not excessive leaching from the wetted area. Figure 3.8 shows the number of wetting fronts detected at 30 and 55 cm. The solid line shows the irrigation strategy described above. This is not the exact amount applied for this season, but it is a close approximation, and totals 320 mm. During the irrigation season (Sept to May), 789 wetting fronts were detected at a depth of 30 cm. Up to 15 fronts were detected on a single day, although sometimes the detector was not able to reset between pulses. The 55 cm detector responded only 27 times, and usually just once per day as the first few pulses of irrigation had coalesced to form one front.

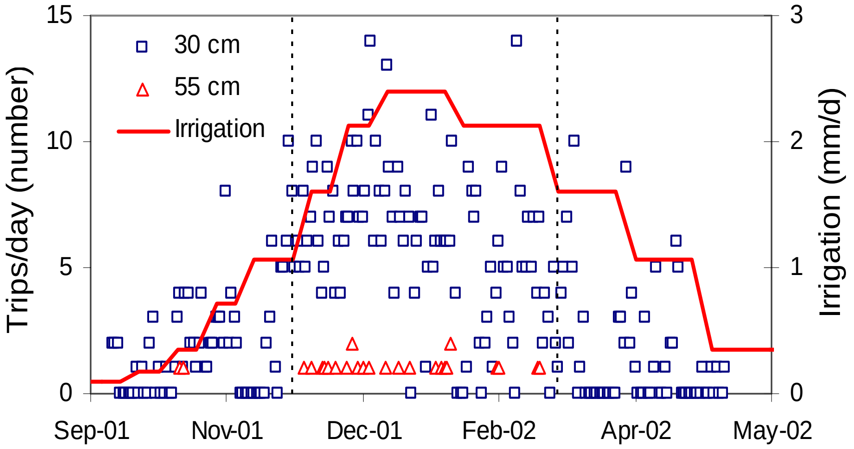


Figure 3.8
The number of wetting fronts detected at 30 (squares) and 55 cm (triangles). The solid line shows the irrigation in mm per day (right hand axis)

At first sight Figure 3.8 looks hard to interpret, but there are some clear lessons. First, it is remarkable that 762 of the 789 fronts detected at 30 cm did not proceed past 55 cm. This suggests excellent irrigation management. Second, there were 66 days on which the shallow detector did not respond. This in itself is not a problem, unless it occurs on consecutive days, in which case the soil could be getting drier and drier. This did happen. There were 10 consecutive days from 10 Nov and 12 consecutive days from 17 March during which there was not a single trip at 30 cm, despite irrigation, and the crop may have been stressed during these periods. During the period of peak water demand, between 29 Nov and 7 Mar, there were only 7 days when no trips were recorded. No trips were recorded on 25 days before that period when irrigation was less than 1.1 mm/d and 35 after that period when irrigation was less than 1.6 mm/d.

Third there was a short period where there may have been slight over irrigation. Figure 3.9 shows the length of time that the 55 cm deep detector remained in the tripped state i.e. the length of time between when the detector first tripped to when the soil had been able to suck the water out of the detector. Over half the trips at 55 cm occurred in December/early January and 24 of the 27 trips occurred during the period of relatively high irrigation (1.6-2.1 mm/d).

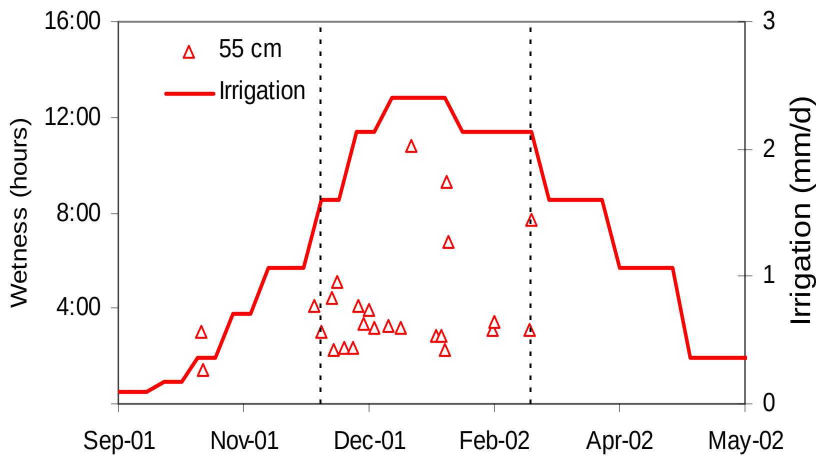


Figure 3.9
The "wetness index" is the number of hours the 55 cm detector remained in the "tripped" state. The solid line shows the irrigation in mm per day (right hand axis)

As was the case for the Mpumalanga case study, it appears remarkable that daily applications of less than 2 mm could penetrate to 55 cm. Again, rainfall during winter provides an opportunity to learn the difference between 1 dimensional and 3 dimensional wetting patterns. Volunteer weeds and grasses grew on the vineyard floor during May to August, and we would expect evapotranspiration to be in the order of 1 to 2 mm/d. Thus we could predict when detectors would respond based on the size of the rainfall event and the days since the detectors last responded.

For example on the 4 May, 13 mm of rain was recorded but the detectors did not respond. They had last responded 9 days ago. On 25 May, 37 mm of rain was recorded and the shallow detector responded. 17 mm of rain and 30 days had elapsed since it last responded. On 8 July we see both detectors responding to only 11 mm of rain, but the soil was wet because the detectors had responded four days earlier. As little as 8 mm set off both detectors on 20 July. However, 33 mm did not set off either detector on 29-30 August, when there had been no trips for 40 days, and the soil would have had the opportunity to dry out. Table 3.1 confirms to the farmer that the amount of water needed to set off the detectors is proportional to the initial water content. It also highlights the enormous difference between completely wetting the soil (rain and sprinklers) compared to drip irrigation where only a fraction of the soil is irrigated.

Date	Rain (mm)	Days since last trip	30 cm activated	55 cm activated
4 May	13	9	N	N
20 May	4	25	N	N
25 May	37	30	Y	N
7 June	5	13	N	N
17 June	14	23	N	N
4 July	23	40	Y	Y
8 July	11	4	Y	Y
18 July	37	10	Y	Y
20 July	8	2	Y	Y
10 August	15	21	N	N
22 August	11	33	N	N
24 August	12	35	N	N
29-30 August	33	40	N	N
5 September	37	46	Y	Y
10 September	7	5	N	N

Table 3.1 An evaluation of detector response during the winter as a function of amount of rainfall and days since last rain event.

Learning with the farmer

We held detailed discussions with the farmer on two occasions. From the perspective of the scientist, we found the irrigation scheduling strategy fascinating. It was based on the prediction approach from weather station data, with correction using tensiometer data. The prediction method did not follow all the scientific rules, but it clearly was easy to implement and it worked. The method also met the farmer requirements with respect to planning, fine-tuning and risk management.

During our meetings we spent as much time in “learning mode” as we did in “telling” or technology transfer mode. It took us a long time to understand why a farmer would expend so much effort in building his own scheduling method, rather than applying a "tried and tested" method from the research community. This gave us some insight as to why farmers might take a long time to respond to the scheduling message we provide. It simply does not meet their exact requirements. The main problem with the method employed on this farm is that it is not readily transferable to another district – which is not a problem for the farmer.

Initially the farmer felt that he had a working system, and he was not sure what additional value a wetting front detector would bring. However, he was most interested to see that the detector record backed up his management practice. He then coined the phrase that has helped us in our extension work "To understand the detector record you must first identify the purpose of your irrigation strategy". His "purpose" was to treat the vine as if it were in a 50 cm by 50 cm pot. He wanted to know if the pot was on an "emptying" trend or "over filling". The consecutive days of no response at 30 cm told him the former and consecutive days of response at 55 cm told him the latter.

This sums up the instructions that will be provided with the commercial version of the wetting front detector. The shallow detector should respond most of the time, to ensure the water is penetrating into the lower half of the root zone. The deep detector should respond occasionally, particularly during hot weather or crop yield sensitive stages, to ensure that the entire root system is wet. However, if the deep detector responds regularly there are opportunities for saving water. Our detector record would judge this farmer's irrigation strategy as near perfect.

Photo 3.3
Discussions with irrigation farmers in the Western Cape

Summary of three intensively monitored sites

All three farms monitored, represent leading farmers in their districts, and all attained high yields. Although they were growing the same crop, there were very different management styles, as seen if we compare strategies in early/mid summer. Case study 1 irrigated once per day with drip, applying on average 6 mm/d and always setting off detectors at 60 cm. Case study 2 irrigated every second day with micro-sprinklers, applying an average of 10 mm/d with the wetting front penetrating past 30 cm. Case study 3 pulsed irrigation up to 15 times per day, applying an average of 2 mm/d and rarely pushing water deeper than 30 cm. A fivefold difference could not be put down to differences in potential evaporation at each site.

All were interested in improving irrigation. Case study 1 employed consultants but had not found the experience totally satisfactory. However, they brought together pieces of information from many sources and over time made large changes to their irrigation strategy. The wetting front detector played a role in this process. Our time of interaction with Case Study 2 was too short for any sustained learning, but the site did provide a useful comparison with the others. The farmer in Case Study 3 had trained himself to become a very good irrigator. He had built a system tailored to his own requirements, and although he had bent a few of the scientific “rules”, he had produced a system that worked, could be easily implemented and satisfied his criteria for risk management and accuracy.

Both farmers in Case Studies 1 and 3 demonstrated that change had been incremental. They had started by gleaning information from “an expert” and then embarked on a process of continual improvement. It is sound business for a farmer to err on the side of caution – that is, the cost of applying too little water far exceeds the cost of applying too much. Information is needed to reduce the risk of change, and even then, it needs to be done slowly to ensure yields are not suffering. With astute management, these farmers had been able to halve their water use over a period of five to ten years. The lesson for scientists, is that we should not expect rapid results. Learning, monitoring and record keeping are essential, but it takes time.

Finally the interpretation of detector data with farmers differed from the method we used in the scientific trials described in Part 2. In the Hatfield trials, the irrigation was increased or decreased by a certain percentage depending on how many detectors responded to the last irrigation event. This system was very rigid and had no capacity to “learn” from past mistakes. However, when reviewing the entire season data with a manager, patterns in detector response emerged, and these presented an opportunity to ask questions and learn. The subjective interpretation of the detector response is likely to be more valuable than the search for an objective scientific algorithm.

Photo 3.4
At all sites where logged detectors were installed, the mechanical version was installed nearby. The mode of operation was explained to the farm workers

Photo 3.5 (right)
Installing detectors on food plots at Elandskraal

Photo 3.6
Students from the Tompi Seleka College of Agriculture explaining the use of detectors to farmers at Elandskraal

Centre pivot and furrow irrigation

The Hatfield experimental site used a dense drip irrigation network and the intensively monitored on-farm sites used drip and micro-sprinklers. Little work to date has been done on centre pivot and flood/furrow irrigation. Over 80% of the farmers that were surveyed in Part Four of this report found the wetting front detector was helpful to them. The remaining 18% believed it was not compatible with their existing operation. Most of these were traced back to farmers using centre pivot or furrow irrigation and the problem was that the detector did not respond to irrigation. Studies were therefore carried out to see if the WFD instructions needed to be modified for these irrigation methods.

Centre Pivot

The most striking feature of the centre pivot studies was the low number of times the detector was activated, when compared to the drip irrigation experience. Figure 3.10 shows three trips at 30 cm in 84 days, when the average irrigation rate was 2.9 mm/d. The deeper detector never responded. We also see that the irrigation was applied at very frequent intervals, and it was probably rainfall that set the detectors off.

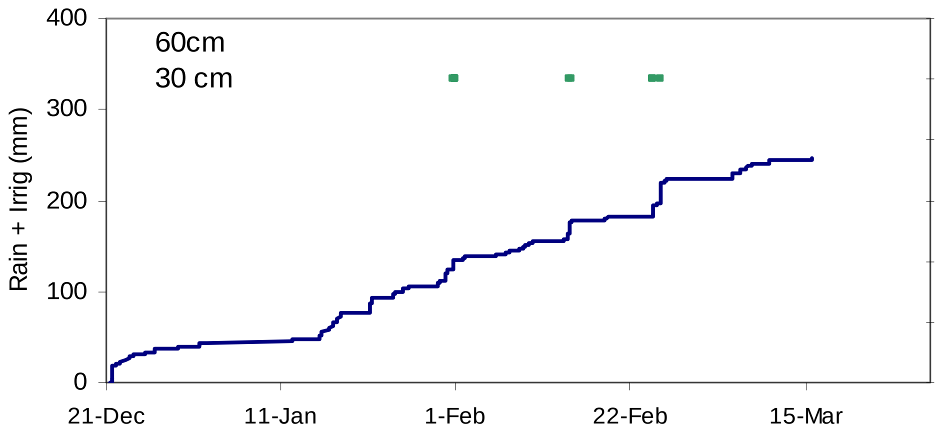


Figure 3.10 Cumulative rain plus irrigation and detector response at 30 and 60 cm under centre pivot. The bar at the top of the figure shows the period during which the 30 cm deep detector was activated.

Figure 3.11 shows a slightly wetter example where water was applied at an average rate of 4 mm/day. In this case the wetting fronts penetrated to 60 cm, but again it only occurred on a few occasions.

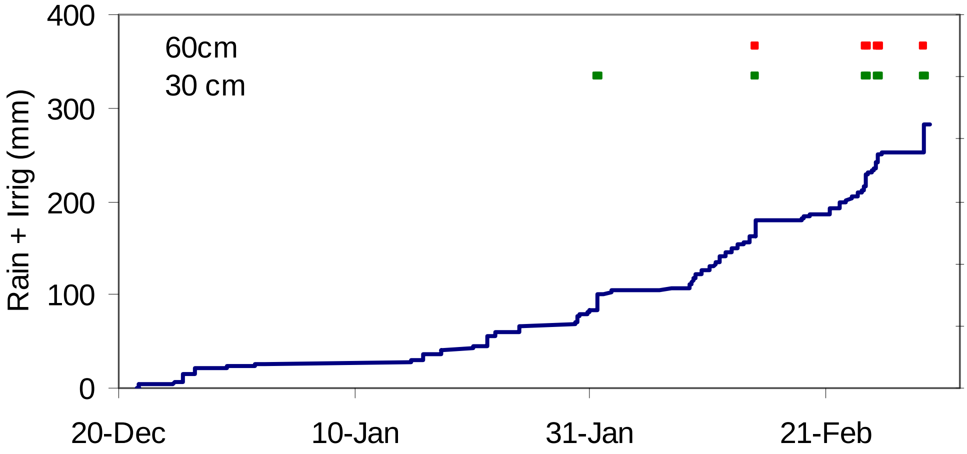


Figure 3.11
Cumulative rain plus irrigation and detector response at 30 and 60 cm under centre pivot. The bar at the top of the figure shows the period during which the detector was activated (the upper bar is 60 cm depth and the lower bar is 30 cm depth)

A third example is shown in Figure 3.12, which shows more detector response. In this case we see occasions where the deep detector responded and the shallow detector did not. We do not know if this is due to non-uniformity of the crop or irrigation, or if there was an impeding layer at 50 cm that caused transient water logging.

There were 38 “events” where more than 2 mm of water was recorded. Of these, 15 were in the range 2-5 mm and 23 in the range 5-10 mm. Clearly the centre pivot was managed at this site to put on frequent small amounts of water. Furthermore, many of the daily totals in the 5-10 mm range were applied in two events more than 12 hours apart. Frequent small applications produce fronts that do not penetrate very far into the soil at a strength that can be detected.

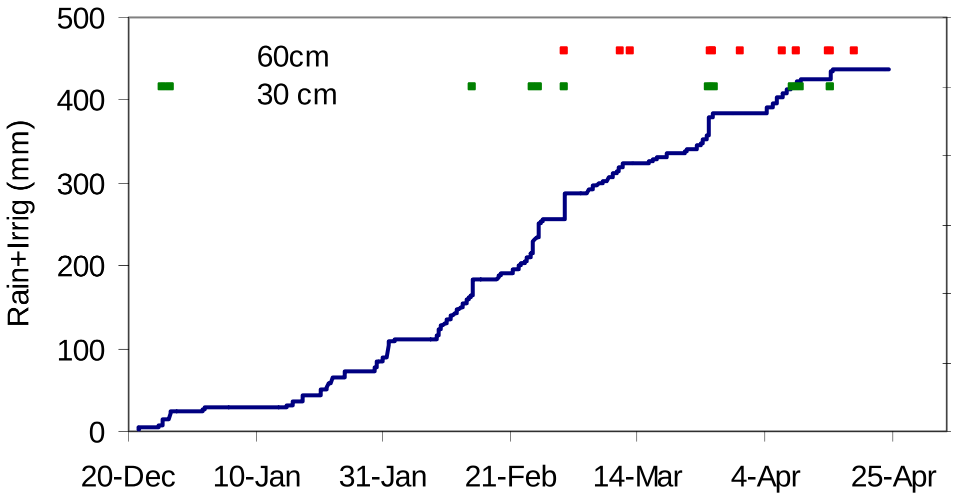


Figure 3.12 Cumulative rain plus irrigation and detector response at 30 and 60 cm under centre pivot. The bar at the top of the figure shows the period during which the detector was activated (the upper bar is 60 cm depth and the lower bar is 30 cm depth)

Figure 3.13 shows the daily irrigation and rainfall amounts for the same data set as in figure 3.12 and the response of the shallow or deep detector after a particular event. The first 2 irrigations on 24/25 December activated the shallow detector, despite being below 10 mm. The next time a detector responded was 51 days later on 14 Feb, when 25.6 mm was received. The rain on 24/25 February, totalling 42 mm over 2 days, activated the shallow detectors but not the deep ones. Fours days later, following 31 mm of rain, the deep detector was activated. No detectors responded to the subsequent 16 irrigation events, which were all under 10 mm. Shallow and deep detectors responded to 24.9 mm on 25 Mar, and again to just 6 mm the following day. During April both detectors responded frequently to a number of light irrigations, suggesting the soil was wet.

It appears the soil profile started off wet and the evapotranspiration exceeded rainfall plus irrigation for the next two months, as it took 73 mm over 5 days to get the wetting front to 50 cm. For the rest of March irrigation was about right, as it only took one rainfall event to get water to the bottom detector. At the end of the season the deep detectors went off with very small amounts of water.

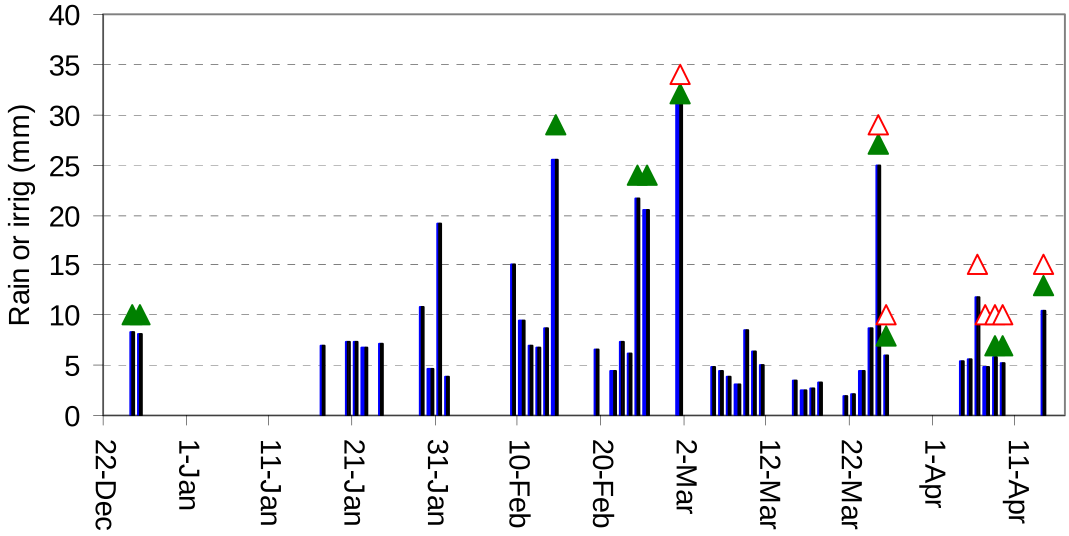


Figure 3.13 The amount of rain or irrigation on a daily basis. Closed triangles denote that the shallow detector was activated by the event and open triangles that the deep detector was activated

There are two lessons from the above. First, a detector placed at 30 cm will generally not detect fronts produced by 10 mm of irrigation, unless it has just rained or the soil happens to be very wet. The shallow detector should be installed to detect fronts at a depth of 15 or 20 cm. Second, it is not necessary to get a detector to respond after each irrigation, as is typical for drip irrigation. Water application by centre pivot commonly lags slightly behind ET during periods of no rain, but since irrigation is still occurring frequently, the soil store is being slowly mined. The detector tells when a rainfall event or series of irrigation event has brought the profile back to the full point, and this may only need to happen several times during the season to let the farmer know he is ‘on track’.

Furrow irrigation

A pilot trial was carried out in a short furrow system with beds 15 cm high and 100 cm from centre to centre. Two detectors were placed at 30 cm and two detectors at 40 cm below the top of the bed. Detectors were placed such that the float housing passed through the shoulder of the bed, which resulted in half the funnel being under the furrow and half under the bed. In adjacent beds detectors were placed directly under the centre of the bed.

Tensiometers that could be read accurately (+/- 2 cm tension) with a pressure transducer were installed to measure soil tension about 20 cm away from the detectors at the same depth. Tensiometers were read daily when possible. By way of explanation, a tension between 30 and 100 cm is considered to be field capacity and irrigation is recommended at tensions of around -500 cm. The sensitivity of the detector is around 20 cm, although the tensiometer measurement was not usually taken at the same time as the detector responded.

Figure 3.14 shows 6 flood irrigation events. The tensiometers recorded the soil getting wetter at 30 cm but the front was not sufficiently strong to activate the detectors. The second irrigation dropped soil tensions from between 500 and 400 cm to between 200 and 100 cm, which again was below the detection limit. The subsequent four irrigation events were detected and the soil tensions were close to zero.

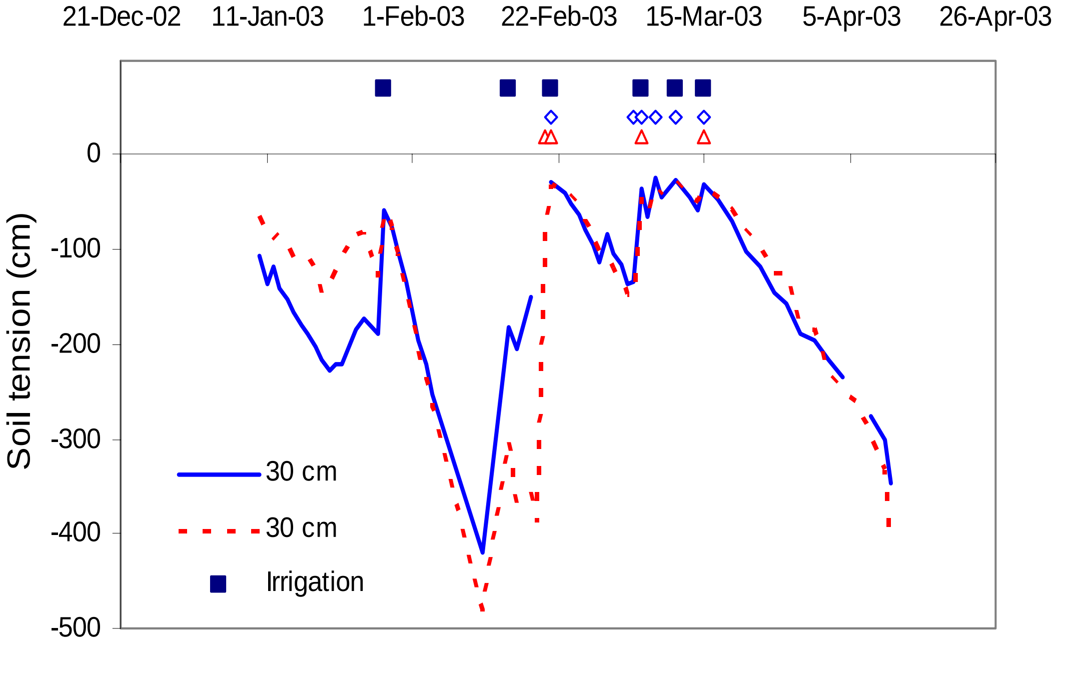


Figure 3.14 The daily tension at 30 cm (two replicates). The solid squares denote the date of flood irrigation. The diamond shows the days when the WFD at rep 1 responded (solid line) and the triangle when the WFD at rep 2 responded (dotted line).

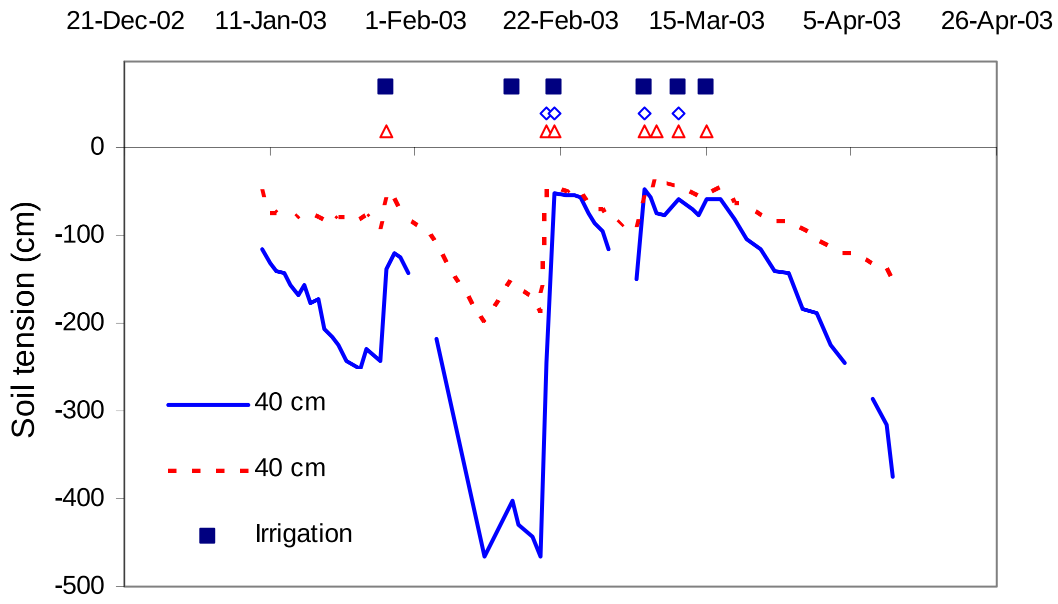


Figure 3.15 The daily tension at 40 cm (two replicates). The solid squares denote the date of flood irrigation. The diamond shows the days when the WFD at rep 1 responded (solid line) and the triangle when the WFD at rep 2 responded (dotted line).

The picture was similar at the 40 cm depth. In this case one of the 40 cm detectors was positioned slightly more under the furrow, and the first irrigation event was recorded. Detectors placed in the centre of the bed did not respond to irrigation.

This pilot trial suggests that the detectors can be used for furrow irrigation, although the original instructions given to participants did not provide the necessary information on how to use it for this application. Specifically the detector must be positioned at the shoulder of the bed, so that part of it is under the furrow.

Subsequent experiments are showing that the LongStop, described in Part Two, would be more suited to furrow irrigation. Drip and micro-sprinkler irrigation tend to occur on a frequent interval, so the “when to turn irrigation off” data provided by the detectors is very useful. Furrow irrigation requires a certain amount of water to fill the furrows, and if a detector responds there is little opportunity for management response. However, LongStops placed towards the bottom of the root zone may be useful in delaying the subsequent irrigation, as well as showing whether the previous irrigation effectively wets the soil profile.

PART FOUR: Acceptability of Wetting Front Detectors by commercial and small scale farmers

Introduction

Irrigation scheduling is a low priority for most farmers, even though the saving of water is a priority on a national scale. A recent survey showed that many farmers ranked irrigation scheduling as priority number four or five amongst their major constraints (Stevens, 2003). Most farmers are prepared to admit that their system is not perfect, but at least it works. After a long period of trial and error many farmers have settled on a management system that satisfies their requirements and they need a good reason to re-evaluate it.

Commercial farmers showed reasonable awareness of technologies that could help them irrigate more accurately, but were less sure how this technology would translate into profitability on their farms (Feather and Amacher 1994). The small-scale farmers interviewed by Stevens (2003) did not even mention irrigation scheduling as one of the major production constraints, but were preoccupied by persistent barriers to progress which included factors such as lack of credit, infrastructure, access to land, access to markets and extension support.

Poor adoption rates of irrigation scheduling technologies demonstrates that linear, reductionist and positivist perspectives, or the 'Transfer of Technology' approach familiar to research organisations (Rőling, 1994) do not work well for this particular problem. The technology transfer perspective does not easily accommodate the dialogue and negotiation among stakeholders necessary for working through a complex issue with many variables.

Adoption of new technology like a wetting front detector is a dynamic process that is determined by various factors, including farmers' perceptions of the relative advantages and disadvantages of new technologies vis-à-vis that of existing technologies, and the efforts made by extension and change agents to disseminate these technologies. Other factors, which influence adoption, are the traditional ones: resource endowments, socio-economic status, demographic characteristics, and access to institutional services (extension, input supply, markets, etc). Griliches (1957) and Mansfield (1961), who conducted contemporaneous empirical studies of adoption rates of a number of industrial innovations, concluded that economic variables were the major determinants of technological change and adoption of innovations.

From a farmer's perspective, implementation of an innovation involves (1) some form of immediate investment with long term expected returns, (2) trade offs between current yield and future yields, (3) trade offs between yield and its production costs, (4) trade offs between yield and its related risk. All decisions to adopt or reject an innovation and the subsequent behaviour or practice change, rest with the individual or the farmer.

Behaviour in its simplest form can be regarded as a movement brought about by forces resulting from the system being in tension (Düvel, 1990). The above implies that for any adoption to occur, the farmer must experience a need or tension. In other words the farmer must have a sense of dissatisfaction with the current method of irrigating and believe that it is within his or her capability to improve.

According to the model of Tolman (1967), behaviour is intentional (there is a motive for a specific action) and behaviour is guided by past experience and expectations concerning the new technology. Tolman (1967) differentiates three sets of variables in his model, namely independent variables (e.g. personal and environmental factors), dependent variables (e.g. behavioural change or adoption and consequences of adoption) and intervening variables like needs, beliefs, perceptions and knowledge. The extension worker cannot do much about the independent variables (the way it is) or change the way people behave. They focus attention on the intervening variables that sit between the *status quo* and the act of successful adoption. By bringing new knowledge to a situation, the extension worker can influence the farmer's perceptions of their situation and stimulate the need for change.

Table 4.1 The relationship between behaviour determining variables in agricultural development (Duvel, 1991 as cited by Stevens, 2002)

Human (psychological)		**Economic –Technical**	
Independent variables	**Intervening variables**	**Dependent variables**	
		Behaviour	**Consequences of behaviour**
Personal and environmental factors (age, education, experience, etc)	Needs Perception Knowledge	Adoption of practices	Efficiency: Yield and Profit (saving of water)

Adoption itself can be partial, in the sense that some farmers may quickly learn a few obvious lessons and then discard the technology, whereas others might persevere and gain a deeper knowledge. Note that the consequent behavioural change, in our case increased irrigation efficiency, is the end product of what can be a long process. Non-adoption of any innovation or practice can be traced back to two basic causes: the individual is either incapable or unwilling to adopt. A farmer may be incapable of adopting the technology either because it is too complex or too expensive.

Willingness to adopt depends on the farmer perception of the technology in relation to their current needs and their current knowledge. The farmer must experience a "needs tension" before they will set themselves the goal of using a wetting front detector. A needs incompatibility occurs when the farmer decides that the new technology does not fit in with their aspirations, goals or problems. However, the extension process can build up the farmer's knowledge base, which in turn affects their perceptions and aspirations.

Part Two of this report provides a quantitative assessment of the WFD performance at a research station where the team was in control of all the management. Part Three gives a detailed treatment of commercial farms that were intensively monitored. These farmers were well informed about the technology and what it was accomplishing on their farm, but the project team had no control over how they irrigated. The case studies reported in this section (Part Four) deals with the next circle of participants, who had very different levels knowledge about the WFD and varying expertise in their ability to interpret results and act on them. The aim is to evaluate the factors that influence the general perception of the wetting front detector that are essential for successful adoption.

The first hypothesis was to determine whether a simple tool could stimulate a dialogue about irrigation and challenge farmers to take another look at something most had already consigned to the 'too hard basket'. The second hypothesis was to test the willingness of the farmers to adopt and persevere with the technology, and their ability to both learn from it and implement what they have learnt.

Selection of commercial and small scale farmers

The original aim was to install detectors at twelve sites comprising a mix of small-scale and commercial operations. Commercial irrigators or irrigation trainers or consultants who heard about the WFD became aware of its potential and therefore wanted to try them out. Thus the project team decided that a process of self-selection would identify the most committed collaborators and early adopters. This resulted in a much larger group of project collaborators than initially envisaged.

The WFD was sometimes introduced directly to commercial farmers, but more often via so called "gatekeepers" who acted as a filter of perceptions and understanding of the technology. These gatekeepers were employed by industry organizations or training institutions and proved to be extremely influential amongst their constituents. Their networks were well connected, so knowledge of the detector spread quickly. Many of the farmers who contacted the project team during the duration of the project had had third or fourth hand information. Most of the farmers that made contact with the team could be categorised as more progressive or innovative farmers.

Experience during the first year showed there was an enormous cost in time and travel to identify and maintain a relationship with small-scale farmers, because the gatekeeper role was virtually absent. However, the fact that many commercial farmers showed interest in the use of the WFD did encourage small-scale farmers to get involved in the project. This manifested very clearly when it became known that some of the big commercial producers started to participate in the project, and small-scale farmers could therefore be associated with the "big guns" of the industry. As was the case for commercial farmers, many more partners became involved in this aspect of the project than originally envisaged.

The degree of contact between the research team and commercial farmers using detectors varied enormously. Some were visited, others made phone contact and some relied solely on the two-page instruction sheet sent out with the detectors. Initiating and maintaining a relationship with small-scale farmers was much more difficult. Five small-scale farmer schemes participated in the project as detailed below.

1. Elandskraal, Olifants-Arabie irrigation scheme, Limpopo Province
   Farmers of Elandskraal scheme were introduced to the WFD during August 2000 at one of the regular meetings held by the Farmers Union and attended by local extension worker and the regional manager for extension service. The

WFD was demonstrated to farmers and one set of the WFDs installed on a food plot.

The food plots are usually 31 x 12 m in size, and farmers use sprinklers or furrow irrigation every second day during the winter season, and every day during the summer. Vegetable crops like spinach, cabbage, onions, cowpeas, chillies, beetroot and tomatoes are produced. On average, twenty farmers participate in the food plot production activities.

The WFDs were subsequently installed in 2.5 ha wheat or maize plots under sprinkler irrigation. The project team from the University of Pretoria built a strong relationship with the farmers at Elandskraal and the site was visited on a monthly basis over a 2 year period.

2. Eksteenskuil, Upington
   WFDs were installed under furrow irrigation at Eksteenskuil, Upington, under the guidance of Dr Philip Myburgh from the Nietvoorbij Institute. This is an irrigation project of 620 ha, where small-scale farmers use flood irrigation to irrigate 200 ha of vineyards and approximately 400 ha of cash crops. The 117 farmers active at Eksteenskuil practice no irrigation scheduling and Dr Myburgh introduced tensiometers and the Vinet 1.1 irrigation-scheduling program to thirty of the table grape growers. A tariff of R67 per hectare per annum is payable for the use of the irrigation water by the farmers.

3. Tlhabologang food plot, Maubane, North West Province
   WFDs were introduced to the Tlhabologang food plot project at Maubane, near Hammanskraal in the North West Province. The food plot project started in 1990 and was made up of fourteen farmers (mostly pensioners). An area of 0.5 ha is irrigated and farmers are pumping water for irrigation directly from a borehole. Vegetable crops including spinach, beetroot, onions, cabbage and tomatoes are produced. Farmers followed a fixed schedule of basin irrigation twice a week and are responsible for the pumping costs. An experienced extension officer based at the Maubane office was willing to take the necessary responsibility for the project. Unfortunately these farmers experienced problems and stopped their production for nearly 6 months due to lack of funds to repair the pump and replace the reservoir tank that was hit by lightning.

4. Walda sugarcane project, Nkomazi, Mpumalanga
   Small-scale sugarcane growers in the Nkomazi area were the fourth small-scale farmer group that participated in the WFD project. Two sets of WFDs were installed at the demonstration site next to the Energy Centre at Walda. The provincial agricultural engineer based in Nelspruit took the responsibility for the coordination, monitoring and demonstration of the WFD to extension officers and farmers of the Walda and Boschfontein production areas.

   One of the biggest production constraints identified by local extension workers was over irrigation. Most of the small-scale farmers in this area acknowledged the high electricity bills as one of the major constraints to production. Farmers use predominantly sprinkler and floppy sprinkler irrigation, providing eight hours of irrigation per day. Some farmers used drip irrigation and irrigated on a daily basis.

5. Driekop food plot projects, Limpopo Province
   The last small-scale farmer project identified for introduction of the WFD was Driekop, in the Burgersfort area near Polekwane, Limpopo Province, as part of the post graduate studies of Mr. Marobane from the University of Pretoria. Three food plot projects in the Driekop area were selected for the introduction of the WFD, namely: *Maputlesebope, Arethusaneng* and *Maroke*. The description of the three projects is shown in Table 4.2.

Table 4.2 Characteristics of the three foods plot projects in Driekop, Limpopo

	Maputlesebope	**Arethusaneng**	**Maroke**
Number of farmers	40	41	184
Size of project (ha)	1.2	2	5.6
Source of irrigation water	Dilokong Chrome Mine	Borehole	Canal from the Motse river
Method of irrigation	Bucket system	Hosepipes and buckets	Short furrow irrigation
Crops produced	Vegetables	Vegetables	Vegetables
Soil types	Red, well drained, SaLm	Black to dark grayish, Clay	Black clay, calcareous, reddish brown, SaClLm

The majority of the farmers at Maputlesebope are women (35) and although boreholes were drilled to supply water to the project, no electricity supply is currently available. Farmers are therefore receiving irrigation water free of charge from the Dilokong Chrome Mine nearby.

All the farmers at the Arethusaneng project are women, and due to the remoteness of this area, vegetable production is playing an essential role in the local food supply. The water source is a borehole and the farmers are responsible for its operation and for the provision of diesel. Because of this, the farmers are very aware of the cost of water, and according to the local extension officer, many of the farmers are guilty of under irrigation.

The irrigation water at Maroke is supplied through a canal from the Motse River free of charge. Seven different farmer groups are actively engaged in farming in the Maroke area. This project was established on land where sisal had been produced in the past.

Training Institutions

In addition to building relationships with small-scale farmer schemes, several training institutions were introduced to the WFD technology (Table 4.3). The Limpopo Province was a key target and a half-day workshop was held during March 2001 at the University of the North (UNIN) to enable the project team to ensure cooperation from the University and extension officers from other irrigation projects in the Limpopo Province. This workshop was attended by approximately 60 delegates, including extension officers from the Central, Southern and Bushveld regions, lecturing staff from the Tompi Seleke Agricultural College and of UNIN, agriculture students, and officials from head office at Polekwane.

WFDs were installed on the experimental farm of UNIN, Syferkuil as part of the demonstration after the workshop and at the Tompi Seleke College of Agriculture. Five extension officers from the three regions of the Limpopo Province were selected to introduce the WFD to their areas and each was given a pair of WFDs to install.

Table 4.3 Training institutions that participated in the WFD project

Training institution	Target audience
University of the North (Limpopo Province)	Black agricultural students, commercial farmers, small-scale farmers, lecturing staff, advisors
University of Pretoria (Gauteng)	Agricultural students, lecturing staff, advisors, project team
Lowveld Agricultural College (Mpumalanga)	Agricultural students, lecturing staff, extension officials, commercial and small scale growers, advisors
Agrofert (Rustenburg, North West Province)	Short courses in irrigation scheduling and fertilisation programmes (commercial and small -scale farmers, advisors)
Tompi Seleke (Limpopo Province)	Agricultural students, lecturing staff, small- scale farmers
Cedara Agricultural College (Kwa Zulu Natal)	Agricultural students, small scale and commercial farmers, extension officers

Survey and Profile of Respondents

Semi-structured interviews were carried out with participants either in person or by phone to determine the following:

- Identify the reasons why farmers showed interest in trialing the WFD
- Identify general perceptions on the acceptability of the use of the WFD
- Identify perceived relative advantages farmers experienced with the trialing of the WFD
- Identify possible constraints that prevent acceptance of the WFD

Of the 54 interviews carried out, 35 were farmers and 19 fell into the category of "gatekeepers", who are opinion leaders in their various industries. The dissemination and diffusion of the information about the WFD via the gatekeepers and from farmer to farmer worked well. These gatekeepers played a major role in bridging the communication flow between the project team and the target audience. Their role was passing on information from the outside of the group, interpreting outside information on the basis of their own experience and most importantly the endorsement and legitimization of new ideas. The endorsement role was critical and two influential gatekeepers were responsible for most of the project activity in the sugar industry. Table 4.4 shows the employers of the gatekeepers.

Table 4.4 Employers of gatekeepers (N=19)

Institution /organization	Number of respondents	% Respondents
SASEX (South Africa Sugar Ass. Experiment Station)	5	26
Department of Agriculture (Limpopo, North West, Kwa Zulu Natal)	6	32
Cooperatives (GWK, MKTV)	2	11
Private organizations	1	5
Training and academic institutions (UP, Tompi Seleke Agric College, Lowveld Agric. College, UNIN, Agrofert)	4	21
ARC (Nietvoorbij, Roodeplaat Ornamental and Vegetable Research Institute)	1	5
Total	**19**	**100**

Age

An individual's age is one of the most important factors determining adoption, as it correlates to their experience and the degree to which they are open to change. The majority of respondents (72%) were between thirty-one and fifty years old. Six percent of the respondents were older than 70, and were predominantly small-scale farmers. This was encouraging, as the WFD technology was perceived to be relatively easy to understand and implement, even for the older farmers not accustomed to change.

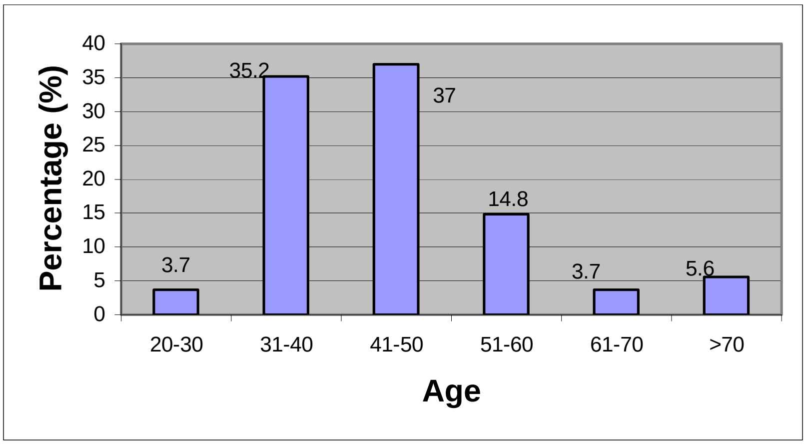


Figure 4.1 The age distribution of the respondents (N=54)

Education

Eighty percent of the respondents had obtained a post matric qualification and 74 % of the farmers had either obtained a Diploma in Agriculture or a related field. This high level of education would not be representative of farmers in South Africa and reflects partly the professional status of the gatekeepers and the fact that the project attracted the more innovative farmers. The positive effect of higher education on farming progressiveness and efficiency is well established (Rogers, 1983), and this project was particularly interested in the impact of the WFD upon poorly educated farmers. Although only four of those surveyed had less than grade 12 qualifications, a number of the gatekeepers summarised the experiences of small-scale farmers.

The education qualifications of the respondents are presented in Table 4.5.

Table 4.5 Educational level of respondents (N=54)

Education level	Number of respondents	%
Lower than Grade 12	4	7
Grade 12	7	13
Diploma (Agric and other)	19	35
BSc and post graduate	24	45
Total	**54**	**100**

Crops grown

Both annual and perennial crops were covered in the survey in equal proportions. Table 4.6 shows the wide range of crops grown, which covered a range of regions, soil types, and production systems. The breadth of this evaluation was important because the project team needed to identify constraints in terms of the practical implementation of the WFD.

Table 4.6 Crops included in the trialing of the WFD (N=54)

Crops	Number of respondents	%
Sugarcane	8	14.9
Maize/wheat	7	13
Potatoes	8	14.9
Subtropical fruit (pecans, mangoes, litchis)	3	5.5
Citrus	2	3.7
Table grapes	7	13
Deciduous fruit (apples, plums, peaches)	8	14.9
Onions /sweet potatoes	2	3.7
Tomatoes	1	1.8
Food plot production	6	11
Soybeans	1	1.8
Tobacco	1	1.8
Total	**54**	**100**

Irrigation systems

The WFD was tested under various types of irrigation systems, of which centre pivot (24%) and drip irrigation (27%) were the most popular. Fruit growers involved with the production of deciduous, citrus and subtropical fruit are using drip and micro irrigation, while centre pivots and the conventional manual sprinkler or set move sprinklers are mainly used for cash crop production. Small-scale farmers from Maubane, Eksteenskuil and Elandskraal (food plots) are using furrow and flood irrigation for food plot and table grape production.

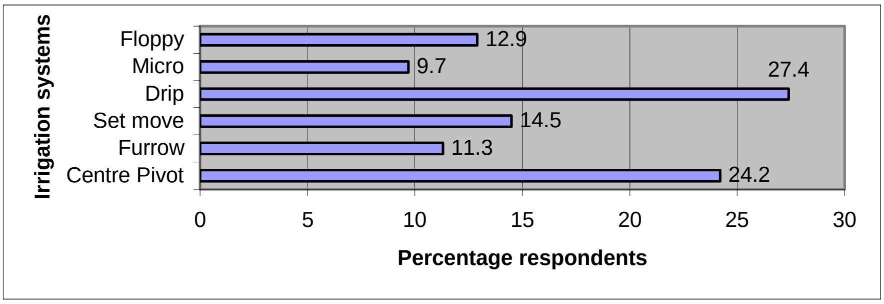


Figure 4.2 Methods of irrigation included in the trialing of the WFD (N=54)

Irrigation Scheduling

The largest group of respondents used a fixed schedule (31%), while nearly 30% used either the neutron probe generally linked to a scheduling program (BEWAB, SWB, BBP17, CANESIM and Donkerhoek). Again the breakdown does not reflect the real situation in South Africa because it is the gatekeepers role to promote such technology and the self-selected farmers already had a keen interest in irrigation. However, it is interesting to note that most farmers who wanted to use the simple technology of a WFD, had prior experience with more complex technology.

Table 4.7 Irrigation scheduling methods used by respondents at the time the WFD was introduced (N=54)

Irrigation scheduling method	% Respondents
Tensiometer	19
Fixed schedule	31
Diviner	6
Neutron probe	2
Neutron probe + Scheduling program	27
Scheduling program	11
Tensiometer +A pan	2
Electronic tensiometers +VPD	2
Total	**100**

Perceptions of the acceptability of the WFD

In most cases the respondents were interviewed after they had tried out the detector for a season or two, but in some cases the detectors had only been used for part of a season. The acceptability of the WFD to farmers was tested according to NCRC (1955), who describes the stages of adoption as follows:

1. Awareness: where the individual is exposed to an innovation
2. Interest: the individual becomes more interested in the new idea and seeks additional information about it
3. Evaluation: the individual mentally applies the innovation to his or her present and anticipated future situation, and then decides whether to try it or not.
4. Trial: making full use of the innovation within his or her current situation
5. Adoption: individual decides to continue or reject the full use of the innovation

1. *Awareness*

   In this context, "awareness" means not just awareness of the existence of an innovation, but the awareness that it is potentially of practical value to the farmer. According to Ghadim & Pannell (1999), when a farmer reaches this point of awareness, it serves as a trigger which prompts the farmer to be willing to "open his ears and eyes" and to begin noting and collecting information about the specific innovation in order to inform the decision as to whether to proceed or not to the next step of adoption, namely trialing of the specific innovation.

   Rogers (1983) determined two basic communication channels for information exchange in the analysis of adoption research; mass media *versus* interpersonal and cosmopolite *versus* localite. The individual information source includes personal influence through contacts of farmers with each other. A fundamental principle in human communication is that dissemination of new ideas occurs most frequently between individuals who are alike, or homophilous. Differences in technical competence, social status and beliefs contribute to heterophily in the language and perceptions of the communication, thereby leading to messages that go unheeded.

   Gatekeepers played a major role in the triggering of awareness, dissemination and diffusion of the WFD technology. Many of the gatekeepers obtained their information from the Micro 2000 Conference (as a mass media channel of communication) held in Cape Town during January 2000. The project team did not make use of the media to introduce the WFD, for fear of raising expectations that could not be fulfilled.

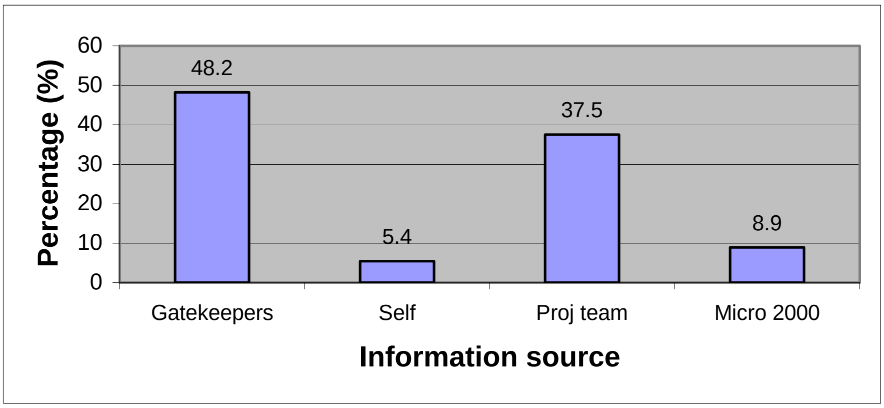


Figure 4.3 Information sources for the Wetting Front Detector (N=54)

2. *Interest*

   Having become aware of the WFD, respondents were asked why they had shown interest in trialing it. Forty eight percent of the respondents perceived the value of the detector in its role as a learning tool (monitoring of the correctness of irrigation scheduling practice), while 32% indicated interest in the device for its use as an alternative or additional scheduling method to what they were already using, and 20 % used the device for sampling soil solution for nutrient analysis.

The 20% who wanted to use the device for nutrient sampling again reflects that the project had captured many innovators. The project team had not offered any help in this area, but it was clearly a felt need. The fact that many wanted to use the WFD as a learning tool or supplementary tool to some other method, also speaks clearly about the nature of the irrigation scheduling problem. No one tool provides all the answers and farmers are willing to try several roads to get deeper insights.

Table 4.8 Respondents' perceptions why they had shown interest in trialing the WFD (N=54)

Reasons why respondents shown interest in the WFD	% of respondents
1.Use of the detector as a learning tool	48
2.Alternative or additional irrigation scheduling tool	32
3.Device that can sample soil solution for nutrient analysis (EC and N leaching)	20
Total	**100**

The widespread interest in the WFD is confirmed by recording some of the actual experiences of farmers that illustrates the needs tension that was common amongst the survey groups.

"I consider myself as a person with good intuition on when and how much to irrigate, but I never definitely know whether I have applied enough irrigation or perhaps have irrigated too much. I desperately need to know what is happening underneath the soil surface after each irrigation."
(Farmer, Brits area)

The initial perceptions of the device were almost always positive. Both farmers and researchers had experienced some difficulty in using or teaching others to use soil water monitoring equipment and the simplicity of the device was welcomed.

"I am very positive about the use of the Machingalana amongst the small-scale farmers in Eksteenskuil. The device is simple and very practical and farmers now for the first time really understand the working of the tensiometers installed at Eksteenskuil. We have installed the Machingalana near to where we have used tensiometers for the last two seasons on table grapes under short furrow irrigation. We have since the installation irrigated once and the tensiometer was first to react followed by the 30cm installation of the Machingalana after about an hour. This experience is helping farmers to understand the working of tensiometers better because the movement of a wetting front is visible."
(Researcher, Eksteenskuil)

The survey does not capture those who became aware of the WFD but did little more about it. Following the workshop at UNIN, only one of the five extension workers who were provided with detectors actually used them. However, it was subsequently pointed out to the project team by a senior member of the Department, that a half-day training session was insufficient to get cooperation. Many extension workers servicing the needs of small-scale farmers already feel ill-equipped to tackle the problems of their clients. The

WFD may be simple, but extension workers who promoted it would invariably come across problems of one sort or another and would not know how to solve them or where to get back up assistance. Training of extension officers, like farmers, requires some hands-on experience, so that the officers have the confidence to challenge their farmers to change practice.

3. *Evaluation*
   Risk assessment is one of the major factors considered during the evaluation phase, particularly in agriculture, as farmers tend to be strongly “risk averse”. Respondents were asked whether the use of WFD held greater risk than their current method of scheduling. Fifteen percent of the respondents perceived the application of the WFD could increase their risk compared to their current practice. Risk was mainly perceived by commercial farmers as a possible decline in crop yield due to cutting back on irrigation. They preferred to practice “insurance” irrigation during critical growth stages and be sure that the crop would not be stressed. Some small-scale farmers were concerned that the WFD may require them to irrigate more. The difference between the two sectors relates back to the proportion of their input costs attributed to irrigation. This was small for most commercial farmers, but could be substantial for small-scale farmers.

Table 4.9 Respondents’ perception of the differences in risk between current irrigation scheduling practices used and the application of the WFD (N=54)

Perceived risk of applying the WFD	Number of respondents
Risk the same, or no additional risk	46
Bigger risk	8
Total	**54**

The initial cost of evaluating a new technology also limits adoption, especially for small-scale farmers. Farmers frequently cite the cost of soil water monitoring equipment as a barrier, and they are reluctant to invest because they are not certain of the benefits. One of the chief design criteria for the WFD was to produce a device as cheaply as practicable. It will be cheaper than other products on the market, but the extent to which this translates into market sales will depend on the benefits of its use as perceived by the farmer. Since WFDs were given out free of charge to participants, we do not know whether cost will be a barrier to commercial farmers. We do know that there were attempts to copy the prototype, but this was due to unavailability, not cost cutting.

4. *Trial*
   The degree to which an innovation may be experimented with on a limited basis is critical in the adoption process (Rogers, 1983, Bembridge, 1991). The trial phase is perhaps the most important stage in determining final adoption. Even financially and socially secure farmers will not plunge blindly into a new practice, but prefer to limit their risk as much as possible by gathering maximum information and extending their knowledge in a cautious way. If possible, they prefer a phased implementation of an innovation, adjusting the scale either upwards towards full adoption, or downwards towards disadoption

as they gain knowledge and confidence in their perceptions about its performance.

The fact that many farmers were prepared to try the device themselves is a good indication of the attributes of the wetting front detector in terms of “trialibility”. Fifty three percent of the respondents were helped with initial installation of the device, while the rest of the respondents were following the two page guidelines included with the wetting front detector on how to install and operate the wetting front detector. It should be noted that the instructions were very generic, and had not been fine-tuned to specific crops, soil types or irrigation systems. Problems did occur where farmers were not sure about the correct installation procedures and placement of the wetting front detector.

During the trial phase, the farmer ascertains the characteristics of new technology against their current practice. The following characteristics are requirements for a successful innovation, and could greatly affect the rate at which it gets adopted (Rogers, 1983):

a. *Relative Advantage*

The relative advantage means the degree to which an innovation like the WFD is perceived as better than the one it supersedes (Rogers, 1983, Bembridge, 1991).

The respondents reported the following relative advantages of using the wetting front detector:

- Simple and understandable method – not “fancy”
- Easy and cheap to maintain
- Like the idea of knowing how deep the water has penetrated – prevents over irrigation
- Can be used in conjunction with other irrigation scheduling tools and help interpret the information they provide
- No valuable components that could be lost due to vandalism
- Not too simple to be used by even the biggest commercial farmers
- Little time needed to observe response and interpret information for decision making
- Great advantage when new irrigation system or new land is in operation
- High visibility of the monitoring response
- No computer skills needed
- Excellent learning tool - practical for literate and illiterate irrigators
- Can be used to monitor EC and other plant nutrients

In the case of the above, the WFD must have responded in a believable way, such that the farmers were willing to interact with the technology. However, problems were inevitably experienced, given the newness of the innovation and the lack of experience of the users. The following quotes sum up the difficulties some farmers experienced.

- “*The wetting front detector is not working for some crops like: potatoes under centre pivot. The device did not respond, perhaps because we are using water very effectively on the farm and do not over irrigate easily.”*
  (Farmer, Limpopo Province)
- *The wetting front detector is functioning better underneath drip and micro irrigation applied to permanent crops, rather than with annual crops like potatoes under a centre pivot.”*
  (Farmer, Douglas)
- *Farmers are not interested in the wetting front detector because they are making use of furrow irrigation and the device is therefore not working for them.”*
  (Extension worker about small-scale farmers in Limpopo Province, Department of Agriculture)
- *“The wetting front detector will only respond once you are over irrigating a little - giving more than field capacity.”*
  (Researcher, Limpopo Province)
- *“We don’t know where to install the wetting front detector: underneath or between the drippers.“*
  (Farmer, Marble Hall)
- *“The soil is disturbed every time you are installing the device, and although we have tried to install it from the side of the ridge, the root zone was still disturbed.”*
  (Farmer, Rustenburg) “
- *The removal of the WFD devices at the end of the crop season should be finished before you start to cut down on the application of water before harvesting, especially when production is coming from heavy clay soils, otherwise you will not be able to remove the device without damaging it.”*
  (Farmer, Settlers)
- *“The installation of the deep detector is not easy and especially not on heavy black clay soils.”*
  (Farmer, Brits)

b. *Complexity*

Determining the farmers’ perception of complexity surrounding the innovation can summarize the pros and cons listed above. Complexity is defined as the degree to which an innovation is perceived as difficult to understand and the difficulty of activities that have to be performed to adopt and use a technology (Rogers, 1983, Bembridge, 1991). All respondents found the technology easy to understand, but 28 % of them (15) did encounter difficulties when applying the technology to their particular situation (Table 4.10).

Table 4.10 Respondents' perceptions of the complexity of WFD (N=54)

Perceived understandability of WFD	Number of respondents	Perceived ease of use of WFD	Number of respondents
Easy	54	Easy	39
Difficult	0	Difficult	15
Total	**54**	**Total**	**54**

c. *Compatibility*

Alongside the farmers' perception of complexity is their perception of whether the technology is compatible. The compatibility of the innovation is the degree to which it is perceived as consistent with the current farming system (which also includes the social system), existing values and past experiences (Rogers, 1983, Bembridge, 1991). Seventeen percent of respondents indicated that the wetting front detector was not compatible with their current farming system and two thirds of these were not willing to reconsider using a wetting front detector.

d. *Observability*

Ultimately the farmers must perceive that the wetting front technology promotes their objectives. Linder (1987), in a wide-ranging review of adoption and diffusion literature, concluded that the objectives of an individual farmer figure centrally in the adoption and diffusion process. He found that there is compelling empirical support that the final decision to adopt or reject is consistent with the producer's self-interest. Self-interest is more than profit alone, but includes the farmer's attitude to risk, environmental protection as well as their general perception of success or failure.

As farmers interact with technology, so their knowledge increases and this affects their perceptions of how it could help them to reach their goals. The respondents' overall perception of the wetting front detector was assigned to one of the four categories below:

i. Positive perception as an irrigation scheduling tool (**PosWat**)
ii. Positive perception that soil water could be collected for the testing of EC and nutrient status (**PosEC**)
iii. Negative towards the application of the WFD for their specific farming situation (**Neg**)
iv. Positive as well as negative perceptions about the use of the WFD (**PosNeg**)

The majority (82 %) of the respondents perceived the use of the WFD favourably, either for possibly more accurate irrigation scheduling (57 %), or for the potential to analyze the nutrient and EC content of the soil water (25 %). Again the interest in nutrient monitoring reflects farmers at the cutting edge, who do not currently have a simple method for doing this.

These positive perceptions indicated by respondents on the use of the WFD through experimentation and trials were also illustrated by some actual experiences of farmers recorded. Some experienced irrigators reported that the WFD had quickly taught them valuable lessons.

"I made the mistake in the past that I have applied too much water at the beginning stages of the season and then during the critical stages of fruit set applied perhaps too little irrigation. The wetting front detector helped me to rectify my scheduling program that was based on twenty four years of farming experience and effective observation."
Farmer, Vredendal

"We had always irrigated until free water was visible on the soil surface of the land, but with the help of the WFD we were able to determine over irrigation in that we were irrigating beyond the active root zone of most of the crops produced in the past"
Researcher, UNIN, Limpopo

Others found that the WFD gave them the confidence that they were more or less on track or had helped some aspects of their management but not others.

"I have tested the WFD for the past season on my onion crop under a centre pivot and have been able to determine with the help of the WFD that I was irrigating enough during the critical stages of the crop. This device helped me to feel less troubled about whether I was irrigating enough. This put me in a position where I could focus on other aspects of the production process."
Farmer, Settlers, Limpopo

"The Machingalana has helped us to reduce the over irrigation by preventing irrigation beyond the active root zone of crops. With the wetting front detector we were able to apply the correct irrigation schedule, but, however, were unable to answer how much irrigation is needed and when"
(Lecturer, Tompi Seleke Agricultural College)

The negative perceptions about the wetting front detector (mainly the incompatibility with irrigation systems like furrow and centre pivot), reflect the fact that the research team had had minimal experience with such systems, and had not developed guidelines for centre pivot and flood irrigation.

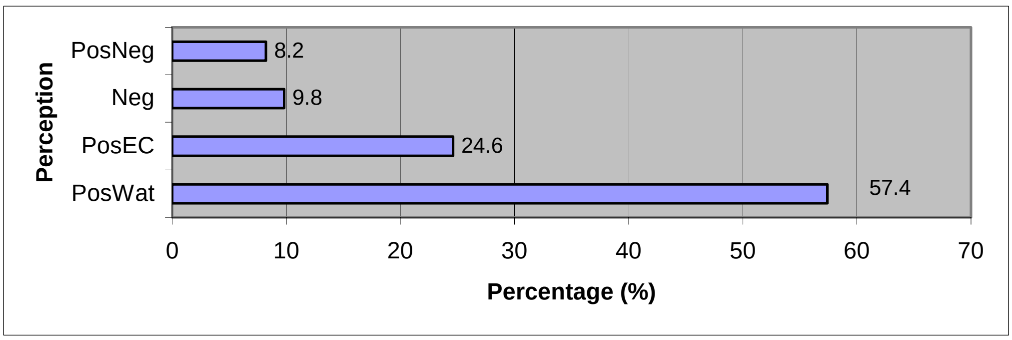


Figure 4.4 General perception of respondents towards the possible use of the WFD (N=54)

e. *Adoption*

Farmer's decisions to adopt new agricultural technology like the use of the WFD depend on complex factors after analyzing the trial results and are indeed part of a social process. Adoption according to Vanclay (2003) is not only an unthinking response to new information; rather it is a deliberate decision by an individual farmer in response to a wide range of issues. The one factor that was tested in this survey was the change in farmers' perception of the potential of the WFD as an irrigation management tool and whether it will fit their current farming system.

Some farmers perception changed very much and surprisingly quickly over time, and led to changed irrigation management very soon after introduction and evaluation of the WFD, while others either indicated lack of compatibility with their current farming systems after initial testing on the farm and therefore discontinue the use of the WFD or took a longer period to evaluate the WFD before they took a decision.

Some farmers also indicated that they have learned enough from the use of the WFD after one or two seasons of testing and they went back to their old (traditional) irrigation practices. It was found in this study that the six stages of adoption as described were not a smooth linear process but more of an action-learning pattern.

Conclusion

Learning, risk and uncertainty play distinctive roles in the process of adoption of technologies (Mara *et al* 2002), in particular:

- Learning which improves the farmer's ability to implement and use the new technology
- Perceptions of the farmer about the present and future probability distribution of economic returns from the new technology
- The strength and the direction of risk attitudes of the farmer (i.e. risk averse, risk neutral, risk preferring)
- And the option value of delaying where there are fixed costs of adoption

This part of the project offered farmers, from very different backgrounds using a variety of irrigation systems and growing a variety of different crops, the opportunity of trialing the WFD. As they went through the learning process they had to evaluate whether the response of the WFD was helping them to reach their goals. That means they had to gain some confidence in the device and the confidence to adjust management in the direction indicated by the device.

The wetting front detector did create a dialogue between researchers, extensionists and farmers, and challenged the perceptions of the different parties. The dialogue was the cornerstone of collective learning from all sides and helped the different parties to understand each other. Some farmers collaborated in this project with prejudices and preconceptions. Almost all of the commercial farmers who have taken part in this project have trialed other irrigation scheduling innovations and concluded that not all lived up to the claims made for them.

Farmer perceptions did change over time through the dialogue that took place between different parties. Some farmer's perceptions changed surprisingly quickly, while others (which included farmers categorised as more progressive or innovative), took nearly three years to reach a stage where the WFD was accepted as a valid decision support aid in irrigation scheduling. Some small-scale farmers changed their management very soon after using the WFD, perhaps because this was the only tool to help them make irrigation decisions.

Dialogue and communicative learning stimulated and supported farmers in exploring just beyond what he or she confidently knows, in what is sometimes also called the "*zone of proximal development*" (Vygotsky, 1978). Through their own experience and at their own pace, farmers could build confidence in the use of the device.

One of the major relative advantages recorded by all of the respondents, is that the WFD is easy to understand and its response it highly visible. This allows farmers to quickly gain insights and understanding, thereby stimulating *individual learning*. The fact that no computer skills are needed to interpret the response, was also perceived very favourably.

This study again reiterated the fact that farmers do not operate in isolation but rather in a social and business relationship situation in which individual's position is progressively influenced as a result of others. Farmers more exposed to mass media, with higher socio-economic status, more formal education and those in regular contact with change agents or advisors are the first to trial the new technology. The classical model assumes that awareness and knowledge will always filter through form these progressive farmers to others in social system- but it is not always appropriate amongst the small-scale farmers, where the sanctions of authority and consensus are important determinants of individual decision-making (Rahim, 1978). For example diffusion did not take place from those who had used the WFD successfully on bigger irrigation plots (5 ha) to those at the same scheme operating the small food plots. We have found that farmers utilize a range of information sources. For researchers and extensionists working in heterogeneous farming communities it is important to identify the different subcultureal farmer groups and then determine which sources of information these farmers are using as well as the trusted leaders for the specific social system or farmer group in order to design more effective extension programmes.

On-going support in the implementation and using of the WFD is very important to ensure that once the technology is implemented, the use is not discontinued. Especially with the small0scale farmers, substantial input is required to acquire the necessary skills to make effective use of the WFD.

The learning based approach used in this project required researchers and extensionists to play new roles which do not always fit well with institutional cultures. Experiential learning processes need to be facilitated and managed well, and the necessary facilitating skills are very important. It is essential to ask the right questions at the right time in order to enhance people's self-reflection, discovery and self-awareness without pre-empting their responses. These different roles need to be better recognized and their implications in terms of training and institutional support better understood.

The first hypothesis, to determine whether the WFD would stimulate a dialogue about irrigation and challenge farmers to take another look at what they were doing, is clearly accepted. The originally proposed methodology for this project had to be completely revised following the enormous interest shown by farmers in the detector. A policy had to be made that no further detectors would be installed – leading some people to make their own.

The second hypothesis, evaluating the farmers' willingness to persevere with the technology, and their ability to learn from it, is a little more complex. The willingness of farmers to adopt the use of the WFD depends on the farmers' perception of the WFD in relation to their current needs and knowledge. Overall 82 % of farmers recorded a positive perception of the detector and therefore a need to persevere with the use of the WFD, but 28 % respondents did record difficulties of one kind or another.

The initial exuberance was not always sustained. As detailed earlier, some farmers, particularly those using centre pivot and furrow irrigation, lost confidence in the device because it was not responding to irrigation. This is most likely due to the fact that the detectors were installed too deep in centre pivot or too far from the furrow in flood. The response of the detectors was not believable and therefore did not challenge current practice.

Farmers and the project team learned valuable lessons from this survey. The most important lesson learnt by the project team was the importance of the on-going relationship and trust between the extension worker and the irrigator. Most of the value of the WFD came from the dialogue between the irrigator.

A second important lesson was that many saw the WFD as a learning tool rather than a stand-alone piece of technology. It helped farmers to re-evaluate what they were doing and even take a fresh look at other scheduling devices that they had given up on. It was clear that the WFD did not answer all the questions, but it helped irrigators take the next step and formulate their next set of questions.

"When the Machingalana was introduced to me, I was initially under the impression that this device was earmarked for farmers who want to be involved in precise scheduling, and therefore not the aid for me! The Machingalana helped me to identify and adjust the application of irrigation of the centre pivot to be able to optimize my crop production. I have not really saved water during the past season but the device helped me with scheduling of the frequency of irrigation. This device is easy to understand and interpret since movement of the wetting front is visible. From this experience I have changed my initial perceptions about the device. This is a simple but very sensitive device that will help all irrigators with irrigation scheduling. I have since the introduction of the wetting front detector also restarted using the tensiometers that were stored, and for the first time the working of the tensiometers also makes more sense to me."
Farmer, Brits area

"The Machinglana has helped us to reduce the wastage of water by irrigating below the effective root zone of planted crops. We have been able to identify the ideal for irrigation, but, however, were not able to answer the question of when and how much to irrigate at a time. We have included the wetting front detector in our curriculum for students who are involved in agronomy. This is a simple and very easy to understand

device to be used by small scale farmers. However, we are still having some problems working out how to use the detectors for furrow irrigation."
Lecturer, Tompi Seleke Agricultural College

The third lesson we have learned is that the farming community is not homogenous and that farmers could be grouped in subcultural groupings that relate to different "farming styles" and therefore are making use of multiple sources of information and support. The experience with the WFD highlights he need for a diversity of information networks, the creation of a "learning environment for a specific group" based on lifelong experience and participation and a multiple support system required to address the different farming styles.

In summary we found that the introduction of the wetting front detector was much more than just testing of a certain technology. It positively affected a number of other important areas listed below:

- The WFD provided an opportunity for discovery and experiential learning. It created curiosity and a spirit of trying together with other farmers.
- The process valued the farmers' own knowledge and further revealed the interrelationship between farmers' knowledge and scientific knowledge.
- It helped the research team and the farmers to work together to develop "better technology" through identification of certain problems in the application of the device.
- Farmers added some "individual perspective" to the problem by re-ordering and synthesizing known facts and arguments. The linking of technical and the social processes generated social learning.

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Capacity building

A project of this kind inevitably brings changes in peoples behaviour and perceptions and presents them with complexities and challenges some of them have never faced before. The wetting front detector has proved itself as a fantastic "learning tool" and the learning was based on interplay between "action and reflection".

The capacity building that took place during the project period was mainly done on two levels:

- The first level was the general attitude towards applying and testing of the wetting front detector as an alternative or additional irrigation-scheduling tool. Awareness of people at various levels within the project was raised, and many have gained from the interaction within the project. Members of the project team and the students of the University of Pretoria, farmers, gatekeepers and many professionals in the irrigation industry have gained knowledge and understanding of the movement of wetting fronts. They also now appreciate the power of knowing how deep wetting fronts move after an irrigation. We have experienced how peoples' attitudes changed over time. Some have changed favourably, while others changed negatively, after trialing the device on their farms.

- Over the period of two and a half years, the know-how and skills of students, farmers, irrigation professionals and the project team has increased substantially regarding the working of the wetting front detector, possible applications of the device as well as the human and environmental factors that hinder the acceptability of the wetting front detector. Much effort and impetus was put into the skills development of students and farmers, especially with reference to the small- scale farmers of Elandskraal, Maubane, Eksteenskuil, Driekop and Walda.

The training institutions, namely the Lowveld Agricultural College, Tompi Seleka Agricultural College, Agrofert, University of the North as well as the University of Pretoria played a major role in the competence training of agricultural students and farmers.

The project team was involved on a national basis in information exchange between the research component at the University of Pretoria and CSIRO, Australia and potential users in SA. During the project period the project team was also in a position to identify certain gaps and areas of need to be addressed to ensure the sustainable development of irrigation farming.

Four students, three of whom are from a disadvantage background, were targeted for postgraduate studies on this project:

- Tshepo Maeko has conducted controlled experiments at the Hatfield Experimental Farm of the University of Pretoria to compare wetting front detectors with other irrigation scheduling methods. In the process of conducting the studies, Tshepo has gained substantial knowledge on the use of wetting front detectors as irrigation scheduling tools, and also in the general aspects of water management. He received his M.Sc. Agric degree for this work at the end of 2003.

- Jairus Nkgapele was involved in developing simple irrigation scheduling procedures by the use of irrigation calendars in combination with wetting front detectors. Irrigation calendars, which are generated with the aid of a computer model (SWB), will then guide farmers with respect to the irrigation amount, while wetting front detectors will give feedback on possible over or under irrigation.

- Wellbeloved Marobane was enrolled for an M Inst Agrar degree in Extension at the University of Pretoria. The aim of his study was to determine whether the wetting front detector helped small-scale farmers at Driekop, Limpopo to improve their decision-making regarding irrigation applications. The general perceptions of farmers regarding the acceptability of the wetting front detector were collected through a survey done in Driekop. Wellbeloved was also very much involved in the assembling of the wetting front detectors at UP before they were distributed to the collaborators. Trained as an Animal Scientist, he gained tremendously in terms of knowledge, skills and competence in the working and assembling of the wetting front detector, as well as irrigation practices and irrigation scheduling.

- Joe Stevens registered for his PhD at the University of Pretoria in Rural Extension, and is basing much of his thesis on the work done in this project.

In addition to these students, Sylvester Mpandeli assisted with the setting up of the field trial and ran the sunflower trial under the rain shelter on the University of Pretoria's Experimental Farm.

Data Archiving

The data gathered in this project will be saved on CD and copies kept by the Department of Plant Production and Soil Science and Department of LEVLO at the University of Pretoria, as well as at CSIRO Land and Water in Canberra.

Hardcopies of the data will also be available in the dissertations of Tshepo Maeko and Wellbeloved Marobane, as well as in the thesis of Joe Stevens.

APPENDIX 1: Relating velocity of wetting front to initial water content

The method of scheduling by position of a wetting front was first proposed by Zur et al. (1994) and is based on the theory of Philip (1957) as modified by Rubin and Steinhardt (1963).

The velocity of a wetting V front is given by

$$V = \frac{IR - K_{\theta i}}{\theta_{wf} - \theta_i} \qquad (1)$$

where IR is the irrigation rate, $K_{\theta i}$ is the unsaturated conductivity at the initial water content, θ_{wf} is the water content behind the wetting front and θ_i the initial water content or water content ahead of the front.

For values of θ_i less than the upper drained limit, $K_{\theta i}$ is very low compared to the irrigation rate and can be omitted from equation 1. We can determine the time t it takes for a wetting front to reach a given depth d using

$$V = \frac{d}{t}$$

and rearrange to give

$$t = \frac{d(\theta_{wf} - \theta_i)}{IR} \qquad (2)$$

The amount of irrigation in mm, I, is the product of the irrigation rate, IR, and t so

$$I = d(\theta_{wf} - \theta_i) \qquad (3)$$

Assuming θ_{wf} remains relatively constant for a given soil-irrigation rate combination, and since d is fixed then

$$I\,(mm) \propto \theta_i \qquad (4)$$

Thus the amount of irrigation applied on any day should be linearly proportional to the initial water content. Put simply, if the soil is dry before irrigation, then the front will travel slowly and a long irrigation will be permitted before the front reaches the detector. Conversely if the soil is wet before irrigation, the front will move quickly and irrigation would be of short duration.

APPENDIX 2: Choosing the irrigation interval

The experiments showed that if detectors are placed too deep or the irrigation interval is too short, then over-irrigation is likely to occur. A farmer can use trial and error to find the correct balance, but there is also a scientific method for doing so.

An example of calculating the irrigation interval is given below for the site where this project was carried out. We choose an active rooting depth of 600 mm. Thus the depth to the shallow detector (d_s) will be half the active rooting depth or 300 mm. From neutron probe measurements we determined that the water content at the wetting front θ_{wf}, drained upper limit θ_{dul}, refill point θ_{rf}, and lower limit θ_{ll} were, 0.21 0.18, 0.14 and 0.09 m m^{-3} respectively..

The amount of water, ***I***, applied to a crop would be,

$I = d_s (\theta_{wf} - \theta_i)$

where θ_i is the water content before irrigation.

Assume θ_i was the refill point or 0.14, then the amount of irrigation applied using a detector in automatic mode would be 300 x (0.21 – 0.14) = 21 mm. If initial water content was at PWP, then 36 mm would be applied, thus 300 x (0.21 – 0.09) = 36 mm. This would represent the most water we could apply.

If irrigation was stopped automatically as soon as the wetting front reached the detector, then some water would redistribute below the detector. We call this the overhead.

The overhead, ***O***, or the amount of water that moves below the detector is

$\boldsymbol{O} = d_s (\theta_{wf} - \theta_{dul}) – T$

Where T is transpiration (T is included because transpiration and redistribution take place simultaneously). For example, if most of the redistribution took place in 24 hours and crop water use was 8 mm/day then the overhead would be 300 x (0.21-0.18) – 8 = 1 mm. However, if ET was only 3mm/day overhead would be more, 6 mm.

Using the above equations and rough estimates of ET, we can calculate appropriate irrigation intervals.

Irrigation Interval = $d_s (\theta_{wf} – \theta_{rf}) / ET$

In summer when the ET may average 8 mm/day, the interval should be just over 3 days. In winter where ET may be 3 mm/day, the interval should be lengthened to 7 days.

The above points are theoretical and only serve to illustrate that detectors could be used incorrectly. If the irrigation interval for a given depth of placement was too long in summer the crop would be run into stress, because there is a finite amount of water that can be added before the wetting front reaches the detector. Conversely, over irrigation is possible if irrigation is carried out too frequently, particularly in winter when ET is low.

APPENDIX 3: Guidelines for using Wetting Front Detectors

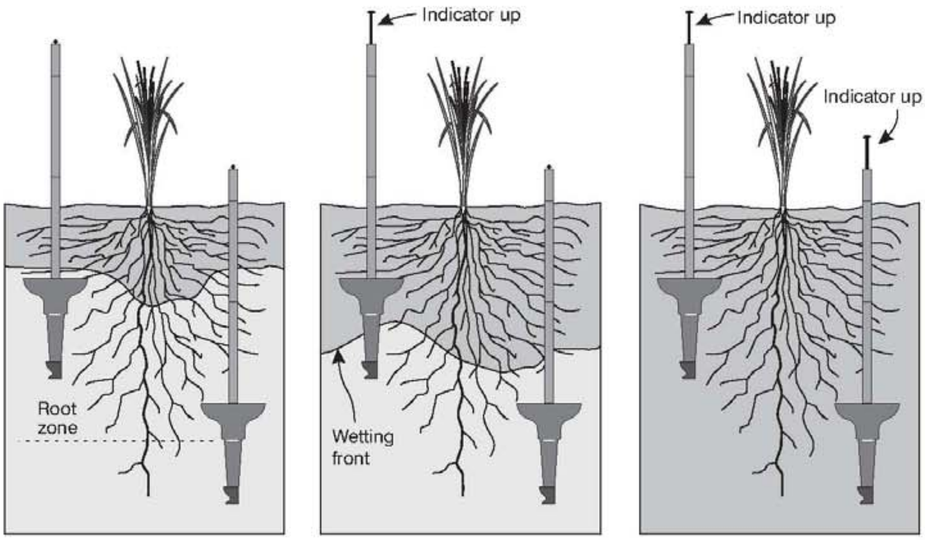
The *Fullstop* Wetting Front Detectors

Learn to match irrigation to a plant's needs

The *FullStop* wetting front detectors are designed to help you adjust irrigation to match plant needs as they grow through the seasons.

FullStop can be used to
- find out if you are irrigating too little or too much
- assist in the management of fertilizer and salt
- detect water-logging.

The concept is simple. A pair of wetting front[1] detectors - one buried in the soil at half the depth of the root zone and the other towards the bottom of the root zone[2] - show the depth to which water (rain or irrigation) has infiltrated into the soil. When the wetting front reaches the detector an indicator pops up which is visible above the soil surface.



Too little water

If the indicator of the shallow detector rarely pops up, then water is not moving deep enough to fill most of the root zone. More water should be applied.

About right

If the indicator of the shallow detector regularly pops up, but the deep one pops up only occasionally, then most of the root zone is filling with water.

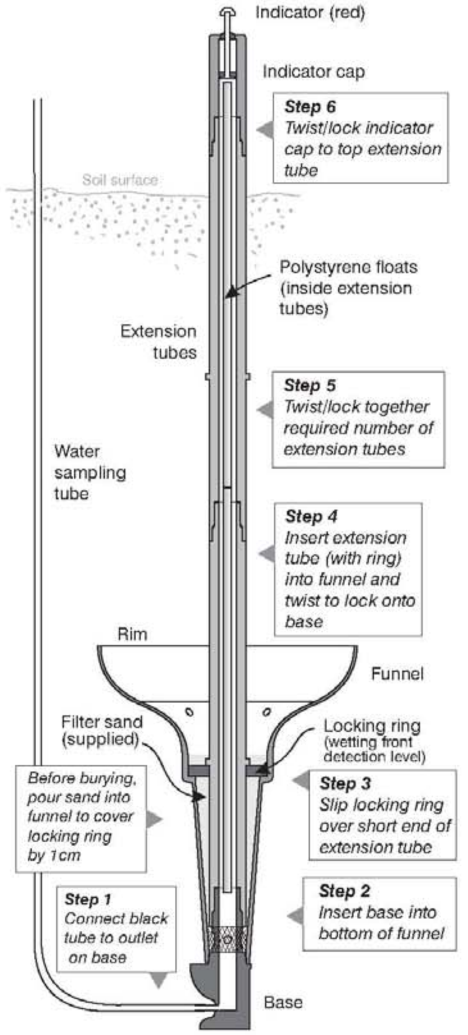
Too much water

If the indicators of both the shallow and deep detectors regularly pop up then water could be wasted. Apply less water or lengthen the period between irrigations.

Definitions

1 Wetting front: When water is added to soil, a wet layer forms over the drier soil below. The wetting front is the boundary between the wet and drier soil. The front moves down through the soil during irrigation and will continue downward after the irrigation ceases.

2 Root zone: This is the layer of soil containing most of the plant roots and therefore the zone that needs to be refilled with water. Some roots grow below the root zone.



Assembly

Each box contains two *FullStop* detectors that require assembly.

The box contains:
2 funnels, 2 bases, 5 extensions tubes containing styrofoam floats, two locking rings, 2 lengths of 4 mm tubing, 2 indicator caps, 1 syringe and one bag of filter sand plus these instructions

To assemble each *FullStop* detector, follow steps shown in the diagram above. The styrofoam floats are secured in the extension tubes with tape. Take care removing the tape as the floats are fragile.

Should a float break, the detector will still work as long as floats are continuous from the base to the indicator (see diagram).

Test each detector after it has been assembled by pouring some water into the funnel, with the black tube held upright to ensure water does not escape. The red indicator will then rise and be held in place by a magnet. Let the water out via the black tube and tap the indicator gently down to release the magnetic 'latch'. The supplied filter sand must not be added until you are ready to install the detector.

Installation

Step 1 - *location and depth of hole*
The diagram on the right shows the recommended depth and location of the detectors for different types of irrigation.

FullStop is easiest to install using two augurs: an auger (20 cm or larger in diameter) for the wide end of the detector funnel and another (5-10 cm in diameter) for the narrow end of the funnel. Alternatively, a spade and trowel could be used.

Keep different soil layers separate when you remove them from the hole if the soil type changes with depth. Installation is easiest when the soil is moist, rather than when it is very wet or dry.

Step 2 - *add the filter sand and insert the FullStop into the hole*
Add the supplied filter sand to the detector as shown in the assembly diagram until it covers the locking ring by about 1 cm. Lower the detector into the hole and measure the distance to the rim of the funnel to check it reaches the suggested depth (see right). Ensure sufficient extension tubes are added so that the indicator cap is at a convenient height above the soil surface.

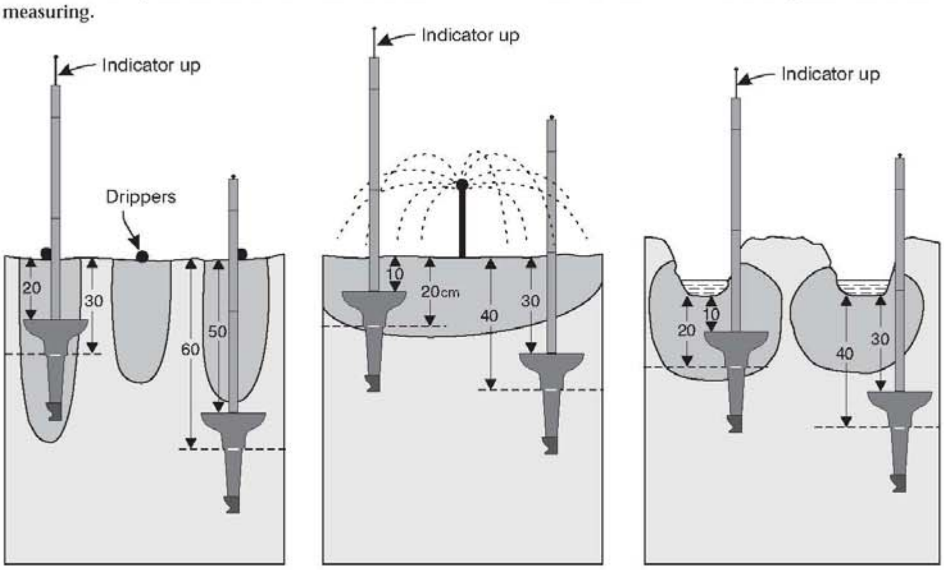
Step 3 - *pack and fill the FullStop detector*
Holding the Fullstop detector vertically upright in the hole, fill the funnel with soil removed from the layer at the same depth and firm down lightly. Hold the flexible black tube alongside the funnel up to the soil surface. Pack soil under and around the sides of the funnel until it is firmly in place.

Step 4 - *bury the FullStop detector*
Break the sides of the hole as you return soil around the detector, as smooth sides may restrict the growth of roots and the movement of water. The hole must be filled by returning the removed soil to its original layer. Soil should be firmed down by hand but not compacted. All the soil should be returned to the hole leaving a slight hump over the installation site that should settle after heavy rain.
After settling, check to make sure the soil level over the installation site is the same as the surrounding soil so that water does not run towards or away from the *FullStop* detector.

Depth and placement of detectors for different irrigation systems

The diagrams below suggest how to install detectors for drip, sprinkler or furrow irrigation. With experience these depths can be altered to suit local conditions and management styles.

Note that the indicator pops up when the wetting front has moved about 10 cm below the rim of the funnel. Therefore the depth from the soil surface to the rim of the funnel will be 10 cm less than the depth the detector is measuring.



Drip Irrigation

The detector must always be placed directly under a dripper. Wetting patterns from drip irrigation only cover a fraction of the soil surface but tend to go deep. Suggested depth for the shallow detector is 30 cm and for the deep detector is 60 cm. If small amounts of water are given frequently, detectors could be buried shallower.

Sprinkler Irrigation

Wetting patters tend to be shallower under sprinkler irrigation than drip irrigation. Suggested depth for the shallow detector is 20 cm and for the deep detector is 40 cm.

For centre pivot irrigation it is common to apply small amounts of water at frequent intervals, so depths of 15 cm and 30 cm may be suitable (5 and 20 cm to the rim).

Furrow Irrigation

The detectors have not been extensively tested for furrow irrigation. We suggest that the detectors should be positioned half under the furrow and half under the bed with the extension tube rising through the shoulder of the bed.

Suggested depth for the shallow detector is 20 cm and 40 cm for the deep detector (from base of furrow).

Things you need to know

1. Wetting fronts always move beyond the detectors

A wetting front will always move deeper after the indicator pops up. If the soil below the detector is dry, the wetting front will only move a short distance into the lower part of the root zone. If the soil below the detector is wet, the wetting front can move double the depth of the detector or more. Therefore it is important not to place detectors too deep.

2. Resetting the indicator on each detector

You must reset the detector if the indicator pops up. As the soil starts to dry water will be 'sucked out' of the detector by the soil around it. Tap the red indicator gently down to release the magnetic latch. This resets the device for the next irrigation. If the indicator pops up again after a short time, it means that the soil is still very wet.

3. Effect of soil disturbance on indicator accuracy

The soil structure is disturbed during installation of the detectors. This is not a problem for installation into ploughed soil. In the case of perennial crops the soil will need to settle and the roots grow back into the disturbed zone before the detector will give reliable information

Improving irrigation practice

When using FullStop detectors for the first time, we recommend you continue to irrigate according to your normal practice while you get a 'feel' for how the detectors are responding. Then compare your normal practice to what the FullStop indicators show you as summarized in the table below.

Shallow Indicator	Deep Indicator	Meaning	Action
Down ↓	Down ↓	Not enough water for established crops	Irrigate for a longer period or shorten the interval between two irrigations
Up ↑	Down ↓	Wetting front has penetrated into the lower half of the root zone	Most of the time no action is required. However there are times, for example during hot weather or when the crop is at a sensitive growth stage when irrigation could be increased. The deep detector will then respond occasionally showing that the entire root zone is wet.
Up ↑	Up ↑	The wetting front has moved below root zone	If this happens regularly then over-watering is occurring. Reduce irrigation or lengthen the period between irrigations.
Down ↓	Up ↑	Soil or irrigation are not uniform or the soil surface is uneven	Ensure the soil is level over the detectors and water is not running towards or away from the installation site. Check position of drip emitter relative to the device. Compare float position after rain and after irrigation to see if there is a problem with irrigation uniformity.

Once you have developed some confidence in the way the detectors are working, you are ready to learn how irrigation, nutrient and salt management can be improved. Change your water use practice at the rate at which you are comfortable, taking into account the growth and/or yield response of the plants.

Monitoring nutrients and salt

Water trapped in the detector can be sucked out with a syringe via the black tube and monitored for its electrical conductivity or nutrient concentration. Samples should be taken immediately after irrigation before capillary action empties the detector. When self-emptying, the detector retains a small sample of water. This should be removed prior to an irrigation from which samples for nutrient analysis are required.

Limitation

The design of the FullStop indicators is a balance between simplicity, accuracy and cost. FullStop has been designed to respond to 'strong' wetting fronts. In soil physics terms, the strength of the front must be around 3 kPa suction or wetter for the indicator to rise. In practice this means that 'weak' fronts may not be detected and some water will move past a detector without activating the indicator. Wetting fronts get weaker as they move deeply into the soil after the irrigation has been turned off. Weak fronts also occur during very light rain, or when the application rate of irrigation water is very low.

For further information: http://www.fullstop.com.au (from 1 December 2003)

APPENDIX 4: Perceptions of the acceptability of the use of the Wetting Front Detector at Driekop food plot projects (Maputlesebope, Arethusaneng and Moroke)

The need for the introduction of the WFD was identified during a pilot survey that was undertaken during 2001. The water sources used at Driekop will not be sufficient for sustainable food plot production unless farmers become more aware of the efficient use and application of irrigation scheduling. Farmers are used to the irrigation of their food gardens on a daily basis, and the major problems that the research team encountered was that farmers have difficulty in estimating the accurate application of water for a specific crop. Over- as well as under irrigating was often observed and effective scheduling of irrigation was identified as a priority activity with the farmers.

Introducing and raising of awareness of the wetting front detector (WFD) to the farmers of Driekop

In the three food plot projects selected at Driekop, farmers are well organised in effective project groups and it was relatively easy with the help of the local extension officers to arrange meetings. At some of the regular weekly meetings held by the farmers the use of the wetting front detector was demonstrated. The first step was to introduce the innovation to the local extension officers who afterwards acted as important gatekeepers for the WFD. The three extension officers immediately saw the potential benefits of the WFD to be introduced to the farmers.

During a regular weekly meeting, demonstration plots were identified in collaboration with farmers and extension officers responsible for the area. This ensured full participation and ownership by farmers for the testing of the device on their plots. This also ensured representative of the different soil types and biophysical conditions.

The owners of the plots selected for testing of the WFD, were also tasked to monitor the working of the WFD, with assistance of the extension officers and committee members. The selected farmers and the responsible extension officer mainly took the responsibility upon themselves for the dissemination and sharing of the lessons learnt from the response of the WFD to other farmers.

Photo A4.1
Introduction of the wetting front detector to the Driekop farmers at a regular weekly meeting

Photo A4.2
Practical training and demonstration of installation procedures with Driekop farmers

Perception of respondents of the acceptability of the wetting front detector

The acceptability of the WFD was tested by making use of the description of Rogers (1983) of the attributes of an innovation.

Relative advantage

Table A4.1 indicates the relative advantages that Driekop farmers perceived by using the wetting front detector.

Table A4.1 Frequency distribution of percentage response on the kinds of improvements seen after the use of WFDs (N=50)

Perception of benefits or relative advantages	Project			Mean
	Maputlesebope (N=15)	Arethusaneng (N=15)	Moroke (N=20)	
I cannot actually tell since it was not in my plot	13.3	6.7	10	10
I can save water	33.3	33.3	25	31
I am able to determine if sufficient water was irrigated	0	6.7	0	2
I can see some saving on diesel	0	6.7	0	2
I can see improvement on the yield	46.7	33.3	55	45
I think I am now applying more water than before	6.7	13.3	10	10
Total	100%	100%	100%	100

From the results indicated in Table A4.1, forty five percent of the respondents perceived an increase in vegetable production, while 31% of the respondents perceived saving of water as a relative advantage. The seven percent respondents (mainly from Arethusaneng) that perceived a saving in the use of diesel to pump irrigation water from the borehole were either members of the project management committee or were interacting regularly with the relevant extension officers. Ten percent of the farmers indicated a relative disadvantage in the use of the wetting front detector in that they perceived they were applying much more water than in the past before they indicated the device responding to the irrigation application.

Profitability (relative advantage)

The comparison of the average income of farmers per annum before and after the wetting front detector was installed on their food plot is indicated in Table A4.2:

Table A4.2 Comparison of the average income of Driekop farmers per annum before and after the use of the wetting front detector (N=50)

	Pre-income (%)	Post-Income (%)
<R100	15	3.9
R101-R200	21.2	17.8
R201-R300	14.4	16.1
R301-R400	14.4	7.8
R401-R500	8.9	3.9
R501-R600	0	11.1
R601-R700	11.7	10
R701-R800	6.1	6.1
R801-R900	1.7	4.5
R901-R1000	2.2	2.2
>R1001	4.4	16.6
Total	100	100%

It is clear from Table A4.2 that the average income per annum of farmers increased after the introduction of the wetting front detector. Before the wetting front detector was introduced, 74% of the respondents indicated an average income less than R500 per farmer. Since the introduction of the WFD the average income slightly increased, and 51% of the farmers indicated an average income more than R500 per farmer per annum. However, the results as indicated above cannot only be accredited to the correct scheduling of irrigation because of the WFD, but also includes other factors like more intensive extension support that was rendered because of the project and the role that the researcher and other members of the project team may have played in terms of technical advise given.

Complexity

Figure A4.1 illustrates the perceptions of farmers in terms of the relative complexity they have experienced in the use and interpretation of the response of the device as measured on a Likert five- point scale.

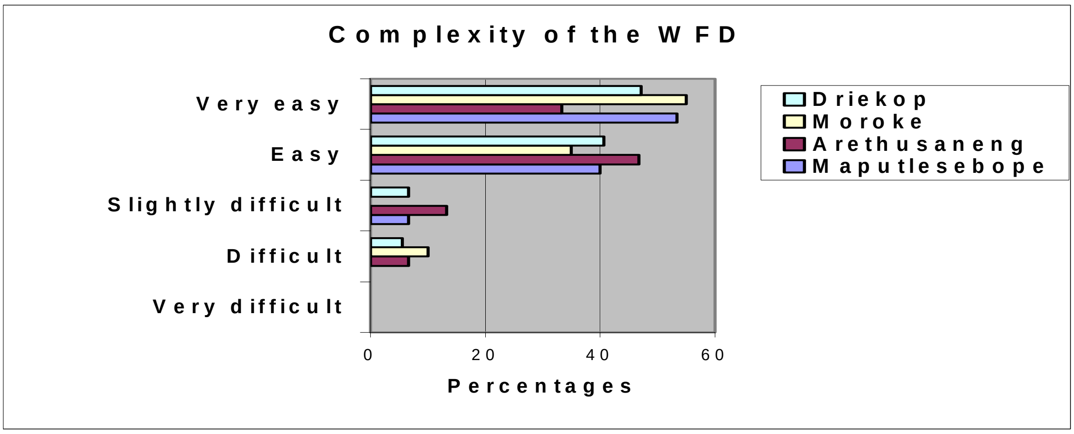


Figure A4.1 Respondents perception of the relative difficulty to apply and interpret results of the wetting front detector on a scale of 1-5.

Figure A4.1 clearly indicated that the majority of farmers (86%) did not encounter any difficulty in interpreting the results of the wetting front detector and found the device relative easy to apply in their farming systems.

Compatibility

The respondents' perception of the relative compatibility of the wetting front detector with their current farming system was measured on a Likert five-point scale and is reflected in Table A4.3.

Table A4.3 The relative compatibility that farmers found with respect to the WFD on their plots. (N=50)

	Projects names		
	Maputlesebope	**Arethusaneng**	**Moroke**
Not compatible	0	0	15
Slightly compatible	7	33	0
Compatible	53	27	30
Highly compatible	40	40	55
TOTAL	100	100	100

The majority of respondents (82 %) found the implementation of the WFD within their current farming system to be relatively compatible.

Stage of adoption

Although the majority of farmers perceived no problems in terms of the installation and implementation of the WFD, not everyone accepted the wetting front detector with open arms. The following perceptions and constraints prevented farmers from accepting and possible adoption of the wetting front detector:

- No need or willingness to accept the testing of the wetting front detector.
- Farmers who are not incurring any cost in getting water are more reluctant or resistant to adopt. (Moroke)
- Unfavourable perception in terms of possible relative advantages.
- Farmers in very scarce water projects are not very willing to make full use of the device since it forces them to put extra effort in increasing their irrigation water. (Maputlesebope)
- Farmers where extension officers are not showing any "awareness" of the technology are also hesitant towards showing interest in the innovation. (Maputle & Moroke)

It was found that farmers from Arethusaneng perceived the use of the wetting front detector very positive as indicated in the following story.

Story 7: We have learnt enough from the previous season…………….

The farmers of Arethusaneng used 210 l diesel during the 2001 season to produce a vegetable crop with the help of the wetting front detector as an irrigation-monitoring device. At the end of the 2001 season the device was removed to be able to prepare the seedbed for the following season. It was, however, not reinstalled at the beginning of the next production season (2002) due to the perception that enough knowledge and skill was gained to ensure successful vegetable production in the future. However, during the middle of the 2002 production season a visit by the researcher revealed that the same quantity of diesel (210 l) had already been used by the farmers as had been used during the whole 2001 season with the help of the WFD. This served as an indicator to the farmers that they were possibly severely over irrigating, and on request of the farmers, the wetting front detectors were immediately reinstalled.
Driekop farmers, Arethusaneng

Extension support rendered to farmers

Effective extension support by enthusiastic and committed extensionists is a prerequisite for sustainable agricultural development. Small-scale farmers need intensive extension support to overcome their relatively low managerial capacity. The farmer's ability to adopt or accept a new innovation is determined by this managerial capacity of a farmer. Small-scale farmers in general need relatively intensive extension support to inform them about a new innovation like the wetting front detector and to help them to became "aware" (testing acceptability) of the potential use of it. These farmers form part of the "managerial capacity dependent" extension target audience of an extension worker. Unfortunately, we have also encountered in Driekop that the traditional bias for extension favours the more "progressive farmers" instead of focusing on this category of farmers who are least able to adopt new practices.

The research team found that in the case of Driekop, two of the three food plots have generally been lacking in terms of committed extension support. We have observed that Driekop farmers in general were willing to trial and test the use of the WFD, but that enthusiasm and support from extension workers were of critical importance.

APPENDIX 5: Enterprise budgets for small-scale farmers

Farmer A: Elandskraal

Wheat production: **June 2000 - November 2001**
Age: 72
Area: 2.5 ha
Cultivar: SST 822
Planting date: June 2001
Harvesting date: 21 November 2001

Gross income	R/ha
5.4 t / ha @ R1000 / t	5400.00
Costs:	
Seed SST 822 @ 80 kg / ha	415.00
Fertiliser cost:	
Todressing (6 weeks) @ 120 kg LAN (28%) / ha	246.00
Weed control:	
Buctril @ 1 l/ ha (6 weeks)	79.00
Irrigation:	
Irrigation water	Free
Electricity costs for irrigation	Free
Seedbed preparation:	
Plough	240.00
Disc	150.00
Planting	0.00
Weed control (spraying)	150.00
Harvesting costs:	
Combine harvesting @ R49 / t	246.60
Transport @ R22.50 / t to OTK	121.50
Total direct cost / ha	**1666.30**
Gross margin / ha	**3733.70**

<u>Irrigation practice</u>:

Irrigation system: Quick coupling moveable sprinkler system
Irrigation schedule: 3.5 day cycle
Standing time: 07h00 - 13h00 (6 hours)
13h00 - 18h00 (5 hours)
Spacing between lines: 18 x 18m

Farmer B: Elandskraal

Wheat production: **June 2002**
Age: 62
Area: 2.5 ha
Cultivar: SST 822
Planting date: 15 June 2002
Harvesting date: Nov 2002

Gross income	R/ha
4.1 t / ha @ R1050 / t	4305.00
Costs:	
Seed SST 822 @ 100 kg / ha	200.00
Fertiliser cost:	
Todressing (6 weeks) @ 160 kg LAN (28%) / ha	368.00
Weed control:	
Mechanical weed control	0
Irrigation:	
Irrigation water	Free
Electricity costs for irrigation @ R50 / month for 5 months	250.00
Seedbed preparation:	
Plough	300.00
Disc	180.00
Planting	0.00
Harvesting costs:	
Combine harvesting @ R190 / ha	190.00
Transport @ R22.50 / t to OTK	92.25
Total direct cost / ha	**1580.25**
Gross margin / ha	**2724.75**

Irrigation practice:

Irrigation system: Quick coupling movable sprinkler system
Irrigation schedule: 3.5 day cycle
Standing time: 06h00 - 12h00 (6 hours)
12h00 - 17h00 (5 hours)
Spacing between lines: 18 x 18m