IRRIGATION INSIGHTS
NUMBER 1

SOIL WATER MONITORING

AN INFORMATION PACKAGE

2nd EDITION

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CSIRO/CRC Irrigation Futures

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CHAPTER 1

ABOUT THIS PUBLICATION

With continuing drought, dwindling dam levels, closure of the Murray River mouth and water restrictions having been experienced recently in many urban centres, most Australians are aware of the sensitive nature of our water resources. Against this background it is not surprising that the irrigation industry is constantly reminded that it consumes almost 70% of Australia's annual freshwater resource and, as such, is seen as a target for meeting increasing urban and environmental demands.

Irrigation farmers are under increasing pressure to manage water more prudently and more efficiently. This pressure is driven by water sharing requirements, product quality requirements, economic factors, demands on labour and the desire to minimise the resource degradation and yield loss that can result from inefficient irrigation. The need for farmers to irrigate more efficiently has led to huge growth in the range of equipment available for measuring the soil water status.

The keys to efficient on-farm irrigation water management are knowing how much water in the soil profile is available to the crop, and how much water the crop needs. Measuring and monitoring soil water status should be essential parts of an integrated management program. Doing this will help you avoid the economic losses and effects that under-irrigation and over-irrigation can have on crop yield and quality. It will also help you avoid the environmentally costly effects of over-irrigation, i.e. wasted water and energy, leaching of nutrients or agricultural chemicals into groundwater supplies, and degradation of surface waters with contaminated irrigation water runoff.

The irrigation service sector and irrigation managers face a huge task in finding out about the range of soil water sensing and monitoring technology available and becoming familiar with the features, advantages and limitations of each system. This publication, the only resource of its kind, is a comprehensive, one-stop guide to all the soil water sensing and monitoring equipment available in Australia.

This *Irrigation Insights* information package brings together information on current equipment and techniques for measuring and monitoring soil water status, extending to their use as controllers in automatic irrigation systems. The main part of the package focuses on equipment with agents and backup within Australia. The hub of the publication is a collection of tables summarising the main product features. This enables product features to be compared quickly. As well as technical data, there is also commercial information on suppliers, contact details, availability and price (accurate at October 2004). Case studies from personal experience and from the literature provide further insight into the advantages and limitations of each device in relation to its potential applications.

This second edition updates the list of equipment and supplier contact details and provides a new range of case studies.

One of the biggest changes we've seen over the past four years since the publication of the first edition of this *Irrigation Insights* information package is that many sensors are now able to link with a variety of measurement systems. This brings the advantage of integrating several instruments on the same logger and having all information telemetered (again with an ever widening range of options) to a central point. User-friendly, handheld systems that greatly reduce or negate cabling are also making collecting, recording and displaying information much easier.

Further development of sensor technology has now produced multi-measurement instruments capable of tracking solute, e.g. salinity and fertiliser, through a soil profile.

Case studies

Case studies are an opportunity to show how people are using soil water monitoring equipment and how the technology is advancing. Six case studies are presented in the second edition, as follows:

Soil moisture sensor-controlled irrigation for maintaining turf. Shahab Pathan, Louise Barton and Tim Colmer from the University of Western Australia irrigated turf plots using an automatic system with sensor feedback for over a year and reduced the water applied by 25% while maintaining turf quality.

Monitoring soil moisture change in a black vertisol using electrical imaging. This case study is an example of monitoring soil moisture from the surface without disturbing the system. Ian Acworth and his team from the University of NSW have shown electrical imaging agrees well with neutron probe readings.

Production and water use efficiency improvements in horticulture from improved irrigation scheduling. Growcom's Water for Profit team has put together six stories, which demonstrate a variety of water savings, higher yields and better quality produce, all including the use of soil moisture monitoring.

Methods for assessing vineyard water use. Shannon Pudney and Mike McCarthy from South Australian Reasearch and Development Institute have spent many years comparing soil moisture monitoring techniques in vineyards. Here they investigate some more variability issues, including different response times for different sensors.

Four lessons from a wetting front detector. In four easy lessons, Richard Stirzaker from CSIRO and Joyce Wilkie from Allsun Farm explain how growers have used a soil moisture tool to tighten their management of both water and fertiliser applications.

International soil moisture sensor comparison. Over the past few years, a comparison of soil moisture monitoring equipment has been undertaken in three regions around the world. According to Steve Evett, USDA ARS, Texas, there is life in the neutron moisture meter, yet!

CHAPTER 2

MEASURES OF SOIL WATER STATUS

There are three ways to describe the wetness of soil:

- gravimetric soil water content (SWC)
- volumetric SWC
- soil water potential.

Which description is used depends partly on how the information will be used. You can use all three methods for the same purpose, i.e. to work out whether you need to irrigate.

Gravimetric SWC refers to how much water is in the soil on a weight basis, e.g. 0.3 g water per 1 g of dry soil. This is the easiest way to measure SWC. All you do is take a small soil sample, weigh it, dry it in an oven for a day, and then weigh it again. The weight difference is the water extracted from the sample.

One problem with gravimetric measurement is that the densities of different soils vary so a unit weight of soil may occupy a different volume. To allow you to compare the water contents of different soils and to calculate how much water to add to the soil to satisfy a plant's requirement, you need to do a volumetric measurement.

Volumetric SWC is the most popular method of reporting the moisture status of soil. It is calculated by multiplying the gravimetric SWC by the soil bulk density, and it uses units of cubic centimetres (or millilitres) of water per cubic centimetre of soil. The bulk density, which is the mass of soil solids per unit volume, is also used to calculate how much water a soil can hold.

Volumetric measurements are convenient for measuring how full the soil is, but they give no indication of how difficult the water is to remove. As the soil becomes drier, the water is held more tightly and more energy is needed to extract it. The **soil water potential** is a measure of this tension and is expressed in kilopascals (kPa). Potential is also referred to as **soil water suction**. This is the term used in this package. Irrigation can be managed to maintain soil water suction within the correct range so that the crop is not stressed. However, trial and error is needed to determine the volume of water to be added.

The relationship between volumetric water content and suction is called the **soil water retention function**. To obtain this information needs specialised equipment and is usually only possible in research situations.

As an introduction to these measurements, Table 1 (over page) shows the average values for a range of soil textures.

Water depth

Most irrigation farmers refer to water applied to a crop in volumetric terms, e.g. in megalitres per hectare (ML/ha) or Dethridge wheel revolution (rpm).

Application volumes can also be expressed in terms of depth, e.g. millimetres. A water depth is merely a volume averaged over a land area. For instance, 1 ML applied over 1 ha is equivalent to 100 mm. This allows comparison with factors such as rainfall and crop water use or evapotranspiration. For example, to help farmers in the Murrumbidgee Irrigation Area, NSW, the potential crop evapotranspiration (in mm) is included in the nightly weather report, and the practice has spread to many newspapers and radio reports. Using a simple calculation, this figure can be converted to a volume to be applied to the crop.

Table 1. Representative gravimetric (g/g) and volumetric SWC (cm^3/cm^3) and soil water suction values (kPa).

	SAND			LOAM			CLAY		
	Bulk density = 1.65 g/cm^3			Bulk density = 1.55 g/cm^3			Bulk density = 1.3 g/cm^3		
	G	**V**	**S**	**G**	**V**	**S**	**G**	**V**	**S**
Saturation	0.23	0.38	0	0.27	0.42	0	0.38	0.5	0
Field capacity	0.10	0.17	10-33	0.24	0.37	10-33	0.33	0.43	10-33
Wilting point	0.07	0.12	1500	0.15	0.23	1500	0.25	0.33	1500

(G)ravimetric, (V)olumetric, (S)uction.

Variability

Agriculturalists are very aware of the variability that exists in their systems. In fact, they put a lot of effort into trying to even out this variability to grow a uniform product. Both subtle and sharp changes in soil type are evident across the paddock and down the soil profile. Variations in crop growth can point to soil changes, past paddock use, disease or irrigation application problems such as blocked drippers. Even very close to a plant where it extracts its water from will vary.

Time brings in another level of variability, with differences throughout the day and season in where and how much water is being extracted from the soil. Consider, for example, a row of drip-irrigated grapevines. Not only is there soil variation to contend with, but the amount of water applied between the drip emitters also will vary, from very wet at the emitter to drier in between. Impose on this a row of plants that alter where the irrigation water spreads, and you can see that the system is complex.

All the available soil water measuring instruments can tell us the soil water status at a particular point in a paddock. If you have a number of sensors, then you can place them throughout the profile to give more information. However, because there are practical limitations in the wiring or in the time taken to read them, you will generally have to place them close together. Depending on the soil water monitoring system there may be only a single reading every few hectares. This reading has to average out all the variability present in the whole area. That is, you are assuming that the instrument is placed in the average soil type, next to the average plant, at the depth of average water uptake and in the zone of average water application. You then design an irrigation schedule to satisfy the plant and soil in this position. Even if there are enough sensors present to show the variation in the field, how do you respond to the variations? Do you water to satisfy the driest part of the field, ensuring no plant is under watered? Or do you water to the wettest instruments, thus using water very efficiently but at the risk of decreased yield?

All these issues must be taken into account when you are designing a soil water monitoring system. It is strongly recommend that you talk to someone experienced in these matters, such as a consultant or irrigation officer, before you go ahead. Relying on poorly placed equipment will result in over- or under-irrigation.

CHAPTER 3

TECHNOLOGIES FOR MEASURING SOIL WATER STATUS

In this publication we use the following definition of a soil water sensor:

A soil water sensor is an instrument which, when placed in a soil for a period of time, provides information related to the soil water status of that soil (Cape 1997).

Gravimetry (in this case drying soil samples and then weighing them) is the only **direct** way to determine how much water is in the soil. All other techniques rely on **indirect** methods that measure other properties of the soil that vary with water content. The 31 products listed in this section use either suction or volumetric water content indirect measurement methods for measuring the soil moisture status. The types of measurement systems within these two methods are as follows:

Suction measurement systems, i.e.

- porous media instruments
- wetting-front detectors.

Volumetric water content measurement systems, i.e.

- soil dielectric, time domain reflectometry, frequency domain reflectometry (FDR or capacitance)
- neutron moderation
- heat dissipation.

The basic concepts behind each of these are explained below.

Suction measurement systems

Porous media

Porous media instruments are made from materials that are porous to water, i.e materials through which water can move and be stored in the pores. Water is drawn out of the porous medium in a dry soil, and from the soil into the medium in a wet soil. Porous media instruments measure soil water potential and take three forms:

- tensiometers
- resistance blocks
- combination volumetric SWC–porous material devices.

The range of measurements that can be achieved with these types of devices is shown in Figure 1.

Tensiometers

A tensiometer is an instrument that directly measures soil moisture suction. It consists of a porous ceramic tip, a sealed water-filled plastic tube and a vacuum gauge. The porous cup is buried in the soil and allows water to move freely between the water-filled tensiometer and the soil. As the soil around the cup dries, the suction increases and water moves out of the tensiometer until the suction within the tensiometer is the same as that of the soil water.

Since the tensiometer is an airtight device (see Figure 2, page 19), as water moves out from the porous cup a negative pressure (a vacuum or suction) equivalent to the soil suction is created in the tensiometer. If the soil around the tensiometer becomes wetter, e.g. from rain or irrigation, the soil suction decreases and soil water flows through the porous walls of the cup into the tensiometer, decreasing the suction.

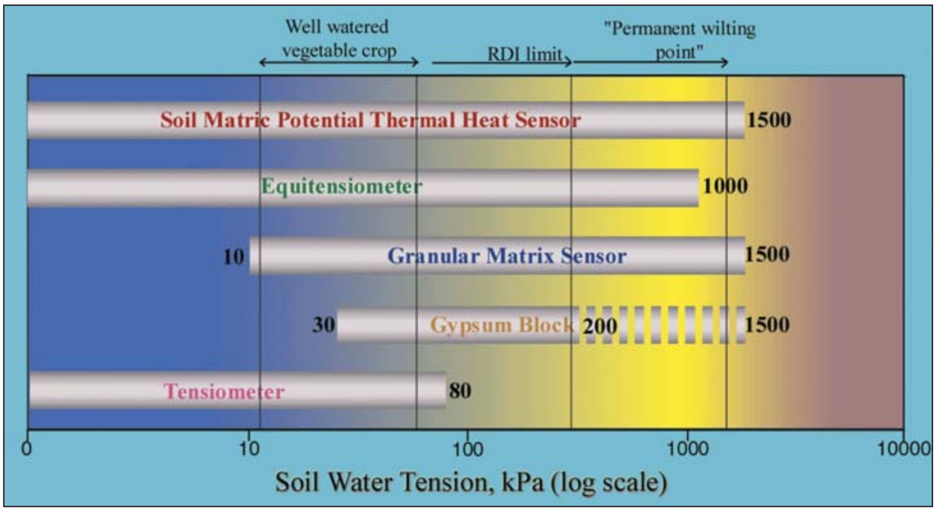
The soil suction reading relates directly to the plant water tension, and hence is a more meaningful measure of plant stress than the soil water content. The suction is measured with a vacuum gauge or pressure transducer. The transducer can either be a handheld device (used to read many tensiometers manually) or be permanently installed in the tensiometer and connected to a logger. The portable device has a hollow needle that is inserted through a rubber bung or septum to measure the vacuum.

Tensiometers cannot be used to measure soil water suction greater than 75 kPa. Suctions above this cause the vacuum in the tensiometer to break down as air enters the ceramic tip. They are fine for most annual vegetable crops, orchards, nuts and pastures, but they are not adequate for the controlled stressing of plants such as grapevines using regulated deficit irrigation and partial rootzone drying, where suctions as high as 200 kPa are recommended to produce good wine quality and reduce vigour.

Resistance blocks

Resistance blocks consist of two electrodes embedded in a block of porous material that is buried in the soil. As with tensiometers, water is drawn into the block from a wet soil and out of the block from a dry soil. The electrical resistance of the block is proportional to its water content, which is related to the soil water suction of the surrounding soil. Compared to tensiometers, resistance blocks can operate in soils that are far drier.

Figure 1. Measurement range of several soil water suction monitoring instruments.



Key points for porous media:

- Tensiometers are suited to vegetable crops, orchards, nuts and pasture.
- Gypsum blocks and granular matrix sensors are suited to regulated deficit irrigation (stone fruit and wine grapes).
- Thermal heat sensors cover the whole range and are best suited to research work.

Wetting-front detectors

by Dr Paul Hutchinson, CSIRO Land and Water, Griffith, NSW

All soil moisture monitoring devices can be used to detect wetting fronts. However, a product was designed to suit the situation where the only information required is the time when the wetting front arrives at a set depth in the soil.

Wetting-front detectors are soil moisture switches that are buried at locations of interest. When soil moisture increases above a set point the detector switches on; when the soil dries to below the set point the detector is activated, giving the signal water has reached a given depth. Wetting-front detectors are cheap because they do not need to have continuous outputs that are calibrated to the soil water content.

Wetting-front detectors provide useful information to farmers in three main ways, as follows:

Warning signals. If a wetting-front detector is placed near the bottom of the rootzone it can act as a warning signal that over-irrigation is occurring. Irrigation beyond this depth is wasted because the crop cannot get access to this water. Farmers can use a wetting-front detector to reduce over-irrigation, fertiliser loss and waterlogging and, as a consequence, to increase crop yield.

Regulating how much water is irrigated. Wetting-front detectors placed within the root-zone can be used to regulate the amount of irrigation to the crop's water demand by turning off the irrigation when the wetting front is detected. This regulation occurs because the wetting-front speed depends on how dry the soil is before irrigation. If the soil is relatively dry, the wetting front moves slowly into the soil. This occurs because the soil absorbs much of the water and slows the progress of the wetting front. Conversely, if the soil is already wet, the wetting front moves fast because the irrigation water finds little available space to occupy.

Collection of soil-water samples. Wetting-front detectors can be designed to collect samples of soil water from the wetting front. These samples contain solutes such as salt and nitrate and, when analysed, can provide useful information about managing fertilisers and the leaching of salt from the root zone.

Volumetric water content systems

Soil dielectric

The dielectric constant is a measure of the capacity of a non-conducting material to transmit electromagnetic waves or pulses. The dielectric of dry soil is much lower than that of water, and small changes in the quantity of free water in the soil have large effects on the electromagnetic properties of the soil water media.

Two approaches have been developed for measuring the dielectric constant of the soil water media and, through calibration, the SWC. These approaches are:

- time domain reflectometry
- frequency domain reflectometry.

Time domain reflectometry. The speed of an electromagnetic signal passing through a material varies with the dielectric of the material. Time domain reflectometry (TDR) instruments, e.g. TRASE and Campbell, send a signal down steel probes, called wave guides, buried in the soil. The signal reaches the end of the probes and is reflected back to the TDR control unit. The time taken for the signal to return varies with the soil dielectric, which is related to the water content of the soil surrounding the probe.

TDR instruments give the most robust SWC data, with little need for recalibration between different soil types. However, they are very expensive and you may need additional electronic equipment to run them.

Frequency domain reflectometry. Frequency domain reflectometry (FDR) measures the soil dielectric by placing the soil (in effect) between two electrical plates to form a capacitor. This explains the term 'capacitance', which is commonly used to describe what these instruments measure. When a voltage is applied to the electric plates a frequency can be measured. This frequency varies with the soil dielectric.

FDR-type products have been the main area of expansion in the production of soil water monitoring equipment. All these products have a relatively small measurement sphere of about 10 cm radius, with 95% of the sphere of influence within 5 cm. This makes them sensitive to inconsistencies introduced during installation, such as air gaps beside access tubes. The Aquaflex®, developed in New Zealand, seeks to integrate such problems over a large soil volume by making the single sensor very long (about 3 m).

Products in this group can be installed in a variety of ways, including by access tube, portable sensors and buried sensors. The Gopher® and Diviner® (see later) are operated similarly to a neutron probe. One sensor is lowered down an access tube to the required depth. It can then be moved to another location. EnviroSCAN® and C-Probe® also use an access tube, but these instruments consist of an array of identical sensors placed permanently at set depths, offering the advantage of both time and depth series logging.

To calibrate dielectric sensors, two-point (wet and dry) gravimetric sampling is used. EnviroSCAN is provided with a 'universal calibration', but there is also a comprehensive calibration procedure that can be used if you need greater accuracy.

For more technical explanations of TDR and FDR see appendixes 2 and 3.

Neutron moderation method

The neutron moisture meter (NMM) was the first device used to measure SWC in the 1950s. In Australia, it became popular in the 1970s and 1980s and was the instrument of choice for irrigation scheduling consultants. Most irrigation areas still have neutron probe services but, as a result of the development of newer electronic equipment with less emphasis on human input, as well as the problem of the nuclear stigma, they are being used less.

The neutron moderation technique is based on measuring fast-moving neutrons that are slowed (thermalised) by an elastic collision with existing hydrogen particles in the soil. Hydrogen is present in the soil as a constituent of soil organic matter, soil clay minerals and water. Water is the only form of hydrogen that will change from measurement to measurement. Therefore, any change in the counts recorded by the NMM is due to a change in the water, with an increase in counts relating to an increase in soil water content.

For a more technical explanation of the NMM see Appendix 4.

Combination devices/heat dissipation

Several of the soil water suction sensors consist of volumetric SWC sensors embedded in porous materials with known water-retention properties. The water content of the material equilibrates with the suction of the surrounding soil and is measured by the sensor.

® registered trade name.

Heat dissipation is a method used to determine soil moisture in combination devices. Heat capacity is the amount of heat energy needed to increase the temperature of a quantity of water by 1^{o}C. Sensors in this category exploit the fact that water has a far greater heat capacity than soil. This means that if a wet soil and a dry soil are subjected to the same amount of heat energy, the temperature of the wet soil won't increase as much as that of the dry soil.

Such sensors measure the heat capacity either directly in the soil or in an intermediate, porous material in contact with the soil. Equipment using this principle consists of a heat source and a temperature sensor and is buried at the depth of choice. A burst of heat energy of known amount is emitted from the heat source. As the heater is turned off the temperature sensor records the peak temperature increase for about a minute. The heat input and peak temperature change are then used to calculate volumetric water content. Calibration is performed by measuring the bulk density and heat capacity of the soil into which the sensors are placed.

The probes have a small measurement sphere (about 1 cm diameter) making them useful for high resolution spatial data gathering where many probes can be placed in a small area. Heat dissipation probes require sophisticated loggers to measure the temperature and power variables and to control the measurement timing. This also makes them suited to time series measurement.

CHAPTER 4

PRODUCT SELECTION

The products discussed in this publication are described by the following nineteen attributes:

1. Reading range
2. Stated accuracy
3. Measurement sphere
4. Output reading
5. Installation method
6. Logging capability
7. Power source
8. Country of origin
9. Remote access
10. Link to other equipment
11. Interface to PC
12. Affected by salinity
13. Expansion potential
14. Technical support
15. Irrigation system suited to
16. Best soil type
17. Application
18. Capital cost
19. Annual operating cost

When you are selecting a product, choose the attributes most important to you from the above list and compare them for each product. However, the key factor in the selection process will not be physical/plant/soil based, but invariably will be the trade-off between your initial capital investment and your ongoing labour cost. For example, a tensiometer is relatively inexpensive but must be read daily and maintained weekly. A modern multi-depth logging system is relatively expensive, but data can be sent straight to the office PC and viewed with little labour input. A further intangible consideration is that it needs great discipline to maintain a regime of manual readings and hence many instruments are either lying dry in the field or in the shed!

An economic analysis of soil-moisture-monitoring equipment demonstrated that the lifetime cost of a product should be included in the selection process (see Appendix 5). Using this method, the lifetime cost of a low initial outlay, manually read instrument such as a tensiometer is similar to that of a high-end electronic logging system.

Also included, as Appendix 4, is an example of a proforma for product selection that incorporates both important attributes and economic aspects.

Accuracy of equipment

The most contentious equipment description is "accuracy". Accuracy can be stated in many ways. Examples are:

- the ability to reproduce actual soil water status (from oven-dried samples) in laboratory-controlled conditions with and without specific calibration
- the ability to reproduce actual soil water status (from oven-dried samples) in field conditions with and without specific calibration
- repeatability as demonstrated by how much variation there is in consecutive readings taken over a short time interval
- resolution, i.e. the number of significant figures to which a measurement can be read, e.g. an 8-bit device gives a resolution of 100 units/256 data steps = 0.4% resolution.

The relevant measurement will depend on how the equipment will be used. For instance, a farmer applying water to relative set points may be interested only in a sensor with a high repeatability.

As there is no universal, objective source of measured accuracy available, we have used the manufacturers' "stated accuracy" in this publication.

Product feature summaries

Features of different soil water measuring products are summarised in tables 2 to 6.

Table 2. Comparison of porous media technologies for measuring soil water tension.

	Tensiometer (meter read)	Tensiometer (gauge read)	Tensiometer (UMS)	Gypsum blocks sensor	Granular matrix	WaterSmart™ (Watermatic)	Soil matric potential thermal heat sensor
Reading range	0 to 80 kPa	0 to 100 kPa	0 to 100 kPa	30 to 1500 kPa	10 to 200 kPa	10 to 30 kPa	0 to –1500 kPa
Stated accuracy	~1 kPa	~ 1 kPa	0.5 kPa	~ 1 kPa	~1 kPa	± 2 %	± 3 %
Measurement sphere	Up to 10 cm	Up to 10 cm	Up to 10 cm	Up to 10 cm	Up to 10 cm	Up to 10 cm	Up to 10 cm
Output reading	kPa from meter	kPa from gauge	V valibrated to kPa	kPa from meter	kPa from meter	Reading is used internally to switch irrigation automatically	kPa from logger
Installation method	Permanently inserted into augered hole	Permanently inserted into augered hole	Permanently inserted into augered hole	Permanently inserted into augered hole	Permanently inserted into augered hole	Permanently buried	Permanently inserted into augered hole
Logging capability	If fitted with transducer	If fitted with transducer	Mandatory	Yes	Yes	Not in manufactured form	Yes
Power source	Meter – 9 V DC	Nil	6 – 20 V DC	Meter – 5 V AC	Meter – 5 V AC		5 V DC from logger
Country of origin	Australia	USA	Germany	Aust/UK/USA	Aust/USA	Australia	USA
Remote access	Subject to logger	Subject to logger	Subject to logger	Subject to logger	Subject to logger	Not in manufactured form	Subject to logger
Link to other equipment	Via logger	Via logger	Via logger	Via logger	Via logger	Solenoid	Via logger
Interface to PC	Meter download or via logger	Via logger	Via logger	Meter download or via logger	Meter download or via logger	No	Via logger
Affected by salinity	No	No	No	No effect < 6 dS/m (Soil solution)	No effect < 6 dS/m (Soil solution)	No	No
Expansion potential	Via logger	Via logger	Via logger	Via logger	Via logger	No	Via logger
Technical support need	Minimal	Minimal	High	Minimal	Minimal	Low	High
Irrigation system suited to	All	All	All	All esp. perennial/ Regulated Deficit	All	Fixed systems	All
Best soil type	All	All	All	Heavier	Medium/heavy	All	Medium/heavy

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Continued
Table 2. Comparison of porous media technologies for measuring soil water tension.

	Tensiometer (meter read)	Tensiometer (gauge read)	Tensiometer (UMS)	Gypsum blocks sensor	Granular matrix	WaterSmart (Watermatic)	Soil matric potential thermal heat sensor
Application	Farmer/Research	Farmer/Research	Research	Farmer	Farmer	Farmer	Farmer/Research
Capital cost	$33 – most lengths (1) $20 – (2) $450 – 550 – Std Meter $993 – storage meter with software (SoilSpec) $6 Tensiometer tips (3)	$130 – $220 $200 – $250 Service Kit	From ~ $700	$15 – $30 Reader $550 $750	$ 65 – $90 $650 – $800 - reader	$500	$165
Annual operating cost	~$2 to 3 $35 for 100 Tensiometer stoppers (Vaccutainer 6430) (4) $27 for 50 stoppers (1) Meter batteries	~$5 (new seals)	Nil	Battery for reader	Battery for reader	Low (replace batteries annually)	Nil
Distributor	1) H & TS Electronics, (SoilSpec) 2). Terra Tech 3). Cooinda Ceramics (minimum order $200) 4). McFarlane Medical & Scientific Equipment	MEA, HR Products, ICT International	UMS	MEA, CSA, ICT International	MEA, CSA, HR Products	Holman Industries	CSA
Reference page	18	19	20	21	23	24	25

Table 3. Comparison of frequency domain reflectometry (capacitance) technologies for measuring SWC (1).

	EnviroSCAN®, EnviroSMART™, EasyAg®, TriSCAN®	Diviner2000®	C-Probe™/ C-Probe III™	Gopher®, Micro-Gopher®	Green Light Red Light™ (Odyssey™)
Reading range	0 - saturation	0 - saturation	0 - saturation	0 - saturation	0 - saturation
Stated accuracy	± 0.1 % when calibrated	± 0.5 % when calibrated	± 1 % when calibrated	± 1 % when calibrated	± 1 % when calibrated
Measurement sphere	10 cm radius (95% within 4 cm)	10 cm radius (95% within 4 cm)	10 cm radius (95% within 4 cm)	10 cm radius (95% within 4 cm)	10 cm radius (95% within 4 cm)
Output reading	mm soil water	mm	0-100 units – uncalibrated OR mm / % soil moisture - calibrated	mm	% - where 100% is Full Point
Installation method	PVC access tube	PVC access tube	C-Probe - PVC access tube C-Probe III – sensors embedded in access tube	PVC access tube	PVC access tube
Logging capability	Intrinsic	No	Intrinsic	No	Available
Power source	12 V DC from solar cell or logger		12 V DC internal rechargeable	6 V DC from solar cell 4 x AA	6 V DC
Country of origin	Australia	Australia	Australia	New Zealand	New Zealand
Remote access	Via range of add-on telemetry	No	Via range of add-on telemetry	No	No
Link to other equipment	Via flexible logging systems	No	Via flexible logging systems	No	No
Interface to PC	Mandatory	Yes, but not necessary	Mandatory	Yes	Yes, but not necessary
Affected by salinity	Minimal at low salinity. TriSCAN measures bulk EC	Minimal	Minimal	Minimal	Minimal
Expansion potential	Yes	No	Yes	No	No
Technical support	High. Installation, interpretation and maintenance	Low. Instructions available	High. Installation, interpretation and maintenance	High. Installation, interpretation	Low. Instructions available
Irrigation system suited to	All permanent and annual	All permanent and annual	All. Permanent plantings & row crops	All. Permanent plantings	All permanent and annual
Best soil type	All	All	All	All	All
Application	Farmer/Research	Farmer/Research	Farmer/Research	Farmer	Farmer
Capital cost	From $1200		From $3285	Gopher $1640 MicroGopher $1550	GLRL with hand reader with Odyssey logger $550
Annual operating cost	$200 - $600	Nil	Replace batteries/Silica gel	$200	
Distributor	Sentek	Sentek	Agrilink	DataFlowSystems	DataFlowSystems
Reference page	26 -28	28	29	30	32

Table 4. Comparison of frequency domain reflectometry (capacitance) technologies for measuring SWC (2).

	PR2 Profile Probe	**ThetaProbe**	**WET sensor**	**MP406**	**ECH_2O®**	**EnviroPro® soil probe**
Reading range Stated accuracy	0 - saturation 1% calibrated, 5% uncalibrated.	0 – saturation 1% calibrated, 5% uncalibrated.	0 - saturation ± 3 %	0 – saturation 2% calibrated 5 % uncalibrated	0 – saturation 1% calibrated, 3 % m^3m^{-3}	0-saturation
Measurement sphere	2-3 cm	2-3 cm	2-3 cm	2-3 cm	2 cm	Untested
Output reading	Voltage calibrated to m^3m^{-3}	Voltage calibrated to m^3m^{-3}	m^3m^{-3}	Voltage calibrated to m^3m^{-3}	Voltage calibrated to % soil moisture	Raw counts or cali brated %, dS/m, ^oC
Installation method	Inserted in carbon fibre access tub	Hand inserted or buried at bottom of access tube.	Hand inserted	Hand inserted or buried at bottom of access tube	Hand inserted, buried in auger hole	Inserted into augered hole
Logging capability	Yes	Yes	No	Yes	Yes	Yes
Power source	5-15 V DC	5-15 V DC	5-7 V DC	5-15 V DC	2.5 V DC and 4-20 mA	7-16 VDC
Country of origin	UK	UK	UK	China	USA	Australia
Remote access	Via logger	Via logger	No	Via logger	Via logger	Via logger
Link to other equipment	Via logger	Via logger	No	Via logger	Via logger	Via logger
Interface to PC	Via logger/handheld reader	Via logger	Via handheld reader	Via logger	Via logger	Via logger
Affected by salinity	Minimal	<-0.0001 m^3m^{-3}/ mSm^{-1}	Measured	Minimal	Minimal	Measured
Expansion potential	Via logger	Via logger	No	Via logger	Via logger	Via logger
Technical support required	Minimal if using included calibration	Minimal if using included calibration	Minimal	Minimal if using included calibration	Low. Instructions available	Low
Irrigation system suited to	All	All permanent and annual	All	All	All permanent and annual	All
Best soil type	All	All	All	All	All	All
Application		Research/Turf	Research/Horticulture	Research/turf	Farmer	Farmer/consultant
Capital cost	0.5 m - 4 sensor - $2180 1 m - 6 sensor - $2480	$700 – probe $1160 – handheld reader	$3100 inc handheld reader	< $600 - probe < $600 - handheld reader	< $300 - probe < $500 - echo reader	0.8m - 8 sensor - $32 Logger with radio - $950
Annual operating cost	Nil	Nil	Nil	Nil	Nil	Nil
Distributor	MEA	MEA	MEA	ICT International	ICT International	APCOS, TekSmart
Reference page	36	34	35	34	33	45

Table 5. Comparison of time domain reflectometry (TDR) and time domain transmission (TDT) technologies for measuring SWC.

	TRASE®/ MiniTRASE®	**Campbell Scientific TDR 100**	**Water Content Reflectometer (616)**	**Aquaflex**	**Gro-Point™**
Reading range	5 – 50%	5 – 50%	0 – 50%	0 – 70%	8 - 42% Standard 5 – 50% Extended
Stated accuracy	0.5 - 1% in field	0.5 - 1% in field.	± 2.5%	± 2% accuracy	± 1%
Measurement sphere	~ 3 cm radius around length of probes (<0.8 litre)	~ 3 cm radius around length of probes (<0.8 litre)	~ 3 cm radius around length of probes (<0.8 litre)	~2.5 cm radius over a 3 m length (cylindrical volume of 6 litres)	~ 3 cm radius around length of probes (0.8 – 4 litres)
Output reading	Nanoseconds calibrated to volumetric SWC	Nanoseconds calibrated to volumetric SWC	Frequency calibrated to volumetric SWC	Volumetric Moisture Content in %	Volumetric SWC
Installation method	Buried *in situ* or inserted for manual readings	Buried *in situ* or inserted for manual readings	Buried *in situ* or inserted for manual readings	Buried *in situ*	Buried *in situ* or inserted for manual readings
Logging capability	Logging available	Via logger	Via logger	Logging available	Via logger
Power source	12 V DC internal rechargeable battery	5-8 V DC	12 V DC	Battery/solar/mains power	5.5 – 18 V DC
Country of origin	USA	USA	USA	New Zealand	Canada
Remote access	Via telemetry	Via logger telemetry	Via logger telemetry	Via logger telemetry	Via logger telemetry
Link to other equipment	Via logger	Via logger	Via logger	Via logger, or to other equipment with 4-20 mA or frequency/pulse output version of sensors	Via logger
Interface to PC	Yes	Via logger	Via logger	Via logger or PalmPilot	Via logger
Affected by salinity	Reduces signal return	Reduces signal return	> 2 dS/m needs recalibration	Sensor measurement adjusted for soil conductivity and soil temperature	At high levels
Expansion potential	Via multiplexing	Via multiplexing	Via multiplexing	See above	Yes
Technical Support	High	High	High	Low support required	Low
Irrigation system suited to	All	All	All	All	All
Best soil type	Difficulty in dense, salt or high clay soils	Difficulty in dense, salt or high clay soils	Difficulty in dense, salt or high clay soils	All	Difficulty in dense, salt or high clay soils
Application	Research	Research	Research/Farmer	Farmer/Research	Farmer
Capital cost	TRASE < $20,000 miniTRASE < $15,000	$6400 + multiplexor	$300 $400 – HydroSense Display	Sensors from $890	$730
Annual operating cost	Nil	Nil	Nil	Nil	Nil
Distributor	ICT International	CSA	CSA	Aquaflex Australia	Netafim Australia
Reference page	38	39	39	40	41

Table 6. Features of the Neutron Moisture Meter and FullStop wetting front detector.

	Neutron Moisture Meter (CPN503)	**FullStop™**
Reading range	0 – 60%	Switches at 2kPa soil suction. Resets at 1 kPa Modified to 4, 7 and 10 kPa
Stated accuracy	± 0.5% when calibrated	-
Measurement sphere	~ 15 cm radius	~ 30 cm radius
Output reading	Raw – counts Calibrated – volumetric water content (%)	Mechanical - flag up or flag down
Installation method	Access tube	Buried in hole same diameter as instrument
Logging capability	No. Manual readings may be recorded onboard for later download.	With external logger
Power source	12 V DC – rechargeable or alkaline batteries	Nil
Country of origin	USA	Australia
Remote access	No	Via telemetry
Link to other equipment	No	Via logger
Interface to PC	Yes – to download	Via logger
Affected by salinity	No	No
Expansion potential	No	Via logger
Technical Support	High at start. User and storage requires licence	High at start
Irrigation system suited to	All	Pressure/annual crop
Best soil type	All	All. Not for deep installation
Application	Consultant/researcher	Farmer
Capital cost $	<7,000 2nd hand $ <15,000 new	~$50
Annual operating cost	New batteries	Nil
Distributor	ICT International	CSIRO Land and Water, MEA
Reference page	42	44s

Table 7. Skill levels required for instrument operation.

How skilled you need to be to operate different soil moisture devices is an important element in choosing a product best suited to your situation. The information describing the level of skill required for instrument operation is based on an objective score that reflects the author's opinion. It is split into three levels; minimal skill, considerable skill and specialist skill.

			Skill required			
Products	**Installation design**	**Installation**	**Calibration**	**Maintenance**	**Data retrieval**	**Data interpretation**
Aquaflex	*	*	*PC/**new	*	*	*
C-Probe/ C-Probe III	**	**	**	**	**	* / **
Campbell 229	*	*	***	Not required	***	*
Campbell 615	*	*	***	Not required	*/***†	*
Campbell TDR 100						
Diviner 2000®	*	*	*	*	*	*
EnviroSCAN/TriSCAN/ EnviroSMART	**	**	**	**	**	* / **
EasyAg	*	*	**	*	*	*
EnviroPro	**	*	**	Not required	*	*
FullStop	**	*	Not required	Not required	*	*
GLRL/Odyssey	*	*	*	*	*	*
Gopher/ MicroGopher	**	**	**	*	*	*
Granular matrix sensors	*	*	Not required	Not required	*	*
Gro-Point	*	*	Not able	Not required	*	*
Gypsum blocks	*	*	Not required	Not required	*	*
Neutron moisture meter (CPN503)	**	*	**	**	**	**
PR2 Profile Probe	*	*				
Tensiometers	*	*	Not required	*	*	*
ThetaProbe/MP406	*/**†	*/**†	***	*	*/***†	*
TRASE/MiniTRASE TDR	*/**†	*/***†	***	*	*/***†	*/***†
WET Sensor	*	*/***†	***	*	*/***†	*

*   Minimal skill – with a small amount of training a person is well able to accomplish the task.
** Considerable – a large investment is required to become proficient, implying that it may be more efficient to hire a consultant.
*** Specialist – either specialised equipment or a high degree of theoretical knowledge is required.
†   When logged.

CHAPTER 5

PRODUCT EXPLANATION

Porous media

Tensiometers measured by handheld transducer

Products: SoilSpec, Terra Tech

Methodology. Meter-read tensiometers can be made or bought. These tensiometers must be read with a portable electronic vacuum gauge. A needle connected to the gauge is inserted into the rubber septum and the reading is displayed on the meter (see Figure 2). Transducers can be added into the tensiometer through a T-piece so it can be connected to a logger. Directions for the construction of tensiometers are included in Goodwin (1995).

The tensiometer must be airtight. To test this fill the tensiometer with water, place it in the sun and read it every half a day. A reading from 70 to 80 kPa should be reached before air enters the tensiometer causing the reading to revert to zero.

To install the tensiometer, a hole is augered to the desired depth. It is then inserted and the tip is surrounded by finely ground, tamped soil to ensure excellent contact. The rest of the hole is then filled with a mixture of bentonite and soil to ensure water doesn't flow down between the tensiometer and the soil.

Tensiometers can read to 80 kPa but become less accurate past 50 kPa as the suction causes the water to de-air.

Calibration. As tensiometers measure soil-water suction, calibration to soil type is not required. The transducer in the handheld meter is pre-calibrated to kPa. No further calibration is required.

Data handling. Meters are available with and without internal memory. Manual readings can be either recorded using graph paper or entered into a computer spreadsheet. The computer gauge (SoilSpec) comes with custom software to allow downloading, viewing and storage of readings.

Maintenance. In a dry soil, water will be drawn out of the tensiometer more quickly than in a wetter soil. If the level drops more than 2 cm from the top, readings become inaccurate. The water level in the viewing tube should be checked at least weekly and refilled if necessary. If located in a frost prone area, methylated spirits (50 mL/L water) can be added to the tube to stop freezing. The rubber septum, which perishes and degrades after being pierced many times by the meter needle, should be covered and replaced regularly.

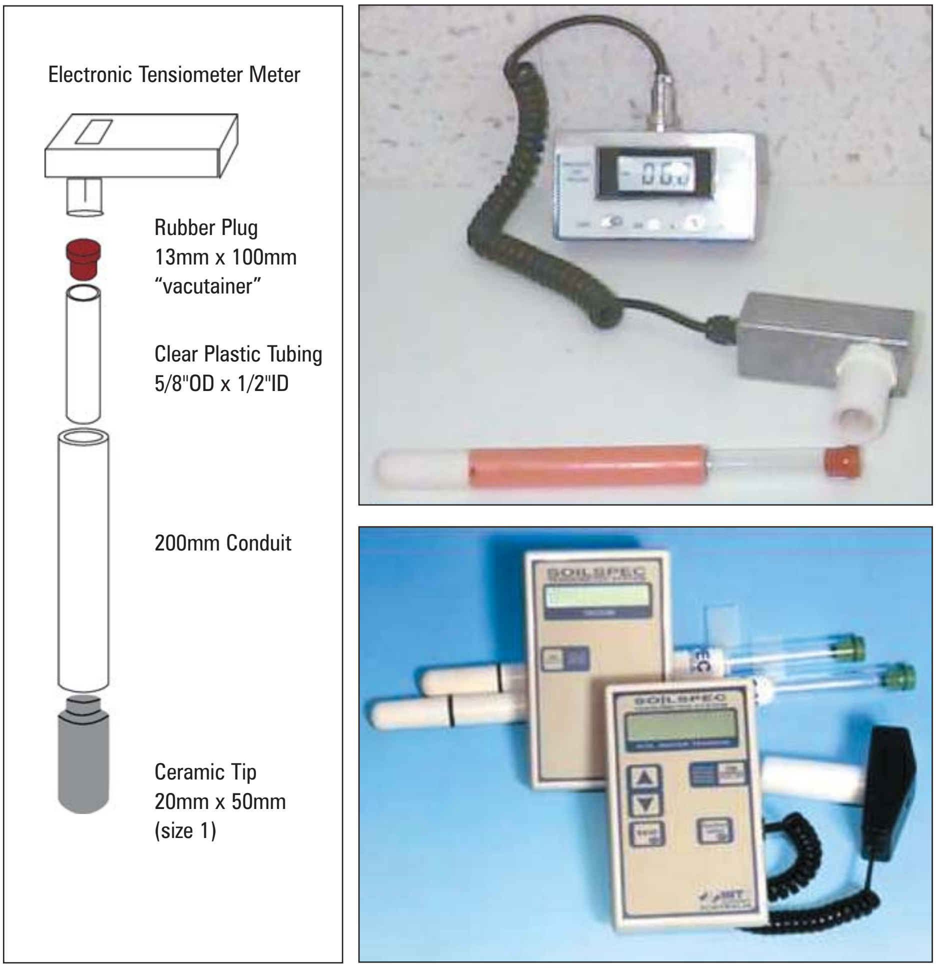
Potential limitations

- Must have meter to take measurement as opposed to a gauge-type tensiometer.
- Manual data collection.
- High maintenance requirement to maintain data quality.
- Difficult to convert to soil water content. Makes calculating irrigation amount needed harder.
- Measurement range limited to from 0 to 80 kPa. Becomes inaccurate after 50 kPa.
- Removing the bung during refilling can lead to the tensiometer moving and problems caused by loss of soil contact.

Positive attributes

- Measures soil water tension, which is more relevant to plant stress.
- Simple, cheap method. Easy to understand.
- No cabling required (except where tensiometers are logged).
- One meter can be used to take readings at many locations and depths.
- Better resolution in wetter soils than, for instance, gypsum blocks.
- Data is useful without further calculations.
- Not affected by salinity.

Figure 2. “Homemade” tensiometer (l) (Goodwin, 1995). Commercial tensiometer/transducer products from Terra Tech (top right), SoilSpec (bottom right).



Gauge type tensiometers

Products: JetFill, Irrometer

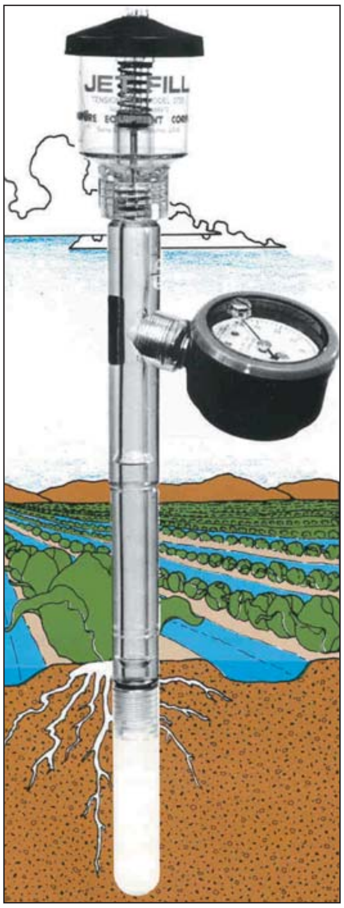
Methodology. These tensiometers are installed and operated the same as a meter-read tensiometer but are read using a permanently attached pressure gauge (see Figure 3). The gauge can be replaced with a pressure transducer to enable logging.

Calibration. The gauges are preset to sea level atmospheric pressure. If used at higher altitudes a screw re-zeroes the gauge. No further calibration is required.

Data handling. The gauge is manually read and the reading can be transferred to graph paper or a computer spreadsheet for storage. Data can be collected with a logger if a transducer is fitted.

Maintenance. Maintenance is similar to that for meter-read tensiometers. A vacuum pump is used to remove trapped air from gauge type tensiometers. The Jetfill tensiometer has a small reservoir which enables rapid refilling.

Figure 3. Gauge type tensiometer.



Potential limitations

- Manual data collection.
- More expensive than meter-read tensiometers.
- High maintenance requirement to maintain data quality.
- Difficult to convert to SWC. Makes calculating amount of irrigation required harder.
- Measurement range limited to 0 to 100 kPa.

Positive attributes

- External meter not required. Can view reading any time tensiometer is passed.
- Easier to maintain than meter-read tensiometers.
- Measures soil water tension, which is more relevant to plant stress.
- No cabling required (except where tensiometers are logged).
- Better resolution in wetter soils than, for instance, gypsum blocks.
- Data is useful without further calculations.
- Not affected by salinity.

UMS tensiometer

Methodology. The UMS is a specialised tensiometer designed to be buried permanently. It incorporates systems that avoid the maintenance limitations of tensiometers. A pressure transducer indicates when the tensiometer needs refilling and an IR sensor monitors when bubbles are present. External tubes are then used for refilling. Different length shafts are available and exchangeable by unscrewing components. The UMS tensiometer also reads soil temperature.

Calibration. Calibration data is stored in each instrument. A handheld reader is available to perform recalibration and update settings.

Data handling. The UMS tensiometer is designed to be read with a data logger. Data is output as 0-2 V, and can be read by a range of loggers. Refilling and bubble presence indicators and soil temperature are also loggable. The refilling indicator can have an LED attached.

Maintenance. The UMS tensiometer is designed to be maintenance free in most situations. Water level and bubble detection indicators are provided to avoid de-airing of the ceramic tip. Equipment is available to de-air and recalibrate if required.

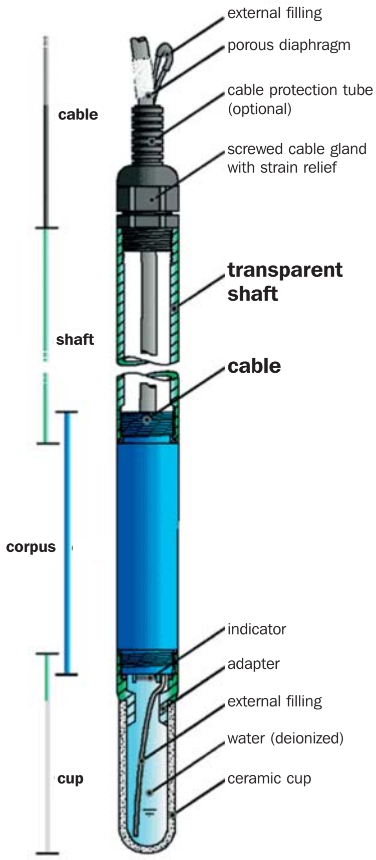
Potential limitations

- High cost.
- Difficult to convert to SWC. Makes calculating amount of irrigation required harder.
- Measurement range limited to 0 to 100 kPa.
- Higher level of expertise needed to link with and program logger.

Positive attributes

- Designed for extended, unattended performance with indicators to warn when attention is required.
- Better resolution in wetter soils than, for instance, gypsum blocks.
- Data is useful without further calculations.
- Not affected by salinity.

Figure 4. UMS tensiometer (T8).



Gypsum blocks

Products: GBHeavy, Gypsum Block

Methodology. Gypsum blocks consist of a pair of electrodes embedded in a block of plaster of Paris. Gypsum blocks are measured by a portable meter or, remotely, by a datalogger. There are several different brands of gypsum blocks using different dimensions. These will all have different calibration characteristics and **must use** the reader designed for them. People with knowledge of electronics can make their own portable meter. To stop polarisation of the block an alternating current circuit must be used to measure the resistance between the two electrodes. One method is to apply an oscillating voltage and measure, in series with a multimeter, the alternating current through the gypsum block. Calibration curves to convert the current to soil water tension are available for the various commercial gypsum blocks. There are also several commercial meters available.

Before installing gypsum blocks, soak them in water to remove air pockets. The blocks are buried at the required depth, the same as for tensiometers. Put finely ground soil around the block to ensure good contact then the hole is backfilled with a soil-bentonite mix to stop preferential flow. The wires should be marked well and tied to a stake or vine trellis.

Gypsum blocks buffer against the effect of salinity and determinations of soil water tension are not affected up to 3 dS/m (soil water solution), a figure higher than the salt-stress level for most crops.

Calibration. As the gypsum block measures soil water tension, calibration to soil type is not required. The block resistance-soil water tension relationship is very sensitive to block size, gypsum composition and electrode separation distance. It is thus recommended that you buy commercially available blocks to ensure uniformity.

Data handling. Data is recorded by a handheld meter and manually recorded or stored on a computer. Soil water tension data requires no further calculations and can be compared with target figures for the specific crop and growth stage.

Maintenance. Gypsum blocks are maintenance-free although they will dissolve over time changing their calibration properties. Depending on soil type, rainfall/irrigation amount and type of gypsum block, they should last for up to 8 years.

Potential limitations

- Gypsum blocks are insensitive to tension changes in wet soil (<30 kPa).
- Manually read. A logging system is produced by an Australian company.
- Measures soil water tension which is good indication of **when** to irrigate not **how much**.
- Blocks dissolve over time.
- Do not work well in sandy soils where the moisture drains more quickly than the time needed for the sensor to equilibrate.

Positive attributes

- Simple, cheap method.
- Capable of reading to quite low (dry) tensions (~1000 kPa). Therefore good for drier soils and regulated deficit irrigation.
- Measures soil water tension, which is more meaningful from a plant stress aspect.
- Not affected by salinity <3 dS/m (soil water solution).

Figure 5. Gypsum blocks and reader/loggers.

Granular matrix sensor

Products: GBLite, Watermark

Methodology. Granular matrix sensors use the same principle as the gypsum block. Electrodes are embedded in a patented granular quartz material. This is protected by a synthetic membrane and then a stainless steel mesh (see Figure 6). The material selected enables the sensor to measure wetter soil than a gypsum block (up to 10 kPa). The sensor includes internally installed gypsum which provides buffering against salinity effects.

It is installed in an augered hole and should be surrounded by fine soil and backfilled with soil-bentonite mix to stop preferential flow.

Calibration. As with gypsum blocks, granular matrix sensors are precalibrated to soil water tension (kPa).

Data handling. Data is recorded by a handheld meter and manually recorded or stored on a computer. Soil water tension data requires no further calculation and can be compared with target figures for the specific crop and growth stage.

Maintenance. Granular matrix sensors are maintenance free.

Potential limitations

- Manually read. A logging system is produced by an Australian company.
- Measures soil water tension, which is good indication of **when** to irrigate not **how much**.
- Do not work well in sandy soils, where the moisture drains more quickly than the sensor can equilibrate.
- If it dries out too much the sensor must be removed and wet again.

Positive attributes

- Simple, low cost method.
- Capable of reading to wide range of soil water tensions (10 to 200 kPa) so it is good for range of soils and irrigation management strategies.
- Measures soil water tension, which is more relevant to plant stress.
- Buffers against salinity effects.

Figure 6. Granular matrix sensor.

Dimensions: ~ 70 mm long and 20 mm diameter.

Watermatic sensor (WaterSmart)

Methodology. In the 1970s, Ken Cuming developed the Watermatic sensor. While well researched, the WaterSmart has only recently been commercially available following a licensing agreement with Holman Industries. The Watermatic sensor has a porous ceramic housing which maintains an hydraulic equilibrium with moisture in the surrounding soil. Moisture content in the pores is monitored by the electrical conductivity (EC), which is fully compensated for changes in the temperature and EC of the rootzone solution.

The product is designed as a self-contained feedback system linking the sensor to the irrigation solenoids. The sensor/controller system is marketed as the WaterSmart. Probe sensitivity can be changed on the control panel.

See case study (page 45) for more information about its performance.

Calibration. Calibration is performed during manufacture, is permanent, does not drift and is not user configurable.

Data handling. Soil water suction and temperature are measured continuously.

Maintenance. Only the above-ground controller needs to be maintained.

Potential limitations

- Not suitable for soil suctions > 30 kPa.
- Ideal to fixed rootzone crops e.g. turf.
- Best suited to fixed irrigation systems e.g. sprinkler.
- Cabling required to controller, monitor or field module.

Positive attributes

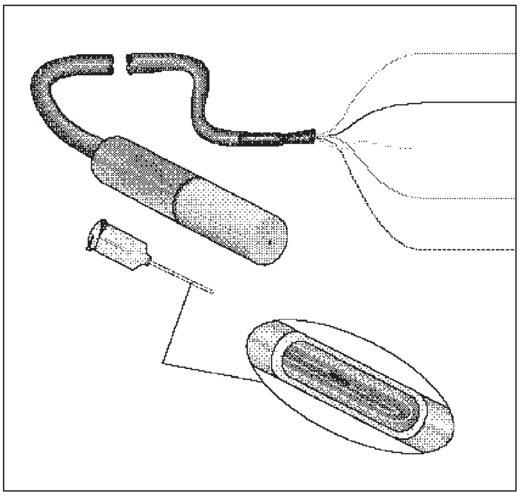
- Measurement relates directly to plant water status.
- Automatically switches irrigation based on sensor set point (nominally 15 kPa, varied from 10 to 30 kPa).
- EC and temperature compensated.
- Permanent calibration.
- Sensor design life 20 years with a five-year warranty.

Figure 7. Watersmart sensor and controller.

Soil matric potential thermal heat sensor (Campbell Scientific CS229)

Methodology. The CS229 is an example of a volumetric SWC measuring device embedded in a cylinder of porous ceramic material resulting in a composite instrument measuring soil water tension.

Figure 8. Campbell Scientific's CS229 sensor.



The device uses the heat pulse concept, explained in Chapter 4, to determine the water content of the ceramic, which in turn is in equilibrium with the water tension of the surrounding soil. A heating element is placed inside a hypodermic needle and the ceramic surrounds the needle. When a constant power is applied to the heater the temperature increase near the needle is related to the thermal conductivity of the material, which in turn depends on the amount of water present. Practically, the device temperature is measured before and after the heater is powered for 24 seconds. The change in temperature is the only measurement required.

The sensor is capable of reading from saturation to air dry soil, however, this is limited by the extent of the calibration (typically –1500 kPa).

The sensor is installed in an augered hole and should be surrounded by fine soil and backfilled with a soil-bentonite mix to stop preferential flow.

Calibration. The CS229 is provided with a calibration relating measured change in temperature to soil water tension (kPa). This calibration is enough for tasks where measurement changes are more important than absolute values but individual calibration is recommended where greater accuracy is required.

Data handling. The CS229 must be controlled by a sophisticated data logger capable of applying a timed voltage and measuring thermocouple temperatures. These loggers can also be programmed with the calibration equation to directly output soil water tension. This data can then be downloaded to a computer spreadsheet.

Maintenance. No maintenance is required.

Potential limitations

- Requires sophisticated data logger and knowledge of logger programming.
- Measures soil water tension which is good indication of **when** to irrigate, not **how much**.
- Does not work well in sandy soils where the moisture drains more quickly than the sensor can equilibrate.
- Cabling is required from logger to each sensor.

Positive attributes

- Measures wide range of tensions (only limited by calibration range).
- Data logger operation enables automatic data collection.
- Not affected by salinity.

Frequency domain reflectometry (capacitance)

Sentek EnviroSCAN, EnviroSMART, TriSCAN

Methodology. The EnviroSCAN system (see Figure 9) consists of an array of capacitance sensors installed at different depths within a PVC access tube. The sensors are connected by cable to a central data logger which powers the probes with a solar panel. A range of telemetry options can offset the cable length. All sensors in the same access tube share one electronic measuring circuit located at the top of each probe. Reading intervals as close as 1 minute are set by the user. The standard probe lengths are 0.5, 1.0, and 1.5 m, and maximum number of probes per data logger is eight.

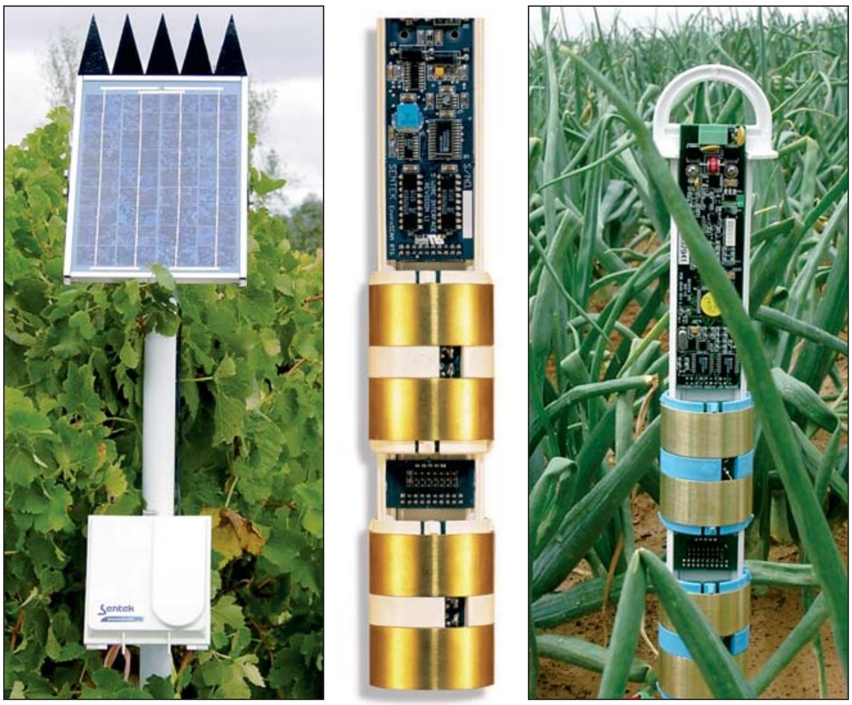
EnviroSMART incorporates a range of generic data transfer formats (SDI-12, voltage, current, RS232 and RS485) that enables the sensor to be connected directly to a variety of logging systems. Such compatibility allows easy integration of soil moisture with other data such as weather information.

TriSCAN is Sentek's newest product and uses twin frequencies to measure the soil bulk electrical conductivity from which soil salinity and nutrient status can be interpreted.

Installation is critical to the performance of devices using the capacitance technique. The manufacturers of EnviroSCAN have developed equipment and techniques which they claim eliminate this problem. Once equipment is installed no further disturbance is necessary.

Calibration. A default calibration equation is provided with the unit which is enough for most irrigation scheduling applications where only changes in stored soil water are required. However, if absolute volumetric data is required Sentek recommends a specific site calibration be performed. A comprehensive procedure is provided which basically involves sampling the soil around tubes to determine volumetric water content in wet, moist and dry soil. Site-specific calibration coefficients can then be entered into the software for more accurate results. A similar procedure involving ground-truthing soil electrical conductivity is essential when using TriSCAN to ensure the correct solute concentration is calculated.

Figure 9. Sentek EnviroSCAN, EnviroSMART and TriSCAN probes.



Data handling. For EnviroSCAN, all data is collected at the central data logger. Each EnviroSCAN data logger can reference up to thirty two sensors in a 500 m radius. To view the data it must be downloaded to a computer using proprietary software. Either a laptop is taken to the logger, the removable logger is taken to the computer, or telemetry is used to transfer the data straight to the computer. The software provides several presentation options, including time series, total profile water content and separate sensor readouts. Irrigation target set points can be entered for field capacity and lower limit water contents.

For EnviroSMART, all data is collected by and subject to the limitations of the logger being used.

Maintenance. The equipment consists of sensitive circuitry and therefore the most important maintenance is protection against moisture getting into the access tubes. The sealing caps have gaskets and silica gel bags are placed inside the tubes. These must be changed regularly.

An annual maintenance check by the local distributor is recommended. This may include battery charging, gasket changing, and backing-up of data.

Potential limitations

- Training and support required. Skill required to interpret results.
- Computer and software required.
- Not portable. Sensors fixed into access tubes.
- If used with annual crops, cabling and tubes may need to be removed after the crop is harvested.
- Measurement very sensitive to access tube installation.

Positive attributes

- Robust, repeatable measurements.
- Precise depth resolution because of disc-like zone of influence.
- Automatic operation reduces labour requirement.
- Continuous recording.
- Infiltration rate, root activity, and crop water use may be inferred.
- Can monitor multiple depths at once.
- Well suited to permanent plantings.
- Can display trends in soil water and salinity as well as irrigation and rainfall events on the one computer screen.

Sentek EasyAg

Methodology. The EasyAg is a mini-EnviroSCAN. The sensor is designed for simple installation in shallow-rooted, annual crops and has a diameter of 26 mm compared with 51 mm for EnviroSCAN. EasyAg uses the same methodology, calibration and data handling as the EnviroSCAN. Two lengths are available: 50 cm (sensors at 10, 20, 30, 50 cm) and 80 cm (10, 30, 50, 80 cm).

Calibration. Calibration issues are identical to those facing EnviroSCAN (see previous page).

Data handling. EasyAg has the same flexible data transfer formats as EnviroSMART (SDI-12, voltage, current, RS232 and RS485), enabling it to link to Sentek or other manufacturers' loggers.

Figure 10. Sentek EasyAg (r) and installation method (l).

Maintenance. The equipment consists of sensitive circuitry and therefore the most important maintenance is protecting against moisture getting into the access tubes. The sealing caps have gaskets, and silica gel bags are placed inside the tubes and must be changed regularly.

An annual maintenance check by the local distributor is recommended. This may include battery charging, gasket changing, and backing-up of data.

Potential limitations

- Training and support required. Skill required to interpret results.
- Computer and software required.
- Not portable. Sensors fixed into access tubes.
- If used with annual crops, cabling and tubes may need to be removed after the crop is harvested.
- Measurement very sensitive to access tube installation.

Positive attributes

- Robust repeatable measurements.
- Precise depth resolution because of disc-like zone of influence.
- Automatic operation reduces labour requirement.
- Continuous recording.
- Infiltration rate, drainage, root activity, and crop water use are easily interpreted.
- Can monitor multiple depths at once.
- Small diameter and low installation disturbance means product is well suited to shallow rooted, annual plantings.

Sentek Diviner 2000

Figure 11. Sentek Diviner 2000 sensor and display unit.

Methodology. The Diviner uses the same soil water content sensing technology as the EnviroSCAN. However, the Diviner is a portable system designed to be moved from site to site in much the same way as a neutron probe moisture meter. The probe consists of one capacitance sensor at the end of a rod. As the rod is passed down the access tube the handheld display unit automatically records the SWC at each 10 cm depth increment. Probes are available in 1.0 m and 1.6 m lengths. It takes about two seconds to measure a 1.6 m tube.

A user manual describes all operating features, including installation procedures.

Calibration. Diviner uses a similar universal calibration to the EnviroSCAN. Customised calibration can also be entered for each depth increment for each site after performing the same soil sampling operation as for the EnviroSCAN. Claimed accuracy is ± 0.5%.

Data handling. A time series record of up to 99 sites can be stored in the handheld logger. The data can be presented either graphically or numerically. Irrigation set points can be input to indicate the allowable range of soil moisture to avoid crop stress.

Although not required, a computer can be used to download, store and view data in standard spreadsheets.

Maintenance. None is required. The handheld logger is powered by a rechargeable battery.

Potential limitations

- Portable manual recorder. Logging not possible.
- Some skill required to interpret results.
- Measurement very sensitive to access tube installation.
- The effect of salinity is unclear.

Positive attributes

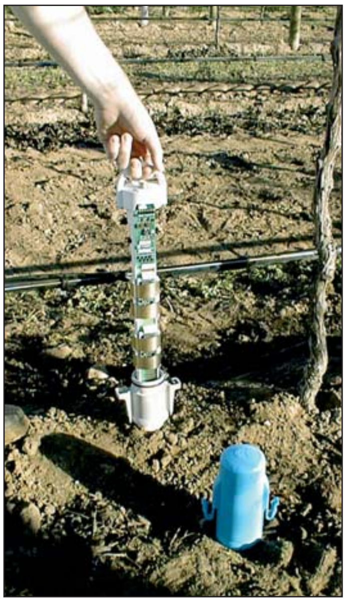
- Not radioactive (unlike neutron probe).
- Economical method for covering many sites.
- Rapid, easy measurement.
- Avoids expensive, sensitive instruments being left in field.

C-Probe and C-Probe III

Methodology. C-Probe was based on a very similar system to EnviroSCAN and consists of an array of capacitance sensors installed at different depths within a PVC access tube.

The new C-Probe III has incorporated the capacitance sensors into the wall of the installation tube. This is a major departure from the separate installation tube-sensor system and was designed to eliminate the air gap between the sensor and internal installation tube wall. It has also enabled a 1.0 m/ten-sensor C-Probe to be sold at a lower cost than an equivalent five-sensor C-Probe of the current model.

Figure 12. C-Probe (l) and C-Probe III (r).



The C-Probe incorporates a range of generic data transfer formats (SDI-12, RS232 and RS485) that enables the sensor to be connected directly to a variety of logging systems. Such compatibility allows easy integration of soil moisture with other data such as weather information.

The C-Probe is available in 0.5, 1.0, 1.5 m and longer lengths. C-Probe III consists of sensors every 10 cm.

Installation issues and procedures are similar to the EnviroSCAN. The only cabling required is from the sensor to the logging unit. Both the measurement and telemetry systems are powered by a small solar cell.

Calibration. C-Probe can use either a universal calibration equation or users can select calibrations for sand, loam, clay and other soil types or provide their own calibration. While a universal calibration equation is enough in many irrigation scheduling applications, the flexibility to finetune the calibration for each sensor depth can be valuable in situations such as duplex soils. If absolute volumetric data is required, specific calibration is recommended. Information is available for users who need a higher degree of calibration accuracy.

Data handling. Telemetry is fitted as standard with C-Probe installations and data is automatically collected and downloaded on a continual basis. Various telemetry options are available, including radio, GPRS and CDMA 1x. Data is accessed online through the AgWISE™ website and several presentation options are available, including time series graphs and statistics showing total profile water content and separate sensor readouts. Irrigation target set points may be entered for full and refill points along with a comprehensive set of agronomic markers and crop stage markers. There is also a summary page showing alarms and status to illustrate available soil moisture status from all monitoring sites at a glance.

Maintenance. The equipment consists of sensitive circuitry so the most important maintenance is protecting against moisture getting into the access tubes. The sealing caps have O-rings and silica gel bags are placed inside the tubes. The silica gel bags should be checked at least twice a year.

A maintenance check by the local distributor twice a year is recommended. This will include checking the O-ring, swapping the silica gel bag, checking battery and solar panel performance and checking all connections.

Potential limitations

- Training and support required. Basic skill required to interpret results.
- Computer and software required.
- If used with annual crops above-ground equipment may need to be removed after the crop is harvested.
- Measurement is very sensitive to access tube installation.

Positive attributes

- Robust repeatable measurements.
- Only cabling required is from sensor to telemetry-logging unit.
- Precise depth resolution because of disc-like zone of influence.
- Automatic operation reduces labour requirement.
- Continual recording.
- Infiltration rate, root activity and crop water use are easily interpreted.
- Monitors multiple depths at once.
- Well suited to permanent plantings.

Gopher and MicroGopher

By Robert Hoogers, NSW Department of Primary Industry and Fisheries, Yanco

Methodology. The Gopher is a portable system designed to be moved from site to site in much the same way as a neutron moisture meter. The probe consists of one capacitance sensor at the end of a rod. As the rod is passed down the access tube, a handheld display unit records the SWC at each 10 cm depth increment. The MicroGopher is a smaller-diameter version (15 mm compared with 50 mm for the Gopher).

The LCD display performs all functions of displaying and storing information, and carrying out calibration. Although not necessary, the display can be linked to a computer for data storage and viewing.

Figure 13. Gopher is a manually operated soil moisture monitor.

Calibration. The equipment is calibrated by taking readings when the soil is at "field capacity". The display module then calculates coefficients for each depth increment and uses these in all future readings. As with most equipment, if greater accuracy is required a volumetric soil sampling program needs to be performed at two SWC levels. Coefficients calculated from this procedure can then be entered into the display.

Data handling. The display can store data for up to 48 profiles (times) from fifty four sites with 16 depths for each site. Data can be displayed as either a volumetric SWC value or as a histograph. The histographs are used to estimate the time interval before the next irrigation cycle and also to display the usage pattern from different depths in the soil by the plants being irrigated. There are also summed graphs indicating total available water in the indicated profile depth.

Maintenance. The Gopher soil moisture profiler and the soil moisture sensor are not waterproof and should never be handled with wet hands or left exposed to the weather or irrigation sprinklers. For this reason maintenance will revolve around ensuring access tubes are moisture free.

The equipment is fragile and should be handled with care. The sensor staff cable should never be used to pull the staff. The 9-way connector must always be unplugged by holding the body of the plug.

The Gopher or the sensor should never be left unprotected in full sunlight. This will cause excessive temperature rise and may damage the LCD display in the Gopher. Temperature increases in the sensor can produce unstable readings because of expansion of the PVC housing.

Potential limitations

- Portable manual recorder. Logging not possible.
- Some skill required to interpret results.
- Measurement is very sensitive to access tube installation.
- The effect of salinity is unclear.
- The equipment is not waterproof.
- Cable connections need special care to stop them breaking.

Positive attributes

- Not radioactive (unlike neutron probe).
- Inexpensive.
- Economical method for covering many sites.
- Rapid, easy measurement.
- Avoids expensive, sensitive instruments being left in the field.

GLRL - Odyssey

Methodology. The GLRL (Green Light Red Light) consists of a string of capacitance sensors inserted in an access tube. The sensor can be used either in portable mode, using a handheld reader, or permanently installed for automatic time series logging through use of the Odyssey logger (see Figure 14). The standard sensor depths are 10, 20, 30 and 50 cm while a non-standard version is available with sensors at 20, 40, 60 and 80 cm spacing.

The standard configuration includes four sensors.

Calibration. Each sensor is automatically calibrated when the soil is at full point by simply pushing the calibrate button on the handheld display. The bottom end of the readily available water is about 55% when the display will indicate irrigation is about to start.

Data handling. The handheld display stores up to 81 soil moisture profiles for ninety nine sites. A PC is not required but can be used to download, store and graph data from the handheld display. The Odyssey logger can store up to 4000 measurements or more than one month when reading hourly.

Maintenance. Instrument connectors need to be handled carefully.

Potential limitations

- Not suitable for measuring profiles deeper than 80 cm.
- If used with annual crops sensors may need to be removed after the crop is harvested.
- Measurement is very sensitive to access tube installation.
- The effect of salinity is unclear.

Positive attributes

- Low cost
- Precise depth resolution because of disc-like zone of influence.
- Automatic operation reduces labour requirement.
- Continual recording.
- Can monitor multiple depths at once.
- Well suited to permanent, shallow-rooted plantings.

Figure 14. GLRL portable or *in situ* soil moisture sensor and logger/handheld reader.

ECH$_2$O Probe

Methodology. The ECH$_2$O is basically a fibreglass printed circuit board inserted into the soil. Copper traces embedded in the fibreglass generate an electromagnetic field which varies with the surrounding soil dielectric. The ECH$_2$O probe measures the rate of change of voltage which has been calibrated against volumetric water content.

The probe is 20 cm long. It can be installed using a pilot hole made with, for example, a steel ruler, or at depth using an auger hole and backfilling.

Calibration. The ECH$_2$O comes pre-calibrated for most soil types. If, however, your soil type has high sand or salt content, the standard calibration will not be accurate. In such cases soil-specific calibration will be required and instructions on how to do this are included in the users guide.

Data handling. Data from the ECH$_2$O is put out as either voltage or current. The probe can be read by most logging systems and the calibration equation to convert to volumetric SWC can be applied in a spreadsheet. A handheld reader, which includes the calibration equation and outputs directly in SWC, is also available.

Maintenance. The product is maintenance free and can be expected to last from 3 to 5 years.

Potential limitations

- May lose some sensitivity at high water contents.
- Good soil contact critical.

Positive attributes

- Low cost.
- Low power requirement.
- Best suited to near surface measurements.
- Low amount of disturbance if installing near surface.

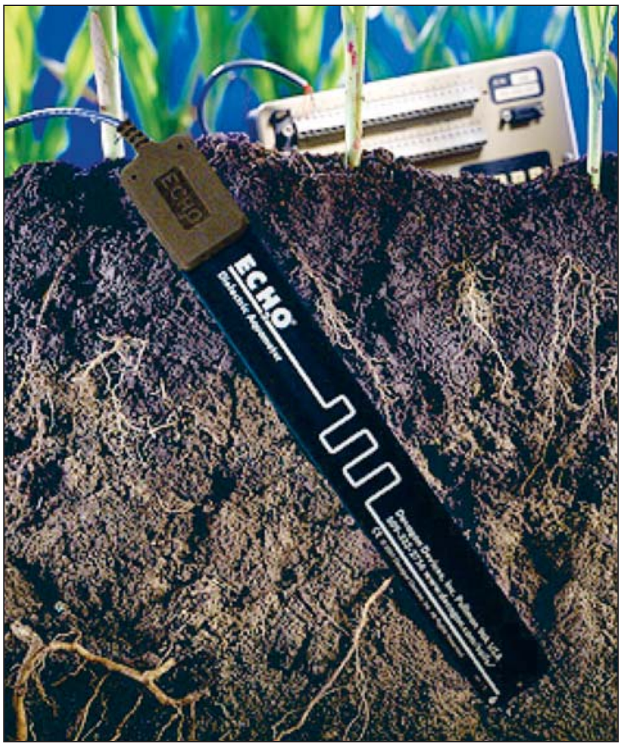


Figure 15. ECH$_2$O Probe.

ThetaProbe and MP406

Methodology. The ThetaProbe and MP406 sensors avoid the limitations of an access tube by using steel pins which can be driven into the soil. The pins act as a transmission line and detect changes in the soil's dielectric constant by monitoring changes in the way radio frequency energy is transmitted into and reflected by the soil. Whereas the permanently installed multi-sensor products have one circuit which analyses each sensor serially, each ThetaProbe/MP406 has its own measurement electronics within the probe head. The instrument can be either inserted into the soil surface to make one-off readings or buried for continual *in situ* readings. The sensors can be buried at the required depth in permanent installations. If the probes need to be easily removed, they can be installed using an extension tube. These tubes can be left in the ground and the ThetaProbe/MP406 inserted or removed when required.

Calibration. The probe outputs a measurement in volts. A calibration is then applied to the raw voltage to give volumetric water content. The literature states there is virtually a linear relationship between the voltage (0 to1 V) and SWC (0 to 0.5 m^3/m^3). Two "generalised" calibrations for "mineral" and "organic" soils are provided which guarantee accuracy of 5% (0.05 m^3/m^3). A two-point calibration is recommended to achieve an accuracy of 1% (0.01 m^3/m^3).

Data handling. Handheld displays are available with each sensor which applies the operating voltage (5 to 15 V DC) and outputs either raw voltage readings or volumetric water content using the two "generalised" calibrations. If a two-point calibration is performed the reader supplied with the Theta probe allows the constants for up to 6 "custom" soil types to be stored. Alternatively, a voltmeter and DC power supply or standard logger can be used and calibration applied in a spreadsheet. For continual monitoring systems, the calibration can be programmed into the data logger. If the raw milli-volt readings from the probes are stored, calibrations can be applied to the data after collection.

Maintenance. The manufacturers state no maintenance is required.

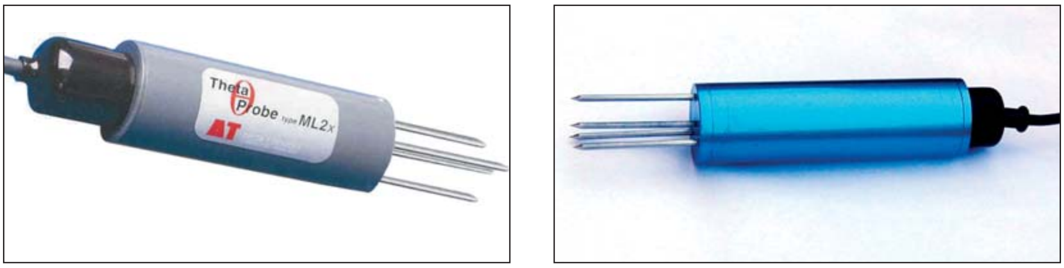
Potential limitations

- Replication of circuitry leads to greater expense when using instrument arrays.
- Hard to push probe into dry soil although an insertion kit is available.

Positive attributes

- Minimal salinity effect.
- Inserting probes into soil greatly enhances contact.
- Signal processing is completed at the instrument leaving a simple voltage output.
- Instrument arrays can be spatially distributed e.g. throughout a rootzone.

Figure 16. ThetaProbe (l) and MP406 (r).



Dimensions of each sensor : length = 200mm, diameter = 40mm.

SOIL WATER MONITORING

WET Sensor

Methodology. The WET sensor measures **w**ater content, **e**lectrical conductivity, and **t**emperature. The sensor uses three pins to maintain an electromagnetic field at a frequency of 20 MHz. Like other capacitance sensors, the WET sensor measures changes in the EM field which are related to the dielectric constant. The raw measurements taken are soil permittivity, conductivity and temperature and these are converted to SWC and bulk EC using calibration equations. The sensor pins are 7 cm long and, with a measurement radius of 2 cm, this gives a measurement volume of about 220 cm^3.

The WET sensor is designed for use in agriculture, horticulture and environmental monitoring.

Calibration. The sensor is supplied pre-calibrated with a standard function which fits most mineral soils. Calibrations for other substrates, especially horticultural media (mineral wools, coir, glass wool, potting mixes), are also available. Where different situations are encountered the user's guide includes instructions on performing specific calibration.

Data handling. The off-the-shelf product is designed for use with a handheld reader. Calibration information is stored in the reader. The reader is only able to store information for a single WET sensor and a PC is required to download the calibration equations for other sensors. If measuring a series of sensors, one reader per sensor is recommended. There are detailed instructions for connecting the sensor to other logging systems.

Maintenance. The sensor is designed to be maintenance free.

Potential limitations

- Only one sensor can be practically handled per handheld reader.
- High cost.
- Automatic logging of the sensor needs a high level of electronic knowledge.

Positive attributes

- Measures three important soil parameters in one reading.
- Small sensor size allows use in small areas such as plant pots.
- Maintenance free.

Figure 17. WET sensor with handheld reader.

PR2 Profile Probe

Methodology. The PR2 Profile Probe measures soil moisture down a profile using a rod consisting of a series of capacitance sensors. Rather than the variable frequency approach of most access tube-based sensors, the PR2 uses the same fixed frequency technique used by the ThetaProbe. The PR2 is inserted into a thin-walled, carbon-fibre tube with a small diameter (28 mm). The sensor can be used with the same handheld reader used by the ThetaProbe and WET sensors or, with an SDI-12 interface fitted, can be linked to a range of loggers.

The standard lengths are 50 cm with four sensors and 100 cm with six sensors.

Calibration. The PR2 outputs data in millivolts and this is converted to VWC (%) using the two variable, polynomial calibration equations from the ThetaProbe. Several default calibrations are available for common soil types. There is also a simple procedure for performing custom calibrations. The calibration variables are stored in the handheld reader and different variables can be selected for each profile depth. Similarly, when using the SDI-12 interface, the variables are stored onboard.

Data handling. Data is recorded with the handheld reader and downloaded to a computer or through the SDI-12 interface to a logger. In both cases, the raw reading (millivolts) and calibrated VWC data is stored.

Maintenance. The PR2 is designed for maintenance-free operation.

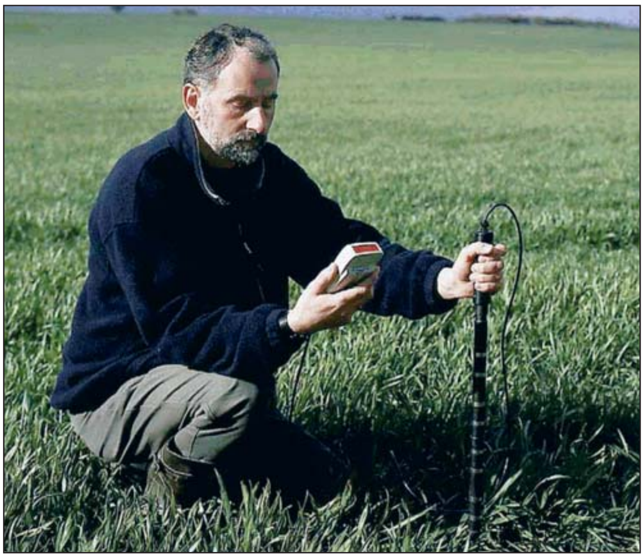
Potential limitations

- Very small measurement sphere.
- If used with annual crops sensors may need to be removed after harvest.
- Measurement is very sensitive to access tube installation.
- The effect of salinity is unclear.

Positive attributes

- Small size and low level of disturbance.
- Precise depth resolution because of disc-like zone of influence.
- Automatic operation reduces labour requirement.
- Continual recording when connected to logger.
- Can monitor multiple depths at once.
- Well suited to permanent, shallow-rooted plantings.

Figure 18. PR2 Profile Probe.



The EnviroPro soil probe (EP100A)

Methodology. The EnviroPro probe is another option in the multi-probe logging range. It consists of a series of capacitance sensors on a central spine. The spine is completely encapsulated and sealed inside a 35 mm diameter PVC tube which is inserted into the soil.

Sensors are placed at standard 100 mm depth increments in 400 mm segments. Therefore, standard models consist of four, eight, twelve or sixteen sensors to 1600 mm depth (EP100A-04 to EP100A-16).

The sensor measures soil moisture, electrical conductivity and temperature.

Calibration. Two options are available:

- output probe data in uncalibrated form and any calibration equations are applied at the PC after download
- convert the raw data to standard units (%, dS/m, °C) inside the probe. The salinity reading can also be used to adjust errors in the soil moisture reading.

Data handling. The EnviroPro communication protocol (SDI-12, RS232, RS485 etc) can be changed by simple modification to the firmware. This allows linking to a range of logging facilities.

The TekSmart system packages the EnviroPro with a custom logger and integral VHF radio for remote communication.

Maintenance. The EnviroPro soil probe is maintenance free.

Potential limitations

- Sensor failure requires complete replacement.
- Salinity measurement of model EP100 is limited to 4 dS/m bulk conductivity.
- If used with annual crops sensors may need to be removed after harvest.
- Measurement is very sensitive to installation.

Positive attributes

- Sensor can link to various logging systems by up loading different firmware to support SDI-12, RS232, RS485 etc.
- The electronic circuits are encapsulated, potted and sealed, protecting them from movement, moisture and chemicals.
- Probe measures soil moisture, salinity and temperature.
- Moisture measurement error caused by salinity, is minimised.
- Maintenance free.

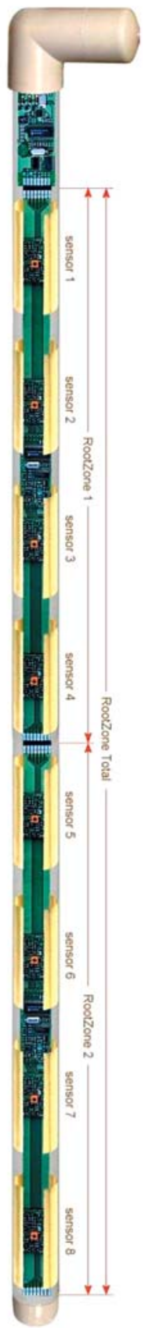


Figure 19. EnviroPro soil probe.

Time Domain Reflectometry (TDR) and Time Delay Transmission

TRASE System 1 and MiniTRASE TDR

Methodology. The TRASE is purpose-built as a soil (or other media) moisture meter. Therefore, in addition to the pulse generator, timing circuit, and display, onboard software is able to analyse the waveform and detect signal trace start and end points. The TRASE is also equipped with memory to store both locations and SWC values or whole waveforms for later reference.

Accessories are available to enable autologging and multiplexing.

The System 1 unit is large (200 x 300 x 400 mm) and heavy (7 kg). The MiniTRASE is smaller, lighter and cheaper.

Wave guides are usually 2- or 3-prong stainless steel probes. The optimal probe length is 30 cm but in soils with high attenuation, shorter lengths (minimum 10 cm) may be required. When burying the probes it is suggested they be inserted into the side of a small trench to ensure they are installed into undisturbed soil.

Calibration. The universal calibration presented in the TDR explanation is included with the TRASE. As stated in the TDR introduction, this gives very good accuracy for a wide range of mineral soils. If using in other materials or organic soils, a custom calibration involving oven drying soil samples maybe needed.

Data handling. The TRASE outputs the dielectric constant and volumetric SWC. These can be manually recorded or stored in memory and downloaded to a computer. The System 1 has an onboard information display whereas the MiniTRASE provides this function using a PDA. Accessories are available for directly downloading data from a remote unit to a computer through telemetry.

Potential limitations

- Moisture getting into connections of buried wave guides can lead to unstable traces.
- Relatively heavy and cumbersome when used as a portable unit.
- High bulk density, clay or saline soils cause weak signal return which makes end point recognition difficult.
- Wave guide to analyser distance limited to 35 m from the unit.
- High cost.
- If using as portable system, wave guides are hard to insert into dry or crusted soil.

Positive attributes

- Benchmark in accurate soil moisture monitoring.
- Easily expanded by multiplexing.
- Onboard data storage.
- Immediate output of absolute SWC.

Figure 20. MiniTRASE (r) and TRASE System 1 (l).

Campbell Scientific TDR100

Methodology. The TDR100 is the smallest true TDR processor available. It requires a logger or computer to operate. From the basic specifications the unit is very small (21 x 11 x 5.5 cm) and weighs 700 g.

Calibration. The universal calibration presented in the TDR explanation is included with the TDR100. As stated in the TDR introduction, this is very accurate in a wide range of mineral soils. If using other materials or organic soils, a custom calibration involving oven drying soil samples maybe required.

Data handling. The most common configuration of the TDR100 is as part of a multiple-wave-guide, multiplexing system. Campbell dataloggers and multiplexers are available to manage the readings and log the data. Software is available to enable a computer to make readings and switch the multiplexor.

Potential limitations

- Must be used with a computer or logger. High level of technical knowledge is required.
- Moisture getting into connections of buried wave guides can lead to unstable traces.
- Small size of measurement sphere; sensitivity to the region immediately next to the probe wires.
- Attenuation of the signal caused by salinity or highly conductive heavy clay soils can lead to inaccurate readings.
- Limited cable length between wave guide and voltage generator.

Positive attributes

- Very small and light.
- Excellent accuracy.
- Easily expanded by multiplexing.

Figure 21. Campbell Scientific TDR 100.

Water Content Reflectometer (Campbell 615)

Methodology. The Campbell 615 consists of a 30 cm wave guide with the measurement electronics built into the probe head. The major difference between the 615 and the “true” TDR equipment is that the 615 doesn’t directly measure the wave guide signal reflection time. Instead, the signal return from the guides causes a circuit (a bistable multivibrator) to change states between two discrete values. The output of the sensor is a frequency which reflects the number of state changes per second (or Hz). As with all TDR sensors a wetter soil will cause a longer signal return time and will cause the 615 circuit to vibrate at a lower frequency.

The wave guides can be buried for *in situ* readings or used as a portable probe.

Figure 22. Campbell 615 Water Content Reflectometer with HydroSense handheld reader.

Calibration. Calibration relates the output signal frequency to volumetric water content. A calibration equation was developed for a loamy fine sand which produces an accuracy of ±2%. The literature states the same equation has been used with a range of mineral soils resulting in an accuracy of ±2.5%.

The 615 has the disadvantage of being affected by salinity in soils >2 dS/m. Custom re-calibration is required to optimise accuracy. The probe output becomes unstable at conductivities > 20 dS/m.

Data handling. A meter or datalogger capable of frequency measurement is required. A handheld meter, the HydroSense™, which outputs volumetric water content is produced by Campbell Scientific Australia. This meter can also store multiple calibration equations.

Potential limitations

- Needs a meter capable of reading a frequency.
- Affected by salinity >2 dS/m.

Positive attributes

- Handheld mode for manual readings at multiple sites.
- Good accuracy.
- Large measurement volume.

Aquaflex

Methodology. Aquaflex uses time delay transmission (TDT) to measure the soil dielectric. The sensor consists of a 3 m long, dual-core wire with a flexible plastic coating. The two wires are joined at the end to form two complete loops for signal transmission. Similar to the Campbell Reflectometer, the sensor measures the signal oscillation frequency, which is related to the surrounding material dielectric. Information is extracted from the shape of the transmitted pulse, which gives a good indication of soil conductivity and is used to compensate the moisture measurement reading to maintain accuracy in conductive soils.

The length of the sensor (3 m) is specifically designed to overcome the problem of a small measurement sphere common to most instruments. Aquaflex sensors sample about 6 L of soil when taking a measurement.

The probes are installed horizontally or diagonally into a trench. Any soil disturbance can cause unrepresentative conditions so it is recommended that probes be installed during initial land preparation to ensure all parts of the field settle to an even condition.

Calibration. The manufacturer provides a range of calibration equations easily selected in the computer software which may be used for a wide range of soil types. Again, this is sufficient for most irrigation scheduling applications where only changes in stored soil water are required. However, if absolute volumetric data is required, specific calibration is recommended. As the instrument is both long and installed horizontally, this is easily achieved with soil samples or TDR probes for SWC or tensiometers for calibrating to soil water tension.

Figure 23. Aquaflex Sensor with high quality data cable and connector.

Data handling. Each sensor is connected through a cable back to a logger that stores both soil water content and temperature data. An Aquaflex logger is available but other commercially available loggers can be used. A palm or laptop computer can then be used to download data and shuttle back to a computer or telemetry is available for remote download. Data can be viewed either in the custom software or a spreadsheet program. An Aquaflex handheld reader can also be used. The custom software allows for soil full and refill points for irrigation scheduling to be inserted.

Maintenance. Wood (1999) states the only maintenance issues concerned keeping the solar panels clean of dust and bird droppings, ensuring batteries were charging and keeping logging units free of pests such as ants and spiders. The device proved to be extremely reliable.

Potential limitations

- Soil disturbance during installation.
- Cable to logger is susceptible to damage.
- As with all dielectric sensors, the calibration is non-linear, which means more samples must be taken if non-standard calibration is to be made.

Positive attributes

- Moisture measurement is averaged over a 3 m long cylindrical volume (6 L of soil).
- Direct measurement of soil temperature.
- Moisture measurement compensated for both soil conductivity and soil temperature.

Gro-Point

Methodology. The Gro-Point uses the time delay transmission concept to measure the soil dielectric. The probe is available in two configurations. The standard device consists of three stainless steel rods about 25 cm long with the outside two joined to form a loop. An extended range sensor is also available which measures a larger soil volume and is designed for greater accuracy in both high clay and high sand soils.

Figure 24. Gro-Point Soil Moisture Sensor. Standard and Extended models and handheld reader.

The Gro-Point is buried at the required position in the rootzone.

Calibration. The probes are factory calibrated for which an accuracy of ±1% is stated.

Data handling. Cabling leads either to where the handheld reader can be attached or to a logger. Gro-Point software enables data collection and graphing.

Maintenance. The only maintenance required is cleaning and changing batteries in the handheld sensor or logger.

Possible limitations

- Calibration cannot be changed.
- Probe design precludes insertion into undisturbed soil.
- Salinity effects at high levels.

***Positive* attributes**

- Relatively large sampling area, especially the extended model.
- Simple to read.
- Relatively inexpensive sensors, loggers and software.
- Can be integrated into larger irrigation system using a logger.

Neutron moderation

Neutron Moisture Meter (CPN503)

Methodology. Because of their cost Neutron Moisture Meters (NMMs) are usually only bought by larger organisations. For smaller operations most regions have consultant services that provide both measurement and advice on irrigation scheduling.

The NMM consists of a nuclear source/detector suspended from a cable and a housing which contains the count/storage electronics and a shield for safe transportation of the source.

Aluminium access tubes with bottom stops are installed at the required site using either an auger or hydraulic ram. As with all instruments using access tubes, care must be taken to ensure good contact. The top of the tube should be protected from rain: an aluminium can is usually enough.

The NMM is placed on top of the access tube and the source/detector is lowered down the tube to the required depth. For ease of use metal tags are attached to the cable to mark depth increments. At each depth a timer button is pushed to start the NMM counting returning neutrons. Accuracy of the readings is related to the length of measurement time with 16 or 32 seconds recommended.

When finished readings for one tube the source is retracted into the shield and either moved to the next tube or returned to its shipping case.

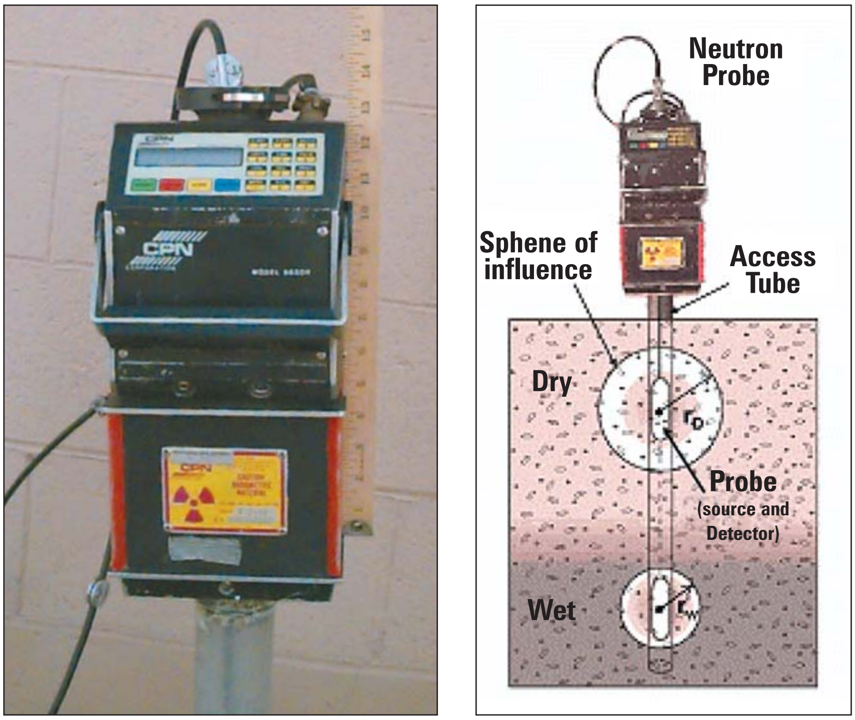
The soil volume the NMM measures varies inversely with water content but an average figure of about 15 cm radius may be assumed. This large measurement radius means access tube air gaps have only minimal effect on readings.

In Australia a licence is required to own, operate and store a NMM. A radiation exposure tag must also be worn while operating the NMM and returned to the issuing authority for periodic checking.

The perceived threat of radiation exposure is one of the biggest problems facing the NMM. Despite this perception a recent article addressing the safety issue stated that in over 40 years of use there had been no known breach of the doubly encapsulated radiation source even when “incidences” have included instruments being crushed by earth moving equipment or falling from high buildings.

Calibration. Two forms of NMM calibration are required. Firstly, readings are taken relative to a drum count, i.e. the count when the source is lowered down a tube placed in the centre of a drum full of water. A drum count is taken to minimise potential drift in instrument readings and should be done every season.

Figure 25. CPN503 Neutron Moisture Meter (left photograph: Utah State University, 1999).



Secondly, the NMM must be calibrated to the soil in which it will be used. Universal calibration equations are available but, again, where greater accuracy is required custom calibration should be performed. This consists of a two-point linear regression of volumetric water content (measured from soil cores) *vs* NMM reading. Gravimetric soil cores may be taken while installing access tubes, destructively, or near the installed access tube.

Data handling. The raw count appears on a screen and can be manually recorded or logged for later download. The calibration equation can be incorporated into a spreadsheet for easy data interpretation. Alternatively, commercial software packages are available specifically to handle neutron probe data and irrigation scheduling e.g. WATSKED and The Probe.

Maintenance. Instrument drift should be checked each season. The unit is powered by rechargeable AA batteries, which should be cycled regularly. The radiation source is not waterproof so access tubes must be checked for moisture after rain.

Possible limitations

- Manual reading.
- Bad perception of radiation safety threat.
- User and storage must be licensed.
- Time taken for each reading – eight depths at 16 seconds per reading means 2.5 minutes per tube.
- Heavy, cumbersome instrument.
- Calibration. This is especially an issue if carrying instrument between markedly different soils.
- Large volume measurement makes readings close to the surface difficult.

Positive attributes

- The most robust, accurate, proven method of soil water content measurement available.
- Measures a large volume of soil.
- Not affected by access tube air gaps.
- Not affected by salinity.

Wetting front detection

Any soil-moisture sensor that can distinguish between wet and dry soil, and has outputs that reliably indicate these two conditions, can be used as a wetting front detector. Reducing the information output to these two states has great potential to produce low cost sensors. The single product represented in this section uses the method of detecting the flow distortion around a buried object.

FullStop

Methodology. The FullStop is a switch that activates when the soil becomes wetter than 2 kPa. The switch can be either mechanical or electrical. The FullStop is a funnel shaped object with a sand filter at its base allowing water to pass into a float chamber. After the irrigation wetting front arrives at the lip of the funnel the soil-water content in the funnel increases because of the distortion of the wetting front by the funnel. The soil water at the base of the funnel increases to the point of saturation and water flows through the sand filter into the float chamber where it either activates a float switch or raises a float flag. Water can be collected after the irrigation by extraction from the float chamber through a tube using a syringe. As the soil surrounding the FullStop dries, the water remaining in the chamber is withdrawn back into the soil by capillary action and the FullStop is reset ready for the next irrigation.

Figure 26.
The FullStop

The FullStop is designed to complement existing logged equipment or as an entry-level learning tool.

Calibration. The FullStop requires no calibration for soil type or sensitivity. It can detect wetting fronts in all soils, particularly with overhead and drip irrigation.

Data handling and interpretation. The output from a FullStop is **visual** by a mechanical flag.

Maintenance. FullStop requires no maintenance and consumes no power.

Potential limitations

- Soil disturbance/preferential flow. The FullStop is large (20 cm diameter) and requires a hole of the same size to be dug during installation. Preferential flow though the disturbed soil may be an issue until the soil settles. When used with annual crops the sensor is installed after cultivation and when soil is already disturbed.
- Will not detect wetting fronts moving at drier than 2 to 3 kPa.
- Does not record history of soil moisture status.

Positive attributes

- As the FullStop collects soil-water from every wetting front, it can be used as a management tool to monitor the movement of solutes such as salt and nitrate.
- Inexpensive.
- Easily interpreted.
- Not affected by salinity.
- Large measurement zone.

CHAPTER 6

CASE STUDIES

Soil moisture sensor controlled irrigation for maintaining turf

Shahab Pathan, Louise Barton and Tim Colmer, School of Plant Biology, Faculty of Natural and Agricultural Sciences, University of Western Australia, WA

(First published in *Irrigation Australia*, Spring 2003 Vol. 18, no. 4, pp 7-11)

Improved practices in fertiliser agronomy and irrigation scheduling have been suggested as approaches to reduce water consumption and nutrient leaching from turf grass. The greatest opportunity for saving water may be through improved irrigation operation systems. In metropolitan Perth about 60% of household water is used for watering lawns and gardens, and in summer this figure can rise to almost 80%. This figure is lower in the rest of metropolitan Australia, around 25 to 50% depending on the location, but it is still significant.

Excessive irrigation is not only costly as a result of extra pumping of bore water or consumption of scheme water, but can also increase nutrient leaching beyond the rootzone, therefore contributing to groundwater pollution. Using soil-moisture-sensor-controlled irrigation systems should enable automatic implementation of irrigation schedules that match supply of water to turf requirements, even when changes in weather occur. In the US, automatic soil moisture sensor controlled irrigation systems are often operated year-round without the need for adjustments for season or rainfall, and turf grass quality (e.g. colour, growth) can still be maintained. However, little work has been published on the operation of these systems in Australia.

The aim of this research was to evaluate water used and turf quality for plots irrigated using a control system linked to a soil moisture sensor as compared to current best practices as recommended by the Water Corporation in Western Australia. In addition, field lysimeters were used to evaluate water leaching under turf. The sensor evaluated was a Holman soil moisture sensor called *Water Smart™* developed by Cuming and Associates.

Figure 27. Overview of the series of replicated turf plots at the UWA research site, established to research the use of a soil moisture sensor controlled irrigation system.

Experimental approach

Couch grass (cv. 'Wintergreen') was established in six field plots, each 3 x 3 m, on sandy soil at the University of Western Australia Turf Research Facility in Shenton Park, about 8 km west of Perth CBD. The experimental design was two irrigation regimes x three replicates = six plots (see Figure 27). The two irrigation regimes were:

1. 10 mm for each application (frequency was adjusted depending on the time of year as recommended by the Western Australia Water Corporation; Table 8)
2. Soil moisture sensor controlled plots scheduled at 10 mm every day, but only irrigated when the sensor permitted.

The experimental units were arranged in a completely randomised design. A *WaterSmart* soil moisture sensor was installed into the centre of each of three plots by Cuming and Associates Pty Ltd (Melbourne, Victoria) at a depth of 50 mm on 14 February 2002. Studies were also conducted to evaluate the sensor-controlled system using larger areas of turf at Lanchester Park, City of Stirling, Western Australia.

Table 8. Watering frequency for turf grass in metropolitan Perth as recommended by the WA Water Corporation (during times without watering restrictions). Ten millimetres should be applied during each irrigation. Source: *The Waterwise Gardening Guide* by John Colwill.

MONTH	FREQUENCY
January	Every second day
February	Every second day
March	Every third day
April	Every fifth day
May	No watering
June	No watering
July	No watering
August	Once a fortnight (if needed)
September	Once a fortnight (if needed)
October	Every fourth day
November	Every third day
December	Every second day

The sensor, when buried in the rootzone, responds to the capillary tension, which is related to the water availability in the soil. As a soil dries, tension increases and the sensor will switch on the irrigation system when the soil reaches a minimum set point. A delay to ensure watering occurred before 9 am or after 6 pm was also programmed into the controller. The cumulative volume of water applied to each plot was measured using water flow and time meters connected with the irrigation systems. Turf greenness was measured using a chroma meter (Minolta, CR 310, Japan).

Results

The amounts of water applied over twelve months (April 2002 to March 2003), are shown in Figure 28. The total volume of water applied during summer (December to February) to plots controlled by the soil moisture sensor was 25% less than applied to those irrigated according to the WA Water Corporation watering schedule, during times of no watering restrictions (Figure 28). Similarly, the cumulative volume of water applied during 161 days (19/12/02 to 29/05/03) at Lanchester Park, to areas controlled by the soil moisture sensor was 24.7% less than applied to those areas irrigated according to the WA Water Corporation watering schedule (Figure 29). The current best practices conventional method applied 64 to 75% of evaporation and the soil moisture sensor-controlled system applied 48 to 53%, during summer.

Figure 28. A comparison of the amounts of water applied on a monthly basis for a soil moisture sensor-controlled system and 'current best practices' conventional method to turf plots at the UWA research facility. Monthly totals for evaporation and rainfall during the study were from an Automatic Weather Station located 500 m from the plots. Data on water applied are means of 3 replicates ± standard errors (error bars not visible when smaller than the size of symbols). The 12 month study was conducted from April 2002 to March 2003.

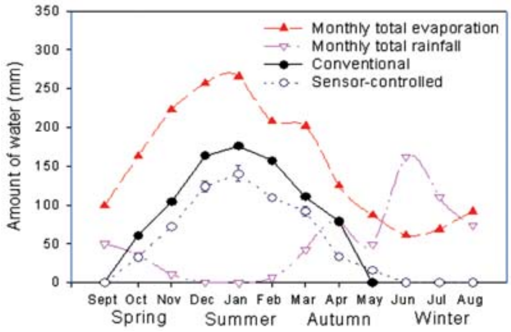
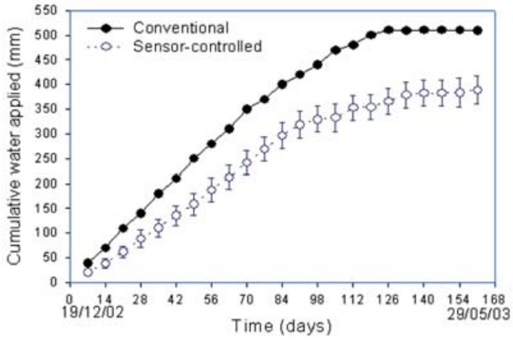


Figure 29. The amounts of water applied to areas of turf at Lanchester Park on a cumulative basis. A comparison of the soil moisture sensor-controlled system and conventional method is given, for the period 19th December 2002 to 29th May 2003 (161 days). Data given are means of 3 replicates ± standard errors (error bars not visible when smaller than the size of symbols).

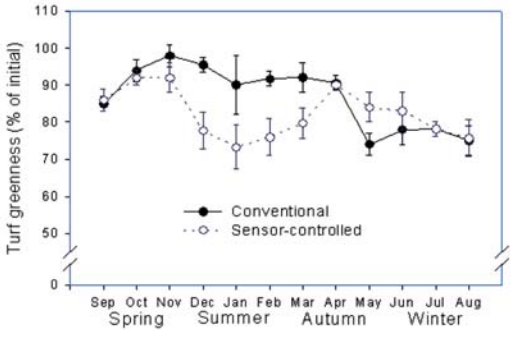


The sensor system triggered irrigation events twice weekly during summer (December to February) and weekly in autumn (March to May), and did not operate during winter (June to August) or early spring (September). During May 2002, rainfall was low (49.2 mm) compared to long-term averages (122.7 mm), therefore the sensor system triggered irrigation events three times while the conventional system was turned off (Figure 30). Sensors automatically terminated irrigation events after 6 to 8 mm had been applied, depending on the delay between the sensor's enable point and the next schedule opportunity.

Lysimeters were installed in each plot so that water leaching below the rootzone could be measured. Leaching was reduced by 100 L of water per square metre in lysimeters in plots with sensor-control compared to those in plots with the conventional irrigation, at least for the 154 days (28/11/02 to 01/05/03) measured in this study (data not shown).

Turf colour (i.e. greenness) was also evaluated. Colour is an important characteristic of turf areas since it is often associated with the quality of the surface. The turf greenness was reduced by 15 to 19% in sensor-controlled plots when sampled during summer (December to February), when compared to the conventionally irrigated plots (Figure 30). However, the naked eye could not pick this reduction (Figure 31). During autumn, winter and spring, there were no significance differences in greenness between plots in the two irrigation treatments. However, greenness had declined during winter in all plots, as is common for couch grass in metropolitan Perth.

Figure 30. Greenness of turf grown in plots at the UWA research facility with irrigation controlled via a soil moisture sensor or conventional methods, for 12 months (April 2002 to March 2003). Measurements were taken using a chroma meter. Data are given expressed as % of initial values at the commencement of treatments (day before sensor installation i.e. 13th February 2002). Data given are means of 3 replicates ± standard errors.



SOIL WATER MONITORING

Figure 31. Visual appearance of turf in plots with irrigation controlled using a soil moisture sensor (right-hand side) or conventional systems (lefthand side). Photos were taken at the end of summer (i.e. 28/02/03) at the UWA research site.

Conclusions

Irrigation water savings of around 25% were obtained in summer for turf irrigated using a soil moisture sensor controlled system over a conventional system. Turf grass quality was maintained at acceptable levels in plots controlled by a soil moisture sensor during the period of this study, although it is important to note that the plots were not subjected to wear.

The soil moisture sensor controlled irrigation system enabled a flexible watering schedule for turf without the need for daily monitoring or seasonal adjustments by personnel. The three replicate sensors gave close agreement indicating reliable and consistent performance. Furthermore, the amounts of water saved for an area with irrigation controlled by sensors was almost identical for the experimental plots at the UWA site and the larger areas at a public park. The *WaterSmart* control system demonstrated the ability to assess the watering requirements of the turf in trials at the UWA site and an industry site at Lanchester Park, City of Stirling, WA.

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Acknowledgments

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Monitoring soil moisture change in a black vertisol using electrical imaging

Ian Acworth, Water Research Laboratory, School of Civil and Environmental Engineering, University of New South Wales

The electrical image method was first developed in the late 1970s for the groundwater industry. Images were collected over weathered granites in Africa (Northern Nigeria) to locate fracture zones suitable for groundwater abstraction. With this method four electrodes are placed into the ground and connected to resistivity measuring equipment. The electrodes are usually placed in line with the outer two electrodes carrying current and a voltage measured between the inner two electrodes, (see Figure 32). The electrodes were originally connected to the measuring equipment using single-core wire and all four electrodes moved manually between each reading. Multi-core cables are now used to speed the process. Figure 33 shows a manual switchbox where an operator selects the combination of electrode positions to be presented to the resistivity meter for a measurement of resistance. More generally, this function is now also carried out automatically.

Figure 32. General configuration of cables and instruments.

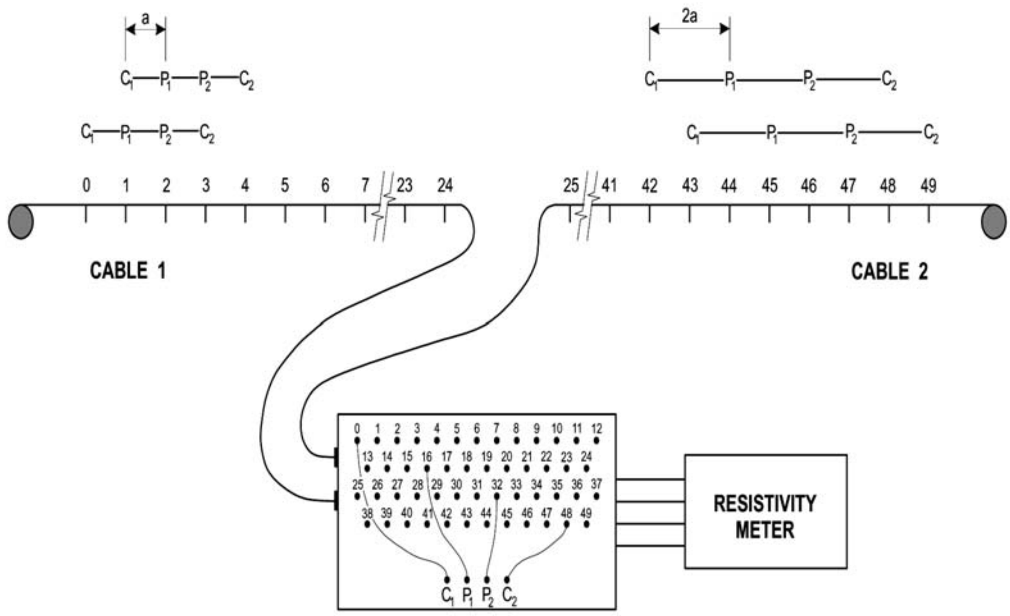


Figure 33. Geopulse resistivity meter used with multi-core cables and a manual switching unit.

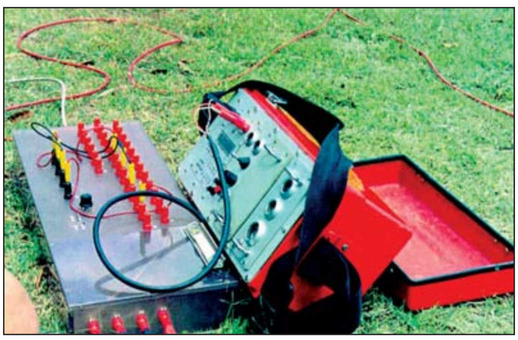


Figure 34a. Repeated electrical images with growing Lucerne in the central plot.

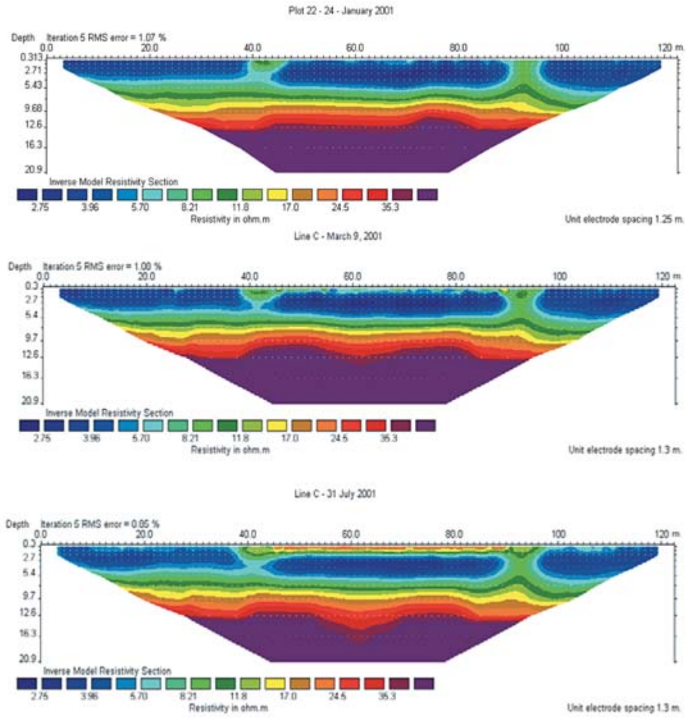


Figure 34b. Change in resistivity at increasing depths between electrical images measured in January and July.

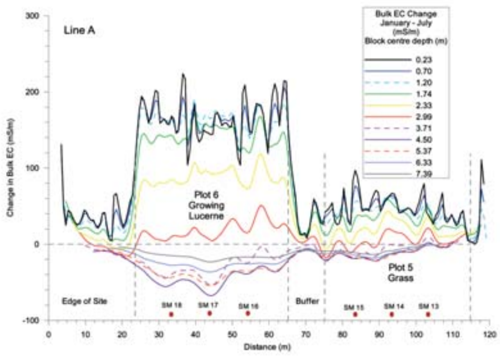


Figure 34c. Neutron soil moisture measurements through the Lucerne plot showing the soil profile drying.

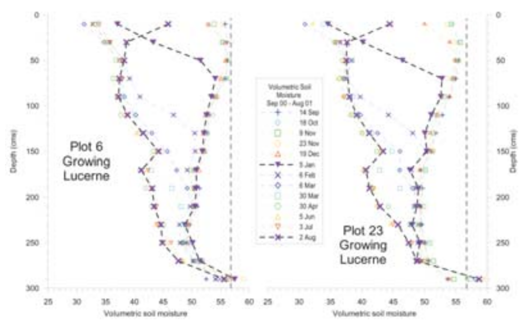
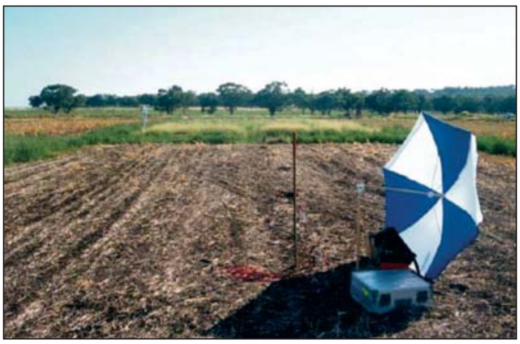


Figure 35. Neutron soil moisture measurements through the Lucerne plot showing the soil profile drying.



Electrical imaging is a development of the widely used electrical sounding method. Whereas sounding produced a model of earth resistivity change in the one vertical dimension, electrical imaging extends the sounding into two or three dimensions and produces a model of true resistivity (or conductivity). The data measurements made in the field are of apparent resistivity and are similar to the apparent conductivity measurements that are routinely made with GEONICS equipment (EM31, EM39). Unlike the EM data, it is possible to invert the apparent resistivity measurements into a model that shows true (real) values of resistivity. These data can then be directly related to the factors that affect resistivity in soils, such as clay type and content, porosity and moisture content, rather than the use of empirical relationships to relate apparent conductivity to site measurements.

Field measurements

The resistivity method (electrical imaging) is ideal for determining moisture change in soils. While it may not be possible to completely resolve all the detail in a single image, the difference between subsequent images measured over exactly the same line can only be due to change in moisture content or change in fluid chemistry. Over deep black vertisols, it is the moisture content change that directly influences the change in bulk resistance of the soil.

The equipment comprises multi-core cables (typically two cables each with thirty two takeouts at 2 or 2.5 m spacing); electrodes and connectors; a resistance measuring device such as the ABEM SAS4000 Terameter; and an automated electrode selector such as the ABEM LUND ES464. This equipment is shown in the photo. The electrical image is comprised of typically 500 measurements of apparent resistivity. Data collection occurs at about five readings a minute. The depth of penetration of the image is directly related to the distance between the electrodes. We have used a spacing of 1.25 m that produces a detailed image to a depth of 10 m over a line length of 80 m.

The Hudson experimental site was established by NSW Agriculture on the southern slopes of the Liverpool Plains. Repeated electrical images were made over plots that were initially at full moisture and then planted with lucerne. The change in bulk resistivity, as measured by the electrical images was related to change detected in neutron soil moisture access tubes. Results are shown in figures 34a, b and c. There is a clear relationship between the bulk electrical resistivity (see Figure 34a), the change in bulk resistivity (see Figure 34b) and the soil moisture change (see Figure 34c). Equipment is shown in Figure 35.

The results of this work have been submitted to the *Australian Journal of Soil Research* in a paper by Acworth, Young and Bernardi titled "Monitoring soil moisture status in a black Vertosol on the Liverpool Plains, NSW", using a combination of neutron scattering and electrical image methods. Further work is underway to characterise the change in moisture beneath growing cotton and to characterise deep drainage beneath an irrigated cotton crop that has been watered using flood irrigation techniques. A significant advantage of this technique is the ability to retrieve soil moisture data by remotely scanning the region rather than installing probes that may disturb and alter the soil properties. The technique also integrates over a large volume to be more representative of soil and subsurface conditions.

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Production and water use efficiency improvements in horticulture from improved irrigation scheduling

Water for Profit team, Growcom, Brisbane

Squeezing the most out of a defined water allocation

A 10% increase in bottom-line profit without any additional outlay on water is a handsome windfall in anyone's language. Tim Ulcoq estimates this is the margin he gained after finetuning irrigation techniques on his Gayndah property in the Central Burnett where he grows citrus.

A dry year highlighted the need to use water to maximum efficiency, and Tim says that paying attention to irrigation details has helped improve tree health, fruit size and therefore overall productivity.

Tim's property is irrigated from the Burnett River, which is completely regulated. He converted to micro sprinklers some years ago to improve delivery and has subsequently refined his monitoring by investing in C-probe soil moisture monitors to track water use. Working with the Queensland Fruit & Vegetable Growers' Water for Profit program on ways to improve water scheduling, Tim is using the same amount of water but has increased the percentage of fruit reaching premium sizes by better matching irrigation with the trees' water requirements.

"Because water is a scarce commodity we were interested in checking out our irrigation system and looking at ways to improve productivity," Tim said.

Water for Profit irrigation field officer Matt Dagan helped him change the timing and efficiency of water use to achieve the best possible result with no waste.

There were no increased costs associated with better water scheduling but tree health improved because they were not subjected to either water stress or over watering.

By being more precise with scheduling he provided the trees with the required soil moisture for the tree's current growth stage.

Tim estimated that he had achieved about a 10% increase in the number of fruit in premium size categories, translating into about a 10% increase in profit.

Tim and his wife Jenni's Ulcoq Citrus Enterprises produces a number of mandarin varieties for the domestic and export market with about 20% of production going to premium markets in Japan, Indonesia, Canada and China. It was the 2002 State Winner of the Water for Profit Awards run by Queensland Fruit & Vegetable Growers.

According to the Ulcoq's, they have made significant changes since being part of the Water for Profit program in terms of increased C-probe use, refining irrigation scheduling changes and having a weather station installed. The program has been of great benefit to their business.

Irrigator takes the "waste not, want not" rule to the edge

Wayne Parr, of Isis River Orchards, manages his irrigation so precisely that in a recent severe drought he knew exactly how much was needed to maintain orchard productivity. His attention to water use efficiency really paid off when the Isis River dried up and he was reliant on poor-quality bore water. The drought forced him to put into practice all the techniques learned during the past few years of working with the Queensland Fruit & Vegetable Growers' Water for Profit program.

The drought was an expensive learning curve but by monitoring soil moisture and water quality, Wayne was able to stretch out the available water to make sure none of it was wasted.

The orchard's water use benchmark for citrus is between 6 and 8 ML/ha a year but through monitoring and learning about the water needs of the crop with the Water for Profit program, Wayne was able to reduce water use to 5 ML/ha a year.

The program helped him really understand what the orchard's true water requirements are. This means future developments for Wayne and his partners at Childers will be undertaken with known water requirements.

He uses the non-traditional method of drip irrigation, which has been pioneered in Australian citrus during the past decade but is used extensively overseas.

Wayne says that drip irrigation is the most efficient technique when you use it properly. When driplines are kept clean, the maintenance factor is minimal and nutrients can be supplied direct to the trees' root systems.

"There has been a tendency in the past to over-water trees but with drip irrigation, the water is put directly on the roots and with the aid of pulse watering the water will move laterally so that overall we use less water than traditional mini sprinkler and spray systems," he explained.

Wayne's grandfather was an industry pioneer who developed the Golden Mile Orchards at Mundubbera in the 1930s.

Although some traditional growers are sceptical of drip irrigation because it requires different management skills, Wayne says that once you gather all the relevant data and get on top of it then much less water is required.

Overcoming under watering leads to production efficiency

Stephen Jeffers' avocado trees were suffering up to 30% fruit drop before he realised that the cause was water stress at critical periods of their growth cycle. Although the soil appeared moist enough, Stephen discovered the trees were suffering from a lack of water in the crucial part of the soil profile. But with enhanced irrigation management, Stephen's trees more than doubled their production during a very dry and difficult season.

Working with the Queensland Fruit & Vegetable Growers' Water for Profit program, Stephen discovered he was not irrigating enough and his avocado and persimmon orchards were under stress despite their high rainfall environment.

Because the surface of the soil always seemed to be moist it took a while for Stephen to identify that water stress was responsible for the fruit drop because the trees draw their water from deeper down in the soil profile.

QFVG field officer Matt Dagan helped Stephen do an irrigation audit and install an Enviroscan system to monitor soil moisture on his 10 ha production area near Nambour on the Sunshine Coast. They monitored his irrigation and made changes to achieve more uniform distribution from sprinklers at the top of the steep hills in the orchard and the bottom sprinklers.

Stephen was fertigating and noticed the top of rows had less growth, which he put down to soil types. However, the system audit showed that the sprinklers at the top were putting out half the water the trees were getting at the bottom which meant these top trees were stressing as a result of not getting enough fertiliser or water. Previously, this sort of information about irrigation had been difficult for him to obtain.

"Some of the equipment we've used, such as the Enviroscan, is really pricey but through the Water for Profit program growers are able to use them for demonstration purposes and realise the benefit they provide," said Stephen.

According to Stephen the extension service Water for Profit offers was a huge benefit of the project as they know their stuff and communicate well with growers. The Enviroscan shows the water through the soil profile and reflects the effects of irrigation in different depths of the soil. It can show what water the tree is using during the day and pinpoint an obvious period of stress when trees are not irrigated enough.

Science cuts guesswork, slashes water use

Atherton Tableland mango, avocado and hay grower, Mark Simonato, slashed water use by up to 66% after closely monitoring and adjusting the watering program around his 55 ha orchard at Mutchilba.

Mark reduced his weekly watering time from 24 hours to 8 hours while working with the Water for Profit program. He had been interested in water use efficiencies for several years, but the support and confidence provided by the program enabled him to rigorously monitor soil moisture using Enviroscan and Buddy systems and then modify irrigation practices accordingly.

Gathering soil moisture information by using the Enviroscan changed Mark's irrigation practices a great deal. As a result he drastically reduced water use and water and nutrient leaching were kept to a minimum, making for a healthier and more sustainable orchard.

Mark said Water for Profit helped him understand the Enviroscan computer software, and provided information and advice to iron out the problems. By being able to do this he could see see that water use can be kept at a constant level, through the soil profile, without always guessing.

"Irrigation farming is all about money these days and when you are using 200 megalitres of water, you have to become efficient," said Mark.

As well, Mark has noticed a 10 to15% increase in the quantity of fruit reaching premium grade.

Tree crops irrigator reduces water use by a third

Queensland primary producer Ross Stuhmcke reduced on-farm water use by more than 30% after using soil moisture monitoring devices to determine the exact water needs of his tree crops.

Ross was named as the Lockyer Valley winner of the Queensland Fruit & Vegetable Growers' 2003 Water for Profit Irrigation Efficiency Awards run as part of the Queensland Government's $40 million Rural Water Use Efficiency Initiative. He has been growing persimmon, peach and nectarines using a micro-sprinkler irrigation system at Blackboy Ridge near Gatton for about two decades

Ross said the QFVG-managed Water for Profit program helped him master Enviroscan technology and discover he was watering trees for too long and wetting deeper down the soil profile than needed.

The program helped him interpret the computer data generated by Enviroscans and provided a better understanding of his light sandy soils and how the water reacts with the soil. It also helped him to understand more about water scheduling and how much water he needed to use.

The monitoring devices show him exactly what moisture is in the soil profile at different depths and he is now watering more often, but for shorter periods. Overall he is now using a lot less water to produce the same amount of fruit.

Moisture monitors the "best thing since sliced bread"

Robert Pin says the devices that monitor soil moisture in his mangoes, avocados and peanuts are the best thing since sliced bread.

Robert now owns 14 of the tensiometers that help him decide when crops need watering and is therefore a much more efficient irrigator. So much so that he was named as the Far North Queensland winner of the 2003 Water for Profit Irrigation Efficiency Awards.

The tensiometers proved Robert's old methods of irrigation were not efficient in providing crops with the correct amount of water. He and his wife Maria have achieved a 38% increase in production on their Mareeba property by combining more efficient watering with management practices such as mulching.

Before they became involved with the Water for Profit program, they didn't use any measurements other than the old farming practices Robert learned from his father and grandfather, which was to water once a week.

When they put the tensiometers in, it was a totally different kettle of fish. When the tensiometers said the ground was dry Robert said that they would dig with a shovel and it was dry. He rapidly concluded that these devices don't lie.

He now relies on them to decide on when and how much to water. When there's fruit on the trees or when the peanuts or watermelon are maturing, then they need to keep the moisture up and he says the accuracy pays off.

Citrus growers halve water use by irrigation changes

Sunshine Coast citrus growers, David and Rhonda Fritz, are on track to halve water use on their Gympie property through changes made while working with the Water for Profit program.

The Fritzes were named as the Sunshine Coast region winners of the 2003 Water Use Efficiency Awards. By auditing their irrigation system, their watering is now more effective and timely, and David expects that further planned changes will create an overall saving of 57% on original water use.

One change was switching from the original sprinkler setup which had a wetting diameter of 5 m for young trees, meaning a lot of the water was unproductively wetting inter-row grasses. By changing to 2.5 m diameter sprinklers, David reduced his watering time by 75% and gained a 38% water saving across the farm.

He also redesigned the irrigation mainline to increase water pressure, flow and pump efficiency. David used to irrigate direct from the bore but now has filling tanks, which are filled overnight to make use of the lower electricity tariff and then the blocks are gravity-fed during the day when he can also check all sprinklers are functioning.

Having fairly steep country, David has controlled pressure variations by using pressure-compensated sprinklers and gate valves at the head of each block. He has improved discharge uniformity by using varying lateral pipe sizes to counteract pressure gains as water travels downhill.

Whereas irrigation scheduling had been based on visual inspections, i.e. that is looking at the state of the trees and soil under the trees, David now uses Gopher soil moisture measurements to determine when to water.

He said the Gopher has enabled him to head off water stress before the trees show any signs of it, leading to a more healthy and productive orchard. Although this soil moisture information has increased his watering time, David expects to gain production benefits from this during the coming season.

The constant logging function of the Gopher system also identified a pumping fault that may otherwise have gone unnoticed.

The Fritzes grow 1000 lemon, lime, mandarin and orange trees on Mary Creek at Gympie and intend planting a further 600 trees in the near future.

Methods for assessing vineyard water use

Shannon Pudney, South Australian Research and Development Institute, Adelaide, and Michael McCarthy, South Australian Research and Development Institute, Nuriootpa

(This paper was presented at the Australian Society of Viticulture and Oenology Seminar 'Managing Water', at Mildura Victoria, 12 July 2002)

Soil water monitoring should be, by now, an integral component of best practice vineyard management. The benefits of using soil water monitoring equipment have been clearly demonstrated and now that Australian grape growers have access to a wide range of soil moisture monitoring devices there should be no reason why they are not in universal use.

Devices vary in price and sophistication, so that there is equipment available to suit nearly every requirement. This in itself creates problems for growers who are often confused about which type of soil water monitoring equipment they should buy. The objectives of this paper are to:

- provide an overview of soil moisture sensors commonly used in southeastern Australia
- discuss sensor response times
- discuss the spatial variability in soil moisture across a vineyard block.

Measuring soil moisture status

Soil water content can be determined gravimetrically. This involves removing a portion of soil from the sample site, so it is not appropriate for continual long term monitoring. To overcome this issue, *in situ* sensors have been developed. It is important to recognise that although all soil moisture sensors (SMS) measure soil moisture status, they use different measurement techniques. The output from SMS systems is recorded as either volumetric soil water content or soil water tension. Volumetric soil water content is a measure of the amount of water contained in a volume of soil whereas soil water tension is a measure of the force (pressure) that a plant must over come to extract water from the soil matrix.

Products that measure soil water tension can be classified as porous media instruments (see Table 9). The operating principle of such devices is relatively simple; water is drawn out of the porous medium in a dry soil and absorbed by the medium in a wet soil. The flux of water is quantified by a pressure gauge or by a change in electrical resistance. Both measures are related to soil moisture content. Products that fall into this category include gypsum blocks (heavy and light) and tensiometers.

Sensors that measure volumetric soil water content are currently more widely available than those that measure soil water tension. Volumetric soil water content sensors are generally placed in one of three categories, i.e. soil dielectric, neutron moderation and heat dissipation (see Table 9), based on the operating principle of the sensor.

Soil dielectric. Sensors included in the soil dielectric category use the dielectric properties of the soil to measure volumetric soil water content. Such instruments apply an electromagnetic pulse or wave to the soil. The ability of the soil to conduct this energy is related to soil water content. There are many subtle differences between the operating principles of 'soil dielectric' sensors, and this is where the terminology capacitance, time domain reflectometry (TDR) and time domain transmissometry (TDT) emerges (see Table 9). While this paper doesn't describe these subtle differences, it is important to appreciate that capacitance, TDR and TDT all use the dielectric properties of the soil to measure volumetric soil water content.

Neutron moderation. Neutron moderation is another technique for measuring volumetric soil water content. In this technique fast moving neutrons emitted from a small radioactive source are slowed or thermalised when they collide with hydrogen ions in the soil. This technique assumes that the components of the soil matrix are constant with the exception of air and water. Air has very little effect on the dielectric property of the soil compared with water so the number of neutrons that are thermalised is related to the water content of the soil.

Heat dissipation. The third category of volumetric soil water sensors is heat dissipation. These sensors consist of a heater separated by a known distance from a thermometer. A known amount of heat energy is emitted from the heater and the peak soil temperature reached is recorded, this information is used to calculate volumetric soil water content.

Table 9. Measurement unit and operating principle of soil moisture sensors commonly used in south-eastern Australia.

Unit of measurement	**Gravimetric**	**Tension**	**Volumetric**		
Operating principle	Destructive soil sampling	Porous media	Soil dielectric	Neutron moderation	Heat dissipation
Products available		Gypsum block Heavy gypsum block Light tensiometer	C-Probe (C) Diviner 2000(C)* EnviroSCAN(C) Gopher (C)* Theta Probe(C) Reflectometer(TDR) GroPoint (TDT)	CPN neutron hydroprobe*	Aqua Sensor

C = Capacitance, TDR = Time Domain Reflectometry, TDT= Time Domain Transmissometry
*It is not possible to continually log these sensors. All other sensors can be continually logged and remotely accessed.

Many of the sensors listed in Table 9 have been trialled at the South Australian Research and Development Institute Nuriootpa Research Station. Over the last two seasons the sensors have produced consistent seasonal soil moisture trends, however, at any one point in time soil moisture readings varied. It is likely that this variation was a combination of differences in response time and spatial variation in soil moisture. The rest of this paper explores these issues.

Soil moisture sensor response times

It is important to understand the response time of a sensor to interpret soil SMS data accurately. Response time must be considered when frequent irrigations are applied or if fine control over irrigation is desired.

We were able to investigate soil moisture sensor response times in May 2002, when over a 40-hour period 56.2 mm rain was received. The rain started at 10:30 am on 18 May and continued until 1:45 am on 20 May. There was no foliage on the vines when it rained so it can be assumed that the water was applied evenly, i.e. not biased by irrigation wetting patterns. The response of four types of SMS to the rain was assessed.

The soil at the Nuriootpa site consists of a sandy loam over heavy clay. Northcote *et al.* (1954) classified the soil as Light Pass Fine Sandy Loam. Ninety per cent of roots are within 60 cm of the soil surface. The sensors have been installed in a 15-year-old block of Chardonnay for about 18 months, and for all of this time they have had an identical irrigation history. Two sensors (numbers 1 and 2) are porous media instruments, while two sensors (numbers 3 and 4) are dielectric instruments. Three sensors of each type were installed alongside consecutive vines in the same relative position in the irrigation wetting zone. One at a depth of 20 cm, one at 40 cm and one at 60 cm. The vine and row spacings are 2.25 m and 3 m respectively

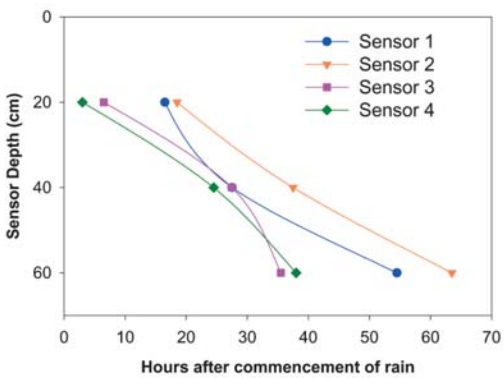
Results

Wetting front at 20 cm. Sensor four detected the wetting front at 20 cm about 3 hours after the rain started (see Figure 36); sensor three 6.5 hours; sensor one 16.5 hours; and sensor two 18.5 hours after the rain started.

Wetting front at 40 cm. Sensors one, three and four all detected the wetting front at 40 cm about twenty five hours after the rain started. Sensor two responded ten hours later (37.5 hours after the rain started, see Figure 36).

Wetting front at 60 cm. At 60 cm the differences were the greatest. There was a 28-hour difference between the first and last sensor responding (sensor three, 35.5 hours after the rain started; sensor four, 38hours; sensor one, 54.5hours; and sensor two, 63.5 hours).

Figure 36. Cumulative hours after rain started when the wetting front was detected by four different types of soil moisture sensors at depths of 20, 40 and 60 cm. Sensors 1 and 2 are porous media instruments and sensors 3 and 4 dielectric instruments.



Discussion

Sensor response times were variable. The dielectric sensors tended to detect the wetting front at each of the sensor depths before the porous media instruments. Factors that could have contributed to such variation can be grouped as site and sensor influences. Site influences include irrigation history and soil factors. Sensor influences include mode of operation, sphere of influence, installation and soil type specificity. Each of these factors is discussed below.

Site influences. Water will move through the soil profile at variable rates depending on the initial soil moisture status. The initial (pre-rainfall) soil moisture content was comparable for each of the sensors as all have identical irrigation (and rainfall) histories. They have also been installed in the same relative position in the irrigation wetting zone. Given these factors it could be assumed that the sensors were in identical soil environments, however, soil is not a homogenous medium. Soil properties will always vary even in the most uniform soil types (such as the Light Pass Fine Sandy Loam into which the sensors have been installed). Variation in soil properties (and the presence of preferential pathways) will inevitably contribute to the observed variation in response time.

Sensor influences. Some of the observed variation in response time can be attributed to how the sensors operate. Two of the trialled devices were porous media instruments and two were dielectric sensors. When moisture levels are raised in the soil surrounding a porous media instrument, matric potential (and capillary action) will drive water into the porous medium. It is only after water has been "absorbed" by the medium that an increase in soil moisture content is indicated in the soil moisture sensor output. When the soil moisture content increases in the soil surrounding a dielectric instrument, the dielectric properties of the soil are altered and this is immediately reflected in the sensor's output. For this reason it is not surprising that the dielectric sensors detected the wetting front at each of the depths before the porous media instruments.

Sensors also differ in their spheres of influence. The sphere of influence of a sensor can be defined as the volume of soil surrounding the sensor within which a change in soil moisture content will alter the sensors output. Although the sensors in this study were installed at the same depths they had different sized spheres of influence. The effect of such a phenomena is that different sensors installed at the same depth are 'reading' different soil volumes. Once again, this will inevitably contribute to the variation in response time.

Installation is yet another factor that may be responsible for the observed differences in response time. The soil profile has to be disturbed to install a soil moisture sensor. There are various installation techniques. Some involve augering a hole, placing the soil moisture sensor in the bottom and backfilling with the original soil, with or without a foreign medium to plug the hole. Others involve augering a hole and then inserting an access tube into which the sensors are placed. Every method has the potential to alter soil properties, particularly bulk density, which will of course affect infiltration rates and consequently response times.

Finally, the soil type into which the sensor has been installed must be considered. Some soil moisture sensors are designed for use in a specific soil type, referred to above as soil type specificity. For example, the composition of porous media instruments (ratio of macro to micro pores) is designed to mimic the soil type in which it is to be used. This is necessary as pore size influences the rate of water movement. Sensor number one is suited for use in heavier soils, whereas sensor number two is designed for use in lighter soils. This is perhaps why sensor two was the last sensor to detect the wetting front at 40 and 60 cm.

Summary

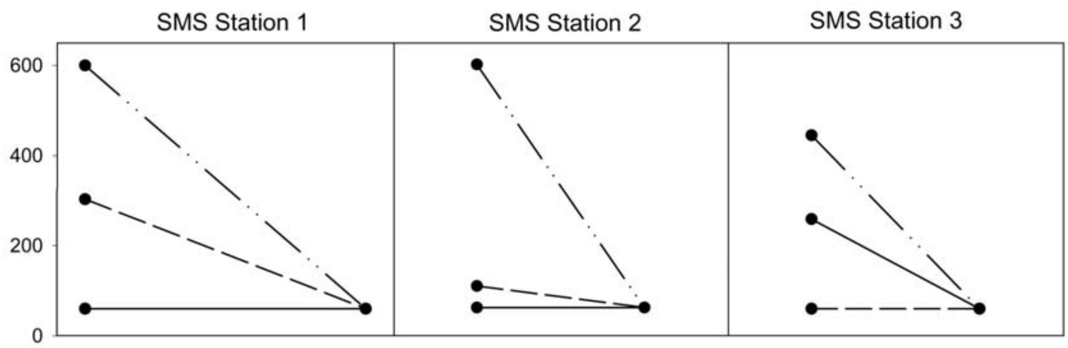
The data presented in this paper shows that the response times of soil moisture sensors do vary. The time that a sensor takes to respond to a wetting event is the product of complex interactions between sensor and site factors. These factors include irrigation history, mode of operation, sphere of influence, soil specificity, soil variability and installation. It is imperative that these factors are understood when SMS data are used to schedule irrigations.

It may be appropriate to use a sensor with a slow response time when irrigations are infrequent, however, in vineyards where daily crop water use is high and water may be applied every day, or second day, sensors with a short response time may be needed. The ideal SMS will behave in a manner that perfectly mirrors the soil dynamics.

Spatial variation in soil moisture

The rain on 18 May 2002 also provided the opportunity to investigate the spatial variation in soil moisture across a vineyard block. Data are presented from three sets of soil moistures sensors (soil moisture stations) installed in different locations in a one-hectare vineyard block (described above). Sensors of the same type were installed in June 2000 at depths of 20, 60, and 80 cm at each of the three locations. They have received the same level of irrigation since 2 April 2002.

Figure 37. Soil moisture sensor readings from three locations within the same irrigation shift before and after rain on 18 May 2002. Sensors are installed at depths of 20 cm (——), 40 cm (– – –) and 60 cm (— ·· —), at each of the three locations.



Results and discussion

Spatial variability in soil moisture was assessed by comparing pre- and post-rainfall soil moisture readings at each of the three locations (see Figure 37).
Each of the sensors responded to the rain so they were all operating satisfactorily. Following the rain all sensors indicated that the soil was wet (wetter than the lower measuring limit of the device). However, values before it rained were highly variable. The soil moisture readings from location 1 (SMS Station 1) indicated that the soil was wet at 20 cm, drying at 60 cm and completely dry at 80 cm (see Figure 37).

The readings from location 2 (SMS Station 2) indicated that the soil was wet to 60 cm and completely dry at 80 cm. The group of sensors at Location 3 (SMS Station 3), indicated that before the rain the soil was drying at a depth of 20 cm, wet at 60 cm and drying at 80 cm. If the block was being managed to maintain high rootzone soil moisture levels, based on pre-rainfall data, three very different management decisions could be reached (see Table 10).

Table 10. Interpretation of data generated by three SMS stations located within the same irrigation shift.

LOCATION	MOST APPROPRIATE COURSE OF ACTION
Station 1	Apply a deep penetrating irrigation
Station 2	No need to irrigate
Station 3	Apply a light irrigation Summary

This data set highlights the problem with point monitoring in a vineyard. In this study soil moisture status was found to vary in a small vineyard block, planted on a uniform soil type, with an identical irrigation history. While vineyard managers try to reduce differences in soil water content within a vineyard irrigation shift (by matching readily available water and variety to valve shifts) it must be recognised that variation will still exist. A single SMS installation site in an irrigation shift may not give information that is accurate enough to enable best practice irrigation scheduling.

Conclusion

There are many types of soil moisture sensors. They differ in the way they express soil moisture content and in their mode of operation. To gain the maximum benefit from the use of soil moisture sensor data it is important to understand how the information is generated. Soil moisture sensors generate data values that reflect the soil moisture status within the sensor's sphere of influence. This value may or may not reflect the water status in the entire irrigation shift. Soil moisture sensors will take varying lengths of time to respond to a wetting event. Factors such as irrigation history, mode of operation, sphere of influence, soil specificity, soil variability and installation will all influence the response time of a sensor. Soil moisture sensors are a powerful management tool, however, their limitations must be appreciated. Data from SMS should always be integrated with other plant based vineyard measures.

Acknowledgments

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Four lessons from a wetting front detector

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Key findings

Wetting front detectors were installed on-farm in a drip irrigated pumpkin crop and a sprinkler irrigated garlic crop. The wetting front detector is a funnel-shaped instrument that is buried in the soil. The funnel concentrates the downward movement of water particles so that saturation occurs at the base of the funnel. The free (liquid) water produced from the unsaturated soil activates an electronic or mechanical float, alerting the farmer that water has penetrated to the desired depth. The detectors retain a sample of soil water that is used for nutrient monitoring.

Four principles emerged that challenged the farmers' perceptions of how they were irrigating. These were as follows:

1. The wetting patterns under drip penetrated deeper into the soil than they had imagined.
2. The wetting fronts from rain or sprinkler irrigation did not penetrate as deeply as they expected.
3. High concentrations of nitrate were measured during the first month after planting from the water samples retained in the detectors.
4. It was easy to misjudge the onset of exponential growth and its impact on water use.

In each case the farmers found it easy to take remedial action. Irrigation intervals were shortened for drip and irrigation time was made longer for sprinklers. Extra effort was made to limit water applications in the early stages so that nitrate was not moved below the rootzone. And, lastly, the farmers were alert to the rapidly escalating demand for water at the onset of exponential growth and the importance of avoiding water deficits during the period when yield is most affected. The experience showed that the basics of irrigation scheduling could be captured using a simple tool and simple information in a relatively short period of time.

Introduction

Against the background of poor adoption of irrigation scheduling tools by farmers, the FullStop wetting front detector was developed in answer to the question, "What is the simplest information that would help a farmer make a better decision?" In a range of trials, the wetting front detector performed well in comparison to other methods of scheduling. This paper evaluates how useful the detectors were in the hands of farmers.

The evaluation took place on a small market garden near the town of Gundaroo in the Southern Tablelands of NSW. A range of high quality organic vegetables is direct marketed to subscription clients and restaurants. The owners had not used irrigation scheduling tools before, but were highly motivated to save water both because of limited supply and their commitment to environmental stewardship. They were keen to use the wetting front detector because of its simplicity and low cost.

In previous work the wetting front detectors had been used in "control" mode. Electronic detectors were connected to solenoid valves and automatically shut off irrigation when the water reached the required depth. The control method worked well, but its success depended on choosing the right combination of detector depth and irrigation frequency. In this study wetting front detectors were used as a learning tool; that is the farmers started with their own experience and then modified their practice according to feedback from the detectors.

Trial design

The soil was a red chromosol with a sandy loam topsoil 300 mm deep overlying a light clay. The pumpkin crop *Cucurbita pepo* var *delicata* was planted 30 December 2000 on raised beds spaced 1 m centre-to-centre. Each bed had a row of drip tape with 2 L/hr emitters spaced 0.5 m apart, with seeds planted next to each emitter. Compost was added before planting at a rate of about 60 m^3/ha. This was incorporated in the top 200 mm of soil.

The pumpkin crop was harvested 20 March 2001, and the crop residues removed. The beds were reformed, and compost added at the same rate as above. The drip irrigation was removed and sprinklers set up with an application rate of between 10 and 15 mm/hr. Garlic, *Allium sativum,* was planted on 25 April in four rows per bed with 100 mm between the bulbs.

Ten electronic wetting front detectors and five mechanical detectors were installed in the pumpkin crop. All detectors were placed with the rim of the funnel 200 mm below the soil surface directly below an emitter. Earlier work showed that the detectors record the wetting front when it is about 100 mm below the rim of the funnel, hence the depth of measurement for this crop was 300 mm. The electronic detectors were connected to a Campbell Scientific CR10X logger that recorded the time the float was up (water in the detector) and time the detector reset (water withdrawn from the detector by capillary action). The time and length of irrigation were logged by a pressure transducer and rainfall logged using an automatic rain gauge. One emitter was connected to a short length of 4 mm tubing and placed directly into the rain gauge to monitor variations in irrigation rate.

Ten electronic and ten mechanical detectors were set up in pairs for the sprinkler irrigated garlic crop. The upper detector of each pair monitored wetting fronts at a depth of about 200 mm and the deeper detector at a depth of 300 mm. Electronic detectors, rainfall and irrigation were logged as above.

The farmers stayed in complete control of the irrigation timing and duration. The mechanical detectors send up a float to give a visible indication that water has reached them. This information was immediately available to the farmers and influenced subsequent irrigations. The logged record was viewed several times during each crop, which further influenced their irrigation decisions.

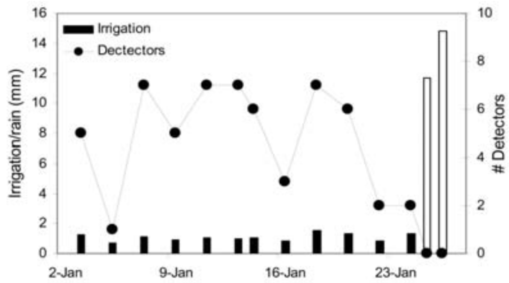
Water samples were removed from the detectors at weekly (summer) or fortnightly (winter) intervals. Nitrate test strips (Quantofix, Macherey-Nagel and Duren) were used to give an immediate approximate measure of the concentration of nitrate moving past the detectors.

Lesson 1. Drip: shorten the interval between irrigation events

The detector installation depth of 300 mm in the drip-irrigated pumpkin crop was chosen because it marked the transition between the topsoil and subsoil. Since fewer roots were observed in the subsoil, it was reasoned that there was little point in pushing wetting fronts below 300 mm if the water might subsequently be difficult for young plants to extract. The very first irrigation showed how hard this goal could be. Just 14 minutes of irrigation, or 612 cm^3 per emitter, was enough to activate five out of ten electronic detectors at 300 mm. On an area basis this equated to an irrigation depth of 1.2 mm (see Figure 38).

The next irrigation on January 5 was 0.7 mm, and only one detector responded. Two days later an irrigation of 1.1 mm set off seven of the ten electronic detectors. Over the first three weeks it became clear that from 1 to 1.5 mm (12 to18 minutes) would set off five to seven detectors; less than 1 mm would set of just one or two of the ten. Clearly very small changes in irrigation elicited a large response from the detectors.

Figure 38. The relationship between the amount of drip irrigation (left axis) and number of detectors that responded to each irrigation (right axis). The open bars at the right represent rainfall, not irrigation.



Rain on January 25 showed the difference between complete and partial wetting of the soil surface (open bars in Figure 38). Rainfall of 11.7 mm was not enough to set off any detectors, and a further 14.8 mm the following day still had no impact. It took 25.1 mm of rain a week later to set off three detectors, before a large rainfall event of 31.9 mm set off nine of the ten detectors.

There are two reasons for the small amounts of drip irrigation required during the early stages. First, the diameters of the wetting patterns averaged 20 cm, representing 6% of the soil surface. Second, the only loss of water was soil evaporation from the small wetted area and some transpiration from the seedling. Once a detector had tripped, the soil between 100 and 300 mm stayed close to the upper drained limit. Wetting fronts move quickly through wet soil, hence the short irrigation required.

Lesson 2. Sprinkler irrigation: make each event longer

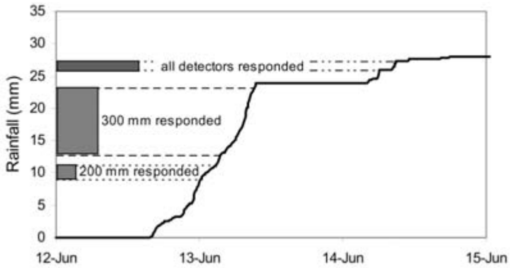
Rain during the drip irrigated pumpkin crop had already alerted the farmer to the fact that more than 15 mm was required to get the wetting front down to 300 mm, unless the soil was very wet. The actual amount of water required is a function of initial water content of the soil. This is the principle behind the operation of the wetting front detector. For a given soil/irrigation rate combination, the speed of propagation of the front is proportional to the initial water content. Dry soil would therefore need a long irrigation and wet soil, a short irrigation.

Detectors were placed at depths of 200 and 300 mm for the sprinkler irrigated garlic crop. It is preferable that wetting fronts do not penetrate as deep under sprinklers as they do under drip irrigation. This is mainly because the entire soil area is wetted by sprinklers. A second reason relates to the way soil water redistributes after irrigation has ceased. Under drip irrigation, water is pulled sideways by capillarity, as well as downwards. Under sprinkler irrigation, all redistribution is downward.

The garlic crop was planted in late autumn, and no irrigation was needed until late spring. Figure 39 gives an example of how the detectors responded to rain during the early stages. Over an 18-hour period there was 23.9 mm of rain falling at a fairly constant rate of 1.3 mm/hr. The soil was moist before this, as rain had fallen four days earlier. All five of the electronic detectors at a depth of 200 mm responded after 9.1 to 11.2 mm of rain. The five electronic detectors at 300 mm responded after 12.8 to 23.3 mm.

After a break of eighteen hours the rain started again with a further 4 mm. In this case all ten detectors at 200 and 300 mm responded after just 2.1 to 3.5 mm. This illustrates the point concerning initial water content and amount of water needed to trip the detectors. It took 23.3 mm to trip all detectors when the soil was moist, and just 3.5 mm when the soil was very wet.

Figure 39. The response of detectors to rainfall during the early stages of the garlic crop. The solid line shows the cumulative rainfall over a three-day period. The horizontal bands denote the period when the first and last detectors at depths of 200 and 300 mm responded. The horizontal band on 14 June shows the period in which all detectors.



Five sprinkler irrigations were applied in the spring and summer. Though the weather was now warm and the crop at maximum leaf area, the detector record shows that, in general, too much water was applied. For each irrigation, except 22 November, all five detectors at 200 mm were activated. On 20 October and 6 and 28 November, three or more detectors at 300 mm were activated. This demonstrates that water was moving past 300 mm and into the clayey subsoil. From this small data set, it appears from 20 to 30 mm per irrigation would be appropriate. The time between irrigations could be longer if more detectors responded and shorter if fewer responded the previous time.

Table 11. The dates and amount of irrigation water applied to the garlic crop and the number of mechanical detectors that responded at 200 and 300 mm.

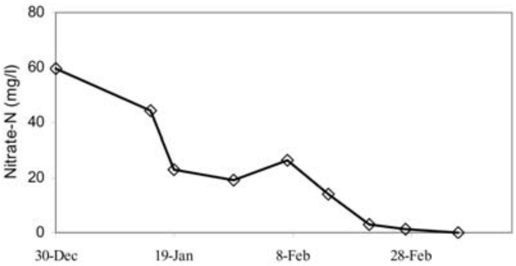
DATE	IRRIGATION (MM)	# FULLSTOPS 200 MM	# FULLSTOPS 300 MM
20 Oct	35.5	5	4
6 Nov	49.5*	5	5
22 Nov	23.4	4	1
28 Nov	46.9	5	3
5 Dec	39.8	5	1

*16 mm irrigation followed by 33.5 mm rain

Lesson 3. Nitrate leaching when the crop is young

Each time a wetting front is detected, a sample of water is retained in the detector. This sample was used to quickly assess the nitrate status of the soil using nitrate test strips. At the start of the season the nitrate-N levels were high for both crops, even though no artificial fertilisers were used. In the case of the drip irrigated pumpkin crop nitrate-N dropped from 60 to 23 mg/L during the early crop stage when total irrigation was only 10 mm. Thereafter nitrate N stayed fairly constant before falling sharply again during the period of exponential growth. It is important to note that the nutrient concentrations would be much higher in the 80% of the soil volume outside that wetted by the drip emitters. Thus the timing of rainfall and hence water and nutrient uptake would have an enormous impact on crop nutrition.

Figure 40. The change in nitrate-N measured from samples stored in the detectors at 300 mm from the drip irrigated pumpkin crop.



Fewer water samples were available from the garlic crop. Since it was not irrigated during the early stages, samples could only be collected after rain. Nevertheless, nitrate-N levels fell sharply after the rains in early June. The nitrate-N levels at 200 mm were quite low by early August, but still moderate at 300 mm, indicating that the topsoil had not been fully flushed. The nitrate-N level at 300 mm had fallen to low levels by mid October, the period when the crop was growing rapidly.

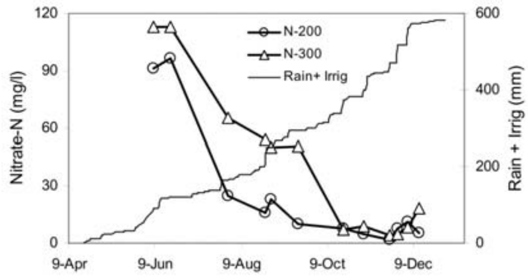


Figure 41. The change in nitrate-N measured from samples stored in the detectors at 200 and 300 mm from the sprinkler irrigated garlic crop (left axis). The line without symbols shows the cumulative.

Lesson 4. Misjudging the onset of exponential growth

The pumpkin crop was irrigated every second day during the first month. With one exception, the first nine irrigations activated five or more detectors. The subsequent nine irrigations activated two detectors or less. Even after the heavy rain on 4 and 5 February, when the soil profile was fully wetted, too little irrigation was given. It was not until 14 February, when the irrigation amount was increased to over 6 mm and the interval shortened to daily, that five or more detectors were consistently activated.

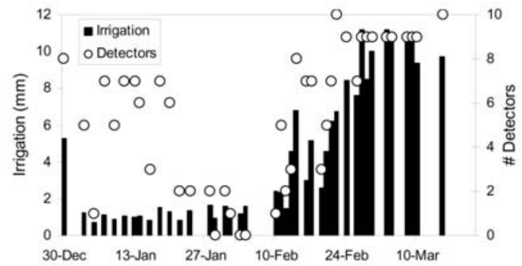


Figure 42. The response of detectors (right axis) to irrigation amount (left axis) in the pumpkin crop from sowing to harvest. The total number of detectors was ten.

The rapid escalation in water use, from around 0.5 mm a day in mid January to 5 mm a day in mid February, reflects the period of exponential vegetative growth. The crop was also growing into increasing temperatures. Flowering and fruitset occur during the latter part of this period, the time when the yield of many vegetable crops is most susceptible to water deficits. Thus, if stress is going to occur at all, it is most likely to occur when the yield is most vulnerable, as deficits accumulate over the exponential growth period.

Conclusion

Irrigation scheduling is often portrayed by scientists as an exercise in accuracy - the idea that there is a defined refill point and upper drained limit and a precise amount of water can be added to satisfy the crop without waste. Things look different on the farm. There are clear differences in the size of plants and hence transpiration, especially during the early stages of growth. The drip emitters in this study were rated at 2 L/hr but varied between 2.3 and 2.7 L/hr. The sprinklers were less uniform.

Farmers are well aware of this variability. Moreover, they often cannot irrigate exactly on cue, either because water is being used elsewhere on the farm, or some other cultural operation requires the irrigation to be withheld. More important is the fact that the farmer must optimise many tasks simultaneously, from soil preparation to marketing. The key questions from the farmer's point of view are what is the value of information in reducing uncertainty, and what does it cost to get that information.

In this study the wetting front detectors quickly honed in on the most important issues to be addressed by the farmer, as outlined in the four lessons above. They did not resolve the question of accuracy but helped the farmer to move in the right direction. After all the soil is a buffer and each irrigation event need not be accurate. It is not important to be right every time – just important not to be consistently wrong.

In the words of the farmer involved in this trial, "the detectors provided a point of dialogue between the experience of the farmer and the language of the scientist". Essentially the detectors are a learning tool. They help the farmer to evaluate their own practice and to modify this practice as their knowledge and confidence grows.

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International soil moisture sensor comparison

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A four-year effort to compare and test soil moisture sensors is drawing to a close. The cooperative research project was sponsored by the International Atomic Energy Agency (IAEA) and included scientists from Australia, Austria, France, Tunisia, and the United States. The laboratory and field comparisons were desired by the IAEA to find if technologies existed that could replace the neutron thermalisation method for soil profile water content estimation. Neutron thermalisation measurements are done with the neutron moisture meter (NMM), a device invented 50 years ago for measurements at any depth desired within an access tube placed vertically in the soil. Accurate profile water content measurements are crucial to determining crop water use and irrigation infiltration, and thus are key to studies of crop water use efficiency and irrigation efficiency. These are two important elements in the goal of producing more crop per drop in our increasingly water-short world. Soon after its invention the NMM was shown to be superior to standard gravimetric sampling because of its repeatability and large soil volume measured.

Devices studied included those measuring frequency domain (capacitance) and time domain responses to changes in soil water content, most of which operated within plastic access tubes. Tests conducted at Bushland included several devices that worked within access tubes: the NMM (model 503DR1.5, Campbell Pacific Nuclear International[1]), the Sentek EnviroScan and Diviner2000, the Trime T3 tube probe, and the Delta-T PR1/6.

The Sentek and Delta-T devices measure the frequency of oscillation of an electronic circuit including a capacitor that is coupled with the soil outside the access tube. The oscillation frequency decreases as soil water content increases. Thus, these are capacitance devices, also known as frequency domain devices. The Trime T3 device attempts to measure the travel time of an electronic pulse along wave guides that are placed in contact with the inside wall of a plastic access tube. Thus, it is a sort of time domain reflectometry device.

These sensors were compared with a conventional time domain reflectometry (TDR) system in large soil columns (three replicates each of three soils important in the Southern High Plains) placed on scales so that column mean water content was determined independently by mass balance to better than 0.01 $m^3 m^{-3}$ (see Figure 43). Tests of sensitivity to soil temperature and sensitivity to the soil-air interface were conducted in these columns.

Figure 43. Soil columns on scales. Columns were 55 cm in diameter and contained a soil depth of 75 cm. Sides of columns were covered with aluminum foil to reflect radiant energy. Columns were covered with plastic sheeting after saturation. In foreground is the Delta-T PR1/6 capacitance probe.

[1] The mention of trade or manufacturer names is made for information only and does not imply an endorsement, recommendation or exclusion by USDA - Agricultural Research Service.

In a winter wheat field, transects of ten access tubes for each device were installed with a spacing of 10 m to study the devices' ability to accurately portray the spatial variability of soil profile water content. The soil was a Pullman silty clay loam, a fine, mixed, superactive, thermic Torrertic Paleustoll with mixed clay mineralogy including large proportions of illite and montmorillonite (Soil Survey Staff, 2004). This soil has an A horizon containing 35% clay, a strong Bt horizon containing 50% clay, and a Btk horizon containing up to 50% $CaCO_3$; from which horizons, the A, B, and C soils, respectively, were derived for packing the soil columns. Measurements were taken over several months, beginning in a relatively dry soil profile and continuing as rain and evapotranspiration wetted and dried the field, and as one half of the field was irrigated periodically.

Soil column tests showed that factory calibrations were not accurate for the devices used in access tubes, all of which would require soil-specific calibrations to yield more accurate results (see Table 12). The three soils varied most in clay content, which was of mixed mineralogy (largely illitic and montmorillonitic), and in calcium carbonate content.

Using manufacturer calibrations, conventional TDR, which used a Tektronix cable tester (model 1502C) and three-rod probes (20 cm long) buried in the soil, was at least twice as accurate as any of the devices used in access tubes, being within ± 0.024 m^3 m^{-3} of mass balance water content on average in saturated soil. Only the NMM and conventional TDR were not significantly sensitive to soil temperature (see Table 13).

Temperature sensitivity of both Sentek devices was small enough not to be problematic in field studies; but sensitivities of the Delta-T PR1/6 and Trime T3 were problematic, particularly in wet soil. Tests of response to nearness to the soil-air interface revealed that the soil volume measured by all the devices used in access tubes decreased as water content increased, except for the Trime T3 probe. Only the NMM and Delta-T PR1/6 had volumes larger than the sensor height in wet soil.

Table 12. Saturated column mean volumetric water contents (VWC) by mass balance, and device errors (m^3 m^{-3}).

		Difference from VWC by mass balance					
SOIL	VWC BY MASS BALANCE	DELTA-T PR1/6	DIVINER-2000	ENVIRO-SCAN	TRIME T3	NEUTRON[1]	TDR
A	0.433	1.339	0.084	-0.037	0.064	0.000	0.002
B	0.474	1.312	0.001	-0.062	0.088	-0.016	0.004
C	0.481	1.244	-0.037	-0.104	0.055	-0.014	-0.042
RMSD[2]		1.299	0.053	0.073	0.070	0.012	0.024

[1] The neutron moisture meter was field calibrated.
[2] Root mean squared difference from VWC by mass balance.

Table 13. Temperature sensitivity[1] in saturated soil[2].

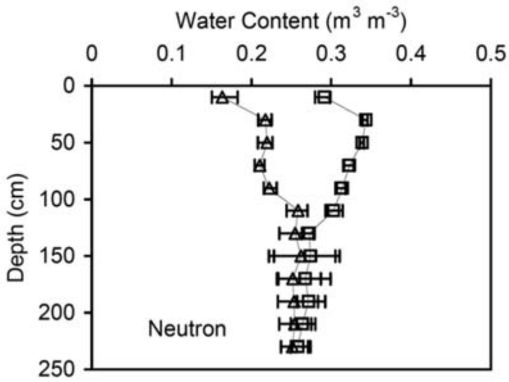
INSTRUMENT	SLOPE (M^3 M^{-3}) ºC-1	R2	RMSE (M^3 M^{-3})
Trime T3	0.0204	0.75	0.0012
Delta-T PR1/6	0.0250	0.94	0.0002
EnviroSCAN	0.0010	0.88	0.00001
Diviner2000	0.0019	0.77	0.0001

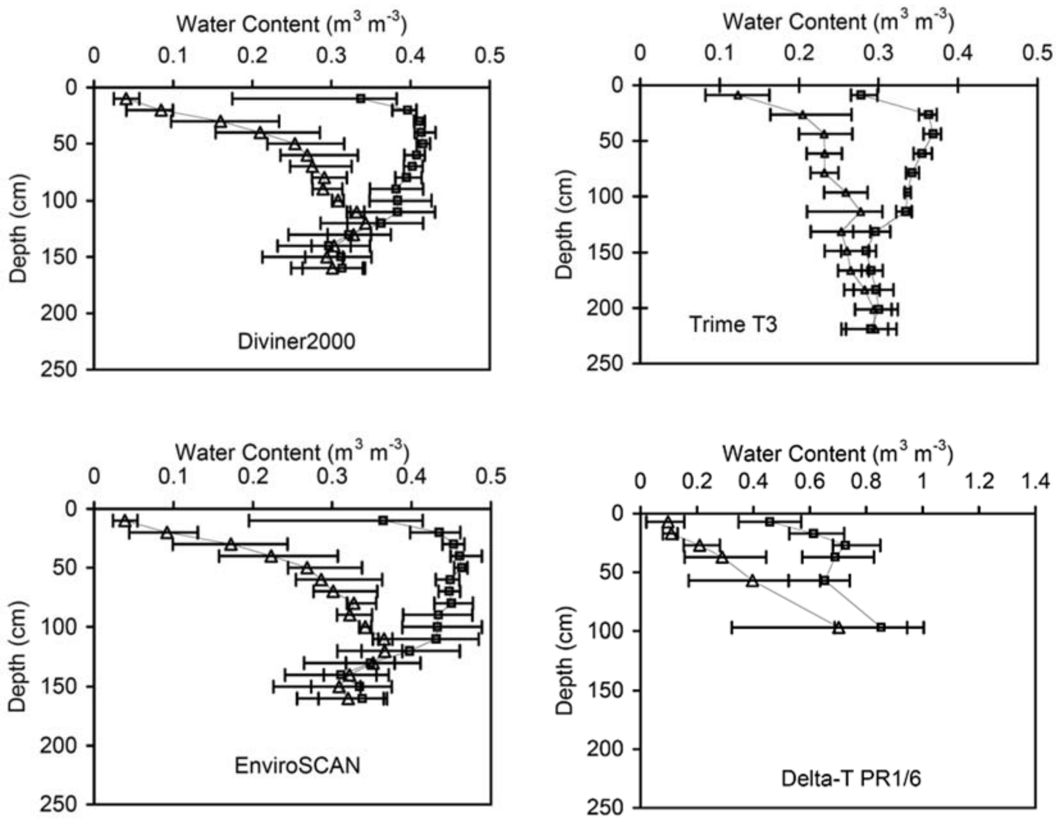
[1] Measured at 25 cm depth.
[2] Regressions and regression slopes were not significant for conventional TDR and the neutron moisture meter.

Field tests revealed that variability across the ten access tubes was smallest for the NMM, followed by the Trime T3, both Sentek devices, and the Delta-T PR1/6 in increasing order of variability (see Figure 44). Variability in transects of gravimetric moisture measurements, accomplished with a hydraulically pushed sampling tube, was close to that of the NMM, but was widely variable from one date to the next because of the destructive nature of gravimetric sampling, which required that sampling locations be changed at each sampling date.

The ability to accurately sense changes in profile water content due to irrigation was best for the NMM and Trime T3 devices, and worst for the Delta-T PR1/6. The larger variability of the capacitance devices (Sentek and Delta-T) was probably due to the much smaller soil volumes sensed by capacitance methods, which renders these devices more sensitive to both small scale variability of soil water content in volumes smaller than the representative elemental volume, and sensitive to any soil disturbance or air voids that might be created during access tube installation (all access tubes were installed according to manufacturer recommendations and with extreme care, sometimes requiring several hours to a day to install one plastic access tube).

Figure 44. Plots of field profile soil water content as reported by five moisture sensing devices discussed in the text using the factory calibrations, except for the neutron probe for which a field calibration had been previously accomplished. Data are from transects of ten access tubes for each device, spaced at 10 intervals across a winter wheat field, one half of which was irrigated. Plots are for the mean of five access tubes in each half of the field on 19 November 2003. Error bars around the mean values represent the maximum and minimum readings. Note the expanded scale for the Delta-T PR1/6 plot.





In general, the comparison studies revealed that there is not yet a suitable replacement for the NMM for soil water balance studies. Some alternative devices are too sensitive to soil temperature. Most measure such small volumes that they produce highly variable readings in the field, probably because they are sensing volumes smaller than the representative elemental volume for soil water content. Similarly, they are rendered sensitive to soil disturbance or voids caused by access tube installation. Also, the alternative devices are difficult to field calibrate for two reasons. First, they measure volumes that are too small to allow volumetric soil sampling within the device-measured volume surrounding an access tube. Second, unlike the NMM and conventional TDR, their measurand is nonlinearly related to water content, requiring at least three widely different water contents in the field to be measured to establish a calibration curve. Only the Trime T3 tube probe and the NMM allowed measurements deep enough to completely assess changes in profile water content due to crop water extraction and infiltration of irrigation and rain in all foreseeable circumstances. This is deeper than 2.5 m to even 3 m.

Studies at other locations produced results similar to those described here, but differed in soil environments, sensors compared, experimental methods and other aspects. The final Consultants' Meeting on "Comparison of Soil Moisture Sensors between Neutron Probe, Time Domain Reflectometry, and Capacitance Probes," was held March 24-28, 2003 at IAEA Headquarters in Vienna, Austria. Research reports detailing the studies are expected to be published in a special issue of the *Vadose Zone Journal* in 2005.

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CHAPTER 7.

RESOURCES AND CONTACTS

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Web resources and recent publications

http://www.microirrigationforum.com/new/sensors/

http://www.sowacs.com

International Soil Moisture Equipment Comparison -
http://www.cprl.ars.usda.gov/wmru/pdfs/WF-vol5-No2.pdf -

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APPENDIX 1

TIME DOMAIN REFLECTOMETRY – AN INTRODUCTION

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Introduction

Time-domain reflectometry (TDR) has been used in various cable industries for decades, to locate the position along a cable at which a break or other damage has occurred. The approach was based upon sending an electro-magnetic wave pulse along the cable in question, and "looking" for an echo to be reflected back. Part of the pulse will be reflected wherever the pulse meets a partial "interface", such as some damage or a crossed wire. The entire pulse may be reflected should it meet a complete interface with a non-conducting material, such as in the case of a break. Knowing the speed, at which the pulse moved through the cable, and the timing of the reflected pulse(s), allowed the operator to calculate where to look for a problem. This application is also used in counter-surveillance activities to find where taps might have been placed on telecommunication conduits (a big problem in the cloak and dagger world of soil espionage). This relies upon an unauthorised wire attached to a cable causing a partial reflection of a pulse.

So, if we know the speed at which a pulse travels along a cable, we can measure the travel-time of the pulse to get to the end and back (using an oscilliscope), and thereby calculate the distance the pulse travelled. Conversely, if we know the distance over which the pulse travelled, the travel-time tells us the speed at which the pulse travelled and therefore something about the properties of the conducting material.

The key property that influences the speed of conduct of an electro-magnetic wave through a material is the dielectric constant (κ) of that material. When an electric field or electro-magnetic signal is imposed on a material, a partial displacement of electrons occurs within the atoms and molecules of the material. The molecules of polar liquids will also become aligned with the field. The dielectric of a medium is a measure of how much an electric field is reduced (relative to a vacuum) by these polarization effects. With increasing dielectric constant, not only is the electric field reduced, but the velocity of propagation of an electromagnetic signal is also reduced. That is, the higher the dielectric constant, the slower a pulse will travel through that medium. The velocity (v) of the propagation is inversely proportional to the square root of the dielectric constant (κ):

$$v = \frac{c}{\sqrt{\kappa}} \qquad \text{Equation 1}$$

where c is the speed of light.

Therefore, if we know the velocity of a pulse, we can calculate the bulk dielectric constant. Because water molecules are dipolar and mostly unbound, they readily twist to align with electro-magnetic fields, therefore water has a high dielectric constant (80.4 at 20 °C, 78.5 at 25 °C, **κ is unitless as it is a ratio of energies**). Molecules in soil solids are mostly fixed, therefore the solids have a low dielectric constant (between 3 and 5). The dielectric of air is effectively 1. Metals and magnetic materials have very high values for the dielectric constant. So, in soil that contains no magnetic or metallic components, water dominates the value of the dielectric constant; the more water, the closer to the value for water. All we need to do is to send a pulse a known distance into the soil and back again, and measure the time between sending the pulse and receiving the reflection.

The adaptation of the time-domain reflectometry (TDR) technique for soil moisture measurement occurred in the late 1970s with the seminal work of Topp, Davis and Annan published in 1980. This research linked the measured travel time of an electro-magnetic wave with the volumetric moisture content (θv, m^3 m^{-3}) of different soil. The relationship, a third-order polynomial, is still the most widely used calibration for conversion of the measured apparent dielectric to estimated θv.

The time-domain reflectometry (TDR) technique is based on the reflection of a fast rise-time voltage pulse generated in either a step-wave or impulse formation. Essentially, the travel time of the EM wave along probes buried in the porous media is measured and the k calculated. The κ is then related to θv either empirically or via various physically based mixing models. Instruments may be adapted cable testers or dedicated instruments operating in a portable or stationary capacity.

Principles of TDR

A waveform in the transverse electromagnetic mode (TEM) is generated and propagated using a shielded extension cable to an unshielded guide (called a waveguide or probe) of known length embedded in the soil. At the end of the probe the wave is reflected because of the high impedance and returns to the TDR instrument. The phase velocity (v_p) of a TEM in a medium is related to the apparent dielectric and magnetic permeability (μ H m^{-1}) by the equation:

$$v_p = \frac{1}{\sqrt{(\kappa\mu)}} c_0 \qquad \text{Equation 2}$$

Where c_0 is the velocity of the EM wave in a vacuum (free space). The μ ($4\pi \times 10^{-7}$ H m^{-1} in a vacuum) of the soil usually equals unity and the loss factor is thus neglected. The travel time of the TEM wave along the probes (of length L) is simplified:

$$t = \frac{2L}{v} \qquad \text{Equation 3}$$

If there is negligible loss then Equation 3 with rearrangement simplifies to:

$$\kappa = \left(\frac{c\Delta t}{2L}\right)^2 \qquad \text{Equation 4}$$

This equation is fundamental to the TDR technique and dielectric determination in porous media. Note that either L or $2L$ are used in this equation depending on the software of the TDR system. Some systems, such as TRASE TDR (SEC) automatically considers the travel length 'down and back' along the probes (Soilmoisture Equipment Corporation, 1993). If soil is saturated, the travel time of the EM wave along the probes is prolonged and the calculated κ is high. If the soil is dry the travel time along the probes is short and the κ is therefore low.

Equipment

1. One TDR unit, consisting of a modified cable tester with an impedance matching transformer connected to a parallel rod wave connector. (Triple rod wave guides do not require a balance transformer.) We use a Tectronix 1502b cable tester modified with a RS232 interface. This is a simple addition, though the interface switches probably need changing.
2. Wave guides consisting of matching pairs or triplets (depending on the TDR system) of 5.0 to 6.35 mm diameter stainless steel rods with lengths between 0.1 and 0.6 m. We use triplets of various lengths

3. One installation implement and drop hammer for installing the rods in the soil, if needed.
4. One alignment guide for maintaining the rods parallel when inserting them in the soil and an extracting device for retrieving the rods after measurements are taken. We have taken to fixing the cable to the three rods and encasing the join in resin.
5. One 12 volt rechargeable external battery with power cable and fuse as specified by the manufacturer.
6. A battery charger for internal and external 12 volt batteries that are used with the TDR unit.
7. Steel core sampling equipment as specified for the neutron probe, for use whenever the TDR measurements of κ require calibrating against θv, by a field core sampling procedure. This is not really a necessity, as the universal calibration generally holds.
8. Some way of analysing the trace (we use a computer, with TDR software supplied free of charge from HortResearch, Palmerston North, NZ (for a DOS program), or from Utah State University's Soil Physics Group (http://psb.usu.edu/wintdr98/index.html) for a Windows program). Commercial ready to go TDR units, of course, have their own software.
9. Optional multiplexing unit and power supply.

Procedure

The details of procedure for initiating and obtaining a TDR reading of the trace displayed on the oscilloscope depend on the software provided either with a microprocessor inside the TDR unit or separately with a laptop computer connected to the unit. Two modes of operation are used. The manual mode is used first to introduce the voltage pulses that the unit uses to produce the graph or "trace" of voltage *vs* time, and secondly to adjust and scale a "capture window". The "capture window" is for isolating that portion of the trace which is used to determine the travel time "*t*" of the voltage pulses within the parallel steel rods that comprise the wave guide.

With TDR units using three parallel rods as wave guides, the automatic mode may then determine t, κ and θv directly, provided the appropriate calibrations of wave guide and κ versus θv have been entered in the software programme. With TDR units using two parallel rods as wave guides, the "zero set time" (or time to the start of the wave guides) is set manually, and the "time to point of reflection" (time to the end of the wave guides) is read automatically to determine the travel time t from which the software calculates κ.

The software then refers the value of κ to a calibration of κ versus θv to determine θv. Both types of TDR systems also provide for independent measurement of the travel time "*t*" using the manual mode, because the software in automatic mode cannot always cope with the range of possible TDR traces. Hence it is essential for the operator to be able to view the trace and verify the analysis obtained from the automatic mode.

Most of the electric field intensity associated with the voltage pulses in the wave guide is located in the medium, e.g. soil, water or air, immediately next to the metal rods. Consequently, θv determinations derived from TDR measurements require that good contact is always maintained between the soil and metal surfaces of the rods. Cracks and air gaps forming around the rods, as may occur when inserting the rods in hard dry soil, or when they are left in the ground and the soil dries, can pose significant problems. Parallel alignment of the rods that comprise the wave guide is not as critical, nevertheless, their degree of non-alignment may affect the precision with which the travel time "*t*" is determined.

Both of the above effects demand that care be taken when inserting the rods in the soil and maintaining them parallel. For soil at or near field capacity, rods of 0.15 m or less can be connected directly to the waveguide connector and pushed by hand into the soil. Rods longer than 0.15 m require an alignment guide (item 4 on the equipment list) to maintain them parallel as they are pushed into the soil. The alignment guide is then removed within the last 10 cm of insertion so that the bottom surface of the wave guide connector can be pushed firmly against the surface of the soil. For soil of greater resistance than mere pushing by hand allows, it is advisable to first secure the rods in a separate installation implement and then insert the rods into the soil through the alignment guide using a drop hammer, as specified in items 3 and 4 of the equipment list. Some models of wave guide connector may also serve as an installation implement using the same procedure. This combined feature has the advantage of facilitating the last stage of rod insertion following the removal of alignment guide and of ensuring a firm contact of the wave guide connector with the surface of the soil as described above.

Calibration

The travel time as read directly from the trace will also include the signal time within the wave guide connector and very likely other artefacts associated mainly with the instrumentation. Calibration of the parallel rod wave guide assembly and the TDR unit is therefore essential to determine their measurement characteristics before inserting the rods of the wave guide into the soil. This calibration is done by reading the travel time "*t*" from the trace first with rods in air and then again when they are completely immersed in water so that the bottom surface of the wave guide connector contacts the water surface. The water container should provide ample clearance around the sides and ends of the rods at least equal to the spacing between the rods and the temperature of the water should be measured.

The dielectric constant of air can be taken as $\kappa_{air} = 1$ and is independent of temperature. Water at 25°C has a value $\kappa_{water} = 78.54$ which can also be specified to within ± 0.03 % at other temperatures (T °C) by the following relationship:

$$\kappa_{water} = 78.54[1 - 4.579x10^{-3}(T-25) + 1.19x10^{-5}(T-25)^2 - 2.8x10^{-1}(T-25)^3] \qquad \text{Equation 5}$$

By knowing the exact values of κ in air and water, and the measured values of the travel times in air and water as read from the trace of the TDR unit, the calibration constants A and B of the instrument for a specified rod length are determined from the relationship:

$$\sqrt{\kappa} = A(t + B) \qquad \text{Equation 6}$$

which is the actual working equation that the software uses to calculate the bulk dielectric constant κ of the soil, as described in the "Pyelab" TDR users guide.

Air and water are nearly ideal dielectric media and serve to calibrate the instrument for obtaining κ. A separate calibration is also necessary in order to derive the θv of the soil from the measured valued of κ. For this purpose a "universal" calibration relating θv to κ as measured by TDR was determined by Topp *et al.* (1980) for a wide range of soil textures and porosities in the form of a third order polynomial:

$$\theta v = -5.3x10^{-2} + 2.92x10^{-2}\kappa - 5.5x10^{-4}\kappa^2 + 4.3x10^{-6}\kappa^{-3} \qquad \text{Equation 7}$$

it can be used to determine θv between 0.05 and 0.55 m^3m^{-3} from TDR measured values of between 3 and 40. If absolute values of θv are required, then it is best to perform a separate calibration for the particular soil type. The procedure for calibration is the same as for the neutron probe, involving soil core sampling in the same volume of soil that the TDR measurements are taken. However, in irrigation scheduling where it is usually only necessary to monitor changes in water stored within the root depth of the crop, the estimates derived from the "universal" TDR calibration are acceptable.

The universal calibration predicted the θv (± 0.025 m^3m^{-3}) from measured κ for mineral soil between 10 °C < T < 36 °C for the range of moisture contents $0 < \theta v < 0.55$ m^3m^{-3} with a variation in ρ_b from 1.14 to 1.44 Mg m^{-3}. This equation still forms the basis of most reported θv by the TDR technique. To account for organic soil Roth *et al.* (1992) developed Equation 8 and Equation 9 for ferric soil. The ferric soil (Rhodic ferralsols, FAO) contained 18.4 % and 18.5 % iron respectively (Roth *et al.*, 1992). They concluded that if errors of ± 0.015 m^3m^{-3} for mineral soil and ± 0.035 m^3m^{-3} for organic soil are acceptable then site specific calibration was unnecessary.

$$\kappa(\theta) = 0.994+10.51\theta+88.54\theta^2+28.92\theta^3 \text{ (organic soil, } R^2 = 0.996, \text{ SD} = 2.52) \quad \text{Equation 8}$$

$$\kappa(\theta) = 3.92\text{-}46.07\theta+374\theta^2+320\theta^3 \text{ (ferric soil, } R^2 = 0.987, \text{ SD} = 1.59) \quad \text{Equation 9}$$

The empirical relationship $\kappa(\theta)$ is limited by conditions such as dry soil ($\theta < 0.05$) where the κ_{soil} dominates and in other porous media such as grain and ore. Further questions relating heavy soil types and the effect of bound water, especially in Australian conditions, have focussed research towards determining a physically based relationship between measured κ and reported θv.

Considerable effort has been undertaken on the development of a physically based calibration for the TDR technique. To date the ability to use the refractive index (the square root of the apparent dielectric, $\sqrt{\kappa}$) indicates a linear relationship with some change in the coefficients still depending on soil type. A physically based calibration is preferred in determining the $\kappa(\theta v)$ relationship in soil. However, until now the extra parameters required have deterred most users from employing physically derived mixing models and the use of the refractive index. White *et al.* (1994) though acknowledging the benefit of such an approach, suggest that most physically derived models are in fact "semi-empirical". And the majority of reported θv measurements by the TDR technique are still determined by the Topp *et al.* (1980) "universal" empirical Equation 10 or derivatives thereof.

Bulk density effect on TDR calibration. Particular attention has focussed on the effect of soil bulk density or porosity on the measurement of κ by TDR. An increase in ρ_b may yield a corresponding increase in specific surface area leading to higher apparent κ. Incorporating ρ_b into their calibration of θv against time Ledieu *et al* (1986) showed a change of 0.1 Mg m^{-3} caused a variation of 0.0034 m^3m^{-3} in reported ρ. Jacobsen & Schjonning (1993a) included ρ_b, clay content and organic matter content in a third order polynomial equation (Equation 10) from their study of five topsoil and subsoil samples. The incorporation of ρ_b, clay content and organic matter (OM) though significant, improved the fit (adjusted r^2) only marginally from an already very good 0.980 to 0.989.

$$\theta = -3.41\times10^{-2}+3.45\times10^{-2}\kappa-1.14\times10^{-3}\kappa^2+1.71\times10^{-5}\kappa^3-3.70\times10^{-2}\rho_b +7.36\times10^{-4}\%\text{clay}+4.77\times10^{-3}\%\text{OM} \quad \text{Equation 10}$$

A calibration of θv to κ to increase sensitivity to change in ρ_b by normalising with respect to ρ_b gives (Malicki *et al.*, 1996):

$$\theta(\kappa,\rho_b) = \frac{\sqrt{\kappa}-0.819-0.168\,\rho_b-0.159\rho_b^2}{7.17+1.18\rho_b} \quad \text{Equation 11}$$

In a field study conducted by Jacobsen & Schjonning (1993b) the authors found that the inclusion of ρ_b did not improve their laboratory calibration equation (Equation 10) concluding this was due to the small improvement offered versus the uncertainty of measurement.

Bulk soil electrical conductivity (EC) effect on θv measurement

The bulk soil electrical conductivity (EC) can affect the determination of θv in two ways. Firstly, there is an increase in the apparent dielectric constant. The TDR technique is then susceptible to overestimation of the θv as is detailed by Dalton (1992), who concluded when *pore-water* reaches 0.8 S m^{-1} overestimation of θv occurs. Vanclooster *et al.* (1993) suggest this figure could be 1.0 S m^{-1}. It is likely then, that at large EC calibration will be required. It has been suggested that to avoid this situation, short extension cables and reduced length of probes will assist in end-point determination. To date there is no indicative study of this limitation in Australian soil. Secondly, in highly saline soils, conductivity losses may result in insufficient reflectance for trace interpretation. Clearly the interaction of the EC and κ in relation to dielectric losses is complex and requires further detailed understanding. However, remember that EM loss can be minimised by generating frequencies between 50 MHz and 10 GHz.

Field operation

In the field, probes (mainly stainless steel) are generally of two forms, being either balanced (two-wire) or unbalanced (three-wire). Generally, two wire probes are used for portable measurement and the three wire probes for permanently placed probes. For detailed discussion on this see Zegelin *et al.* (1989).

Effective length of probes (and therefore the depth of measurement) will be determined by the power of the step pulse generated by the TDR, the soil type (heavy clay attenuates the EM wave more than sandier soil types) and the moisture content of the soil. Probes of 2 m length have been successfully used to measure moisture content in a gravelly Australian soil. However, in wet heavy clay soil probe (waveguide) length has sometimes been reduced to as little as 200 mm. This current problem is being rectified by increasing the power and stability of the EM wave and by coating probes with a thin cover of a low dielectric material. The aim is to ensure that a percentage of the wave will travel the length of the probes and be reflected allowing determination of Δt. Coated rods are particularly useful for difficult to replace installation and highly saline conditions (e.g. in cement).

A practical application of the TDR technique is in irrigation scheduling. Optimum rod lengths and rod diameter for this purpose are specified in item 2 of the equipment list. The rods are held parallel in the wave guide connector or installation implement and inserted vertically into the soil to determine the "full" and "refill" points for the particular stage of growth and root depth of the crop, as previously described. For longer term monitoring of the changes in water content within the rootzone, the parallel rods of the wave guide are inserted at an angle of 45° off the vertical to reduce the tendency for initiating cracks and holes which can act as preferential paths for water during irrigation or rainfall. Alternatively, to be able to elucidate moisture profiles, waveguides can be installed horizontally at various depths from a pit. The pit is then backfilled leaving the BNC end of the cable accessible at the surface. The main advantage of the TDR technique for irrigation scheduling is that individual soil profile calibrations involving separate determinations of θv, are usually not necessary. This advantage allows for routine multi-sited monitoring of changes in water stored, using only the TDR measurements of κ and the "universal" calibration of θv vs κ.

When used in conjunction with a multiplexer, a single TDR unit can be used to monitor several waveguide locations (typically 16). Most TDR software allows the measurement of θv (and σ) at several sites (through the multiplexer), at selected time intervals, with data logging. This is very useful for monitoring dynamic processes, such as profile wetting and solute transport.

Another advantage is that the volume that the TDR technique samples is suitably large for most field applications. For dual rod wave guides, the soil sampled is essentially an elliptical cylinder around the length of the rods. For the triple rod waveguide, the volume sampled is approximately a right cylinder around the central rod with a radius equal to the spacing (50 mm) between the rods. Nevertheless, good contact should always be maintained between the soil and the metal surfaces of the rods, as emphasised previously.

Other factors which may limit the use of the TDR technique are the large proportion of bound water found in some expansive clay soil coupled with high surface conduction and sharp breaks in moisture content. Bound water has values of dielectric constant approaching that of the soil solids to point where the water contributing to the bulk dielectric constant can no longer be distinguished from that of the solids. Surface conductive soil limits the rod length that can be used in the wave guide connector by reducing the amplitude of the reflected signal to the point where it can no longer be detected, even though the soil may not necessarily be high in free salt content. The electric conduction in this case occurs significantly through the ions associated with the electric double layer of the clay particles. Sharp breaks in soil moisture content along the length of the rods produce "traces" that may not always be analyzable by the software in the automatic mode and must be verified manually. Stony soils offer difficulties for waveguide insertion and, depending on the nature of the stones, for calibration. Extremes in temperature may need to be considered also, and taken into account when calibrating the TDR κ value for water. Long-term buried installations sometimes have degraded traces, due to deterioration of the waveguide-cable join. With time, the traces become increasingly difficult to interpret. Buried waveguides should have the cable-waveguide link protected, such as encased in resin.

TDR for measuring solute concentration

Dalton *et al.* (1984) first proposed the use of TDR for measuring the electrical conductivity (σ) of the soil. They demonstrated that the attenuation of a voltage pulse along the probe could be used to deduce σ. This attenuation was used to infer the solute resident concentration (C_r). Since then several different approaches have been suggested for using the attenuation of the reflected signal to determine σ, and they are based on use of various values of the voltage at different points along the TDR-trace. However, so far it remains unresolved as to which of the alternative expressions is the most appropriate for the calculation of σ.

It must be remembered that bulk soil electrical conductivity is quite different to the electrical conductivity of the soil solution. Conductance is also influenced by surface charges of minerals and ions in the electric double layer (surface conductance). There is also a strong dependence of electrical conductivity on the moisture content of the soil. As the soil dries, pathlengths of conductivity increase (tortuosity), increasing the resistivity and thereby decreasing the conductivity for the same solution electrical conductivity. It is conceivable that the conductivity mediated by solids may change, if the mineral's surface electrical properties are changed, such as through pH change or *P* adsorption. All these factors will then be affected by temperature. These difficulties mean that a universal calibration between bulk electrical conductivity and solution electrical conductivity is unlikely. Nevertheless, the simultaneous measurement of θv and σ has meant that TDR has become a valuable tool in solute transport studies.

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APPENDIX 2

FREQUENCY DOMAIN REFLECTOMETRY

The following critique is an excerpt from White and Zegelin (1995).

When a potential is placed across the plates of a capacitor containing a dielectric, charges induced by polarisation of the material act to counter the charges imposed on the plates. Ideally, the capacitance between two parallel plates is related to the dielectric constant.

It is assumed that the lateral dimensions of the plate are much larger than the plate spacing and that all other sources of capacitance (C_e) are insignificant. However, these conditions are seldom met.

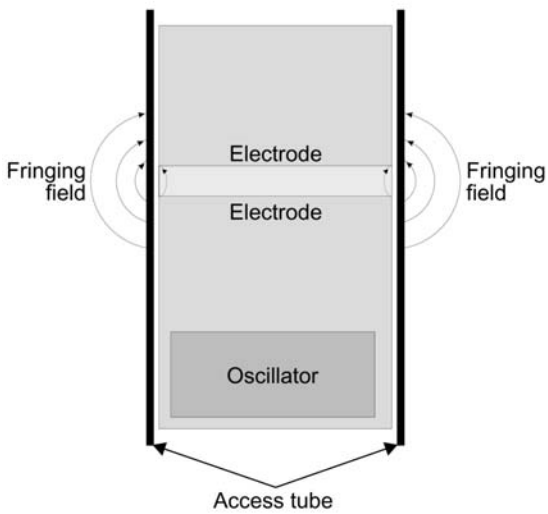
The presence of electrolytes and mobile surface charges in soils tends, at low measurement frequencies, to produce interfacial polarisation at the electrode surfaces, causing C_e to swamp the contribution by the soil's dielectric constant.

These problems plagued early attempts to use direct measurements of capacitance to determine soil-water content and for a long time discouraged interest in the technique (Gardner, 1987). The recognition that interfacial polarisation could be overcome by using measurement frequencies above 50 MHz has renewed interest in the capacitance technique as an effective tool for monitoring *in situ* changes in soil-water content (Thomas, 1966). Advances in electronics have permitted the routine use of cheap high frequency circuits in the 50 to 150 MHz range thus increasing the accessibility of the technique (Dean *et al.*, 1987).

Measurement principles. In recent improvements to the capacitance technique, the capacitor containing the volume of soil to be measured forms part of the feedback loop of an inductance-capacitance resonance circuit of a Colpitts or Clapp high frequency oscillator (Wobschall, 1980; Dean *et al.*, 1987). The resonance angular frequency of the oscillator, ω_r, is related to the capacitance of the soil probe which is in turn related to the dielectric constant of the soil.

Probe geometry. The geometry of the parallel plate capacitor is optimal since almost all the electric field is contained between the plates and the contained field strength distribution varies as the reciprocal of distance from the plate. Such parallel plate probes have been widely used in laboratory determinations of water content of porous materials, particularly samples of stored grains, but their use in the field is less convenient because of plate insertion and soil disturbance problems.

Figure 45. Capacitance probe cylindrical electrodes for use with plastic access tubes.



More recently designed capacitance probes use split cylindrical electrodes that may be buried in the soil or positioned at different depths down plastic access tubes embedded in soil, as shown in Figure 45. The oscillator circuit and other electronics are placed within the cylindrical electrode probe (Dean *et al.*, 1987). It is clear from Figure 45 that not all the field between the cylindrical electrodes propagates into the soil. Some also flows through the plastic access tube and through the interior of the probe. The relative amounts of the field penetrating the probe, access tube and soil compartments will depend on the radius of the cylindrical electrodes, the gap between the probes and the relative dielectric constants of the compartments. As the radius and gap becomes smaller and as the soil becomes wetter we expect less of the field will be proportioned to the soil compartment. The dielectric material between the cylindrical electrodes must have a low dielectric constant to ensure an adequate and accurate response to low soil dielectric constant, i.e., low soil-water content.

Zone of influence. Two critical questions arise concerning any measurement probe placed in a porous material: over what region does the probe measure; and what is the spatial weighting of its response within that region? Dean *et al.* (1987) attempted to address those questions for the capacitance probe through an approximate experimental analysis of the region of influence of a probe similar to that in Figure 45. It is clear from Figure 45 that most of the field strength will be concentrated in the gap region between the plates. In normal use at least part of this region is occupied by the plastic access tube.

Dean *et al.* (1987) found that the region of influence is indeed restricted to a relatively narrow disc-shaped region surrounding the probe and centred on the gap between the electrodes. The probe is most sensitive to the region immediately adjacent to this gap. This means that the probe is very sensitive to any air gap between the probe, access tube and the soil and that special care must be exercised in installation (Bell *et al.*, 1987). A rigorous analysis of the effect of probe radius, plate gap width, plate width and access tube thickness on the zone of influence and the spatial sensitivity of capacitance probes has yet to be undertaken.

Response to water content changes

The relationship between the circuit's resonance frequency and the volumetric water content of the clearly shows that as θ increases, there is a non-linear decrease ω_r. Published data do show such a decline in resonance frequency with ω_r decreasing by 29% when the capacitance probe is moved from air to pure water (Bell *et al.*, 1987).

Extant calibration curves for different soils have used a very narrow water content range and have assumed that calibration is linear over that range. Somewhat disturbingly, these calibration curves show an almost ninefold variation in slope (Bell *et al.*, 1987). This may indicate that the assumed constants in the calibration equation are in practice not constant, or it may be due to electrical conductivity of the soil, whose effect on the capacitance probe's performance appear not to have been explored systematically. Whatever the reason for the considerable disparity been calibration curves, these differences mean that calibration curves must be constructed for each site.

The stability, sensitivity to temperature change, and repeatability of measurements with the capacitance probe have been examined. It is found that measurement repeatability is better than 0.005 volumetric water content, and sensitivity to small changes in volumetric water content in dry materials is large. This repeatability and sensitivity are part of the strength of the capacitance probe technique.

APPENDIX 3

NEUTRON MODERATION METHOD

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Introduction

The neutron moderation method (NMM) is widely used in soil water measurement studies in Australia and throughout the world. Indeed as reported in the July 1999 (no. 73) edition of *Wispas* (HortResearch, NZ), the neutron method has finally "made it" into mainstream science. The technique is indeed well established and its ubiquitous use a testimony to those who developed the *in situ* capabilities.

The neutron moderation technique is based on the measurement of fast moving neutrons that are slowed (thermalised) by an elastic collision with existing hydrogen particles in the soil. Gardner & Kirkham (1952) developed the NMM technique with others such as van Bavel *et al.*, (1956), Holmes (1956), and Williams *et al.* (1981).

The high energy, fast moving neutrons are a product of radioactive decay. Originally the source utilised was Radium/Beryllium, however more commonly used today is Americium/Beryllium. For example, Campbell Scientific Nuclear utilise a sealed Am^{241}/Be source of strength 100 mCi ($=3.7 \times 10^{-8}$ Bq). Fast neutrons (> 5 MeV) are expelled from the decaying source following interaction between an alpha emitter (Am^{241}) and Be. The high-energy neutrons travel into the soil matrix where continued collisions with soil constituent nuclei thermalise the neutrons, that is the neutron energy dissipates to a level of less than 0.25 eV. The returning thermalised neutrons collide in the detector tube (BF_3) with the Boron nuclei emitting an alpha particle that in turn creates a charge that is counted by a scalar. This is related to the ratio of emitted fast neutrons.

The transfer of energy from the emitted fast neutron (where mass is 1.67×10^{-21}kg) is greatest when it collides with particles of a similar size. In the soil matrix H^+ is a similar mass yielding elastic collisions with emitted high-energy neutrons. Hydrogen (H^+) is present in the soil as a constituent of soil organic matter, soil clay minerals, and water. Water is the only form of H^+ that will change from measurement to measurement. Therefore any change in the counts recorded by the NMM is due to a change in the water with an increase in counts relating to an increase in soil water content.

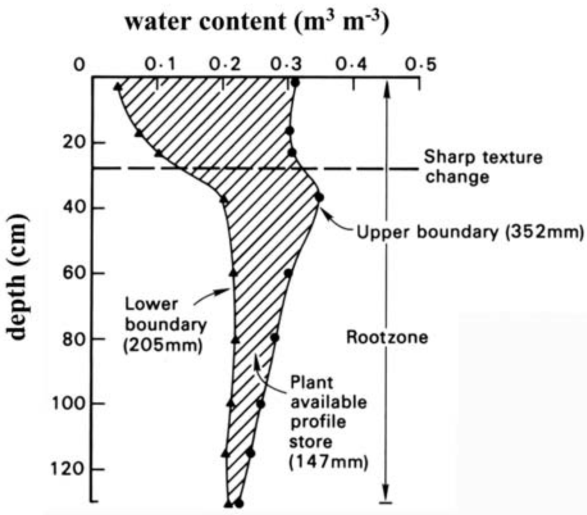
Gardner & Kirkham (1952) indicated (their Table 1) that hydrogen, because of its high nuclear cross-section (probability that the fast neutron will interact with the atom), and increasing scattering cross-section (relative to other atoms present) as the neutrons lost energy, was very efficient in slowing neutrons. Fast neutrons may be "lost" (captured) to the soil matrix when elements such as fluorine, chlorine, potassium, iron, boron and manganese are present. Other factors also influence the relationship between emission of fast neutrons and soil water content affecting calibration and are discussed later.

Neutron meter design and production have been much refined in the last 45 years with units now more portable and electronics more stable. Factors including the effect of source and detector separation and temperature stabilisation of electronics have been incorporated in modern neutron meter design.

Methodology

A particular advantage of the NMM technique is the ability to obtain repeated measurements down the soil profile as shown in Figure 46. In the field, aluminium or PVC tubes are inserted into the soil and stoppered to minimise water entry. Installation should minimise soil compaction while ensuring reasonable contact with the surrounding soil. Prebble *et al.* (1981) with data from Shrale (1976) showed a significant impact of an infinitely long air-gap (greater than > 2 mm) surrounding a 51 mm diameter tube when saturated (say immediately after irrigation). However, in field situations with careful installation using a suitably sized auger, air-gaps in excess of > 2 mm should be minimised. Where air-gaps are unavoidable, e.g. occasionally experienced in active shrink-swell clay soil, the addition of sand around access tubes does not improve the measurement of soil water. The addition of a slurry (made from a mixture of bentonite and/or other clay materials and cement) along the access tube should be minimised (< 2 mm). Larger thickness can introduce a material with different characteristics to the measured soil.

Figure 46. An example of a typical soil soil water profile determined by NMM technique (after Williams et al. 1981)



The count time is an important consideration to increase the instrument precision while reducing the time for measurements. Table 14 shows the increase in count time (CPN 503DR probe, 50 readings in a dry sand drum and a water drum) and the associated error and precision for two extreme conditions with a NMM.

Table 14. Influence of NMM count time on the reported raw counts by a CPN Hydroprobe® in a drum filled with water and a drum filled with dry sand.

COUNT TIME (SECONDS)	MEAN COUNT	STANDARD DEVIATION	STANDARD ERROR OF THE MEAN	RANGE	COEFFICIENT OF VARIATION (%)	PRECISION (% ERROR)
Sand						
1	384.64	68.645	9.708	304	0.178	39.50
4	390.32	35.476	5.017	204	0.091	19.60
16	393.8	19.878	2.811	87	0.050	9.76
32	393.48	15.471	2.188	67	0.039	6.90
64	396.5	9.384	1.327	37	0.024	4.86
Water						
1	36784.0	825.73	116.78	3360	0.022	4.04
4	36673.4	311.542	44.06	1341	0.008	2.02
16	36722.7	198.415	28.06	841	0.005	1.01
32	36737.6	141.995	20.08	672	0.004	0.71
64	36677.0	96.969	13.71	383	0.003	0.51

Readings are taken at depths down the profile with a nominated count time, e.g. 16 seconds. Commonly in irrigated production systems, three aluminium tubes are then averaged and soil water reported as a single reading. This aims to counter the effect of spatial variability reducing the value of the measured soil water content data. Readings can be taken with the neutron meter as a raw count or a count relative to a reading in a drum of water or in the instrument shield. The count ratio is utilised to minimise potential drift in instrument readings. Improved stability of electronics and reduced drift in counting mechanisms in the past fifteen years has diminished the importance of this process. However, instruments differ in their stability and regular normalisation in a large (> 200 L) water drum on a monthly or seasonal basis should be carried out.

NMM calibration

The need for calibration of the NMM in different porous materials invokes interesting discussion. Neutron meters are commonly provided with (factory) standard calibrations for use in common soil types. In Australia, Cull (1979) established a series of standard calibrations and currently these calibrations are extensively used in the irrigation industry.

Other research indicates support for a "universal calibration" encompassing the difference in neutron scattering due to bulk density and texture. In irrigated agriculture, in many soil types, farmers who measure changes in soil water content commonly use "universal calibrations" with reasonable success. Success of "universal calibration" in scientific studies is limited with field studies indicating other influences present affecting soil water determination by the neutron moderation method. Greacen *et al.* (1981) detailed, in field and laboratory conditions, a calibration procedure for the neutron moisture method in Australian soil.

Consideration of bulk density (ρ_b, Mg m^{-3}) is the major concern in calibrating the NMM in field studies. Holmes (1966) discussed the influence of ρ_b on calibration with the change in ρ_b affecting the macroscopic absorption cross section (for thermal neutrons). Olgaard & Haahr (1968) disagreed with Holmes (1966) indicating the effect of ρ_b actually influenced the transport cross sections of fast and slow neutrons. A multi-group neutron diffusion theory was used by Wilson & Ritchie (1986) to show a linear response of the neutron moisture meter to a change in matrix density and neutron scattering cross section. Comparing *in situ* determination to re-packed soil Carneiro & De Jong (1985) found a linear relationship yielded a suitable calibration for their soil, a red-yellow Podzolic. However, Wilson & Ritchie (1986) differed in their findings indicating that a non-linear response of the neutron moisture meter was evident with respect to the thermal neutron absorption cross section and soil-water density.

The error associated with deriving the water content indicating the minimum error likely to be achieved (dependent on chemical limitations of soil description) is ± 1.6% to ± 3.5%. Little consideration of these parameters occurs in many field studies regarding calibration of NMM response to soil water content. Most calibrations undertaken encompass the errors associated with neutron capture, thermal neutron cross-section and neutron scattering cross section as is evident by exclusion of these parameters in discussion. An example of this is the discussion of Carneiro & de Jong (1985), where the authors contend that the difference in slope estimation between two soils is probably due to differences in clay content, Fe and Ti content or ρ_b of re-packed columns.

Field calibration of neutron meters is most commonly carried out with a linear equation (from regression analysis) derived for a particular soil type and/or horizon in the form:

$$\theta = a + b \times n \qquad \text{Equation 1}$$

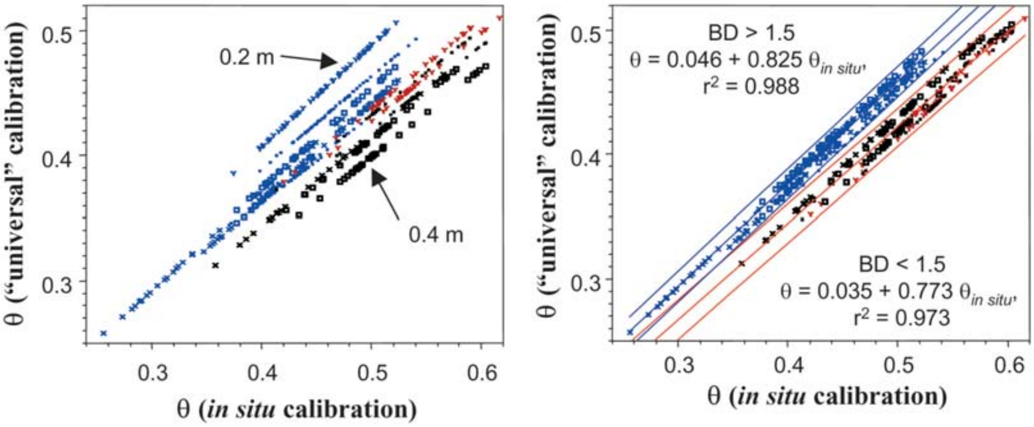
Where θ is the volumetric water content (m^3 m^{-3}); a is a constant (intercept); b is a constant (slope); n is the neutron count or neutron count ratio. Greacen *et al.* (1981) indicated that correct regression of count (ratio) on water content (water content as the independent variable) reduced the possibility of introducing a bias to the calibration.

Consideration of the soil bulk density is important especially in duplex soil where there is the potential for significant change in bulk density in the B-horizon. An empirical relationship can be used to correct for bulk density effects:

$$n_c = n \times \sqrt{\frac{\rho_s}{\rho}} \qquad \text{Equation 2}$$

Where n_c is the corrected count ratio; n is the count ratio relating to a bulk density (ρ); and ρ_s is the average bulk density for the site calibration. Figure 47 (George, 1999) shows the effect of including bulk density in comparing the (uncorrected for bulk density) "universal calibration" supplied by the manufacturer and a local calibration determined in a Brown Chromosol.

Figure 47. Plot of the factory supplied "universal calibration" in a Brown Chromosol (a) without accounting for measured bulk density change at the site and (b) including the ratio of the depth based bulk density with the average site bulk density.



The neutron moisture calibration generally involves taking neutron readings in the extremes of wet (field capacity) and dry soil and relating this to wetness (w). ρ_b is either calculated or estimated to yield a neutron moisture content to known water content relationship. The collection of gravimetric samples can involve either careful removal of samples during access tube installation, destructive sampling around access tubes, or sampling from soil near the installed access tubes.

A second method of calibration relates the determination of the neutron thermal adsorption and diffusion constants as shown by Vachaud *et al.* (1977). This method is not used much for field calibration of the NMM as the equipment is not readily available and difficult to use in some field situations.

Data handling and interpretation

Readings from NMMs can be written down and entered into a computer or stored on the instrument and downloaded to PC for analysis. Assuming the calibration is determined results can be readily interpreted in a general spreadsheet (e.g. Excel) or with dedicated software, e.g. Watsked (CSIRO), or "the Probe". Information can be readily displayed down the soil profile (see Figure 46) indicating the amount of water available and activity in the rootzone where water is extracted; or temporally identifying the soil water content at nominated depths or an integrated profile soil water content (e.g. George & Finch, 1995).

Figure 48 shows the measurement of soil moisture content with time at different depths in a (Chromosol) soil profile when irrigated with effluent. This is output is typical of commercially available software (in this case "the Probe"). In Figure 48, one-hour irrigation was inefficient (little change in θ) with rainfall (30 + mm) causing water movement through the soil profile to a depth 1.0 m. For irrigation scheduling and management display of such information is common practice and required for decision making.

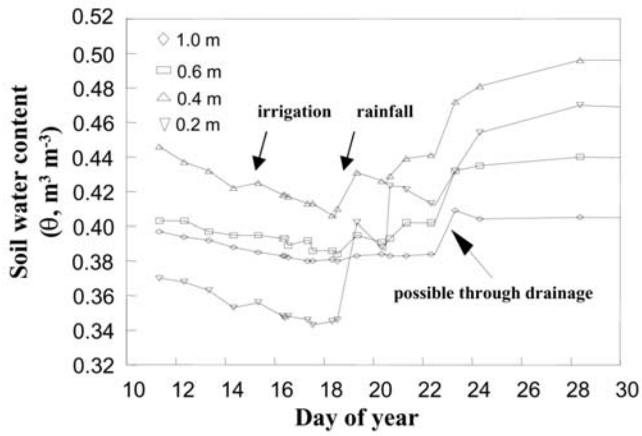


Figure 48. Measurement of soil water content with time during an irrigation cycle in an effluent irrigated eucalypt plantation.

Potential limitations

A disadvantage of the NMM technique is the radioactive source. In NSW and other Australian states a licence is required to own, operate and store neutron meters. Gee *et al.* (1976) reported the radiation hazards associated with neutron fluxes in two neutron meters with an activity of 100 mCu. They indicated that safe operation incorporated an awareness with respect to time spent close to the source, i.e. carrying the meter, and neutron escape through the soil surface.

Neutron meters are commercially available with differing activities commonly between 10 and 100 mCu. The activity needs to be considered with respect to the radiation hazard, however, as shown by van Bavel *et al.* (1961) and Haverkamp *et al.* (1984), higher source activities will yield lower variation in recorded neutron counts. An alternative action is to increase the count time of the meter however economically this is often difficult to justify.

Another concern about widespread and continued use of NMM technology is the time taken for readings. As shown in Table 14 the increasing count-time will improve confidence in the recorded soil water content through improving the instrument precision. However, the longer count time will obviously increase the total time for measurement, always a concern in the current budgeting parameters we operate in. Also field staff often have to collect readings in adverse conditions and other occupational health and safety factors may require some consideration.

Finally, the need for calibration is a limitation with NMM technique as most (currently all!) soil water measurement procedures. In general irrigation the need for calibration is reduced because of the manager's (farmer's) ability to improve efficiencies in other components of the irrigation system. For example, in surface irrigation large amounts of water (1+ ML ha^{-1}) are added with each irrigation, an error of 5% in soil water content determination due to calibration will not significantly alter the managers decision when to irrigate given ordering time, delivery and volume of water applied.

However, in scientific studies we are interested in minimising error and calibration in some form is required. Argument regarding what parameters should be considered continues. Ideally for a given soil type and conditions, e.g. range of bulk density, calibrations should be available and used. No single database is available for this purpose and site calibration is recommended in long-term and significant research applications.

Maintenance

Maintaining neutron moisture meters is instrument dependent. Progress in the past 45 years has improved the instrument stability and the NMM is now considered a robust field instrument. As with all scientific equipment, care should be taken to minimise moisture (an enclosed wet storage case causes accelerated corrosion because of the high relative humidity) and dust. Also, the detector tubes are not known to survive "bouncing" at the bottom of access tubes. Care should be taken when lowering the sensor down tubes.

If using a NMM with a NiCad based battery, cycling of battery charge is strongly recommended. To do this, fully charge the batteries then take readings. When the low battery signal illuminates and readings are complete, either continually download (transfer data to computer) from the probe till the batteries are flat, or take extended readings (of no value so as not to lose information). Then the instrument should be fully charged before proceeding with more readings. If the nicad batteries are continually charged the effective life is reduced and time between recharging will decrease leading to shorter time-periods for data collection and storage. If data is stored on the NMM and transferred to computer this process should be done with the NMM connected to the instrument charger to ensure that the batteries do not go flat during data transfer.

Tubes should be stoppered at the bottom to minimise water ingression and covered at the top. An aluminium can is ideal though inquisitive animals can remove light aluminium cans. If so a rubber stopper in the top of the tube with the aluminum can placed on top is generally sufficient. Tubes should be free from moisture, and if condensation occurs remove it with a rag attached to a length of wire or broom handle.

Positive attributes

The neutron moderation technique is very robust in operation and the field technique is well established. A good standard procedure for installation allows rapid deployment of access tubes and relatively straightforward data collection. There are many NMM instruments in use in Australia for agriculture and other enterprises. Calibration equations for many soils have already been developed (e.g. O'Leary and Incerti, 1993; McKenzie *et al.*, 1990; Jayawardane *et al.*, 1983) and this background information should help in ready application in many instances.

The neutron technique measures a large volume of soil compared to dielectric techniques in particular. The integration over a large volume of soil can be viewed a positive aspect of the technique with respect to soil heterogeneity. In duplex soil or where there is a sharp wetting front, the large measured volume can however lead to difficulty in data interpretation.

The NMM technique is especially suited for (non-intensive) temporally based measurement through the soil profile, particularly at depth (> 2 m). Where time costs are minimal then the use of the NMM is very cost effective once the equipment is bought. I envisage continued widespread of the NMM technique for some years.

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APPENDIX 4

A VALUE SELECTION METHOD FOR CHOOSING BETWEEN ALTERNATIVE SOIL MOISTURE SENSORS

(Extract from: Cape, J. (1997). ***Development of Value Selection Method for Choosing between Alternative Soil Moisture Sensors.*** **Land and Water Resources Research and Development Corporation Project No. AIT2, Canberra, ACT)**

Table 15 details the questions to be answered for each attribute. Table 16 is a worked example comparing two hypothetical devices, Device A and Device B. It is stressed that a comparison or judgement about devices was not within the scope of this study. Devices A and B are not intended to represent particular devices, merely to demonstrate the value selection methodology.

It is clear that the further adoption of soil water sensing devices is limited by the lack of a universally accepted method of appraisal. In spite of the relative simplicity of the selection method outlined in this paper, there is still scope for people to make their own interpretations and score some attributes incorrectly. This problem would be overcome if a universal test and calibration method for soil water sensors could be developed.

The following steps are used in the evaluation procedure.

1. For each *Yes* or *No* answer score a *one* (1) or *zero* (0) in column B of Table 1. In the operation and maintenance section each answer has a value of a quarter (.25) since there are four answers required.

2. For each attribute multiply the point in column B with the weight in column A to obtain column C. Column C is the relative importance.

3. Total all the numbers in column C to obtain total relative importance, T.

4. Calculate COST, the total estimated life cost of the sensor, by estimating capital, installation, running and maintenance costs for the expected life of the sensor.

5. Divide COST by LIFE, the expected life of the sensor in years, to determine A, the annual cost of the sensor.

6. A = COST/LIFE

7. Divide the total T with the annual cost of the sensor to obtain the value V of the sensors.

8. V = T/A

9. The lowest valued sensor may be more suited to your needs and gives you the best value for money expended.

Table 15. Evaluation procedure table.

ATTRIBUTES	WEIGHT (A)	POINT (B)	SCORE (C)
Effective range of measurement *Is sws able to measure all ranges of soil water of interest to you?* *(Yes =1; No =0)*	8		
Accuracy *Is sensor accuracy enough for your purpose? (Yes =1; No =0)*	14		
Soil types (For use with range of soils) *Is sensor's accuracy affected by the soil type?(Yes=0; No =1)*	11		
Reliability *Do you have any personal, other users' or literature based idea of the reliability of sensor and is the failure rate satisfactory to you?* (Yes =1; No=0)	13		
Frequency/soil disturbance *Can the sensor provide quick or frequent readings in undisturbed soil?* *(Yes=1; No=0)*	8		
Data handling *Will you have difficulty in reading or interpreting data? (Yes = 0; No =1)*	8		
Communication (for remote data manipulation) *Does sensor provides data logging and down loading capabilities and a friendly software for analysing & interpreting the data?* *(Yes =1; No =0)*	10		
Operation and maintenance *Is sensor calibration universal?* *Does sws have long life (> 5yrs)?* *Is sensor maintenance free?* *Is sensor easy to install?* *Give sensor ¼ for each Yes answer.* *Total*	10		
Safety *Does use of sensor entail any danger?* *(Yes =0; No = 1)*	8		
Total			

Table 16. Evaluation procedure example.

ATTRIBUTES	WEIGHT (A)	DEVICE A POINT (B)	DEVICE A SCORE(C)	DEVICE B POINT(B)	DEVICE B SCORE(C)
Effective range of measurement	**8**				
Is sws able to measure all ranges soil water of interest to you?(Yes =1; No =0)		0	0	1	8
Accuracy	**14**				
Is sensor accuracy enough for your purpose? (Yes =1; No =0)		0	0	1	14
Soil types (For use with range of soils)	**11**				
Is sensor's accuracy affected by the soil type? (Yes=0; No =1)		1	11	0	0
Reliability	**13**				
Do you have any personal, other users' or literature based idea of the reliability of sensor and is the failure rate satisfactory to you? (Yes =1; No=0)		0	0	1	13
Frequency/soil disturbance	**8**				
Can the sensor provide quick or frequent readings in undisturbed soil? (Yes=1; No=0)		1	8	0	0
Data handling	**8**				
Will you have difficulty in reading or interpreting data? (Yes = 0; No =1)		1	8	1	8
Communication (for remote data manipulation)	**10**				
Does sensor provides data logging and down loading capabilities and a friendly software for analysing & interpreting the data? (Yes =1; No =0)		0	0	1	10
Operation and maintenance	**10**				
Is sensor calibration universal?		¼		¼	
Has sws got long life (> 5yrs)?		¼		0	
Is sensor maintenance free?		0		¼	
Is sensor easy to install?		¼		0	
Give sensor ¼ for each Yes answer.					
Total		¾	7.5	½	5
		1	8	0	0
5 Safety	**8**				
Does use of sensor entail any danger? (Yes =0; No = 1)		1	8	0	0
Total			**42.5**		**58**

APPENDIX 5

ANNUAL CROP SOIL MOISTURE MONITORING COST COMPARISON

Costs per ha (based on one site per 50 ha field of uniform soil type and crop) without data interpretation, maintenance, interest, depreciation, consumer price index etc.

SOIL MOISTURE MONITORING TOOL CATEGORIES BASED ON FEATURES AND USE	CONFIGURATION FOR ONE SITE ON 50 HA	DATA COLLECTION LABOUR COST OVER A 5 MONTH SEASON @ $20/HR FOR1 SITE	SITE SETUP COST INC INSTALLATION	EXTRA EQUIP. COST TO BE SPLIT - SEASONS	TOTAL COST - 1ST SEASON PER SITE	$/HA 1 YR	$/HA 5 YRS	$/HA 10 YRS	DATA RANK *
Category 1 - low purchase cost, high labour, user takes readings, fixed depths									
Tensiometer - Puncture type	3 units - 3 depths	$300	$125	$800 / 10	$505	$10.10	$6.82	$6.41	4
Gauge type		$300	$650	Nil	$950	$19.00	$8.60	$7.30	4
Gypsum blocks	3 blocks - 3 depths	$250	$85	$600 / 10	$395	$7.90	$5.58	$5.29	4
Category 2 - low purchase cost, high labour, user takes readings, multi depth									
Gopher	1 Tube < 12 depths	$200	$40	$1650 / 10 #	$405	$8.10	$4.82	$4.41	3
Sentek Diviner 2000	1 Tube < 11 depths	$200	$40	$3200 / 10 #	$560	$11.20	$5.44	$4.72	3
Category 3 – low purchase cost, low labour, constant readings, fixed depths									
Netafim soil moisture probe	1 unit – 3 depths	$100	$1200	Nil	$1300	$26 6.80		$4.40	3
Category 4 - high purchase cost, low labour, constant readings, multi depth									
Sentek Enviroscan	1 Tube - 4 depths	$100	$1500	$1500 / 8	$1790	$35.80	$8.75	$5.38	1
C-Probe	1 Tube - 4 depths	Nil	$1300	$3300 5km	$1630	$32.60	$6.52	$3.26	1
				$8100 40km #	$2110	$42.20	$8.44	$4.22	
Category 5 - high purchase cost, high labour, user takes readings, multi depth									
Neutron Probe – Contractor	3 averaged tubes	Contractor	$1100	Contractor	$1100	$22	$22	$22	2
– Second hand	1 tube only	$300	$40	$7000 / 10 #	$1040	$20.80	$9.60	$8.20	3
– New	3 averaged tubes	$400	$120	$12000 / 10 #	$1720	$34.40	$15.20	$12.80	2
– New with 50 sites	3 averaged tubes	$400	$120	$12000 / 50	$760	$15.20	$11.36	$10.88	2

* Data rank is related to how comprehensive the data is, ranging between 1 (high) and 4 (low).

Would be more economical over more sites, i.e. 20 to 50 sites.