

## Devices for measuring soil moisture:

### Selecting sensors for use with the SoilWaterApp

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#### Objectives of the review

1. To consider the economics of investing in modelling and monitoring soil water,
2. To outline the main limitations different types of soil water sensors, and
3. To choose two or three types of sensor for field use, connection to iPhones and for integration with the Soilwaterapp.



## Summary

Besides the difficulty of interpreting soil moisture data, the main limitations to deploying soil moisture sensors in dryland grain production are likely to be: (i) complexity, (ii) cost, (iii) uncertainty, (iv) safety regulations, (v) installation problems and (vi) operating problems.

Which methods and sensors are unsuitable? Safety regulations preclude the use of neutron probes, which are otherwise excellent sensors. Watermark sensors and tensiometers do not work in dry soils, and can be excluded from consideration. Labour costs preclude methods that require coring for samples (hand feel and psychrometers). Down-tube capacitance sensors (C-probes and others) have a small volume of measurement that is easily affected by artefacts associated with the tube, especially in shrink-swell soils. Time-domain reflectometry (TDR) is expensive and unsuitable for shrink-swell soils due to poor soil contact. Thermal conductivity and spectrometric methods lack commercial development that might validate their accuracy and reliability. Penetrometers (push probes) are very cheap and highly reliable, but are rarely calibrated and have low accuracy without calibration.

Which methods and sensors are suitable? High frequency, buried capacitance sensors (Sentek, Decagon and Vegetronix) are the best of the high-frequency capacitance probes. Unfortunately, the cheapest (Vegetronix) has a small volume of measurement. Gypsum blocks are cheap, but require conversion of soil water tension (kPa) measurements to water content (%). EMI is accurate and measures hundreds of litres of undisturbed soil. However, EMI sensors are expensive (but can be made cheaply). Spectrometric methods require research and commercialisation. Push probes are suitable given quality calibration, but are affected by salinity and compaction.

The following sensors should be tested in dryland grain production.

1. The Decagon HS10 sensor is a very high frequency (VHF) capacitance sensor. They are accurate, reasonably cheap (\$120-\$150 each), may be read manually or logged, and the volume of measurement is useful at approximately 1 litre.
2. The Vegetronics sensor is also a VHF capacitance sensor. It costs less than the Decagon HS10 (at around \$40) but unfortunately has a much smaller volume of measurement.
3. Gypsum blocks are cheap ultra-low frequency (ULF) capacitance sensors (\$25 each), and may be manually metered or logged. They require a calibration curve that varies with soil texture.
4. Penetrometers/'push probes' can be made more accurate with calibration and careful use, adding to their already widespread use as a low-resolution sensor.

# Review of methods and sensors

## Measuring soil water tension (SWT)

### Hand feel and soil appearance

Clearly, this is used by farmers, consultants and scientists alike as a simple approximation of soil wetness and moisture content. Most people have an intuitive understanding of soil wetness. The relevance of this method is increased by standardised observations that can be categorised by classes of soil texture to give tension and water content (see **Figure 1**).

The technique works for a variety of reasons:

- at low tension, pressure in the hand releases water from the soil,
- soil strength is highly correlated with moisture content,
- soil structure depends on moisture content (e.g. some clay soils lose structure when wet), and
- clay is rigid when dry, and mouldable when moist, and is a lubricant when wet



**Figure 1. The difference between a moist soil and a slightly drier soil is obvious.**

<http://www.jmmds.com/2011/04/spring-is-sprung%E2%80%94but-don%E2%80%99t-jump-the-gun/>

Table 1 below is a guide to the characteristics of soils at different levels of wetness (USDA, 1998). Photographs are very helpful. Table 1 also takes into account soil texture and shows estimates of SWC (in imperial units of inches of water per foot of soil depth).

Pros:

- no electronic sensors

Cons:

- difficulty and cost of obtaining samples from the lower soil horizons
- medium accuracy

**Assessment: Coring and hand feel are unsuitable for use in the project**

**Table 1 Advice from the US Dept of Agriculture for estimating SWT from the hand feel and appearance of soil. (SMD = Soil Moisture Deficit)**

<b>Guidelines for Estimating Soil Moisture Conditions</b>				
	<b>Coarse Texture- Fine Sand and Loamy Fine Sand</b>	<b>Moderately Coarse Texture Sandy Loam and Fine Sandy Loam</b>	<b>Medium Texture - Sandy Clay Loam, Loam, and Silt Loam</b>	<b>Fine Texture- Clay, Clay Loam, or Silty Clay Loam</b>
<b>Available Water Capacity (Inches/Foot)</b>				
	0.6-1.2	1.3-1.7	1.5-2.1	1.6-2.4
<b>Available Soil Moisture Percent</b>	Soil Moisture Deficit (SMD) in inches per foot when the feel and appearance of the soil are as described.			
<b>0-25</b>	Dry, loose, will hold together if not disturbed, loose sand grains on fingers with applied pressure.  SMD 1.2-0.5	Dry, forms a very weak ball, aggregated soil grains break away easily from ball.  SMD 1.7 -1.0	Dry. Soil aggregations break away easily. no moisture staining on fingers, clods crumble with applied pressure.  SMD 2.1-1.1	Dry, soil aggregations easily separate, clods are hard to crumble with applied pressure  SMD 2.4-1.2
<b>25-50</b>	Slightly moist, forms a very weak ball with well-defined finger marks, light coating of loose and aggregated sand grains remain on fingers.  SMD 0.9-0.3	Slightly moist, forms a weak ball with defined finger marks, darkened color, no water staining on fingers, grains break away.  SMD 1.3-0.7	Slightly moist, forms a weak ball with rough surfaces, no water staining on fingers, few aggregated soil grains break away.  SMD 1.6-0.8	Slightly moist, forms a weak ball, very few soil aggregations break away, no water stains, clods flatten with applied pressure  SMD 1.8-0.8
<b>50-75</b>	Moist, forms a weak ball with loose and aggregated sand grains on fingers, darkened color, moderate water staining on fingers, will not ribbon.  SMD 0.6-0.2	Moist, forms a ball with defined finger marks. very light soil/water staining on fingers. darkened color, will not slick.  SMD 0.9-0.3	Moist, forms a ball, very light water staining on fingers, darkened color, pliable, forms a weak ribbon between thumb and forefinger.  SMD 1.1- 0.4	Moist. forms a smooth ball with defined finger marks, light soil/water staining on fingers, ribbons between thumb and forefinger.  SMD 1.2-0.4
<b>75-100</b>	Wet, forms a weak ball, loose and aggregated sand grains remain on fingers, darkened color, heavy water staining on fingers, will not ribbon.  SMD 0.3-0.0	Wet, forms a ball with wet outline left on hand, light to medium water staining on fingers, makes a weak ribbon between thumb and forefinger.  SMD 0.4-0.0	Wet, forms a ball with well defined finger marks, light to heavy soil/water coating on fingers, ribbons between , thumb and forefinger.  SMD 0.5 -0.0	Wet, forms a ball, uneven medium to heavy soil/water coating on fingers, ribbons easily between thumb and forefinger.  SMD 0.6-0.0
<b>Field Capacity (100 %)</b>	Wet, forms a weak ball, moderate to heavy soil/ water coating on fingers, wet outline of soft ball remains on hand.  SMD 0.0	Wet, forms a soft ball, free water appears briefly on soil surface after squeezing or shaking, medium to heavy soil/water coating on fingers.  SMD 0.0	Wet, forms a soft ball, free water appears briefly on soil surface after squeezing or shaking, medium to heavy soil/water coating on fingers.  SMD 0.0	Wet, forms a soft ball, free water appears on soil surface after squeezing or shaking, thick soil/water coating on fingers, slick and sticky.  SMD 0.0

## Tensiometers

As suggested by the name, they measure the tension between soil water and the soil. A classic tensiometer has a tube full of water at installation, and water is moved out of the tube by any tension in the surrounding soil water, leaving a vacuum in the tube that is in equilibrium and opposition to the soil water tension in the soil. Hi-tech tensioners use electronic pressure sensors and do not need re-filling if the soil water tension empties the reservoir. A pressure gauge displays the strength of the vacuum.

The tube is about 1 metre long and is capable of producing almost 1 bar of tension (100 kPa). This is too little for dryland agriculture, where volumetrically there is approximately half of the available PAWC 'held' at 1.5 to 15 bars.

Pros:

- long-established and accurate method
- low cost
- new types have electronic modules for continuous measurement

Cons:

- small range of tension measurement (0 to 1 bar)
- requires careful installation

**Assessment: Tensiometers are unsuitable for measurements in dryland agriculture due to their limited range of measurement (wet soils only)**

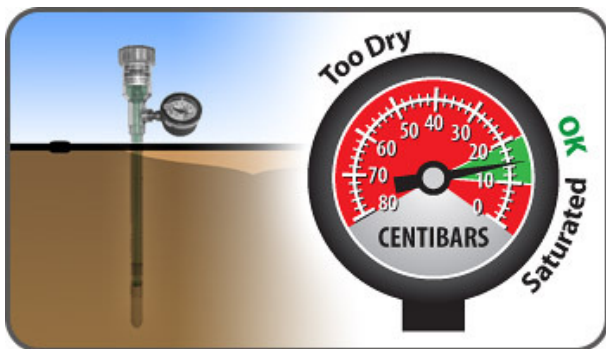


Image courtesy of OreMax ([http://www.ore-max.com/?page=dont\\_drown\\_the\\_oxygen](http://www.ore-max.com/?page=dont_drown_the_oxygen))

Figure 2

## Measuring the moisture content of soil air: Psychrometers

With respect to moisture availability, soil air is in equilibrium with soil water. Psychrometers precisely measure the moisture content of soil air, and by calculation, the soil water potential. They are widely used for atmospheric measurements, such as monitoring the effectiveness of air conditioning units and for calculating evaporation. The common apparatus for doing this is a rotating or 'sling' psychrometer, shown below.



Figure 3

A rotating psychrometer, containing wet and dry bulb thermometers. When swung in the air, the wet bulb temperature is reduced to the dew point and the dry bulb measures the air temperature. The handle contains a scale for calculating relative humidity from the dry bulb temperature and the dry-wet temperature difference.

Photo courtesy of [http://www.plantfog.at/ZU\\_E/Zubehoer\\_E2.htm](http://www.plantfog.at/ZU_E/Zubehoer_E2.htm).

Clearly, unless you are down a mine, a smaller volume of air needs to be measured for soil water.

Several such instruments are available for this, such as the Decagon WP4C shown below (photo from



Figure 4

<http://www.decagon.com/education/water-potential/measuring-water-potential/laboratory-instruments-for-measuring-water-potential/vapor-pressure-instruments-thermocouple-psychrometers-and-dewpoint-water-potential-meters/>).

Unfortunately, these are sensitive devices and are only suitable for use in laboratories. Also, they are not accurate for measuring soil water tension below 5 bars, having an accuracy of approx. +/- 1 bar. Even at 5 bars, the amount of cooling required to reach dew point is only 0.01 C, and a well-controlled environment is required in which to operate

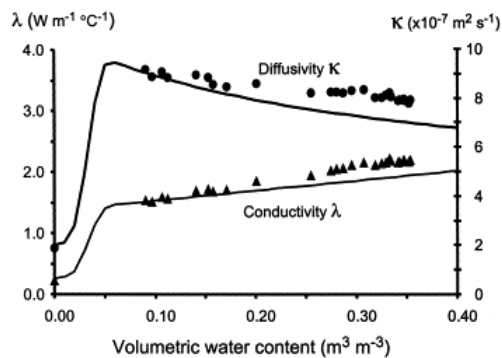
the psychrometer.

It seems unlikely in the near future that psychrometers will be able to economically measure the small temperature changes necessary to measure the humidity of soil air.

**Assessment: Psychrometers are unsuitable due to their sensitivity to the surrounding environment and their limited range of measurement (dry soils only)**

## Thermal conductivity of the soil water in a porous block

Water is a moderately good conductor of heat, while air is a good insulator. Therefore, wet soils and other porous materials become better conductors of heat as they become wetter. This is a precise relationship and is almost unaffected by interference from soil salinity and other factors. Most of these sensors work by heating the water in an area within a porous ceramic material (an insulator) and detecting the rate of heating in another part of the material. Temperature rise per second (C/s) is the usual measurement, taken from thermocouples in the ceramic. The time needed for a measurement ranges from a few seconds to a minute.



**Figure 5. A calibration curve between soil water content and soil thermal conductivity (from Bristow et al. 2001).**

Pros:

- simplicity
- accurate in moist to dry soils (0.1 to 20 bars of tension)
- comes with a calibration curve for SWT
- robust

Cons:

- expensive and sensitive equipment
- low accuracy in wet soils (0 to 0.1 bar)
- not widely used
- requires a programmed datalogger to coordinate the heating pulse and measurements

**Assessment: thermal conductivity is potentially suitable for use in the project. The main limitations are cost and lack of prior commercial application.**



## Penetrometers

Many farmers carry a soil penetrometer, known as a “push probe” in their vehicle. It consists of a length of steel rod that is inserted into the soil. A ball or bead on the end has a larger diameter than the rod and prevents interference from suction on the rod. It is usually easy to push the bead through moist soil, but not through dry soil. The soil is usually assumed to be wet to the depth of penetration on the probe. The method has been used and evaluated by researchers for decades (e.g. Shaw et al. 1942). It has been promoted by a variety of state Depts of Agriculture in Australia, as well as the CSIRO.

However, few soils have equal water-holding capacity down the profile, so there is no unique value for the “mm of water per 10cm of wet soil” parameter for any soil, let alone a constant value between soils. Also, there is also a range of soil wetness where the resistance is intermediate between that for wet or dry soils. As shown in Figure 7. Maximising effort with a push probe. [http://pages.uoregon.edu/ecolrest/equipment\\_list.html](http://pages.uoregon.edu/ecolrest/equipment_list.html) is tempting to apply maximum force to the



penetrometer when the soil is partially wet, rather than use a similar amount of effort each time it is used.

**Figure 6. Normal use of a push probe (photo courtesy of [www.themanagementadvantage.com](http://www.themanagementadvantage.com))**

Pros:

- very robust
- fast, physical measurement
- independent of salinity

Cons:

- moderately affected by soil texture
- ideally requires knowledge of mm water per cm of penetrated soil
- inaccurate at intermediate moisture content (1 bar)
- interference from compaction and rocks



Figure 7. Maximising effort with a push probe.

[http://pages.uoregon.edu/ecolrest/equipment\\_list.htm](http://pages.uoregon.edu/ecolrest/equipment_list.htm)

**Assessment: push probes are potentially suitable for use in the project, but need better calibration.**

## Measuring soil water content (SWC)

### Electromagnetic methods (capacitance, AC resistance, electromagnetic induction)

#### Background to the method

These sensors all measure the dielectric constant of soil. Water has a high volumetric dielectric constant (80) compared to air (1), so soil water content is almost proportional the dielectric value. The measurement is relatively simple, because dielectric materials respond to electro-magnetic fields.

Water reacts strongly to electro-magnetic (EM) fields because it is a polar compound and the molecules align with the field. Air is virtually non-polar and doesn't react. Some minor soil components, such as organic matter, are also dielectrics and have a small effect on the results. Magnetic minerals may have an "anti-dielectric" effect on measurements because they have some responses to EM that are the inverse of the effects of dielectrics.

Some of these sensors are called *capacitance probes* because dielectric compounds have electrical storage capacity and are used to make the capacitors that are widely used in electronic circuits. An easy way to measure the dielectric compounds in soil is to measure the associated soil capacitance, using this relationship:

$$C = 1/(2.\pi.f.Z)$$

where C is capacitance (microFarads), and the other parameters are either known or easily measured. Z is resistance (ohms),  $\pi \approx 3.14$ , and f is frequency (kHz). The frequency (f) may be either low (about 1 kHz for gypsum blocks) or high (about 100 MHz for capacitance probes) to avoid interference that may occur at intermediate frequencies. The different sensors and methods are reviewed separately below.

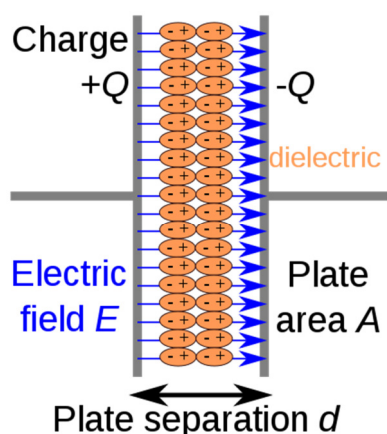


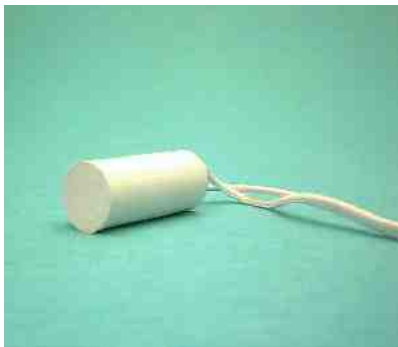
Figure 8. A schematic of a capacitor, including its dielectric material (in orange). The polar molecules of a dielectric are aligned by an external charge on one or other of the plates. Via the dielectric, a charge +Q on one plate induces a charge of -Q on the other, and *vice versa*. An alternating charge on one plate induces an inverse alternating charge on the other, thereby conducting an alternating current in the absence of a conductor (wrt to DC). (Image from [www.wikipedia.com](http://www.wikipedia.com))

## Gypsum blocks.

From <http://www.dpi.vic.gov.au/agriculture/farming-management/soil-water/soil/ag0294-gypsum-blocks-for-measuring-the-dryness-of-soil>

*“Gypsum blocks consist of two electrodes embedded in a block of gypsum.... Wires are joined onto each electrode and extruded from the gypsum block to measure the resistance between the electrodes. The resistance between the two electrodes varies with the water content in the gypsum block, which will depend directly on the soil water tension. As the soil dries out water is extracted from the gypsum block and the resistance between the electrodes increases. Conversely as the soil wets, water is drawn back into the gypsum block and the resistance decreases.”*

A gypsum block has a fine porous structure like many soils, and the gypsum is sparingly soluble, providing a dilute salt solution that masks the effects of variable soil salinity. The dielectric value (and capacitance) of the sensor change almost exclusively with change in the water content. Gypsum blocks are variable from manufacturer to manufacturer and to a lesser extent from device to device, but in general are well-suited to measuring the range of water content and tension of interest in dryland agriculture. It is ironic that their main use has been in irrigated agriculture, as they have least accuracy in wet soils, due to the low density (or absence) of large pores in the blocks.



**Figure 9. A typical gypsum block. It is simply 2 bare wires in a cast block of Plaster of Paris. Typically they are a few centimetres long, and either a rectangular block or cylinder, as shown here (photo from <http://www.trickle-l.com/new/sensors/gypsum.html>)**

Pros:

- available off-the-shelf
- the sensors (\$25) and meters (\$200) are economical
- accurate in moist and dry soils (0.2 to 50 bars of tension)
- iPhone may be able to read and calibrate blocks,

Cons:

- low sensitivity in wet soils (<0.2 bars of tension)
- blocks only last a few years (mainly due to dissolving and weakening)
- installation of blocks requires coring (taking considerable time and effort)

**Assessment: gypsum blocks are well suited to use in dryland agriculture, especially where installation is easy (rigid soils).**

## Porous ceramic probes.

These are similar in operation to gypsum blocks. The best known is the Watermark sensor (shown below). The advantages of ceramic sensors include a higher frequency of larger pores and a more consistent distribution of pore sizes, which means they are suited to measurements in wet soils (larger pores in the sensor fill at less tension) and less variation from sensor to sensor. Some ceramic sensors contain a 'bead' of gypsum that provides a baseline of salinity in the probe, and are therefore unaffected by moderate levels of salinity.



Figure 10 Watermark blocks and the reader. Image from <http://www.ipm.iastate.edu/ipm/icm/2000/4-24-2000/evalsoilmoist.html>

### Pros:

- available off-the-shelf
- the sensors (\$100) and meters (\$400) are economical
- more sensitive in wet soils than gypsum blocks
- iPhone may be able to read and calibrate the sensor

### Cons:

- the meters are only suited to wet and moist soil (0 to 2 bars tension)

**Assessment: porous blocks are not suited to use in the project unless new meters are developed to read at >2 bars tension.**

## Time-Domain reflectometry (TDR).

Probes inserted into the soil are used to propagate an electromagnetic pulse. The pulse typically lasts for 10 milliseconds. The pulse through the probes induces a counter-current in the surrounding soil via the dielectric effect, absorbing energy from the “leading edge” of the pulse. Precise measurements (sub-nanosecond resolution) are made of the “returning” or “reflected” pulse, and the dielectric constant of the surrounding soil is determined from the time-delay due to the dielectric effect (greater dielectric/capacitance stores more energy and is slower to both charge and discharge).

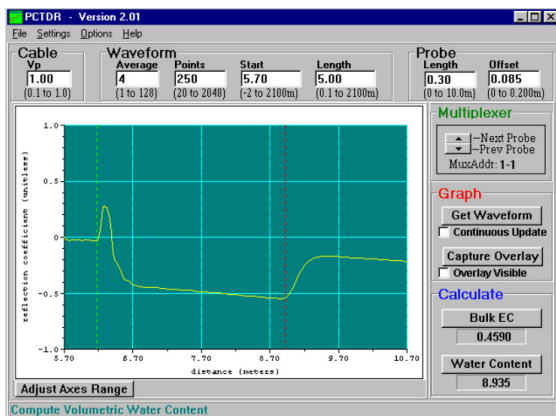


Figure 11 An averaged waveform from a Campbell TDR100. The two vertical lines show the onset of the first and second reflections. (Image from <http://www.campbellsci.com.au/documents/manuals/tdr100.pdf>).

The theory and practical use of TDR is described in Wikipedia: [http://en.wikipedia.org/wiki/Time-domain\\_reflectometer#TDR\\_used\\_in\\_the\\_Earth\\_and\\_Agricultural\\_Sciences](http://en.wikipedia.org/wiki/Time-domain_reflectometer#TDR_used_in_the_Earth_and_Agricultural_Sciences)

Pros:

- accuracy
- not affected by interference from salinity

Cons:

- expensive and fragile equipment
- high level of skill required
- correct installation of the probes is import and demanding
- probe contact is often poor in shrink-swell soils

**Assessment: TDR is not suited to use in the project due to cost and complexity**

## Electro-Magnetic Induction (EMI).

The EM38 from the Geonics Corporation is a well-known example of an EMI device. In a process similar to TDR and capacitance probes, a current is induced in the soil, and the “reflected” current is measured. These devices operate at low frequency (38kHz for the EM38) and respond to soil salinity, water content, clay content, magnetic minerals and other factors. The low frequency and wide coil spacing measures a large volume of soil. Whereas capacitance sensors have vertical separation between the transmitter and receiver coils, EMI devices have horizontal separation between the coils. This avoids issues with drilling cores and down-tube installations.

As early as 1987, Williams and Hoey used EMI for detecting spatial variability in the salt and clay contents of Australian soils. It was some time before the potential for repeated measurements was used to determine temporal changes in soil water content (e.g. Robinson et al. 2010).



Figure 12. An EM38 being used in vertical mode. The coils are located at each end of the device. Image from (<http://www.usyd.edu.au/agric/web04/Group%201%20Web%20page/EM38%20Final.htm>)

### Pros:

- fast measurement
- accurate
- easy access to deep soil layers

### Cons:

- very expensive and sensitive equipment
- interference from electro-magnetic materials and devices

**Assessment:** EMI methods would be suited to use in the project if the expense was less

Addendum: There is potential for the development of a new EMI method, using multiple coil spacing, for measuring a range of depths. In horizontal mode, about 90% of the EM38 measurement is made to a depth equal to the coil spacing. With overlapping measurements, multiple coils would greatly reduce the errors in measurements at intermediate depths. The development of such a device would be a significant advance in EMI methods.

## Non-contact capacitance sensors (high frequency 'probes').

Capacitance probes use a high-frequency current (approx. 100 MHz) and coils with close vertical spacing. The sensors may be permanently located within PVC access tubes (C-probe) or placed in a tube as needed (Gopher) or encapsulated and buried. It is usual for 3 or 4 depths to be measured by 6 or 8 coils. The measurements are typically logged at frequent intervals (sub-daily).

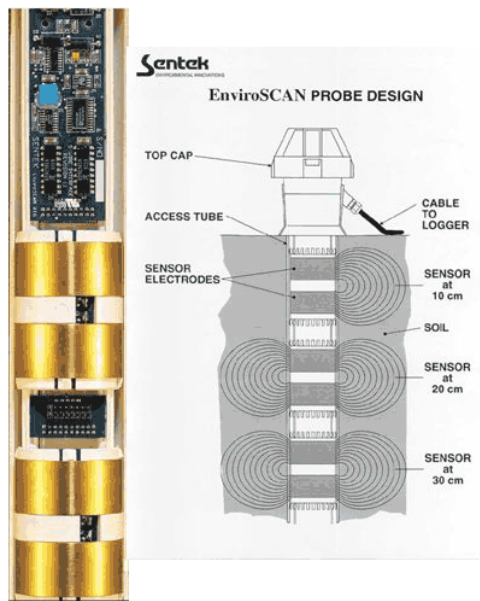


Figure 13. An EnviroScan probe, with multiple sensors that are positioned down a PVC tube.

Image from

([http://web.fi.ibimet.cnr.it/idri/s\\_enviroscan.htm](http://web.fi.ibimet.cnr.it/idri/s_enviroscan.htm))

An excellent summary of the use of these sensors in agriculture is available here:

[http://www.dpi.nsw.gov.au/data/assets/pdf\\_file/0009/165078/capacitance-probes.pdf](http://www.dpi.nsw.gov.au/data/assets/pdf_file/0009/165078/capacitance-probes.pdf)

Frequency domain sensors, including those known as capacitance probes, are described in these articles: [http://en.wikipedia.org/wiki/Frequency\\_domain\\_sensor](http://en.wikipedia.org/wiki/Frequency_domain_sensor)

[http://en.wikipedia.org/wiki/Capacitance\\_probe](http://en.wikipedia.org/wiki/Capacitance_probe)

Pros:

- accurate
- easy access to deep soil layers

Cons:

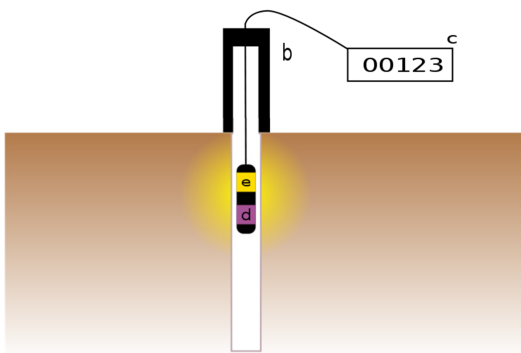
- expensive, sensitive equipment
- requires expert installation
- effects of the access tube

**Assessment: Non-contact capacitance sensors are more expensive and complex than other capacitance methods, and the results may be affected by the presence of the access tube**



## Neutron modification (Neutron “probe”)

This method is based on the interaction between ‘fast’ neutrons and water. A radioactive source of neutrons (‘fast’ neutrons) is placed down a narrow access tube (Figure 14). A nearby detector measures neutrons that have interacted with water (‘slow’ neutrons). Typically, the source and detector are moved up and down the tube to measure soil water at different depths. The method requires calibration for different soils and depths, which can be arduous. Another disadvantage is that the radioactive source requires that probe users complete radiation safety courses, and that the source is safely housed. Transport of the source may require permits and signage on the vehicle. The method is widely used in research, where the technical difficulties of calibration and safety issues are considered acceptable in order to obtain highly accurate results.



**Figure 14. The neutron modification method uses an emitter of fast neutrons (e), a detector of slow neutrons (d), a counter of detected neutrons (c) and a protective shield (b) ([http://en.wikipedia.org/wiki/Neutron\\_probe](http://en.wikipedia.org/wiki/Neutron_probe))**

Pros:

- accuracy,
- ready access to depth,
- free from electrical and magnetic interference

Cons:

- cost
- calibration is time-consuming
- safety and regulatory issues associated with using a radioactive source

**Assessment: Neutron probes are not suited to use in the project, due to the very high cost, difficult calibration, and safety and regulatory issues**

## Spectrometric methods (infra-red, near infra-red, visible, UV)

Wet soil is darker than dry soil due to the absorption of visible radiation by water in soil, hinting at the ease with which spectrometric methods might measure soil water content. Similarly, water has characteristic absorption of electro-magnetic radiation (EMR) in the near infra-red spectra (NIR).

Spectrometers are cheap, small and robust compared with those from last century. One is contained in the USB stick shown in Figure 15. Typically, these methods measure absorption at several frequencies, which improves accuracy and reduces interference when compared with single frequency methods. NIR methods for measuring water content were developed in the late 1990s and have continued to be researched since then (Viscarra Rossel and McBratney 1998, Hummel et al. 2001). Sibusawa et al. (2001, 2003) used NIR and visible spectrometers mounted on a tine for spatial, real-time sensing.



Image from [www.rgb-laser.com](http://www.rgb-laser.com)

Figure 15

A simple sensor might involve emission from one or more light-emitting diodes (LEDs) that only cost a few cents each and emit EMR in narrow frequency ranges, reception of a reflected image by a digital camera (in a phone) and analysis by the processor in that phone.

Figure 1. LED Emission Spectra

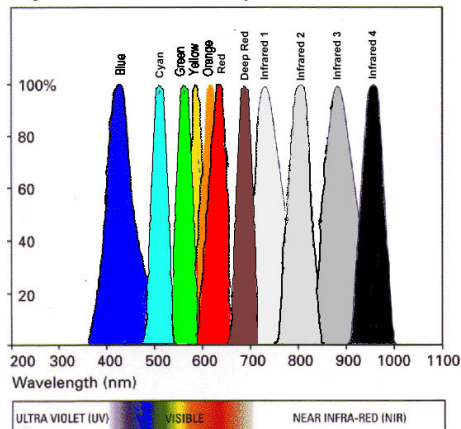


Figure 16 The narrow emission spectra of a range of LEDs that may be used in optical sensors.

<http://www.lpi.usra.edu/education/products/spectrometer/>

Pros:

- potentially very cheap
- ease of use
- potentially accurate

Cons:

- calibration may be complex
- not yet commercialised

**Assessment: Spectrometric methods are not suited to use in the project, but have great potential and are likely to become important in the future.**

## Plant-based methods for estimating available soil water

Via their root network, plants extract water from soil and release it to the atmosphere in order to grow. It is common in irrigated horticulture to estimate plant water status to improve irrigation scheduling (Jones 2004).

Some methods estimate plant water status pre-dawn, in the absence of evaporative demand, when plant water potential is approximately equal to the soil water potential. In the last few years, continuous monitoring of plant water status has made this method more popular.

Other methods measure plant water stress during the day, with evaporative demand on the crop, and measure reductions in sap flow and stomatal conduction (Woodruff and Meinzer 2011, Jones 2004), reductions in growth (Jones 2004), breakages in water-conducting tissues (Meinzer et al. 2009, Johnson et al. 2009) and heating of the crop canopy due to a reduction in transpiration and associated evaporative cooling (Jackson et al. 1981).

This last method is cheap - usually based on non-contact measurements of canopy temperature with an infra-red thermometer (costing about \$25). The crop temperature measurements are combined with weather data to determine the amount of moisture stress. For example, on a sunny day with high evaporative demand, a well-watered crop canopy is cooler than air temperature, whereas canopy temperatures are closer to air temperatures when evaporative demand is low. Jackson et al. (1981) found that canopy heating is closely correlated with soil water content and crop water stress.

In simple trials, I have used dry and wet paper as references for well-watered and desiccated canopies. These reference temperatures integrate effects of relative humidity, temperature, windspeed and other factors on evaporative cooling from the canopy. An IR temperature measurement of the crop canopy is likely to fall between the extremes of wet and dry, with the crop temperature being proportional to a linear scale between the zero transpiration case (dry paper) and potential transpiration (wet paper). For example, if the dry-wet difference is 10 C, and the canopy is 5 C above the wet value, transpiration is at approximately 50% of its maximum rate.



**Figure 17. A typical infra-red thermometer, suitable for measuring heating of a crop canopy due to reduced evaporative cooling associated with crop water stress.**

[http://www.iitk.ac.in/erl/Index\\_files/Fas/infrared\\_thermometer.jpg](http://www.iitk.ac.in/erl/Index_files/Fas/infrared_thermometer.jpg)

**Assessment: Plant-based methods may be suitable for measuring soil water tension, and soil water content by calibration. With a little development, infra-red thermometry may be used to interpret soil water content in terms of crop water stress.**

## Summary tables

Table 2. A summary of methods for measurement of soil water tension (SWT) or soil water content (SWC). Orange shading indicates a major constraint to adoption of the method. Cost and complexity are based on weekly to monthly measurements (i.e. the App has no need for sub-weekly measurements).

Type	Commercial examples	Method	Range of measurement Maximum bars of tension	Volume measured Litres (approx.)	Cost and complexity
SWT	Jetfill/Irrrometer	Tensiometer (+gauge)	<1	1	Low
SWT	SoilSpec/TerraTech	Tensiometer (no gauge)	<1	1	Low
SWT	NA	Coring + hand feel	50	1	High
SWT	Decagon WP4C	Psychrometer	mininum = 5	0.01	High
SWT	Campbell 229	Thermal conductivity (porous block)	20	1	High
SWC	NA	Coring + drying (volumetric SWC)	20	1	High
SWC	Push-probe	Penetrometer	50	5	Low
SWC	NA	NIR/vis spectrum (develop new sensor)	10 (?)	1	Medium
SWC	Campbell TDR100	TDR	20	1	High
SWC	Aquaflex	TDR (+long sensor)	20	20	High
SWC	Campbell 229	Soil thermal conductivity	20	1	High
SWC	Geonics EM38	EMI	20	100	High
SWC	NA	"El-cheapo" EMI (develop new sensor)	20	50	Medium
SWC	Enviroscan/ C-probe/Diviner2000	EMI (high frequency, down-tube sensor)	20	1	High
SWC	Thetaprobe/Netafilm	EMI (high frequency, buried sensor)	5	1	High
SWC	Decagon EC-5/ Vegetronix VH400	EMI (high frequency, buried mini-sensor)	20	0.3	Medium
SWT (+SWC)	Gypsum blocks	EMI (very low frequency)	20	1	Medium
SWT (+SWC)	GBLite/Watermark	EMI (very low frequency)	3-5	1	Medium

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## Appendix 1

### Economic costs and benefits of investing in collecting soil water information

The costs and benefits of investing in soil water information will be highly variable between farms and over time. The calculations below are a crude attempt to reveal possible savings and returns from investing in modelling and measuring soil water *in a particular scenario*. The scenario involves conditions similar to those found across the grain belt of northern Australia. Steps 1 and 2 describe the background to the scenario and set out assumptions and intermediate results, while step 3 estimates savings (\$/ha/year) and step 4 estimates the response in returns (\$/ha/year).

1. Consider a farm of 2000ha with 50% cropped, so there is 1000ha of crop. For a conservative estimate of **variable costs of cropping of \$100 per hectare**, variable costs = \$100,000 for the cropped area. In northern Australia, cropped areas aren't often put through a pasture ley, so **let's assume that there is always 1000 ha of cropping each year**. In southern Australia there may be leys or long fallows that reduce the cropping intensity to 50%, reducing many of the costs and returns from cropping by a factor of 2.
2. **If, in any one year, 50% of the 1000 ha is subject to variable rates of inputs** according to weather and soil moisture conditions, **there is \$50,000 of variable-rate expenditure**. The 50% area of variable inputs reflects that some areas might not need certain fertilisers, or that the rate is determined by factors other than weather and soil moisture (e.g. chickpeas don't need N, barley needs less N than wheat, sorghum after chickpeas or long fallow needs less N). Anything from 20 to 80% of the \$25,000 may be spent on climate-responsive inputs such as N fertiliser, seed, and some types of sprays. If we assume 50%, then **the inputs cost affected by soil-water are \$25,000**.
3. What percentage of the variable costs – can be saved with the App and soil sensors? Research by Peter Hayman (ex NSW, now at SARDI) indicates that long-term average management is remarkably profitable relative to climate-responsive management for dryland farming. Residual benefits are one reason. For example, over-fertilising this year will boost next year's crop. Under-fertilising reduces yields, but saves money too. Based on the available research, and **assuming that over a long period, 10% of this expenditure would be wasted without monitoring, the saving is \$2,500 per year, or \$2.50 per cropped hectare per year**.
4. By what percentage can the returns from cropping be improved with the App and soil sensors? This is one of the most important and difficult assumptions in this analysis, partly because the returns are large relative to the costs. However, drought is a major constraint on grain production and identifying situations with an abundant crop water supply and high yield potential is undoubtedly important. **Assuming a 1% increase in returns** may appear a conservative amount, but for a return from cropping of \$500 per hectare, the result is an

average increase of **\$5/ha/year**. While this is only an educated guess, and is designed to be conservative, it suggests that for 1000 ha of cropping the average increase in income per year may be \$5,000.

The **total benefit of \$7.50/ha/year** may be put in perspective by comparison with using the phases of the SOI to manage N fertiliser rates on wheat at Dalby, which has been estimated to increase profit by \$0.50/ha/year (data from Robinson and Butler, 2000).

Charlesworth (2000) estimated that the total cost of investing in soil water measurement is \$4 to \$22 per hectare per year for a range of systems. These amounts were based on a 50 ha paddock and spreading the capital costs over 10 years. Using the costing system of Charlesworth (2000) for an area of 500ha, and a nominal set of capital and labour costs (Table 3), the annual costs of the 3 hypothetical systems are suitably low. However, I suggest that depreciating the capital cost over 10 years is optimistic. Conversely, in the future there will almost certainly be substantial improvements in the technology and reductions in costs.

**Table 3. The annual cost (\$/ha/year) of three hypothetical soil water measurement systems, annualised over 10 years for 500 ha.**

Type	Capital cost \$	Installation labour @\$40/hour	Annual labour @\$40/hour	Annualised cost \$/ha/year
Low capital cost, manual measurement	\$1000	\$320	\$400	\$1.10
Mid capital cost, automated measurement	\$4000	\$480	\$400	\$1.70
High capital cost, automated measurement	\$8000	\$600	\$400	\$2.50

There are far too many assumptions in these analyses to reach firm conclusions. However, these figures demonstrate that both the costs and returns from modelling and monitoring soil water are low relative to the costs and returns from cropping, and that it is *potentially* profitable to invest in modelling and measuring soil water status to improve agronomic decisions.



## Appendix 2

### Soil water content and soil wetness

Those new to the science and technology of soil water are easily confused by the jargon and units of measurement. Soil water availability may be expressed in centimetres of water, centimetres of mercury, metres of water, kiloPascals, bars, pounds per square inch, megajoules per kilogram and several less common units. The experts are sometimes confused as well.

In particular, it is not intuitive or obvious to many people that soil water content and soil wetness are not the same thing. Soil water content (SWC) is, as the name suggests, how much water the soil contains (usually on a gravimetric or volumetric basis), whereas soil wetness is how “available” the water is in the soil. The relationship between the two differs between soils. Sand can be wet with less water than other soils.

Soil wetness is often called the soil water tension, because moisture is ‘held’ to the soil by surface tension – a product of polar nature of H<sub>2</sub>O. The less water in a soil, the greater the relative surface area of the water (per unit mass) and the greater the tension between the water and the soil solids. Matric tension (units of pressure, often kPa or bars), matric suction (units of pressure, where suction is usually the inverse of tension, kPa or bars) and matric potential (units of energy per unit mass, often MJ/kg) have equivalent meaning, and can be converted from one to the other.

SWC is often expressed as the volume of water (mL) in a 100 mL volume of soil - the % volumetric water content. Perhaps the simplest method of measuring SWC is by weighing a sample of soil (A, kg), drying it, and re-weighing (B, kg), and using this formula to calculate volumetric SWC:

$$\text{SWC (\%)} = (B-A) / A \times 100 \times \text{bulk density}$$

The bulk density (kg/L) converts mass to volume.

Soil water tension (kPa) can be measured with tensiometers, pressure chambers, psychrometers and artificial matrices (gypsum and ceramic blocks, filter paper, *etc.*). For tensiometers and pressure chambers, water is extracted from soil in equilibrium with a vacuum (tensiometer) or pressure (pressure chamber) acting against matric tension. Materials such as gypsum blocks and filter paper have more-or-less constant relationships between their gravimetric or volumetric moisture content and water tension. When placed in contact with soil, they come to equilibrium with the soil water tension, and a measurement of their moisture content reveals the soil water tension. In the case of gypsum and ceramic blocks, the moisture content is measured electronically, whereas for filter paper it is measured gravimetrically. Psychrometers measure the water content of soil by cooling it and optically detecting the dew point. Moist air has a higher dew point than dry air.

The relationship between SWC and SWT is known as the soil water retention function. To accurately determine the relationship, soils of varying wetness have their SWC and SWT measured. In particular, scientists and farmers often want to know the range of SWC at which plants are healthy and able to use the soil water. The permanent wilting point (PWP), also known as the lower limit (LL), is the SWC (%) where plants can no longer extract water and maintain their normal internal water pressure. It is widely assumed to be the SWC when SWT is approximately 15 bars or 1.5 MPa. This is a low value for coarse materials such as sand (e.g. 6% volumetric SWC) because the surface

area is low, and water isn't 'held' tightly. For clay, with orders of magnitude higher surface area, the SWC for permanent wilting point is much greater (e.g. 25% volumetric SWC). See Table 44 for some examples.

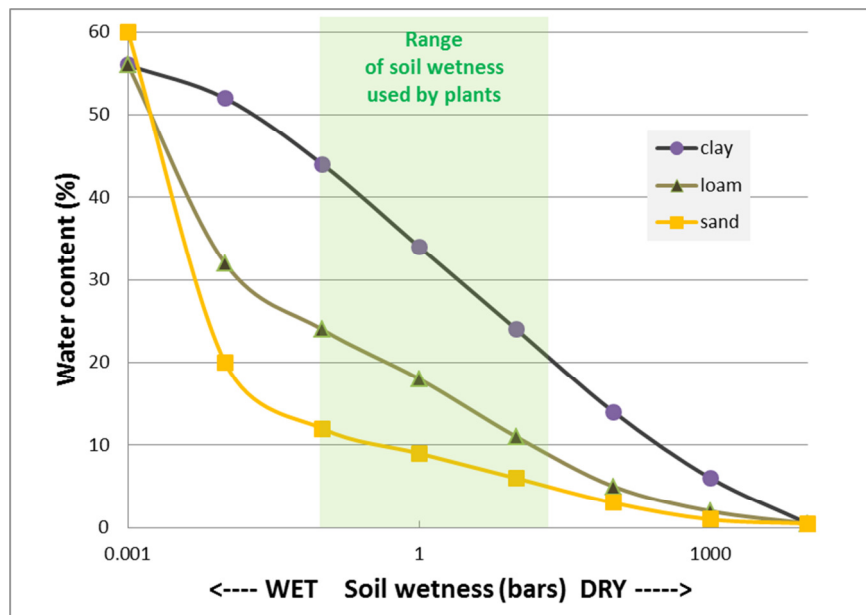
**Table 4. A comparison of the soil water content (SWC, %) of different soils at similar wetness (SWT, bars).**

Soil dryness (SWT) (bars of suction*)	Soil type		
	Sand SWC (%)	Loam SWC (%)	Clay SWC (%)
Plant Wilting Point (15 bars)	6	9	25
Field Capacity (0.03 bars)	12	25	44
Saturation (0 bars)	60	55	55

\*Metric values of suction and tension are kiloPascals (kPa) and megaPascals (MPa). 1 bar is approximately 100 kPa and 0.1 MPa.

**More detailed technical information about soil water :**

There is considerable variation between the SWC and SWT for soils of different texture, as mentioned above. The relationship between SWC and SWT is called the "characteristic curve" because it is characteristic of a particular soil. Fortunately, we don't usually need to know *exactly* the moisture characteristic curve of soils in order to make a fair estimate SWC or SWT from the other, as the relationship depends on the proportions of fine and coarse materials in the soil, that in turn determines the soil water tension at different moisture contents.



**Figure 18. The relationship between soil water content (%) and soil wetness (bars) for 3 soil types.**

There are another 2 factors affecting the total 'availability' of soil water (known as the soil water potential, SWP): the gravitational potential and osmotic potential. Gravitational potential refers to the difference between water high up and water low down. For example, water at the top of a hill is more available than water at the bottom of a well. One can release energy to reach a given level, while the other needs energy input to reach the same level. It is this effect that limits the height of trees to approximately 100 metres - the maximum height to which trees can lift water from very wet soil to the leaves.

The osmotic potential is the effect of ions, atoms, molecules and other particles in water to reduce the availability of the water. To filter the water out of salty water requires reverse-osmosis, which is an energy-intensive process. From this we can deduce that the water in salty water is less available than the water in pure water.