WATER CONSERVATION TECHNICAL BRIEFS

TB12 – Field Devices for Monitoring Soil Water Content

SAI Platform

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TB12 – Field Devices for Monitoring Soil Water Content

The keys to efficient on-farm irrigation water management know how much water in the soil profile is available to the crop, and how much water the crop needs. Measuring and monitoring soil water moisture should be essential parts of an efficient irrigation programme. This technical brief aims at providing an overview of different technologies and products available to measure the soil moisture. It is strongly recommended that farmers contact local expert to consult for the best option considering their local characteristics of the soil. Relying on poorly placed equipment will result in over- or under-irrigation.

The structure of the technical brief is as follows: Sections 1 provides a categorisation of the different types of methods to measure soil moisture. Section 2, 3 and 4 set out different technologies available to measure soil moisture at farm level, its advantages and disadvantages. Section 5 presents some guidelines farmers should consider when selecting an instrument. Section 6 explores some challenges that developed countries had faced in the implementation of these technologies. Section 7 outlines some specific products available in the US and in the Australian market. Finally, Section 8 recommends some further reading.

Contents

Section 1: Classification of soil moisture meters.......... 3

Section 2: Volumetric Field technologies 3

Section 3: Tensiometric Technologies.......... 10

Section 4: Wireless sensor networks.......... 16

Section 5: How to choose the right instrument? 17

Section 6: Challenges on implementation of soil moistures meters.......... 19

Section 7: Products available in the market.......... 20

Section 8: References and further reading 24

SECTION 1: CLASSIFICATION OF SOIL MOISTURE METERS

Soil moisture meters devices can be classified into direct and indirect monitoring methods.

- The **direct methods** are usually referred to as the *gravimetric method* and *volumetric method.* The gravimetric method expresses water content as weight of water over weight of dry soil e.g. 0.3 g water per 1 g of dry soil. 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. The *volumetric method* expresses the water content as volume of water in a volume of undisturbed soil. It is used to compare the water contents of different soils. The main advantages of direct methods are its accuracy and low cost. However the drawbacks are destructive, slow, time-consuming and do not allow for making repetitions in the same location.

- The **indirect methods** monitor soil water content by estimating the soil moisture by a calibrated relationship with some other measurable variable. The suitability of each method depends on several issues like cost, accuracy, response time, installation, management and durability. Indirect techniques can be classified into **volumetric** (gives volumetric soil moisture) and **tensiometric** methods (yields soil suction or water potential). The sections below document will describe indirect volumetric and tensiometric technologies.

SECTION 2: VOLUMETRIC FIELD TECHNOLOGIES

The table below depicts a comparative analysis between different volumetric technologies (Neutron Moderation; TDR (Time Domain Reflectometry); FD (Capacitance and FDR); ADR (Amplitude Domain Reflectometry); Phase Transmission; TDT (Time Domain Transmission)) used to estimate the volume of water in a sample volume of undisturbed soil.

This quantity is useful for determining how saturated the soil is (i.e., fraction of total soil volume filled with the soil aqueous solution). When it is expressed in terms of depth (i.e., volume of water in soil down to a given depth over a unit surface area (inches of water)), it can be compared with other hydrological variables like precipitation, evaporation, transpiration, deep drainage, etc.

Among the volumetric technologies described below, the International Atomic Energy Agency (IAEA, 2005) suggest that the field calibrated neutron moisture meter (NMM) remains the most accurate and precise method for soil profile water content determination in the field, and is the only indirect method capable of providing accurate soil water balance data for studies of crop water use, water use efficiency, irrigation efficiency and irrigation water use efficiency, with a minimum number of access tubes.[1]

Table 1: Comparative analysis of volumetric technologies

	Neutron Moderation	TDR (Time Domain Reflectometry)	FD (Capacitance and FDR)	ADR (Amplitude Domain Reflectometry)	Phase Transmission	TDT (Time Domain Transmission)
Reading range	0-0.60 ft^{3}/ft^{3}	0.05-0.50 ft^{3}/ft^{3}or 0.05-Saturation (with soil specific calibration)	0-Saturation	0-Saturation	0.05-0.50 ft^{3}/ft^{3}	0.05-0.50 ft^{3}/ft^{3} or 0-0.70 ft^{3}/ft^{3} Depending on instrument
Accuracy (with soil-specific calibration)	±0.005 ft^{3}/ft^{3}	±0.01 ft^{3}/ft^{3}	±0.01 ft^{3}/ft^{3}	±0.01-0.05 ft^{3}/ft^{3}	±0.01 ft^{3}/ft^{3}	±0.05 ft^{3}/ft^{3}
Measurement volume	Sphere (6-16 in. radius)	about 1.2 in. radius around length of waveguides	Sphere (about 1.6 in. effective radius)	Cylinder (about 1.2 in.)	Cylinder (4-5 gallons)	Cylinder (0.2-1.6 gallons) of 2 in. radius
Installation method	Access tube	Permanently buried *in situ* or inserted for manual readings	Permanently buried *in situ* or PVC access tube	Permanently buried *in situ* or inserted for manual readings	Permanently buried *in situ*	Permanently buried *in situ*
Logging capability	No	Depending on instrument	Yes	Yes	Yes	Yes
Affected by salinity	No	High levels	Minimal	No	>3 dS/m	At high levels
Soil types not recommended	None	Organic, dense, salt or high clay soils	None	None	None	Organic, dense, salt or high clay soils (depending on instrument)
Field maintenance	No	No	No	No	No	No
Safety hazard	Yes	No	No	No	No	No
Application	Irrigation, Research, Consultants	Irrigation, Research, Consultants	Irrigation, Research	Irrigation, Research	Irrigation	Irrigation
Cost (includes reader/logger/ interface if required)[a]	$10,000-15,000	$400-23,000	$100-3,500	$500-700	$200-400	$400-1,300

Source: University of Florida. Field Devices for Monitoring Soil Water Content. Available at: http://edis.ifas.ufl.edu/ae266

[a] Please consider that these costs might not be updated.

TB 12 – Field Devices for Monitoring Soil Water Content

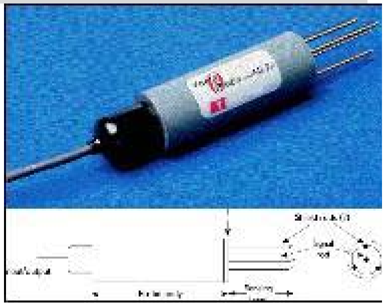
The table below provides with a more detail description, advantages and disadvantages of different volumetric technologies.

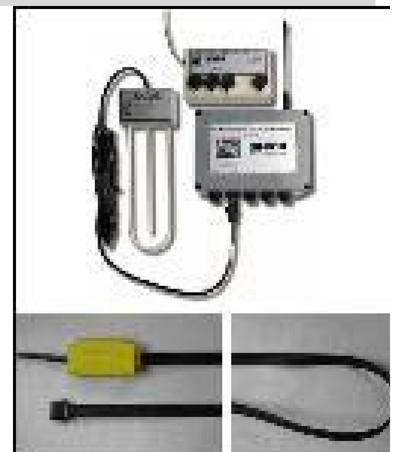
Table 2: Description, advantages and disadvantages for volumetric water monitoring technologies

Technologies	Working Principle	Description	Advantages	Disadvantages	Picture
Neutron Moderation	*Measure: Count of slow neutrons around a source of fast neutrons.* Neutron probes emit fast moving neutrons. When the neutrons collide with hydrogen in the soil they are slowed and deflected. A detector on the probe counts returning slow neutrons. The number of slow neutrons detected can be used to calculate soil water content because changes in the amount of hydrogen in the soil between readings will only come about from changes in water content. A wet soil will contain more hydrogen than a dry soil and therefore more slow neutrons will be detected.	The probe configuration is in the form of a long and narrow cylinder, containing a source and detector. Measurements are made by introducing the probe into an access tube (previously installed into the soil). It is possible to determine soil moisture at different depths by hanging the probe in the tube at different depths. The soil moisture is obtained from the device based on a linear calibration between the count rate of slowed-down neutrons at the field (read from the probe), and the soil moisture content obtained from nearby field samples.	• Robust and accurate (±0.005 ft^3/ft^3) • One probe allows for measuring at different soil depths • Large soil sensing volume (sphere of influence with 4–16 in. radius, depending on moisture content) • Not affected by salinity or air gaps • Stable soil-specific calibration	• Safety hazard, since it implies working with radiation. Even at 16 in. depth, radiation losses through soil surface have been detected • Requires certified personnel • Requires soil-specific calibration • Heavy, cumbersome instrument • Takes relative long time for each reading • Readings close to the soil surface are difficult and not accurate • Manual readings; cannot be automated due to hazard • Expensive to buy • Difficult to use[2]	 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.

Time Domain Reflectometry (TDR)	*Measure: Travel time of an Electromagnetic pulse.* The TDR probe usually consists of 2–3 parallel metal rods that are inserted into the soil acting as waveguides in a similar way as an antenna used for television reception. This is a *dielectric method* that estimate soil water content by measuring the soil bulk permittivity (or dielectric constant), Ka_b, that determines the velocity of an electromagnetic wave or pulse through the soil. In a composite material like the soil (i.e., made up of different components like minerals, air and water), the value of the permittivity is made up by the relative contribution of each of the components. Since the dielectric constant of liquid water (Ka_w = 81) is much larger than that of the other soil constituents (e.g. Ka_s = 2–5 for soil minerals and 1 for air), the total permittivity of the soil or bulk permittivity is mainly governed by the presence of liquid water.	The speed of an electromagnetic signal passing through a material varies with the dielectric of the material. Time domain reflectometry (TDR) instruments e 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.[3]	• Accurate (±0.01 ft^3/ft^3) • Soil specific-calibration is usually not required • Easily expanded by multiplexing • Wide variety of probe configurations • Minimal soil disturbance • Relatively insensitive to normal salinity levels • Can provide simultaneous measurements of soil electrical conductivity.	• Relatively expensive equipment due to complex electronics • Potentially limited applicability under highly saline conditions or in highly conductive heavy clay soils • Soil-specific calibration required for soils having large amounts of bound water (i.e., those with high organic matter content, volcanic soils, etc.) • Relatively small sensing volume (about 1.2 inch radius around length of waveguides) • Difficult to use.[4]	 TDR devices operate similarly to capacitance devices as they use the dielectric constant of the soil water media to calculate soil water content. An electromagnetic signal is sent down a steel probe which is buried in the soil at the desired depth. The signal reaches the end of the probe and is reflected back to the control unit. The return time of the signal varies with the soil dielectric constant and therefore relates to the water content of the soil surrounding the probe.

Frequency Domain (FD): Capacitance and FDR	*Measure: Frequency of an oscillating circuit* This is also a dielectric method developed for measuring the dielectric constant of the soil water media and, through calibration. The electrical capacitance of a capacitor that uses the soil as a dielectric depends on the soil water content. When connecting this capacitor (made of metal plates or rods imbedded in the soil) together with an oscillator to form an electrical circuit, changes in soil moisture can be detected by changes in the circuit operating frequency. This is the basis of the Frequency Domain (FD) technique used in Capacitance and Frequency Domain Reflectometry (FDR) sensors.	Probes usually consist of two or more electrodes (i.e., plates, rods, or metal rings around a cylinder) that are inserted into the soil. On the ring configuration the probe is introduced into an access tube installed in the field. Thus, when an electrical field is applied, the soil around the electrodes (or around the tube) forms the dielectric of the capacitor that completes the oscillating circuit. The use of an access tube allows for multiple sensors to take measurements at different depths.	• Accurate after soil-specific calibration (±0.01 ft^{3}/ft^{3}) • Can read in high salinity levels, where TDR fails • Better resolution than TDR (avoids the noise that is implied in the waveform analysis performed by TDRs) • Can be connected to conventional loggers (DC output signal) • Flexibility in probe design (more than TDR) • Some devices are relatively inexpensive compared to TDR due to use of low frequency standard circuitry.	• The sensing sphere of influence is relatively small (about 1.6 in.) • For reliable measurements, it is extremely critical to have good contact between the sensor (or tube) and soil • Careful installation is necessary to avoid air gaps • Tends to have larger sensitivity to temperature, bulk density, clay content and air gaps than TDR • Needs soil-specific calibration • Exhibit much more variability in the field than neutron moderation method or direct soil water measurements, and they are not recommended for soil water balance studies for this reason.[5] • Too inaccurate.[6]	 FDR devices use the dielectric constant of the soil water media to calculate soil water content. These types of instruments work on the basis that the dielectric of dry soil is much lower than that of water. The soil dielectric is calculated by applying a voltage to the plates and measuring the frequency. In Capacitance sensors the dielectric permittivity of a medium is determined by measuring the charge time of a capacitor made with that medium. In FDR the oscillator frequency is swept under control within a certain frequency range to find the resonant frequency (at which the amplitude is greatest), which is a measure of water content in the soil.

Amplitude Domain Reflectometry (ADR): Impedance	When an electromagnetic wave (energy) travelling along a transmission line (TL) reaches a section with different impedance (which has two components: electrical conductivity and dielectric constant), part of the energy transmitted is reflected back into the transmitter. The reflected wave interacts with the incident wave producing a voltage standing wave along the TL, i.e., change of wave amplitude along the length of the TL. If the soil/probe combination is the cause for the impedance change in the TL, measuring the amplitude difference will give the impedance of the probe. The influence of the soil electrical conductivity is minimised by choosing a signal frequency, so that the soil water content can be estimated from the soil/probe impedance.	Impedance sensors use an oscillator to generate a sinusoidal signal (electromagnetic wave at a fixed frequency, e.g., 100 MHz) that is applied to a coaxial TL that extends into the soil through an array of parallel metal rods, the outer of which forms an electrical shield around the central signal rod. This rod arrangement acts as an additional section of the TL, having impedance that depends on the dielectric constant of the soil between the rods.	• Accurate with soil-specific calibration (±0.01 ft^{3}/ft^{3}; ±0.05 ft^{3}/ft^{3} without it) • Allows measurements in highly saline conditions (up to 20 dS/m). • Minimal soil disturbance • Can be connected to conventional loggers (DC output signal) • Inexpensive due to standard circuitry • Not affected by temperature • In situ estimation of soil bulk density possible	• Soil-specific calibration recommended for reliable measurements • Measurement affected by air gaps, stones or channeling water directly onto the probe rods • Small sensing volume (0.27 in^{3})	

Phase Transmission	After having travelled a fixed distance, a sinusoidal wave will show a phase shift relative to the phase at the origin. This phase shift depends on the length of travel along the TL, the frequency and the velocity of propagation. Since velocity of propagation is related to soil moisture content, for a fixed frequency and length of travel soil water content can be determined by this phase shift.	The probe uses a particular waveguide design (two open concentric metal rings), so that phase measuring electronics can be applied at the beginning and ending of the waveguides	• Accurate with soil-specific calibration (±0.01 ft3ft-3) • Large sensing soil volume (4–5 gallons) • Can be connected to conventional loggers (DC output signal) • Inexpensive	• Significant soil disturbance during installation due to concentric rings sensor configuration • Requires soil-specific calibration • Sensitive to salinity levels >3 dS/m • Reduced precision, because the generated pulse gets distorted during transmission • Needs to be permanently installed in the field	
Time Domain Transmission (TDT)	This method measures the one-way time for an electromagnetic pulse to propagate along a transmission line (TL). Thus, it is similar to TDR, but requires an electrical connection at the beginning and ending of the TL. Notwithstanding, the circuit is simple compared with TDR instruments.	The probe has a waveguide design (bent metal rods), so that the beginning and ending of the transmission line are inserted into the electronic block. Alternatively, the sensor consists of a long band (~3 ft), having an electronic block at both ends	• Accurate (±0.01–0.02 ft^{3}/ft^{3}) • Large sensing soil volume (0.2–1.6 gallons) • Can be connected to conventional loggers (DC output signal) • Inexpensive due to standard circuitry	• Reduced precision, because the generated pulse is distorted during transmission • Soil disturbance during installation • Needs to be permanently installed in the field	

Source: University of Florida. Field Devices for Monitoring Soil Water Content. Available at: http://edis.ifas.ufl.edu/ae266

Section 3: Tensiometric Technologies

All available tensiometric instruments have a porous material in contact with the soil, through which water can move. Thereby, water is drawn out of the porous medium in a dry soil and from the soil into the medium in a wet soil. It is worth noticing, that in general, they do not need a soil specific calibration, however, in most cases they have to be permanently installed in the field, or a sufficiently long time must be allowed for equilibration between the device and the soil before making a reading.

Table 3: Comparative criteria for tensiometric water monitoring technologies

	Tensiometer	Gypsum block	GMS	Heat dissipation	Soil psychrometer
Reading range	0-0.80 bar [b]	0.3-2.0 bar	0.1-2.0 bar	0.1-10 bar	0.5-30 bar
Accuracy (with soil- specific calibration)	±0.01 bar	±0.01 bar	±0.01 bar	7% absolute deviation	±0.2 bar
Measurement volume	Sphere (>4 in. radius)	Sphere (>4 in. radius)	Sphere (about 0.8 in. radius)		Sphere (>4 in. radius)
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
Logging capability	Only when using transducers	Yes	Yes	Yes	Yes
Affected by salinity	No	>6 dS/m	>6 dS/m	No	Yes, for ceramic cup type (use screen type)
Soil types not recommended	Sandy or coarse soils	Sandy or coarse soils, avoid swelling soils	Sandy or coarse soils, avoid swelling soils	Coarse	Sandy or coarse soils, avoid swelling soils
Field maintenance	Yes	No	Medium	No	No
Safety hazard	No	No	No	No	No
Application	Irrigation, Research	Irrigation	Irrigation	Irrigation, Research	Research
Cost (includes reader/logger/ interface if required)	$75-250	$400-700	$200-500	$300-500	$500-1,000

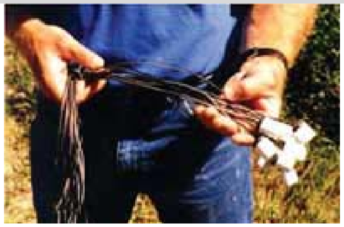
Source: University of Florida. Field Devices for Monitoring Soil Water Content. Available at: http://edis.ifas.ufl.edu/ae266

[b] Note : 1 bar = 100 kPa

According to a study conducted by the IAEA, tensiometers and the granular matrix resistance sensors are practical for on-farm irrigation scheduling.[7]

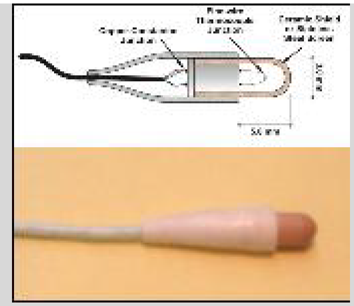
Table 4 : Description, advantages and disadvantages for tensiometric water monitoring technologies

Technologies	Working Principle	Description	Advantages	Disadvantages	Picture
Tensiometer	Measure: Matric and gravitational soil water potential components. When a sealed water-filled tube is placed in contact with the soil through a permeable and saturated porous material, water (inside the tube) comes into equilibrium with the soil solution (i.e., it is at the same pressure potential as the water held in the soil matrix). Hence, the soil water matric potential is equivalent to the vacuum or suction created inside the tube	The tensiometer consists of a sealed water-filled plastic tube with a ceramic cup at one end and a negative pressure gauge (vacuometer) at the other. The shape and size of the ceramic cup can be variable and the accuracy depends on the gauge or transducer used (about 0.01 bar). Typically the measurement range is 0–0.80 bar, although there are low-tension versions (0–0.40 bar) designed for coarse soils	• Direct reading • Up to 4 inch measurement sphere radius • Continuous reading possible when using pressure transducer • Electronics and power consumption avoidable • Well-suited for high frequency sampling or irrigation schedules • Minimal skill required for maintenance • Not affected by soil salinity, because salts can move freely in and out across the porous ceramic cup • Inexpensive They are fine for most annual vegetable crops, orchards, nuts and pastures, but	• Limited soil suction range (<1 bar) • Relatively slow response time • Requires intimate contact with soil around the ceramic cup for consistent readings and to avoid frequent discharge (breaking of water column inside) • Especially in swelling or coarse soils, the ceramic cup can lose contact with soil, thus requiring reinstallation • Requires frequent maintenance (refilling) to keep the tube full of water, especially in hot dry weather	

			they are not adequate for the controlled stressing of plants such as grapevines using regulated deficit irrigation and partial rootzone drying.[8]		
Gypsum Block	*Measure: Electrical conductivity of a porous medium in contact with the soil.* The electrical resistance between electrodes embedded in a porous medium (block) is proportional to its water content, which is related to the soil water matric potential of the surrounding soil. Electrical resistance reduces as the soil, hence the block, dries.	A gypsum block sensor constitutes an electrochemical cell with a saturated solution of calcium sulphate as electrolyte. The resistance between the block-embedded electrodes is determined by applying a small AC voltage (to prevent block polarization) using a Wheatstone bridge. Since changes to the soil electrical conductivity would affect readings, gypsum is used as a buffer against soil salinity changes (up to a certain level). The inherent problem is that the block dissolves and degrades over time (especially in saline soils) losing its calibration properties. It is recommended that the block pore size distribution match the soil texture being used. The readings are temperature dependent (up to 3% change/°C) and field measured resistance should be corrected	• Up to 4 inch measurement cylinder radius • No maintenance needed • Simple and inexpensive • Salinity effects buffered up to 6 dS/m • Well suited for irrigation where only "full" and "refill" points are required • Suited to regulated-deficit irrigation. • Gypsum blocks and granular matrix sensors are suited to regulated deficit irrigation (stone fruit and wine grapes).[9]	• Low resolution, limited use in research • Block cannot be used for measurements around saturation (0–0.3 bar) • Block properties change with time, because of clay deposition and gypsum dissolution. Degradation speed depends on soil type, amount of rainfall and irrigation, and also the type of gypsum block used • Very slow reaction time. It does not work well in sandy soils, where water drains more quickly than the instrument	

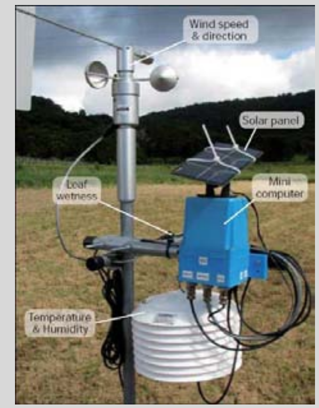
		for differences between calibration and field temperatures. Some reading devices contain manual or self-compensating features for temperature or the manufacture provides correction charts or equations. Measurement range is 0.3–2.0 bar.		can equilibrate • Not suitable for swelling soils • Inaccurate readings due to the block hysteresis (i.e., at a fixed soil water potential, the sensor can display different resistance when wetting than when drying) • Temperature dependent. If connected to a logging system, another variable and sensor for temperature must be added to the system.	
Granular Matrix Sensors (GMS)	*Measure: Electrical conductivity of a porous medium in contact with the soil.* The sensor consists of electrodes embedded in a granular quartz material, surrounded by a synthetic membrane and a protective stainless steel mesh. Inside, gypsum is used to	Even with good sensor-soil contact, GMS have rewetting problems after they have been dried to very dry levels. This is because of the reduced ability of water films to re-enter the coarse medium of the GMS from a fine soil. The GMS material allows for measurements closer to saturation. Measurement range is 0.10–2.0 bar.	• Reduces the problems inherent to gypsum blocks (i.e., loss of contact with the soil by dissolving, and inconsistent pore size distribution) • Up to 4 inch measurement cylinder radius • No maintenance	• Low resolution, limited use in research • Slow reaction time. It does not work well in sandy soils, where water drains more quickly than the instrument can equilibrate • Not suitable for swelling soils	

	buffer against salinity effects. This kind of porous medium allows for measuring in wetter soil conditions and lasts longer than the gypsum blocks.		needed • Simple and inexpensive • Salinity effects buffered up to 6 dS/m • Suited to regulated-deficit irrigation.	• If the soil becomes too dry, the sensor must be pulled out, re-saturated and installed again • Temperature dependence. If connected to a logging system, another variable and sensor for temperature must be added to the system.	
Heat Dissipation	The thermal conductivity of water produces heat dissipation, so that a dry material will heat up faster than a wet one. In other words, the heat flow in a porous material is proportional to its water content.	A thermal heat probe consists of a porous block containing a heat source and an accurate temperature sensor. The block temperature is measured before and after the heater is powered for a few seconds. Thereby, block moisture is obtained from the temperature variation. Since the porous block, placed in contact with the soil, is equilibrated with the soil water, its characteristic curve will give the soil water potential. Hence, the sensor must be provided with the calibrated relationship between the measured change in temperature and soil water	• Wide measurement range • No maintenance required • Up to 4 inch measurement cylinder radius • Continuous reading possible • Not affected by salinity because measurements are based on thermal conductivity.	• Needs a sophisticated controller/logger to control heating and measurement operations • Slow reaction time. It does not work well in sandy soils, where water drains more quickly than the instrument can equilibrate • Fairly large power consumption for frequent readings.	 

		potential. Measurement range: 0.1–30 bar (less accurate for 10–30 bar range).			
Soil Psychrometer	Under vapour equilibrium conditions, water potential of a porous material is directly related to the vapour pressure of the air surrounding the porous medium. This means that the soil water potential is determined by measuring the ***RH*** of a chamber inside a porous cup equilibrated with the soil solution.	A soil psychrometer consists of a ceramic shield or screen building an air chamber, where a thermocouple is located. The screen type is recommended for high salinity environments. ***RH*** in the air chamber is calculated from the "wet bulb" vs "dry bulb" temperature difference. Measurement range: 0.5–30 bar (less accurate for 10–30 bar range)	• High sensitivity • Scientifically rigorous readings (except in wetter soil conditions) • Suitable where typical moisture conditions are very dry.	• Not recommended at shallow soil depths, due to high susceptibility to thermal gradient • Small sensing volume • Very slow reaction time, because reaching vapour equilibrium takes time • Low accuracy in the wet range • Specialized equipment is required for the sensor's excitation and reading.	

Source: University of Florida. Field Devices for Monitoring Soil Water Content. Available at: http://edis.ifas.ufl.edu/ae266

SECTION 4: WIRELESS SENSOR NETWORKS[10]

Technologies	Working Principle	Description	Advantages	Disadvantages	Picture
Wireless sensor network	This method includes satellite, radar (microwaves), and other non-contact techniques. The remote sensing of soil moisture depends on the measurement of electromagnetic energy that has been either reflected or emitted from the soil surface.	The intensity of this radiation with soil moisture may vary depending on dielectric properties, soil temperature, or some combination of both. For active radar, the attenuation of microwave energy may be used to indicate the moisture content of porous media because of the effect of moisture content on the dielectric constant. Thermal infrared wavelengths are commonly used for this measurement.	• Method allows remote measurements to be taken. • Enables measurements to be taken over a large area.	• System large and complex. • Costly.	

Source: http://www.p2pays.org/ref/08/07697.pdf

SECTION 5: HOW TO CHOOSE THE RIGHT INSTRUMENT?

Devices vary in their complexity, cost, accuracy and labour requirement for the installation, monitoring and during the servicing. Individual requirements should be indentified before purchasing a soil moisture monitoring device. As a minimum, a soil moisture monitoring instrument needs to provide water content readings for the plant root zone before and after irrigation and rainfall.

It is crucial to consider how farmers receive water because farmers need to have the ability to modify the duration of the water delivery before measuring soil moisture and scheduling irrigation. Unless the field's water is available on a demand or true arranged schedule soil moisture measurement wouldn't apply. If the farmer receive water on a rotation basis (such as rigid warabundi schedule[c]) it wouldn't apply.[11]

Before deciding on a soil moisture monitoring device farmers should consider the type of information that the soil water monitoring device provides and the way how information would be used, the labour intensity of the device and assess its labour capacity, the suitability of the device for the farmers soil type/s and crop/s, the investment and maintenance cost and the accuracy and repeatability of measurements.

The followings questions can guide farmers to choose a device that matches their management style, crop and situation, the amount of information needed, and their budget.[12]

1. What information do I need from a soil moisture monitoring device?
2. How labour intensive is the device?
3. How useable is the information from the device?
4. What level of accuracy do I need?
5. Does soil type affect my choice?
6. Does the irrigation system I use limit my choice?
7. Does crop type limit my choice of device?
8. What other site factors affect my choice?
9. How durable is the product?
10. How much maintenance will it need?
11. Can I afford it?
12. What are the next steps to take?

[c] The list of rotational turns or times when each shareholder in a watercourse obtains his water supply. As an example, this is applied in Pakistan.

TB 12 – Field Devices for Monitoring Soil Water Content

Value Selection Method help to decide which soil moisture measuring technique is most applicable to a particular situation. This procedure consists of answering a number of questions (Yes = 1, No = 0). The relative importance of each question is quantified with appropriate weights, and a total relative importance (T) of each sensor for a specific application is obtained by adding the individual scores from all questions and multiplying it by the score for the "effective range of measurement" criterion. The total estimated life cost of the sensor (Cost) is estimated from capital, installation, running, and maintenance costs for the expected life of the sensor (L). The annual cost (A) of the sensor is obtained by Cost divided by L (A = Cost/L). The final sensor value for the application (V) is obtained by T divided by A (T/A).

The device with the highest value V is more suited to the needs and budget considered.

Attributes		Weight	Instrument	
			Point (b)	Score (c)
Effective range of measurement (Point: Yes = 1; No = 0 sensor is not recommended for application and total score T = 0)	Is the soil water sensor (sws) able to measure all ranges of soil water of interest to you?	-		
Accuracy (Point: Yes = 1; No = 0)	Is the sensor accuracy enough for your purpose?	14		
Soil types (for use with range of soils) (Point: Yes = 0; No = 1)	Is the sensor's accuracy affected by the soil type?	11		
Reliability (Point: Yes = 1; No = 0)	Do you have any personal, other users' or literature-based idea of the reliability of the sensor, and is the failure rate satisfactory to you?	13		
Frequency/soil disturbance (Point: Yes = 1; No = 0)	Can the sensor provide quick or frequent readings in undisturbed soil?	8		
Data handling (Point: Yes = 0; No = 1)	Will you have difficulty in reading or interpreting data?	8		
Communication (for remote data manipulation (Point: Yes = 1; No = 0)	Does the sensor provide data logging and downloading capabilities and friendly software for analyzing and interpreting the data?	10		
Operation and maintenance (Point: Give the sensor 1/4 for each Yes answer; No = 0)	Is the sensor calibration universal? Does the sws have a long life (>5 years)? Is the sensor maintenance free? Is the sensor easy to install?	10		
Safety (Point: Yes = 0; No = 1)	Does use of the sensor entail any danger?	8		
Total (T)				
Cost (Cost) (in $)				
Life (L) (in years)				

Annual cost of sensor (A = Cost/L) (in $/year)	
Value of sensor (V = T/A)	

SECTION 6: CHALLENGES ON IMPLEMENTATION OF SOIL MOISTURES METERS

There are practical limitations in the implementation of soil moisture meters such as the time consuming. Depending on the soil water monitoring system there may be only a single reading every few hectares which add variability to the system. This reading has to average out all the variability present in the whole area. Decision of irrigation will be taken on an average soil type, average plant, at the depth of average water uptake and in the zone of average water application.

In Australia, the uptake of soil water monitoring equipment has been promoted as essential to irrigators wanting to optimise water use on-farm. Uptake has been slow for many reasons, including awareness by irrigation managers of the variability that exists across their paddocks and the large number of monitors that would reasonably be required to overcome some of these variability issues. Some equipment is complex to install, calibrate and maintain. There is often a need to be computer literate. These problems can be overcome through the use of specialist irrigation consultants, however there remains reluctance by many to pay for what has been seen as a non-essential service.[13]

In the United States, water-use efficiency can be improved by proper irrigation scheduling and precise measurement of water as well as new technology. Nearly, 80% of irrigated farms simply use visual observations or "feel the soil" approaches. Other rely on the decisions of neighbors, published evapotranspiration reports or scheduled water deliveries than take no account of actual soil moisture or real time weather information.[14]

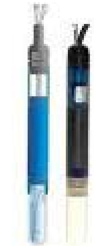
Section 7: Products available in the market

The following table describe some limitations and attributes of some products available in the Australian and American market. Please note that this is not an exhaustive list but will provide with an idea of the different choices.

Table: Products available in the market

Type of product **(Type of technology)**	**Potential** Limitations	**Potential** Attributes	**Picture**
SoilSpec, Terra Tech **(Tensiometers measured by handheld transducer)**	• 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 0.8 bar. Becomes inaccurate after 0.50 bar. • Removing the bung during refilling can lead to the tensiometer moving and problems caused by loss of soil contact.	• 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.	
JetFill, Irrometer **(Gauge type tensiometers)**	• 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 1 bar.	• 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.	

TB 12 – Field Devices for Monitoring Soil Water Content

		• Data is useful without further calculations. • Not affected by salinity.	
UMS tensiometer	• High cost. • Difficult to convert to SWC. Makes calculating amount of irrigation required harder. • Measurement range limited to 0 to 1bar. • Higher level of expertise needed to link with and program logger.	• 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.	 
GBHeavy, Gypsum Block **(Gypsum blocks)**	• Gypsum blocks are insensitive to tension changes in wet soil (<0.30 bar). • 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.	• Simple, cheap method. • Capable of reading to quite low (dry) tensions (~10 bar). 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).	 
GBLite, Watermark **(Granular matrix sensor)**	• Manually read. • 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.	• Simple, low cost method. • Capable of reading to wide range of soil water tensions (0.1 to 2 bar) 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.	
WaterSmart **(Watermatic sensor)**	• Not suitable for soil suctions > 0.30 bar. • 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.	• Measurement relates directly to plant water status. • Automatically switches irrigation based on sensor set point (nominally 0. 15 bar, varied from 0.10 to 0.30 bar). • EC and temperature compensated.	 

		• Permanent calibration. • Sensor design life 20 years with a five-year warranty.	
Sentek EnviroSCAN, EnviroSMART, TriSCAN **Frequency domain reflectometry (capacitance)**	• 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.	• 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.	
ECH2O Probe **Frequency domain reflectometry (capacitance)**	• May lose some sensitivity at high water contents. • Good soil contact critical.	• Low cost. • Low power requirement. • Best suited to near surface measurements. • Low amount of disturbance if installing near surface. • High resolution allows daily or hourly tracking of water use • Voltage output proportional to water content • Low-cost dielectric water content sensor • Low sensitivity to salt and temperature • Very low power requirement	

TB 12 – Field Devices for Monitoring Soil Water Content

WET Sensor **Frequency domain reflectometry (capacitance)**	• Only one sensor can be practically handled per handheld reader. • High cost. • Automatic logging of the sensor needs a high level of electronic knowledge.	• Measures three important soil parameters in one reading. • Small sensor size allows use in small areas such as plant pots. • Maintenance free.	
Mini-TRASE **Time Domain Reflectometry (TDR) Soil Moisture Measurement**	• 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.	• Benchmark in accurate soil moisture monitoring. • Easily expanded by multiplexing. • Onboard data storage. • Immediate output of absolute SWC.	

Source: Irrigation Insights.http://www.irrigationfutures.org.au/imagesDB/news/soilwatermonitoring2ed.pdf

SECTION 8: REFERENCES AND FURTHER READING

Soil water monitoring - an information package-2nd edition (2005)
http://www.irrigationfutures.org.au/imagesDB/news/soilwatermonitoring2ed.pdf
This guide discusses and analyses different products to measure soil moisture according to nineteen attributes such as the reading rang, country of origin , irrigation system suited to, stated accuracy, remote access, best soil type, measurement sphere, application, output reading, interface to pc , capital cost, installation method, affected by salinity, annual operating cost, logging capability, expansion potential, power source and technical support.

Field Estimation of Soil Water Content A Practical Guide to Methods, Instrumentation and Sensor Technology. INTERNATIONAL ATOMIC ENERGY AGENCY (2008)
http://www-pub.iaea.org/mtcd/publications/pdf/tcs-30_web.pdf

Field Devices For Monitoring Soil Water Content. University of Florida. Rafael Muñoz-Carpena
http://edis.ifas.ufl.edu/pdffiles/AE/AE26600.pdf

Development of value selection method for choosing between alternative soil moisture sensors. Australian Irrigation Technology Centre. (1997)
http://npsi.gov.au/files/products/national-program-sustainable-irrigation/er970334/er970334.pdf

Opportunities for improving irrigation efficiency with quantitative models, soil water sensors and wireless technology. Faculty of Science, Warwick HRI (2009)
http://wrap.warwick.ac.uk/2301/

The WATER-BEE project (Seventh Framework Programme (European Commission) (7FP)
http://www.water-bee.eu/
The WATER-BEE project developed a prototype of an intelligent, flexible, easy-to-use but accurate irrigation scheduling system at an affordable cost that takes advantage of recent technological advances in wireless networking (ZigBee), environmental sensors and improvements in crop modelling.

Designing Wireless Sensor Networks as a Shared Resource for Sustainable Development
http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.131.9589&rep=rep1&type=pdf

Measurement of soil Moisture. World Meteorological Organisation.
http://www.wmo.int/pages/prog/www/IMOP/publications/CIMO-Guide/CIMO%20Guide%207th%20Edition,%202008/Part%20I/Chapter%2011.pdf

Soil Moisture Monitoring: Low-Cost Tools and Methods
http://attra.ncat.org/attra-pub/soil_moisture.html

National Audit of On-farm Irrigation Information Tools Chapman, M., Chapman, L., and Dore, D. (2007). Final report prepared for the Australian Government Department of the Environment, Water, Heritage and the Arts by RuralPlan Pty. Ltd.
http://www.environment.gov.au/water/publications/agriculture/pubs/irrigation-information-tools.pdf

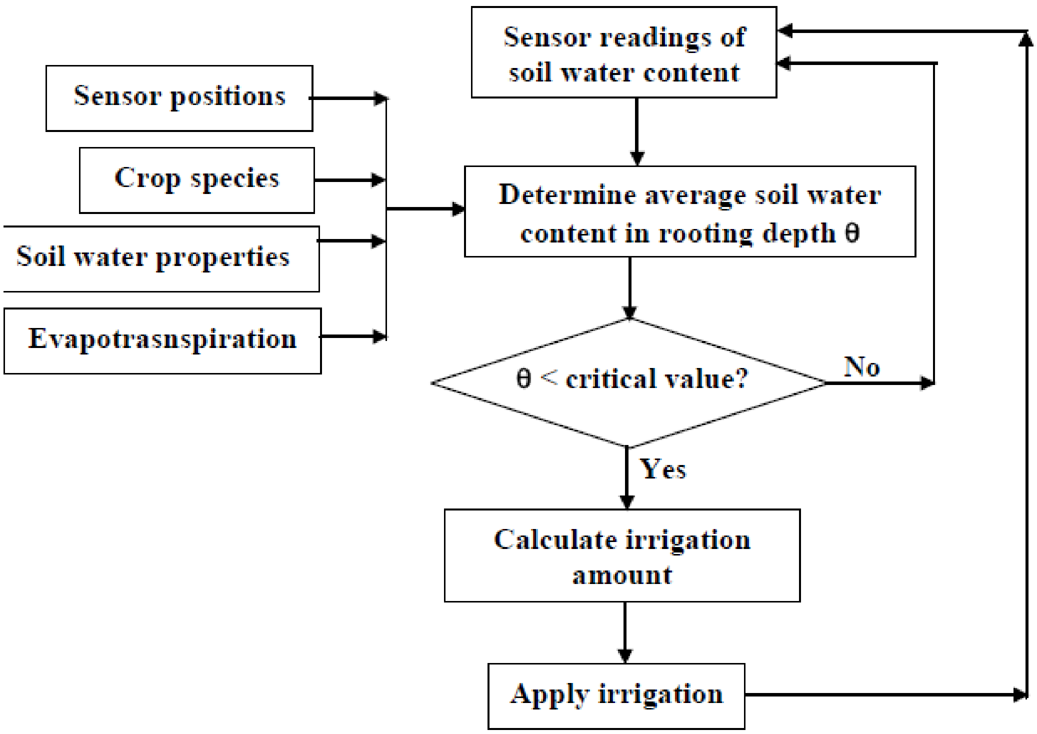
ICT International

http://www.ictinternational.com.au/soils.htm#tension

This website display different soil tension products available in the market.

SECTION 8: REFERENCES AND FURTHER READING

Table 5: Flow chart of irrigation scheme based on sensor readings and model predictions



Source: http://wrap.warwick.ac.uk/2301/1/WRAP_Greenwood_0380313-hr-231109-agricsc29.pdf Pg 61/62

[1] http://www-pub.iaea.org/mtcd/publications/pdf/tcs-30_web.pdf
[2] http://www-pub.iaea.org/mtcd/publications/pdf/tcs-30_web.pdf
[3] http://www.irrigationfutures.org.au/imagesDB/news/soilwatermonitoring2ed.pdf pg7
[4] http://www-pub.iaea.org/mtcd/publications/pdf/tcs-30_web.pdf
[5] http://www-pub.iaea.org/mtcd/publications/pdf/tcs-30_web.pdf
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[7] http://www-pub.iaea.org/mtcd/publications/pdf/tcs-30_web.pdf
[8] http://www.irrigationfutures.org.au/imagesDB/news/soilwatermonitoring2ed.pdf pg6
[9] http://www.irrigationfutures.org.au/imagesDB/news/soilwatermonitoring2ed.pdf pg6
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[13] http://www.environment.gov.au/water/publications/agriculture/pubs/irrigation-information-tools.pdf

[14]Pacific Institute. http://cssp.us/pdf/PeterGleick--Agricultural%20Water%20White%20Paper.pdf Pg7.