SMART

IRRIGATION NEW ZEALAND

Soil Moisture Monitoring

BOOK 11

Contents

This book is part of a series providing a comprehensive training resource for irrigation industry participants in New Zealand.

It provides a comprehensive resource for soil moisture monitoring in New Zealand.

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Using soil moisture monitoring for irrigation

The increased investment in precision irrigation infrastructure and control systems, coupled with a need for irrigators to be more accountable for their water use and nutrient loss, is resulting in an increase in the adoption of soil moisture monitoring. However, the use of soil moisture monitoring within irrigation decision making is not a simple task. Irrigators must choose the right equipment for their soil, land use activities and irrigation system type. This sits alongside locating, installing and calibrating (if necessary) soil moisture monitoring systems correctly to ensure they accurately inform irrigation decisions. Accessing, managing and understanding the measured data is also important to the water scheduling process. If soil moisture monitoring is to be used successfully each of these aspects has to be carefully worked through.

This book has been divided into three parts:

1. The first covers technology options available for soil moisture monitoring including their benefits and limitations. It also lists the common sensors available in New Zealand. More detail can be found on the technology options in the soil moisture monitoring methods section of this book.
2. The second covers considerations for installing soil moisture sensors, selecting how many are required, their location, when calibration is necessary, and capturing and understanding the information they produce.
3. The third provides a list of simple questions for irrigators to work through in order to successfully choose, install and use soil moisture sensors.

Soil moisture monitoring technologies

There are three ways to measure soil moisture;

1. **Gravimetric Soil Water Content** ($SWC_{g/g}$) refers to how much water is in the soil on a weight basis, for example 0.3g water per 1g of dry soil = 30%$SWC_{g/g}$;
2. **Volumetric Soil Water Content** ($SWC_{v/v}$) refers to the percentage fraction of the total volume of water contained in a volume of soil and is determined by $SWC_{g/g}$ multiplied by the soil bulk density. For example, the volume of soil could consist of 50% soil particles, 30% air filled pores and 20% water;
3. **Soil Water Potential:** As soil becomes drier, the remaining water contained within the soil becomes more tightly bound under a capillary force and the plant requires more energy to extract it. The soil water potential is a measure of this tension and is expressed in kilopascals (kPa).

Selecting the right soil moisture monitoring option

Options for soil moisture monitoring fall into direct or indirect soil moisture measurement. Gravimetric is the only direct way to determine how much water is in the soil. All other techniques rely on indirect methods that measure properties of the soil which vary with water content.

The range of indirect soil moisture measurement methods, their benefits, limitations and example sensors sold in New Zealand are summarised in Table 1 on the following page.

Table 1.

Sensor Type	Cost	Benefits	Limitations	Examples of sensors sold in NZ
Gravimetric	$	• Good accuracy • Direct measure • Simple to undertake	• Sampling not repeatable • Sample processing time (24 hours)	
Neutron Probe	$$$	• Excellent accuracy and precision • Insensitive to electrical conductivity and temperature	• Regulations on radioactive source • Real-time measurement not possible	• Troxler Model 4300 • CPN International 503DR Hydroprobe
Time Domain Reflectometry	$$–$$$	• Excellent accuracy and precision • Insensitive to electrical conductivity	• High cost	• Campbell Scientific TDR-100 • TRASE System I • Acclima TDR-315
Capacitance	$–$$$	• Simple electronics	• Sensitive to soil texture, electrical conductivity and temperature • Small measurement volume	• Aquacheck classic & sub-surface • Aquaspy Vector Probe • Decagon 5TM, 5TE & 10HS • Delta-T PR2 Profile Probe, SM150, SM300 & WET2 • Envirotek Enviro-pro • IMKO PICO-PROBE, TRIME-PICO 32, 64 & IPH/T3 • Sentek Diviner, EnviroSCAN & Drill & Drop probes • Spectrum WaterScout SM 100 & SMEC 300
Transmission Line Oscillator	$$	• Larger measurement volume than capacitance	• Sensitive to texture, electrical conductivity and temperature	• Campbell Scientific CS650, CS616, and Hydrosense • Delta-T ML3 Thetaprobe • Spectrum FieldScout 100 & 300 • Stevens Hydra Probe II
Note: Capacitance and to a lesser extent Transmission Line Oscillator sensors have a wide range of performance. Generally, cheaper sensors have challenges with both precision (repeatability of measured value) and accuracy (measured value in relation to actual value), expensive ones just accuracy. The sensor calibration section in this book explains precision and accuracy considerations. In summary, precision is critical accuracy is application specific.				
Time Domain Transmissivity	$$–$$$	• Insensitive to electrical conductivity • Larger measurement volume • Good precision	• Installation requires significant soil disturbance	• Acclima • Aquaflex • Baseline
Tensiometer	$	• High accuracy • Quick response • Close correlation to plant	• Narrow measurement range • Requires regular maintenance	• Decagon T4, T8 & TS1 • Delta-T SWT4 & SWT5 • Irrometer R, P & LT • 2900F QuickDraw, 2710L Standard & 2725ARL JetFill • Skye Standard & Electronic
Gypsum Block	$	• Wide measurement range	• Slow response • Relatively short life span	• Delmhorst KS-D1 • Frizzell Visual Soil Moisture Sensor & Hydrotec • GB Lite (Watermark), GB Heavy & G-dot • Willowbank Electonics Soil Moisture Probe
Heat Pulse Probe	$	• Best sensor for very dry soil	• Fragile • Sensitive to temperature gradients	• Campbell Scientific 229

How do I install a soil moisture sensor?

The simple answer to this question is with upmost care. All sensors, with the exception of neutron probe, rely on 'good sensor-soil contact' for accurate results. Quality sensors come with detailed instructions for their successful installation, and provide specialised installation tools, augers for example. Some sensors, particularly those that require significant soil disturbance during installation, recommend only experienced service providers install them. Sensors with no installation manual should be avoided.

The key considerations for sensor installations are:

- Ensuring there is no pathway for water (irrigation or rainfall) to flow directly to the sensor (preferential flow paths). This includes removing any air-gaps around sensor casings or cables, and caps being placed upon all access tubes
- Ensuring any soil removed during sensor installation is repacked so it is representative of the soil profile (texture and density)
- Ensuring the soil surface around the sensor is not compacted and does not allow water to pond.

Generally, the more destructive the installation method the longer it will take for a sensor to 'settle-down' and give accurate readings. For optimal outcomes sensors should be installed in the autumn or winter. This also allows the field capacity to be estimated and refined prior to the start of the irrigation season.

How many soil moisture sensor sites do I need?

The number of soil moisture monitoring sites depends on;

- the number of crops or different crop varieties being irrigated;
- the site characteristics, predominantly soil differences but for irrigation in hill country also slope and aspect;
- the type of irrigation system being used.

A minimum standard when considering the number and location of sites is;

- one site per irrigation block; and/or
- one site per crop/variety type.

This means a monitoring site should ideally be placed in each unique 'management zone'.

However, for horticultural enterprises (where multiple crops or varieties are grown in a relatively small area) or for extremely variable landscapes, the cost of monitoring each management zone can be prohibitive. Crop value and production potential or risk therefore also become valid considerations.

Where do I install soil moisture sensors?

WITHIN THE PADDOCK

There are some basic principles that apply to all crop types and irrigation systems when selecting a representative site to install a soil moisture sensor;

- Stay away from the edges of the crop or near areas of heavy traffic where compaction may occur;
- Avoid locations that are not typical of the irrigation being applied, e.g. next to pivot towers or directly under drippers or micro-sprinklers; and
- Avoid high spots where surface runoff may occur due to slopes, mounding or terracing, and avoid low spots where water may pond.

The uniformity of an irrigation system (how evenly the water is applied) is also a key consideration for locating sensors.

Drip, micro-sprinkler and fixed grid irrigation systems require precise selection of monitoring sites. The amount of water applied between emitters can vary significantly, from very wet at the emitter itself to much drier in between. In coarse soils, the lack of lateral spread (sideways movement) of water may accentuate the variance between emitters, although if the irrigation system is designed correctly it should compensate for this through closer emitter spacing. Soils of low water holding capacity should be given special consideration when locating sensors because irrigation will need to first manage the area most sensitive to stress.

It is widely accepted that soil moisture sensors should be placed within the wetted area but at least 100–300mm away from any emitter. The actual spacing depends upon the emitter flow rate and soil type. For low rate emitters, in combination with coarse textured soils, the sensor needs to be located closer to the emitter. Soil moisture sensors must not be installed directly beneath an emitter.

For **centre pivot irrigation**, sensors should be placed in a location that receives an average irrigation application depth measured across the pivot length. The first and second spans should be avoided. Areas outside the last tower, particularly if it is watered by a corner arm or end gun, should be avoided. Even though the end gun may irrigate 10% of the area, the irrigation application depth is variable, and thus quite different from the average depth found beneath the pivot spans.

A pivot has a start point and end point with the return period between them typically being two to five days. On any given day, soil water content will vary between start and end points depending on pivot location, e.g. after an irrigation event sensors located in the portion of the field where irrigation has occurred show higher soil water content than those areas yet to be irrigated. If the sensor is only being used to determine when to start irrigation, it is recommended that it is located in a suitable soil type near to the start point.

Sprayline and long lateral systems often have uniformity issues as a result of sprinkler placement challenges and poor design. These irrigation systems also typically operate in highly variable landscapes (soil water holding, slope and aspect). A portable sensor is usually the best option for this scenario. This allows multiple readings to be taken over an area.

For **variable rate irrigation**, sensors should be located within each of the management zones.

For **moveable irrigation** systems, sensors should be located away from the overlaps between runs or the gun/boom carriage and not at the beginning or end of a run.

DOWN THE SOIL PROFILE

Changes in soil type, different soil horizons (layers), and plant rooting depth are the two key considerations for determining the number and location of sensors down the profile.

Sensors should be located within a soil horizon, and avoid crossing the boundary between them. If multiple thin horizons exist, then the most significant horizons should be selected.

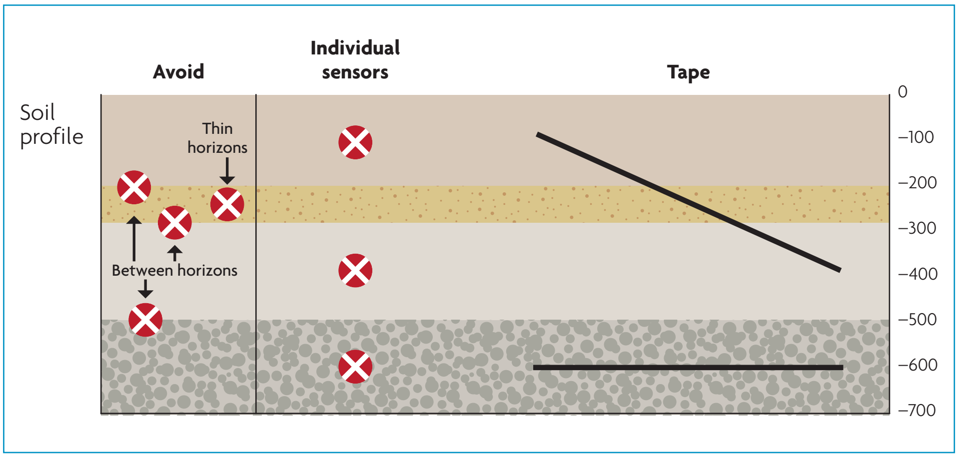

Figure 1. Sensor placement through the soil profile.

For **permanent crops (trees and vines)**, depending on the number of soil horizons and the crop's plant rooting depth, three to five sensor points should be placed in the root zone (ideally one every 200mm), with the bottom sensor located just below the root zone to detect drainage.

In **annual and shallow rooted crops**, depending upon the number of soil horizons and plant rooting depth, two to four sensor points should be placed in the root zone (ideally one every 100mm), with one located just below the root zone to detect drainage.

For **pasture**, depending upon the number of soil horizons and plant rooting depth, two to four sensor points should be placed in the root zone (ideally one every 100mm), again with one located just below the root zone to detect drainage.

The depths at which the sensors are placed depends on the soil horizons and crop root depth. However, in general:

- The first soil sensor is installed closest to the surface, usually between 100–200mm. The 100mm depth is frequently used if the sensor also records soil temperature as this is the standard measurement depth. Soil moisture readings from this sensor fluctuate greatly which make irrigation decision making difficult if based on this sensor alone.
- The second soil moisture sensor is installed at mid-depth (300–400mm). Soil moisture readings from this sensor are more stable and important in scheduling irrigation. This depth is focussed upon the rooting mass.
- The third soil moisture sensor is installed at a deeper depth (500–900mm). Soil moisture readings from this sensor change slowly and are a good indicator of whether the irrigation strategy is adequate. If the line trends up or remains flat over the season, over-irrigation is occurring. If the line has a slight downward trend then irrigation is being well managed. A sharply declining line means under-irrigation is occurring. For many crops, the soil moisture level is managed so that the deeper level sensors are unchanged during the first part of the season and then trend downwards as the crop matures.

Do I need to field calibrate my sensor?

To answer this question, the concepts of accuracy and precision need to be understood..

- Precision is the repeatability of measurement. Are the same readings measured for a given soil water content over time?
- Accuracy refers to how close the reading is to the actual level of soil moisture in the soil.

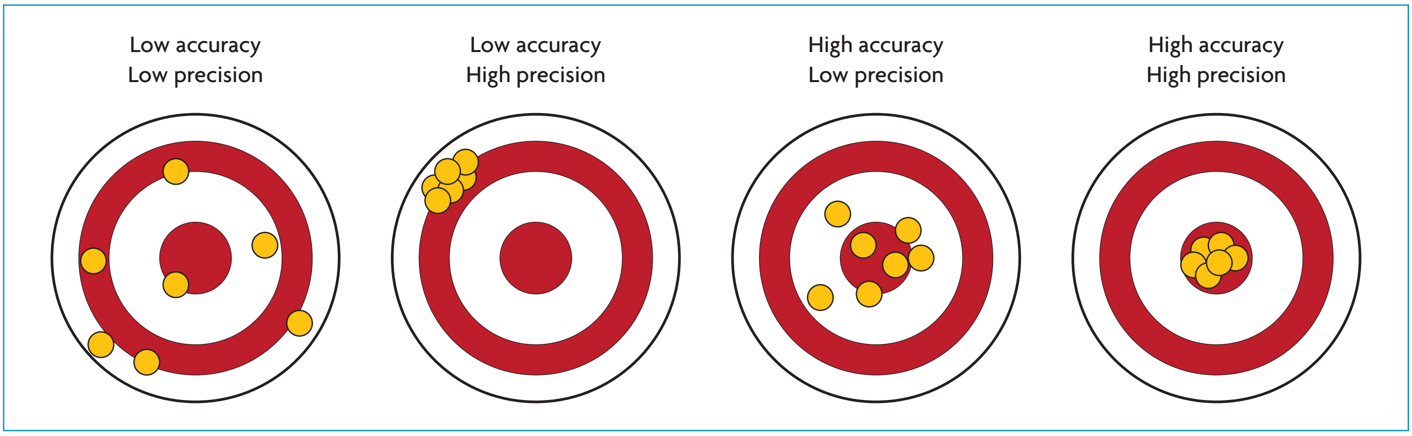

Figure 2. Precision and accuracy.

Sensors need a level of accuracy that matches the irrigation system and the degree of control it allows. If the irrigation system is capable of delivering varying amounts of water along its length (variable rate irrigation), sensors need to provide accurate soil water measurements across a paddock so that data from one sensor can be compared with another. This allows different irrigation depths to be applied to the different areas with confidence. Less accurate information is required when system management is restricted to a set irrigation depth each rotation or where water supply is restricted.

However, all sensors used for soil moisture monitoring need to be precise and provide consistent and repeatable measurements.

New Zealand trials clearly demonstrate that most sensors require field calibration to give confidence in their accuracy. However, for most irrigators, soil moisture sensors are mainly used for trend based start/stop decision making, not to provide absolute measurements. Field calibration is therefore a nice-to-have rather than a necessity. The value of un-calibrated sensors is well proven; they have been used successfully for a number of decades to improve crop production, water use efficiency and energy efficiency.

Despite this, in some regions growing expectations for environmental monitoring are starting to change this approach, driving the need for accuracy and thus field calibration. The ability to provide more accurate soil water holding data for modelled estimates of nutrient loss (changing from the default soil water values in OVERSEER) can be advantageous for regulatory purposes. Field calibration involves readings from the sensor being compared and then adjusted to an independent measurement of soil moisture content.

The level of sensor accuracy and precision often relates to cost, however correct installation is also critical. Many sensors state they have a certain level of accuracy. Any manufacturer's claim should be supported with field based evidence, preferably relating to New Zealand conditions.

What are the options to capture data from my sensor?

There are three main options to capture data from a sensor:

1. Manual readings
2. Data loggers that are manually downloaded
3. Data loggers that are telemetered to a computer network or the cloud.

For good decision making trends over time need to be regularly monitored. Permanent manual read sensors without data logging capability should be avoided, unless sensor reading becomes an important daily or weekly task for a dedicated staff member or contractor.

Portable manual read sensors are ideal for extremely variable sites, such as irrigated rolling hill country, or for horticultural blocks with multiple crops or varieties. For these scenarios, the cost to install permanent sensors is often prohibitive. A good quality portable sensor will log the data with a time, date and location stamp which can then be downloaded. Using a good quality portable device, at critical times, can be a very useful tool.

A continuous record of soil moisture can be combined with other information, like production records and water use, to provide excellent irrigation decision support. A well maintained and quantified record will also provide an excellent basis for further professional advice for agronomists or other advisors. Good quality loggers have a date and time stamp and will continue logging during power outages ensuring data is not lost. Loggers can be manually downloaded through cables or wireless technologies, or telemetered in real time to a business computer network or the cloud. There are various telemetry solutions available that broadly fall into radio or cellular or a combination of the two. The optimal solution depends on the nature of the site and the proximity to the cellular network.

How do I interpret the data?

The information from soil moisture monitoring sensors is most useful when presented as graphs or charts, this makes it easier to compare and interpret data trends. Some sensors come with software or equipment to view and interpret the data, but for others this is only available as an optional purchase. Most sensors that continuously log now come with software which converts and presents the data into a convenient format. For other products, you will need to manually enter data into a spreadsheet to make sense of it.

Although soil moisture trace graphs come in various forms, they all display the same trends and can therefore be read in a very similar way.

There are a range of companies in New Zealand that offer a service where data can be fully managed by the sensor supplier. The irrigator accesses this data via the internet. Regardless of the method, initial training in interpreting and analysing the data is essential. Being unsure of how soil moisture sensor data can inform irrigation is one of the key reasons why irrigators stop using them. Therefore, if there is no support within New Zealand, you should consider not purchasing the equipment

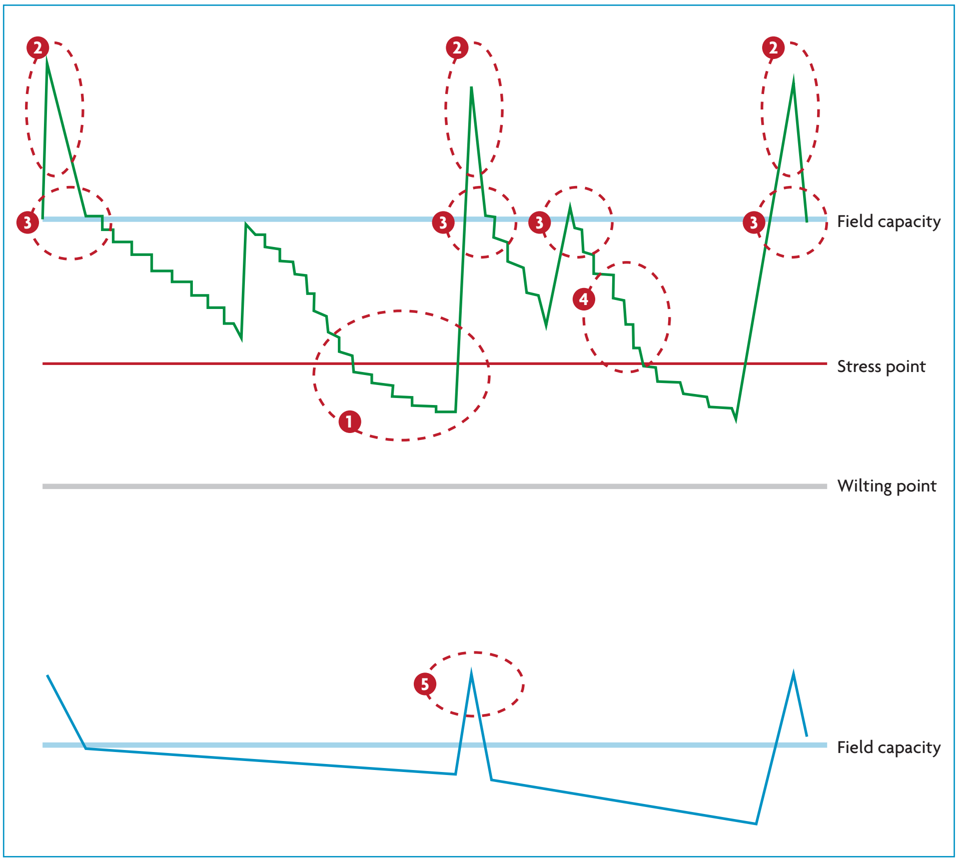

Figure 3. A double sensor trace. One recording moisture in the root zone (Green) and one in the subsoil (Blue) monitoring drainage events.

The diagrams above show a typical 'real-time' soil moisture trace. In general, the vertical axis shows the volumetric water content and the horizontal axis shows time. Five key interpretation points have been highlighted. Once understood they will allow you to easily interpret any trace.

1. As soil moisture drops below the stress point (irrigation trigger point), the soil moisture trace line levels out (the slope of the line becomes shallower). When soil moisture drops below stress point, the plant is using more of its energy to extract soil moisture as opposed to productive growth. This results in reduced yield.
2. Spikes above field capacity indicate periods of saturation. This will have a direct effect on drainage and nutrient leaching. On heavier soils, periods of saturation will also decrease crop production as the crop becomes dormant.
3. An indication of field capacity, for each sensor down the profile, is given by looking at where the first step in the trace line occurs. All the water that is drained through gravity has gone and the step effect shows the day time (plants transpire and water evaporates from the soil's surface) and night time (plants don't transpire and there is no evaporation from the soil) water use pattern. However, one of the easiest ways to determine field capacity is monitoring the sensor readings after a large rain event or through saturating the soil around the sensor. This works particularly well in the winter when the crop is dormant (not actively growing). In free draining stony soils field capacity typically occurs one to two days after the event, in silt or clay loams four to five days.
4. As above, the stepping of the trace line indicates the daytime–nighttime plant water use pattern. During the peak of the season the stepping becomes more pronounced (vertically longer).
5. A spike on the soil moisture trace below the root zone indicates a drainage event, either through rainfall or over-irrigation.

Good and Best Management Practice for soil moisture monitoring

IrrigationNZ's inaugural Soil Moisture Monitoring Master Class in 2015 brought together a cross section of experts from research and industry to discuss the issues and increase the understanding of soil moisture monitoring technologies and their applications. One of the outcomes from the master class was agreement on two standards for soil moisture monitoring – Good Management Practice and Best Management Practice.

GOOD MANAGEMENT PRACTICE

This refers to the minimum standard required to achieve good decision making from soil moisture monitoring:

- One site per irrigation system and/or crop.
- The site is located in the soil type with the lowest Water Holding Capacity, but that soil type is representative of at least a quarter of the irrigated area.
- Each site has one sensor located within the active root zone.
- A precise (repeatable) sensor is used.
- The irrigator receives some basic training in interpreting soil water measurements.
- The data from the sensor is transferred to a computer or the cloud so that soil moisture trends can be graphed and analysed.

BEST MANAGEMENT PRACTICE

This refers to the standard that would allow the maximum benefit to decision making from soil moisture monitoring:

- Two sites per irrigation system and/or crop.
- One site is located within the soil type with the lowest Water Holding Capacity but that soil type is representative of at least a quarter of the irrigated area. The second site located within the soil type with the highest Water Holding Capacity but again representative of at least a quarter of the irrigated area.
- Each site has at least two (shallow rooted and pasture) or three (permanent crops) sensors, one or two located within the active root zone, the other located below the active root zone to monitor drainage events.
- A precise (repeatable) sensor is used that is also field calibrated.
- The data from the sensor is telemetered in real-time to a computer or the cloud to allow real time decision making.
- Professional advice is used to help with the initial interpretation of the data.

Guide to purchasing and locating soil moisture sensors

Before you purchase a soil moisture monitoring sensor you must first identify your requirements. This will guide your decision making in the type of equipment you purchase, helping you to match it with your management style, crop and situation, the amount of information you need, and your budget.

Before you buy a product answer each of these questions to ensure you choose what's right for you

1. What information do I need from my soil moisture monitoring?
2. How labour intensive is it?
3. How user friendly is the information?
4. What level of accuracy do I need?
5. Does soil type affect my choice?
6. Does the irrigation system limit my choice?
7. Does crop type limit my choice?
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?

What information do I need from soil moisture monitoring?

Soil moisture monitoring sensors can provide a range of information. Some give simple 'wet/dry' measurements, which provide a guide to reducing plant stress and minimising irrigation water losses in the field. Others can gather more complex information including:

- Depth and amount of irrigation or rainfall,
- Where root activity and development is occurring in the soil profile,
- Extent of water tables within or just below a crop's root zone,
- Irrigation timing and forecasting based on water use (known as irrigation scheduling),
- Soil temperature.

As a minimum, you need the sensor to provide soil moisture readings for the plant root zone before and after an irrigation event. A reading following a rainfall event may also be of benefit.

- The reading before an irrigation shows how dry the soil is,
- The reading after the irrigation or rainfall event shows how deep the moisture has gone, indicates how much irrigation was applied and if under-irrigation has occurred,
- A reading below the active root zone of a crop can indicate whether over-irrigation (drainage) has occurred,
- If you take additional readings between irrigation events, you can determine your crop's pattern of water use and how this relates to growth stage and weather patterns.

How labour intensive is the device?

Sensors that require the irrigator to collect information manually are more labour-intensive than those that collect or log data automatically.

Labour availability is often not considered in the purchasing decision, but lack of time or labour is one of the main reasons why manual monitoring sensors are frequently abandoned. Manually read sensors need to be regularly and consistently read throughout the irrigation season. Missed readings result in incomplete data and may make irrigation decision making challenging.

If you purchase a manually read sensor, you have to commit the labour required to undertake the readings. If you cannot guarantee this labour commitment, then you should select another option such as automatic logging devices, telemetry or a contract service.

Using manual sensors in combination with a continuous logged sensor, can be a valuable tool set to educate yourself about the conditions on your property.

Automatic logging sensors can be downloaded periodically in the field or telemetry options can be added that automatically send the data via radio or mobile phone to your PC, a server or the cloud for viewing over the internet. A contract service can do everything for you, i.e. provide you with a recommendation on when next to next irrigate. Alternatively, the service may process data into an easily understandable form, from which you make irrigation decisions.

How user friendly is the information?

The information from soil moisture monitoring sensors is most useful when presented as graphs or charts, this makes it easier to compare and interpret data.

Some sensors come with software or equipment to view and interpret the data, but for others this is available only as an optional purchase. However, most sensors that continuously log come with software which converts and presents the data in a convenient format. For other products, you may need to manually enter data into a spreadsheet to make sense of it.

There are a range of companies in New Zealand that offer a service where data can be fully managed by the sensor supplier. The irrigator accesses this data via the internet. You need to understand how this works, if any upfront or ongoing costs are associated with it, the knowledge base within the company and how reliable the service is.

Regardless of the option chosen you will need training in operating the sensor and interpreting and analysing the data. Check with the supplier whether training is provided, and to what degree. Also check whether you can easily get ongoing support and software updates. These are critical components for learning how the equipment works and what the data is showing and should continue until you are competent in its use. Being unsure of how to make best use of sensors is one of the key reasons why irrigators stop using monitoring equipment.

Often, a specialist consultant or agronomist will be useful in helping to understand the soil, water and plant interactions. Alternatively, industry bodies run grower support groups where results and other issues can be discussed, either peer to peer or by engaging an expert.

What level of accuracy and precision do I need?

Sensors need a level of accuracy that matches the irrigation system and the degree of control it allows. However, all sensors used for soil moisture monitoring need to be precise and provide consistent and repeatable measurements.

Most sensors require field calibration to give confidence in their accuracy. However, for most irrigators, soil moisture sensors are mainly used for trend based start/stop decision making, not to provide absolute measurements. Field calibration is therefore a nice to have rather than a necessity.

Despite this, in some regions growing expectations for environmental monitoring are starting to change this approach, driving the need for accuracy and thus field calibration.

The level of sensor accuracy and precision often relates to cost, however correct installation is also critical.

Does soil type affect my choice?

Soil type can greatly affect which sensor you choose as some sensors are not suited to certain soil types. For example, gypsum blocks and tensiometers in sands and gravels, and capacitance probes in shrink-swell clays often give inaccurate readings.

Variations in soil type often occur across a farm or paddock. You need to check that you have enough soil moisture monitoring sites to get representative data for the area being irrigated. As a minimum you should ensure the most representative soil type is covered. This is linked to your budget and the level of accuracy or precision you are trying to achieve. There is a trade-off between the number of sensors installed, the cost of the equipment and the accuracy or precision you require.

Does the irrigation system limit my choice?

The characteristics of the irrigation system should help determine what sensor is chosen, and how and where it is installed.

The uniformity (how evenly the water is applied) particularly affects where sensors are located. Drip-micro irrigation in particular requires correct selection of representative monitoring sites as do travelling irrigators. It is important that the spacing between the sensor and the emitter for drip-micro or position in relation to the overlap for travelling irrigators is considered.

Does crop type limit my choice?

The crop type results in some important considerations for sensor choice and location:

- Deep-rooted or permanent plants may need more sensors, or single sensors giving readings at multiple depths. Digging a hole to identify the soil characteristics at different depths and any layers that may limit plant root growth is always recommended prior to choosing a soil sensor. This will also inform the ideal placement of sensors down the profile.
- For annual crops, sensors may have to be installed after emergence and removed at the end of the season before harvest so good installation is critical. The length of time it takes for a sensor to 'bed-in' should be carefully considered.
- Machinery, livestock and human traffic affect how sensors can be placed. For example, centre pivot wheel tracks or stock paths. Irrigators should consider above ground versus buried sensors depending on their situation.

What other factors affect my choice?

Other key factors that should be considered include:

- Sensor installation is critical. Of the many things that influence the quality of data, installation is the most important.
- Livestock grazing's can also affect sensor readings. Pasture cover (height) can increase or decrease water use by approximately 20%. When interpreting the sensor data for irrigation decision making, particularly if only one site is being used, this needs need to be considered.
- Reading sensors manually, if not done carefully, can damage the crop around the sensor and/or compact the soil around the site, impacting on the sensor readings. Telemetry options are often a better choice for these situations.
- How is the device powered? Is power available, and can the power source be protected in the field from either farming operations or theft?
- Soil moisture monitoring sensors provide additional information that can help guide and improve irrigation decisions but they should always be used in conjunction with other tools such as weather forecasts and field observations.
- Is the sensor sensitive to soil temperature or saline soil conditions? Although generally salinity is not an issue in New Zealand.

How durable is the product?

Both portable and permanent products need to be assessed for durability:

- Will the sensor stand up to damage from ultraviolet rays, moisture and extreme temperatures?
- Livestock, pests, machinery traffic and temporary labour can damage fixed devices. How resilient is the sensor in terms of the equipment itself and its installation? For installation, is it buried below the surface or will it require protection around it? If the latter, additional labour maybe required to ensure the area around the sensor is representative of the crop conditions.
- Portable products need to withstand potential damage in transport. Does the equipment come with a robust carry case or do you need to purchase one?
- If the sensor is damaged what back up support is provided by the supplier? Will they come out and repair the damage? Can it be fixed on site or will it need to be removed and sent away to be repaired? Or do I simply just buy-another one?

How much maintenance will it need?

Some sensors may have particular maintenance needs or particular difficulties in servicing:

- What are the during-season and end of season maintenance requirements?
- Can you do it yourself or is outside expertise required?
- Does the product come with supplier support?
- Is the equipment 'plug and play' or will it require specialist installation skills?

Can I afford it?

To answer this question, you need to assess the initial capital and on-going seasonal and annual costs, and compare these with the potential water and energy savings and productions gains or compliance expectations.

COSTS:

- Cheaper products are generally less accurate. A number of the really cheap options have issues with precision. They are also usually manually read and so are labour intensive.
- It is important to consider telemetry as a means of reducing the labour cost of data collection. The trade-off is usually the increased initial purchase cost of the product, but this often pays for itself relatively quickly.
- The annual costs relate to the maintenance both during and after the season, and re-installation costs for annual crops. For this the variation in cost between sensors lies with differing labour requirements and the need for suppler support.

BENEFITS:

- The benefits of installing a soil moisture sensor also need to be considered. This includes:
  — the potential energy savings
  — the reduced operation hours of equipment
  — the productivity gains that may come from better scheduling
  — being able to operate within nutrient discharge limits

However, these benefits will only be achieved if the irrigator understands the equipment and its limitations, uses the equipment appropriately and interprets the information correctly.

There are many cases where a monitoring system has shown financial benefits that far out-weigh costs. In most cases external advice, or a very solid understanding of agronomy, is needed to realise this in the shorter term. Longer term, where the monitoring is well understood and data is well used, this is much easier.

What are my next steps?

Before any purchase, it is recommended you consider the above points while also talking to:

- Irrigators who have successfully used the sensor that you are considering,
- Irrigators that have tried the equipment but no longer use it,
- A range of soil moisture sensor suppliers.

Soil moisture monitoring methods

Gravimetric soil moisture determination

To measure gravimetric soil water content (θ_g), take a small soil sample (about 50gm) and weigh it ($M_{wet\ soil}$), dry the sample in an oven (105 ±5°C) for 24 hours (until the mass stabilises at a constant value) and then weigh it again ($M_{dry\ soil}$). If the soil samples contain organic matter, oxidation may occur at 105°C and some organic matter will be lost. Lowering the oven temperature from 105 to 70°C avoids significant loss of organic matter. The weight difference is the amount of water contained in the sample.

$$\theta_g = \frac{M_{wet\ soil} - M_{dry\ soil}}{M_{dry\ soil}} = \frac{M_{water}}{M_{dry\ soil}}$$

Volumetric soil water content (θ_v) represents the fraction of the total volume of water (V_{water}) contained in total volume of soil (V_{soil}), where, V_{soil} is the volume of dry soil + air + water in the sample.

$$\theta_v = \frac{V_{water}}{V_{soil}}$$

The relationship between gravimetric and volumetric soil water content is:

$$\theta_v = \frac{V_{water}}{V_{soil}} = \frac{\dfrac{M_{water}}{\rho_{water}}}{\dfrac{M_{soil}}{\rho_{soil}}} = \frac{M_{water}}{M_{soil}} \frac{\rho_{soil}}{\rho_{water}} = \theta_g \frac{\rho_b}{\rho_w}$$

Where ρ_b is the bulk density of dry soil and ρ_w is the water density.

Accuracy: Accuracy is very dependant on the amount of care taken, but ±1–2% can be achieved.

Advantages: If undertaken carefully this method can be very accurate for all soil types. Gravimetric measurements are the standard with which all other methods are compared to and often used to calibrate equipment or determine a soil's water holding capacity.

Limitations: The time, process and destructive sampling method means repeat or real-time measurements are not possible. It is therefore not a practical option for irrigation scheduling. Water contents for stony soils can also be misleading unless they are adjusted for stone content.

Neutron moderation

This method is based on the interaction between high-energy (fast) neutrons and hydrogen atoms in the soil. Neutron probes are the tool used to determine soil water content by neutron moderation.

The neutron probe consists of an electronic gauge, a connecting cable, and a source tube containing both the nuclear source and detector tube. Measurements are made by lowering the probe down an access tube (usually made of either aluminium or steel) to the measurement depth. When the source tube is lowered into the access tube, high speed neutrons are emitted from the nuclear source and scattered into the soil. These collide with the hydrogen atoms present in soil water. Through this collision the neutrons lose their energy and become low energy 'slow' neutrons. The number of slow neutrons returning to the source detector are counted, and the soil moisture content then determined from calibration curves that relate the volumetric soil water content with counts. This process can be repeated at several depths to give measures of soil water down the soil profile.

Installation: Access tubes are installed in an appropriately sized auger hole, however for gravel soils a steel tip has to be placed at the bottom of the tube and then driven in. The depth to which the tube is installed relates to the crop root zone, noting soil moisture also needs to be measured below the crop root zone to monitor if drainage has occurred. Ideally the tubes have minimal wall thickness, just large enough for the probe to fit in without an air gap, and are made of materials that do not 'slow' the neutrons. Installing tubes by placing them in an over-sized hole and backfilling is not recommended because it often results in voids adjacent to the tube. It is also difficult to get a truly representative sample of the soil through this method. To avoid surface water flowing down the side or inside of the access tube, it needs to be covered with a cap.

Accuracy: Neutron probes measure between 0 and 60% volumetric soil moisture with ±0.5% accuracy. When calibrated they are a very accurate method and sample a sphere of between 150–700mm radius. Accuracy depends on the number of slow neutrons counted and the count duration (for most soil types the standard is 15 seconds).

Advantages: Neutron probes are suitable for any crop and any soil type. As they are highly accurate across a wide range of conditions they are ideally suited to calibrating sensors.

Limitations: Precautions are necessary when using the equipment. A licence is also required to operate a neutron probe in New Zealand, and it requires a shield due to it being a radiation-emitting device. When the soil water content is high, neutrons are not able to travel far before being 'slowed'. In this situation around 95% of the counted neutrons come from a relatively small soil volume, a 150mm radius. However, in a dry soil the sampling radius is much larger, up to 700mm. Therefore, the measured soil volume varies with water content. It is difficult to use a neutron probe effectively in less than 200mm of soil depth because some neutrons escape from the soil surface into the air affecting the count. However, it is possible to apply a surface calibration to account for this. Due to the expense of this equipment, these devices are rarely used for continuous monitoring.

Example sensors:

- Troxler Model 4300
- CPN International 503DR Hydroprobe

Dielectric methods

Electromagnetic waves travelling through soil are affected by Electrical Conductivity, Dielectric Permittivity and Magnetic Permeability. Dielectric methods estimate the soil moisture content by measuring the soil bulk permittivity (the dielectric constant). A soil's permittivity value is predominantly influenced by the amount of water it holds as the dielectric constant of water (around 80) is much larger than minerals (three to five) and air (one), the other components of soil.

For moisture contents below 50% there is an empirical relationship that can be used to determine the dielectric constant of most soils regardless of mineral composition and texture. The relationship is between the moisture content and the sensor output signal – time, frequency, impedance or wave phase. However, for higher moisture contents, organic or volcanic soils, a specific calibration may be required.

Soil dielectric methods are becoming widely adopted because they have almost instantaneous measurements, require limited maintenance, and can provide continuous readings. A range of different methods used are described below.

TIME DOMAIN REFLECTOMETRY (TDR)

TDR techniques estimate soil water content using the two-way travel time of an electromagnetic signal passing along a probe buried in soil. An electrical signal is applied to the waveguides of the probe (usually between two and four are used), travels along its length and is then reflected back to the TDR control unit. The time taken for the signal to return varies with the soil dielectric, the water content of the soil surrounding the probe. By measuring the travel time, the dielectric constant of the soil can be estimated to give a measure of soil water content. By observing this waveform, a number of properties of the soil can be determined. Water content can relatively easily be differentiated from other effects on the waveform.

Installation: TDR sensors require two to four rods (waveguides) installed in the soil parallel to each other. Generally, they are separated by 50mm and vary in length from 50mm to 1000mm. The rods can be made of any metal and must be installed carefully to ensure there are no air gaps between the sensor and the soil. Some manufacturers recommend placing the rods in a pilot hole and then backfilling the hole with slurry to ensure a tight fit. However, as the slurry is not representative of the surrounding soil, readings taken using this method will not truly reflect the soil being measured.

Accuracy: TDR's can measure between 0% and 100% volumetric soil moisture content with ±0.5% accuracy in the field. They sample a sphere of up to 200mm radius around the probes, depending upon design and wavelength geometry.

Advantages: TDR's allow non-destructive and repetitive measurements of soil moisture at a point in the profile. The methodology uses a time based relationship to derive readings of soil moisture and is therefore not subject to electrical errors (current and voltage). For the majority of soils, the TDR method is generic meaning no soil-specific calibration is required. As a result, TDR's are frequently used to calibrate other sensors. This method works particularly well for loam soils.

Limitations: As good contact between the sensor (rods) and surrounding soil is essential, measurements in stony soils can be extremely challenging. Also in stony soils, the rods are frequently bent when inserted, and so are no longer parallel. Careful installation is critical to minimise both these issue. This method is also challenging for measuring very dry soils as cracks and air gaps can form around the rods when they are inserted. It is also problematic for measuring shrink-swell clays. When these soils dry-out they can shrink away from the rod leaving an air gap. However, if irrigation is being correctly scheduled neither of the above limitations should be an issue as the soils should never dry out to this extent. TDR sensors are relatively expensive and sample a relatively small volume of soil, the actual volume being determined by the wave guide geometry. While this method can be used for real-time monitoring, due to its expense, it is generally considered a research or calibration tool.

Example sensors:

- Campbell Scientific TDR-100
- TRASE System I
- Acclima TDR-315

CAPACITANCE SENSORS

Capacitance sensors consist of two or more electrodes in the form of plates, rods or rings around a cylinder, that are then imbedded in the soil. They use capacitance to measure the dielectric permittivity of the soil. When the amount of soil water changes, the sensor measures a change in capacitance (from the change in dielectric permittivity). Circuitry inside some sensors changes the capacitance measurement into a proportional millivolt output. Other configurations are like a neutron probe. An access tube made of PVC is installed in the soil and the sensor placed inside this at a fixed depth. Capacitance sensors can be very susceptible to electrical errors as soil electrical properties can change with compaction, temperature, water content and ion concentration.

Installation: Capacitance sensors are installed using a variety of methods. Some are installed in a similar way to a neutron probe, an access tube, and readings are taken through the sensor being lowered down or permanently located in the access tube. Others are permanently installed in the soil. As with TDR good soil-sensor contact is crucial.

Accuracy: Capacitance sensors can measure volumetric soil moisture content with ±1–2% accuracy, if they are calibrated. However more typically accuracies of ±4–5% are achievable. They sample a sphere of about 100mm radius, however 95% of the measurement is within 50mm.

Advantages: Capacitance sensors are more flexible in their design than TDR's so can be adapted for a range of scenarios. They are also relatively inexpensive when compared to TDR, due to the less complex and costly electronics. The capacitance method is a widely used soil technique in commercial agriculture, agricultural research and environmental monitoring.

Limitations: As good soil-sensor contact is required these sensors can have the same issues as TDR with stony and dry soils, and shrink-swell clays. These can be overcome with good installation. For accuracy, due to the changing electrical properties of soils (compaction, water content and ion concentration), calibration is essential. Capacitance sensors are also susceptible to temperature changes and readings need to be adjusted for this. Some sensors self-calibrate for this. There are a large number of capacitance sensors on the market and the performance of these varies greatly.

Example sensors:

- Aquacheck classic & sub-surface
- Aquaspy Vector Probe
- Decagon 5TM, 5TE & 10HS
- Delta-T PR2 Profile Probe, SM150, SM300 & WET2
- Envirotek Enviro-pro
- IMKO PICO-PROBE, TRIME-PICO 32, 64 & IPH/T3
- Sentek Diviner, EnviroSCAN & Drill & Drop probes
- Spectrum WaterScout SM 100 & SMEC 300

TRANSMISSION LINE OSCILLATOR SENSORS

An oscillator circuit is connected to the rods that are embedded in the soil, with an oscillator state change triggered by the return of a reflected signal from one of the rods. The two-way travel time of the electromagnetic waves that are induced by the oscillator on the rods varies with changing dielectric permittivity. While this is the same measurement principle as TDR, it is prone to additional error caused by electrical conductivity between the rods, with the electronics unable to differentiate between the influence on wave travel time caused by dielectric permittivity and electrical conductivity. Some of the better sensors using this method correct for this internally by measuring this electrical conductivity, and correcting wave travel time, leaving just the effect of dielectric permittivity.

Installation: These sensors have a number of rods which are installed in the soil parallel to each other. Generally, they vary in length from 100 to 300mm. The rods can be made of any metal and must be installed carefully to ensure there are no air gaps between the sensor and the soil. As with TDR good soil-sensor contact is crucial.

Accuracy: These sensors can measure volumetric soil moisture content with ±1–5% accuracy if they are field calibrated however more typically accuracies of 3–5% are achievable. They sample a sphere of about 100mm radius, however 95% of the measurement is within 50mm.

Advantages: These sensors are relatively inexpensive and are suited to applications where precision is not required.

Limitations: As good soil-sensor contact is required these sensors have the same issues as TDR with stony and dry soils, and shrink-swell clays. These can be overcome with good installation. For accuracy, due to the changing electrical properties of soils (compaction, water content and ion concentration), calibration is essential. However, the better sensors measure these properties and self-correct their outputs accordingly.

Example sensors:

- Campbell Scientific CS650, CS616 & Hydrosense
- Delta-T ML3 Thetaprobe
- Spectrum FieldScout 100 & 300
- Stevens Hydra Probe II

TIME DOMAIN TRANSMISSION (TDT)

TDT measures the time for an electrical pulse to travel along a wire. Measurement requires an electrical connection at both the beginning and end of a wire to do this, either through the wire returning to the same electronic block or through having an electronic block at both ends.

True TDT sensors use only time measurements to determine the soil dielectric. However, some TDT sensors are a hybrid, they use an electrical measurement (voltage) in conjunction with time and are therefore subject to electrical errors as capacitance and transmission line oscillator sensors are.

Installation: TDT sensors are well suited to permanent installations (pasture and tree crops), however with good installation they can also be used for annual cropping. Good installation is critical to minimise sensor 'bedding-in' time. A trench or hole is dug to the required measurement depth, and the sensor then placed vertically at the bottom of it. Soil is then placed on both sides of the sensor, pressed firmly against the sensor to ensure there is good contact with no air gaps. The trench or hole is then backfilled taking care this is reflective of the soil profile, texture and density. As with all dielectric sensors care needs to be taken there is good soil to sensor contact, with no air gaps.

After installation, time is often required for the disturbed soil to settle around the sensor. This can take some time depending on the soil conditions. The settling process can be accelerated by applying irrigation, ideally taking the soil to saturation each time. For pasture a heavy roll over the sensor location can also be beneficial.

Accuracy: TDT sensors measure average soil moisture over the sensor length to an accuracy of ±2% when calibrated however more typically accuracies of 3–5%. They sample a cylinder of about 10–50mm radius (depending on the transmission frequency) along the sensor length.

Advantages: TDT sensors are particularly suitable where there is a need to know the averaged soil moisture over a large sampling area rather than at a particular sampling point. The non-hybrid sensors have good precision. They are also relatively inexpensive.

Limitations: As good soil-sensor contact is required TDT has the same issues as TDR's with stony and dry soils, and shrink-swell clays. These can be overcome with good installation. For accuracy calibration is essential, particularly for hybrid sensors where the electrical properties of soils may influence electrical based measurements. The high level of soil disturbance required during installation can also create issues. A period of 'settling-in' is often required prior to sensor use. The length of time for this can be minimised through good installation.

Example sensors:

- Acclima
- Aquaflex
- Baseline (hybrid)

Soil matric potential

TENSIOMETERS

Tensiometers consist of a porous ceramic cup and a sealed cylindrical tube connecting the cup to a pressure-recording device at the top of the cylinder. The porous ceramic cup acts as a membrane through which water flows. Water is drawn into the tensiometer from a wet soil and out of the tensiometer from a dry soil. In order for a tensiometer to work the ceramic cup and the cylindrical tube must be filled and then remain filled with de-aerated water. Once installed in the soil, the tensiometer will be subject to negative soil water potentials, causing water to move from the tensiometer into the surrounding soil matrix. This creates a negative potential or suction in the tensiometer cylinder, which is displayed on the gauge. Two types of tensiometer exist; meter-read and gauge read.

Installation: The best way to insert a tensiometer into the ground is using an appropriate-sized auger. If the hole drilled is oversized the gap between the tensiometer and the soil must be filled to ensure water doesn't flow down through it and bias readings. In a stony soil, as the ceramic cup must remain in contact with the soil, it is often beneficial for a thin slurry of soil to be poured into the hole before inserting the tensiometer, however this must be done carefully so as not to bias the readings. Care should also be taken with the area surrounding the tensiometer, removing any depressions that may lead to ponding. Readings should be taken at the same time every day, and preferably in the early morning.

GAUGE-READ TENSIOMETERS

These tensiometers are read using a permanently attached pressure gauge.

Accuracy: Gauge-read tensiometers can measure soil tensions between of 0–100 kPa. They sample a sphere of up to 50mm radius.

METER-READ TENSIOMETERS

These tensiometers are read with a portable electronic vacuum gauge. A needle connected to the gauge is inserted into the rubber septum and the reading is displayed on the meter.

Accuracy: Meter-read tensiometer can measure soil tensions between 0–80kPa with up to ±1kPa accuracy. However, they become less accurate past 50kPa. They also ample a sphere of up to 50mm radius.

Advantages: Soil water tension accurately reflects plant stress and is an extremely representative measure of the plant's water needs.

Limitations: Readings can be difficult to convert to soil water content. This makes calculating the amount of irrigation to be applied challenging. Gauge-read tensiometers are typically more expensive than meter-read ones. Maintenance is essential as the water within the tensiometer must be regularly topped up.

Example sensors:

- Decagon T4, T8 & TS1
- Delta-T SWT4 & SWT5
- Irrometer R, P & LT
- 2900F QuickDraw, 2710L Standard & 2725ARL JetFill
- Skye Standard & Electronic

ELECTRICAL RESISTANCE – GYPSUM BLOCK

Electrical resistance soil moisture meters consist of two electrodes embedded in a porous medium. The electrical reading is proportional to the water content of the medium, which is related to the soil water matric potential of the surrounding soil. The output is expressed in kilopascals (kPa). The two most common types of electrical resistance blocks are gypsum blocks and granular matrix sensors.

Gypsum blocks consist of a pair of electrodes embedded in a block of plaster of Paris. Like a tensiometer, water is drawn into the block from wet soil and out of the block from dry soil. The electrical resistance of the block is proportional to its water content, which is related to the soil water suction of the surrounding soil. They work through applying an oscillating voltage and then measuring the alternating current through the gypsum block. A calibration curve is used to convert the current to the equivalent soil water tension.

Installation: To install a gypsum block, an appropriate sized auger is used to drill a hole to the required depth. The gypsum block is then soaked in water, to remove all its air pockets, and then inserted into the hole. As with tensiometers, good soil contact is required and care must also be taken when backfilling around and over the sensor area. It is also recommended that a small trench for the lead wires is dug before preparing the hole for the blocks, this will minimise any water movement along the wires to the sensor.

Accuracy: Gypsum blocks can measure soil tensions between 30 and 1500kPa with an accuracy of ±1kPa. They sample a sphere of up to 50mm radius.

Advantages: Gypsum blocks give good readings in moderately dry soils and loams. They also work well in saline conditions.

Limitations: Gypsum blocks do not work well in shrink-swell clays, coarse sands and gravels. For accuracy the outputs must also be corrected for temperature. Gypsum blocks can dissolve over time and therefore need to be recalibrated, or replaced, on a seasonal basis. Readings can be difficult to convert to soil water content which then makes calculating the amount of irrigation to be applied also difficult.

Example sensors:

- Delmhorst KS-D1
- Frizzell Visual Soil Moisture Sensor & Hydrotec
- GB Lite (Watermark), GB Heavy & G-dot
- Willowbank Electonics Soil Moisture Probe

Heat dissipation

Water has a greater heat capacity (the amount of energy needed to increase the temperature by 1°C) than soil. Therefore, if a wet soil and dry soil are subject to the same amount of heat energy, the temperature of the wet soil will not increase as much as the dry soil. Thermal heat probes use this principle. They consist of a porous block containing a heat source and an accurate temperature sensor buried at the required measurement depth. Heat energy is emitted from the heat source and the temperature sensor records the peak temperature increase over a given time period. The heat input and peak temperature change can then be used to calculate volumetric water content.

Accuracy: Heat Dissipation sensors to an accuracy of ±x%. They sample a sphere of up to 5mm radius

Advantages and limitations: This method is not affected by salinity. The probes have a small measurement sphere of about 5mm radius making them useful for high resolution spatial data gathering where many probes can be placed in a small area. Thermal heat sensors are suitable for the whole range of crops but are generally best suited to research work.

Limitations: It needs a sophisticated controller/logger to control heating and measurement operations alongside a comparatively large power source, particularly if readings are to be taken frequently. The probes have a small measurement sphere.

Example sensors:

- Campbell Scientific 229

NOTES

REFERENCES

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