## Focus Group Fertiliser efficiency in horticulture

# Mini-paper - Irrigation management using soil moisture sensors

## Optimal irrigation management is necessary for optimal nutrient management

**Rodney Thompson[1], Wim Voogt[2]**

[1] Universidad de Almeriá, Spain

[2] Greenhouse Horticulture - Wageningen UR, the Netherlands

Soil moisture sensors can make an important contribution to crop nutrient management by ensuring that crops have adequate water status and by limiting drainage thereby ensuring minimal nutrient leaching loss. Additionally, fertigation in combination with drip irrigation is being increasingly used for high frequency nutrient addition; with these systems, optimal irrigation management must form part of optimal nutrient management. The use of soil moisture sensors to monitor soil water status offers the potential to irrigate in accordance with the crop demand and cropping conditions (e.g. species, crop management, planting dates, climatic conditions, soil characteristics). Additionally, these sensors offer the potential for a fine degree of crop management enabling deficit irrigation strategies to control crop growth or to enhance product quality, and the control of drainage for salinity or environmental management. By providing such information on soil water status, soil water status becomes much less of a black box and something under the direct control of the grower.

Recent technological developments have enabled the development of a new generation sensors that employ advances in electronics, and in information and communication technology (ICT). Information on soil water status can be sent directly to a computer, mobile devices, and internet, or can be used to automatically activate irrigation controllers. In horticultural production, the intensive nature of crop management, the common use of irrigation in certain regions, and the increasing use of fertigation are factors that favour the use of soil moisture monitoring technologies.

## Irrigation scheduling with soil moisture sensors

Soil moisture sensors can be used in several different ways to assist with irrigation management. They can be used on their own as "stand-alone" methods, they can be used in combination with methods for estimating crop water requirements such as the FAO method (Allen *et al.*, 1998) or radiation-based calculations as used in The Netherlands, or they can be used in combination with irrigation management based on experience.

Irrigation management with soil moisture sensors is based on maintaining soil water between two limits, a lower limit (drier value) or threshold value that indicates when to start an irrigation event and an upper limit (wetter value) indicating when to stop the irrigation event (Thompson and Gallardo, 2003). The difference between the two limits is an indication of the volume of irrigation required. The

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lower limit most commonly used is one that permits depletion of soil water without stressing the crop; it can also be used to impose controlled deficit irrigation. The upper limit is normally chosen to prevent excessive drainage from the root zone. Most commonly, soil moisture sensors are used to initiate irrigation for a period of time that is sufficient to "re-fill" the root zone to Field Capacity that is when soils begin to drain. It can also be reduced when controlled deficit irrigation is required.

Soil moisture sensors can be used either manually or automatically to assist with irrigation management. Manual use involves visual reading of the measurement and subsequent manual programming of irrigation (volume, frequency). Automatic use involves either automatic initiation of irrigation for a fixed period, or both automatic initiation and cessation of irrigation. Automatic cessation of irrigation requires automatic data recording with short measurement intervals and sensors with rapid responses to changes in soil water status, and a suitable interface with an irrigation controller. The use of soil moisture sensors for irrigation scheduling has been discussed by Hansen *et al.* (2000); Kuyper & Balendonck (2001); Thompson & Gallardo (2003); Evett (2007) and Balendonck *et al.* (2010).

Automatic data collection and storage together with graphical display enable viewing trends of soil water dynamics over time which can assist in irrigation management. Additionally, stored data sets can be revised by growers and advisors to further optimise management and to troubleshoot.

## Types of soil moisture sensors

Most soil moisture sensors measure (i) soil matric potential (SMP) or (ii) the volumetric soil water content (VSWC). A third type is wetting front detectors. The SMP measures the force of retention of soil water by the soil matrix (particles), and indicates the availability of soil water for crops. The VSWC is the ratio of soil volume occupied by water, normally expressed as $cm^3$ $H_2O/cm^3$ soil. Whereas interpretation of SMP data for irrigation management is straightforward, interpretation of VSWC for practical irrigation management requires site specific experience or the use of dynamic protocols (discussed subsequently).

Both SMP and VSWC sensors are available in different forms, and sensors can be used with different configurations, depending on type of crop, species, irrigation system, cost, and the nature of the sensors (e.g. whether there are multiple sensors mounted on probes etc.) (Thompson and Gallardo, 2003). Soil moisture sensors are a dynamic and constantly changing area of technology for technical and commercial reasons. The current soil sensor technologies are described by IAEA (2008) and many of the principle sensors by Charlesworth (2005). A list of the principal types of soil moisture sensors with examples of models and notes on their use is provided in Table 1.

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**Table 1 Principal types of sensors used for irrigation scheduling with examples of established models.**

| Type of sensor | Format/comments | Manufacturer | Web page |
|---|---|---|---|
| ***Soil matric potential sensors*** | | | |
| Tensiometers | - Visual data reading from manometer,<br>- Manometer with relay to auto. start irrigation,<br>- Electric (with pressure transducer) connected to logger or programmer | - Irrometer, USA<br>- Soilmoisture Equipment, USA<br>- Various other manufacturers | http://www.irrometer.com/<br>http://www.soilmoisture.com |
| Granular matrix sensors | - Hand-held reader;<br>- Can connect to logger or programmer;<br>- Most commonly-used sensor is Watermark sensor | Irrometer, USA | http://www.irrometer.com/ |
| MPS-2 Water potential sensor | - Used with data loggers;<br>- relatively new sensor | Decagon Devices, USA | http://www.decagon.com/products/soils/ |
| ***Volumetric soil water sensors (Frequency domain or similar technology); examples of principal sensor types*** | | | |
| EnviroSCAN sensors<br>(various models) | - Probe with sensors at different depths<br>- connected to logger or programmer<br>- Requires access tubes<br>- Permanent or semi-permanent installation | Sentek Technologies, Australia | http://www.sentek.com.au/home |
| Theta Probe | - Sensor is a unit with 6 cm long metal rods. Sensor is buried in soil or metal rods pushed into soil.<br>- Reader or logger used to collect data<br>- Based on measurement of impedance | Delta-T Devices, UK | http://www.delta-t.co.uk/ |
| Profile probe | - Probe with sensors at different depths<br>- Reader or logger used to collect data<br>- Requires access tubes<br>- Permanent or semi-permanent installation | Delta-T Devices, UK | http://www.delta-t.co.uk/ |
| Decagon sensors<br>(various models) | - Sensor has 5-10 cm long fibre glass or metal rods.<br>- Sensor is buried in soil or metal rods pushed into soil.<br>- Logger used to collect data<br>- Various models with different characteristics, performance, & durability | Decagon Devices, USA | http://www.decagon.com/products/soils/ |
| AquaCheck | Probe with sensors at different depths<br>- Used with hand-held reader, logger or connected to programmer | AquaCheck USA, USA | http://www.aquachecktech.com/ |
| ***Wetting front detector*** | | | |
| Full Stop | - Mechanical signal; flag rises when wetting front arrives at depth of sensor<br>- 20 cm dia. wide funnel buried in soil | fullstop.com.au | http://www.fullstop.com.au/ |

## 1. Soil matric potential sensors

Soil matric potential (SMP) is measured in units of pressure; most commonly kPa or cbars are used which are equivalent. Technically, the units are negative because soil matric potential is effectively suction. Care needs to be taken when discussing SMP data, researchers generally treat the units as being negative whereas people working at field level e.g. growers, Extension staff, generally treat the

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units as being positive. This has important practical implications when discussing relative changes in SMP, e.g. if it is increasing or decreasing.

In non-saline conditions, SMP is a good approximation of the total soil water potential. In saline conditions, osmotic potential may contribute significantly to the total soil water potential. Generally, SMP provides a useful measure of the availability of soil water to plants. When using SMP, the effects of salinity should be considered separately. Some authors (e.g. Hansen *et al.*, 2000; Shock *et al.*, 2007) and equipment manufacturers have indicated the upper and lower limits between which SMP in the root zone should be maintained for horticultural production. These limits vary with crop species, crop developmental stage, soil texture, and the evaporative conditions. In general terms, lower limit values, for a given species and stage of development, are not influenced by soil type. However, in practice some adjustment is made for light and heavy textured soil; higher (i.e. less negative) limit values are used in lighter textured (sandier) soils, and lower values in heavier textured soils. As general guidelines, Irrometer Co., a major manufacturer of SMP sensors for commercial use, suggested lower limits of -30 to -60 kPa for most soils and of -60 to -100 kPa for heavy clay soils, and upper limits of -10 to -30 kPa which represent Field Capacity. In some cases, specific lower limit SMP values have been determined for specific combinations of species, soil type and cropping system. For example, lower limit values of –35 to -58 kPa were determined by Thompson *et al.* (2007a) for different species of vegetable crops in a sandy-loam soil, based on initial detection of plant water stress. Some adjustment of recommended lower limit values may be necessary for adaptation to site specific factors. Hansen *et al.* (2000) described how climate and crop factors can influence lower limit SMP values.

The two types of matric potential sensors most used with horticultural crops are tensiometers and granular matrix sensors (Table 1). **Tensiometers** are relatively cheap and simple devices. However, to provide accurate and reliable data, they require proper preparation, careful placement and proper maintenance (Thompson and Gallardo, 2003). There are (i) manual tensiometers in which data are obtained from the visual reading of a vacuum gauge, (ii) manual tensiometers with a switch to directly activate the irrigation equipment when it reaches a predetermined value, and (iii) electric tensiometers that use pressure transducers to provide continuous measurement and can be used to directly activate irrigation. Most tensiometers usually have a working range from 0 to -80 kPa. This narrow range can be a limitation in open field cropping systems. However, where high frequency drip irrigation is used with vegetable crops, SMP can be maintained within these limits.

**Granular matrix (GM) sensors** measure the electrical resistance between two electrodes in a porous matrix (Thompson and Gallardo, 2003; Charlesworth, 2005; Thompson *et al.*, 2006). The most commonly-used is the Watermark sensor (Irrometer Co. CA, USA; Table 1)). The electrical resistance between the two electrodes is a function of the soil matric potential. The water within the sensor matrix equilibrates with that of the soil. A hand-held reader is used to read SMP values, using a standard calibration. SMP data can be recorded on data loggers or input to an irrigation controller.

GM sensors are cheap, simple, easy to install, and unlike tensiometers require little preparation and maintenance. Their measuring range is reported to be from -10 to -200 kPa, which will cover the requirements of many irrigated vegetable crops. While they have a wider measurement range than that of tensiometers; they tend to be less reliable in wet soils (0 to -10 kPa) and have a slower response in soils that dry quickly (Thompson *et al.*, 2006). In general, GM sensors are somewhat less accurate than tensiometers but require appreciably less attention. They have a lifespan of 5-7 years. Sensor readings are recorded either manually with a manual hand-held reader or automatically with data loggers or irrigation controllers.

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A new generation of SMP sensors are being developed that are similar to di-electric sensors that measure VSWC (see next section). These new generation sensors generally have large operating ranges and have small preparation and maintenance requirements. Currently, there is limited information available concerning the performance of these sensors under realistic field conditions. An example is the MPS-6 Calibrated Water Potential Sensor of Decagon Devices which is claimed to have a working range of -9 to -100,000 kPa.

## 2. Volumetric soil water content sensors

Various groups of sensors measure the volumetric soil water content (VSWC): neutron moisture probe, di-electric sensors, and heat dissipation sensors (Table 1). The di-electric sensors are those mostly used for irrigation scheduling (Thompson and Gallardo, 2003). There are three general types of di-electric sensor, (i) TDR (Time Domain Refractometry), (ii) TDT (Time Domain Transmissiometry), and (iii) capacitance, or FDR (Frequency Domain Refractometry). TDR sensors are widely used in research; however, they are not widely used for irrigation management. TDT sensors are an adaptation of TDR sensors that are generally cheaper and electronically simpler, and consequently more suitable for use in commercial farming. Capacitance (or FDR) sensors are widely used to manage irrigation in commercial farms and also in research applications. Capacitance sensors are available in several different configurations e.g. probes of various centimetres length or rings at various depths positioned on a probe that is located within a vertical plastic tube (Table 1, Thompson & Gallardo, 2003).

The capacitance sensor that is probably most used for irrigation management is the EnviroSCAN (Sentek Technologies, Australia; Table 1) consisting of several ring-type sensors mounted vertically at various depths on a probe which is enclosed in a tube within the soil. This equipment continuously registers soil humidity giving detailed information on the dynamics of soil water both within the root zone and below. These sensors can be used to automatically initiate and stop irrigation. The EnviroSCAN can be sensitive to changes in soil salinity (Thompson *et al.*, 2007b) which can affect its use where salinity is managed to increase fruit quality. Various models and configurations of the EnviroSCAN are available (Charlesworth, 2005). A number of other companies produce similar systems with sensors mounted at various depths on a probe (Table 1).

A commonly-used format for VSWC sensors is of individual sensors with rods of 5-10 cm length made of steel or fibre glass (Table 1). These sensors can be used by either burying the sensor at the desired depth or inserting the rods directly into the soil. Decagon Devices produce a range of relatively cheap sensors of this type.

When using VSWC for irrigation scheduling, the determination of lower irrigation limits, i.e. when to irrigate, is not as straightforward as when using SMP. With VSWC, lower limit values have to be determined for each combination of crops and soil (texture, organic matter content). For a given combination of crop and soil, standard values can be used; however, these must consider crop development stage, depth of soil measured and sensor type. Dynamic protocols can be used in which measured data from the sensors are used to interpret soil water dynamics to determine in-situ lower and upper limits for irrigation scheduling. Different dynamic protocols to determine lower limits for greenhouse vegetable crops in soil were discussed and evaluated by Thompson *et al.* (2007c).

Some models of VSWC di-electric sensor also measure soil electrical conductivity (EC); this is measured in the form of bulk soil EC which is the conductivity for a per unit volume of soil. Bulk soil EC is strongly influenced by soil water content and is appreciably more difficult to interpret than more commonly used measures of soil salinity such as saturated extract EC or soil solution (or pore water)

EC. Some sensor systems use internal equations to calculate pore water EC values from bulk soil EC and VSWC measurements. These equations are still an active research area indicating that the use of VSWC sensors to measure soil salinity is still "work in progress".

### 3. Wetting Front Detectors

A third type of sensor (not SMP or VSWC) is the wetting front detector such as the "Full Stop sensor" which is a useful, simple and cheap sensor that indicates when sufficient irrigation has been applied by indicating the arrival of the wetting front at a given depth by the mechanical movement of a signal (Charlesworth, 2005; Stirzaker *et al.*, 2009; Table 1).

## Practical considerations regarding the use of sensors for irrigation management

Correct placement of sensors is essential to provide effective measurement. Sensors should be located in representative zones of the crop e.g. avoiding border areas, non-representative patches of soil for reasons of depth, texture, compaction, non-representative plants etc. At each measurement location, one sensor should be placed in the zone of maximum concentration of roots. Additional sensors can be placed at different depths e.g. below the roots to control drainage, and in case of drip irrigation to the side of the plants to control the size of the wetting bulb. The most commonly-used sensor configurations are: (i) one sensor within the zone of major root concentration, and (ii) one sensor within the zone of major root concentration complemented by one or more deeper sensors. The use of deeper sensors is recommended to provide information on depth of wetting and water movement. To control drainage to limit nitrate leaching, two deeper sensors, one at the bottom of the root zone and another clearly beneath the root zone are recommended. Replication is necessary; sensors should be located in a minimum of 2-3 locations per field. The use of a single sensor per field in a non-representative location could result in insufficient or excessive irrigation. It is essential that sensor data are revised regularly, and for some sensors such as tensiometers that they are inspected regularly, to ensure that they are functioning correctly.

An optimal strategy for irrigation is the use of soil moisture sensors in combination with locally-adapted decision support systems (DSS) that provide good predictions of crop water use such as the VegSyst-DSS (Gallardo *et al.*, 2014).

## Practical considerations regarding the adoption of soil moisture sensors by growers

Soil moisture sensors are currently used by large numbers of growers throughout the world, particularly in locations where water management is regarded as being environmentally important such as in Australia, California and Florida. Adoption by growers is favoured by the perception that precise irrigation management is important. Factors such as societal pressure, the price of water, the desire to implement deficit irrigation will encourage adoption. Economic incentives, legislation and the requirements of product quality certification schemes are effective measures to encourage adoption.

Practical considerations that affect adoption and continued use are cost, ease of use, preparation and maintenance requirements, technical support, ease of data interpretation, availability of irrigation protocols, working language, and the user-friendliness of software where computer use is required (Thompson & Gallardo, 2003). The provision of practical information such as clearly written manuals

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and on-going support are essential. There is a wide variety of types and models of sensors, and objective guidance to help growers select the most appropriate sensors for their farming and management requirements is desirable. A good example of good practical information for users is the technical book "Soil Water Monitoring: An Information Package" (Charlesworth, 2005) prepared for the irrigation community in Australia. Ideally, Extension service should provide support to assist growers to select and learn to use sensors. The availability of robust wireless sensors will enhance the adoption of soil moisture sensors as the presence of cables can be a disincentive to growers.

Soil moisture sensors are tools that can appreciably enhance irrigation management and nutrient use efficiency in horticulture. With on-going improvements in ICT and with the increasing use of computers and mobile devices that can be used to view data; it is likely that there will be increasing adoption of these sensors in horticulture.

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