Chapter 10. Fertigation management – Irrigation

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10.1. Introduction

10.1.1. These techniques concern the issue
- Estimation of irrigation water amount
- More efficient use of water
- Minimising the impact to the environment by nutrient discharge
- Identification of water needs

10.1.2. Regions
All EU regions

It is essential to adopt efficient irrigation management strategies in all regions; however, for an individual region, or even for a given location within a region, the most effective strategies may differ because the conditions are different.

In the Mediterranean region, the limited rainfall and increasing competition for limited water resources increasingly requires the adoption of strategies, techniques and technologies to optimise the water use efficiency of water applied as irrigation.

In other European regions, water scarcity is generally not yet a consistently limiting factor. However, during summer and during droughts, irrigation can be necessary; and competition for, and the increasingly strict control of water resources, is creating increasing pressure to irrigate more efficiently.

10.1.3. Crops in which the problem is relevant
All crops.

10.1.4. Cropping type
All cropping types.

Because of the limited water holding capacity of many substrates and the small root volume of soilless cropping systems, irrigation management for soilless grown crops differs appreciably from that of soil-grown crops. Also, irrigation management of fruit trees differs from that of vegetable crops because of the much larger soil volume with roots. Within a crop type and growing system, there can be appreciable differences in the irrigation requirements particularly regarding frequency.

10.1.5. General description of the issue
There is considerable and increasing societal pressure to use limited water resources efficiently. There is increasing competition from other sectors such as tourism, industry and for domestic use. Additionally, there is increasing pressure to maintain the recreational value and ecosystems services capacities of water resources. Furthermore, environmental problems, associated with badly managed irrigation, such as aquifer depletion, saltwater intrusion into aquifers, nitrate contamination of aquifers etc. are increasingly considered to be unacceptable and are being increasingly controlled by legislation. Consequently, horticultural growers are under growing pressure to use irrigation water as efficiently as possible. The problems and issues associated with irrigation, in relation with minimising
environmental, are described more fully in Chapter 1 (Introduction) and are associated to issues described in Chapters 7 and 8 (Fertigation Equipment), and Chapter 11 (Optimal Nutrient Management).

Optimising irrigation at farm level requires providing the right amount of water at the right time to cover the needs of the crop at that moment. Those needs vary with crop development, weather conditions, soil type, and other site specific factors. Poor irrigation management can result in less yield and quality, either due to an excess of water or a lack of water at critical growth stages of the crop.

Knowledge of the water requirements of crop is an initial requirement. Monitoring technologies of the soil or the crop can provide important information to guide irrigation management regarding the timing and amounts of irrigation. Information of both crop water requirements and the use of monitoring technologies can be used to implement irrigation management strategies based on applying controlled periodic crop water deficits.

Growers face major uncertainties when irrigating. Some of these questions are: What is the correct estimation of crop water requirements? What irrigation strategies can be used? How to best monitor crop and/or soil water status? How should the irrigation strategies be adjusted according to plant and soil water status? This chapter describes the techniques and technologies that can help provide growers with answers to these questions.

10.1.5.1 Sub-issue A: Correct estimation of crop water needs

The adoption of a programmed irrigation schedule helps to ensure that the supply of irrigation considers local climatic conditions and crop development stage. Water balance estimations and the calculation of crop evapotranspiration (ETc) are methods used to estimate crop water requirements. Water balance estimations consider calculated ETc and the relevant inputs and outputs of water to a given crop such as changes in soil water, effective precipitation, run-off, drainage etc.

Climatic and crop development parameters influence calculations made using these methods. Consideration of climate is important to adjust crop water requirements in different locations. Growers and advisors can input climatic data from climate sensors installed in fields and greenhouses, from national or regional climate monitoring services, or from weather forecast services.

Calculated ETc is the product of the potential evapotranspiration (ETo) and the crop coefficient (Kc). Potential evapotranspiration is calculated using empirical equations, of which several are in use; the most suitable equation depends on the cropping system and the availability of climatic data. Potential evapotranspiration is a function of the atmospheric demand in a given cropping situation. Crop coefficient values are specific to crop species, growth stage and cropping season. Standardised values can be obtained from tables; specific values for a given crop or location can be calculated from different crop simulation models, and more recently from remote sensing or image analysis technologies.

10.1.5.2 Sub-issue B: Irrigation strategies adapted to different crops

Once crop water requirements have been determined, it is necessary to consider the effect of the irrigation volume on each of the different phenological stages. These data will influence a wide range of decisions that have to be made regarding the management of...
water required by the crop, the total volume of which may be limited by a restricted local water supply.

Growers can use irrigation scheduling adapted to meeting crop water requirements, or with some crops can adopt a water saving strategy, such as controlled deficit irrigation, where the volume of water supplied is less than the crop water requirements. During certain development stages of some species, particularly of fruit trees, deficit irrigation does not negatively affect production. When correctly managed, the use of controlled water deficits during insensitive growth stages can save appreciable volumes of irrigation water, without reducing yield. It can, in some cases, result in increased fruit quality or earlier fruit production.

Different deficit irrigation strategies are used in different crops, for example, Sustained Deficit Irrigation; Controlled Deficit Irrigation; and Partial Root Drying.

Information on water requirements and irrigation strategies can be used to develop decision support systems (DSSs) which can be used to advise growers on irrigation scheduling.

10.1.5.3 Sub-issue C: Adjusting irrigation to plant and soil water status

In many cases, theoretical irrigation scheduling and irrigation strategies may induce situations of over-irrigation and/or water stress, and consequently reduce water use efficiency.

New technologies applied to irrigation management can help to have irrigation scheduling that is adapted to the requirements of individual crops. Sensors that monitor crop or soil water status provide information on the adequacy of the water supply available to the crop at a given time, by making measurements on plants or in the soil. Soil sensors use direct and indirect methods to determine soil water content. Plant sensors use measurements of parameters related to plant physiology, such as photosynthesis, transpiration, water potential or biomass variations.

10.1.6. Brief description of the socio-economic impact of the issue

Probably the main issue for growers regarding adoption of technologies for improving irrigation management are the costs. Growers may not see the cost of these technologies as a worthwhile investment considering the financial returns that directly result from their use. The economic benefits for growers will most likely be indirect in terms of reduced purchases of water and of fertilisers where fertigation is used.

Another issue influencing the adoption of these technologies by growers will be their attitude and familiarity with information and communication technologies. Many of the technologies for improving irrigation management involve the use of smart technologies such as computers, internet, smart phones, sensors etc. Older and less educated growers are likely to be more resistant to adopt such technologies. However, considerable effort is being made to make tools, using these technologies, as user-friendly and as intuitive as possible.

Reduced water use by horticulture will benefit the local community by making more water available for other uses. Reduced water use resulting from the adoption of new irrigation management technologies would certainly help the image of a local horticultural industry, suggesting that it was modern, efficient and environmentally responsible.
10.1.7. Brief description of the regulations concerning the issue

There are generally no regulatory limitations concerning tools and technologies for irrigation management, besides those concerning the use of neutron probes because they use radioactive material. Because the regulations on the use and transport of neutron probes are so restrictive, and there are numerous alternatives available, there is now very little use of neutron probes in farming practice.

10.1.8. Existing technologies to solve the issue/sub-issues

There are numerous techniques and technologies that can be used to optimise irrigation of horticultural crops. These can be categorised as being in several broad approaches – estimation of irrigation volumes (crop water requirements), irrigation strategies, information tools for irrigation management, plant/crop measurements for irrigation management, measurements in soil for irrigation management, tools for soilless cropping systems, and the use of weather measurement and forecasting. In this chapter, a total of 26 different techniques and technologies are described. Their distribution within the previously-described classes is as follows:

**Estimation of irrigation volumes**
- Water balance methods
- Irrigation management with soil moisture sensors

**Irrigation strategies**
- Partial Root Drying
- Deficit irrigation

**Plant/crop measurements for irrigation management**
- Plant growth balance analysis system
- Thermal Infrared Sensor
- Dendrometers
- Leaf turgor sensor
- Pressure chamber for plant water potential measurement

**Measurements in soil for irrigation management**
- Neutron probe
- Combined water, EC and temperature sensor
- Auger method
- Wetting Front Detector
- Tensiometers
- Granular Matrix Sensors
- Time Domain Reflectometry
- Capacitance probe
- Digital penetrating radar

**Tools for soilless cropping systems**
- Slab balances
- Drain sensor
- Demand tray system

**Use of weather measurement**
- Weather sensors
10.1.9. Issues/sub-issues that cannot be solved currently: bottlenecks

Among the problems that affect the use of existing techniques and technologies are:

- Non-uniformity of soils within the same field
- Lack of irrigation uniformity
- Damage to sensors or technical equipment (robbery or vandalism)
- The difficulty of introducing complex technologies to growers. Some growers will require technical support to install equipment and to interpret data.

10.1.10. References for more information


### 10.2. Summary of technologies subsequently presented in this chapter in individual technology descriptions (TDs).

<table>
<thead>
<tr>
<th>Technology</th>
<th>Cost</th>
<th>Required</th>
<th>Weaknesses</th>
<th>Strengths</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Estimation of irrigation volumes</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water balance methods</td>
<td>2500 €</td>
<td>Yes</td>
<td>Moderate level of computer skills</td>
<td>Time-consuming when real-time climatic data are used</td>
<td>Good assistance with decision making</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Technical support required for management</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Irrigation management with soil moisture sensors</td>
<td>500-1500 €</td>
<td>120 €</td>
<td>Technical support for sensor installation, determination of SWC thresholds and data interpretation</td>
<td>Difficult management of large data sets (short time intervals)</td>
<td>Identification of problems in irrigation management</td>
</tr>
<tr>
<td><strong>Irrigation strategies</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Partial Rootzone Drying (PRD)</td>
<td>Not applicable</td>
<td>Yes</td>
<td>Management skills required</td>
<td>Reduction of vegetative growth</td>
<td>Potential savings of water and fertilisers</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Potential increase in labour and irrigation system costs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deficit irrigation</td>
<td>Not applicable</td>
<td>No</td>
<td>Identify plant growth stages</td>
<td>Strong technical support needed for implementation</td>
<td>Improves nitrate use efficiency, minimises leaching of nutrients.</td>
</tr>
<tr>
<td><strong>DSS water requirements</strong></td>
<td>0-2000 €</td>
<td>200 €</td>
<td>Computer skills and technical training</td>
<td>Limited access for growers</td>
<td>Reliability adjusts very well water demands if well calibrated</td>
</tr>
<tr>
<td><strong>Information tools for irrigation management</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Integrated sensor in DSS for irrigation management</td>
<td>See technologies “DSS water requirements” and “Irrigation management with soil moisture sensors”</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Transfer of INNOvative techniques for sustainable WAter use in FERTigated crops

<table>
<thead>
<tr>
<th>Technology</th>
<th>Cost</th>
<th>Required</th>
<th>Weaknesses</th>
<th>Strengths</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Remote sensing</td>
<td>700 €</td>
<td>Good command of GIS</td>
<td>High expertise in computer use</td>
<td>Easy to detect problems and crop heterogeneity</td>
<td>Some limits in the operational conditions. High cost if images are processed</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Computer skills</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Growth analysis system</td>
<td>25000 €</td>
<td>Computer skills</td>
<td>Expensive, difficult data interpretation, technical support required</td>
<td>Constant monitoring of the crop</td>
<td>Internet 24/7</td>
</tr>
<tr>
<td></td>
<td>1490 €</td>
<td>No real-time data</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal infrared sensor</td>
<td>500-1000 €</td>
<td>Age applicable</td>
<td>Computer skills and technical knowledge</td>
<td>A non-destructive method to determine crop’s water content</td>
<td>Thermal cameras are more expensive (10000 to 20000 €) Processed image and crop water status with a cost of 20-30 €/Ha.</td>
</tr>
<tr>
<td>Dendrometers</td>
<td>34-475 €</td>
<td>Age applicable</td>
<td>Data can be influenced by climate (fog, rain, overcast weather), crop development stage, fruit load and other factors like insects, birds</td>
<td>They are generally reliable, robust, and relatively inexpensive to buy</td>
<td>Absolute SDV values must be normalised to non-limiting soil water conditions In fast-growing plants repositioning of the sensor is required</td>
</tr>
<tr>
<td>Leaf turgor sensor</td>
<td>4150-6200 €</td>
<td>100 €</td>
<td>Moderate level of computer skills, technical support required</td>
<td>Non-destructive measurement and easy to handle sensor</td>
<td>Growers require assistance to source the instruments It is necessary to have internet access</td>
</tr>
</tbody>
</table>
## Transfer of INNOvative techniques for sustainable WAter use in FERTigated crops

<table>
<thead>
<tr>
<th>Technology</th>
<th>Cost Installation</th>
<th>Cost Maintenance</th>
<th>Required</th>
<th>Weaknesses</th>
<th>Strengths</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure chamber for plant water potential measurement</td>
<td>1000-6000 €</td>
<td>No</td>
<td>Technical training required</td>
<td>The time required to monitor checks, interpret measurements, and take agronomic decisions</td>
<td>Valuable information about the crop water status</td>
<td>Reference values are needed for each crop and irrigation strategy</td>
</tr>
<tr>
<td>Neutron probe</td>
<td>14000 €</td>
<td>3500 €</td>
<td>License and compliance with all regulations concerning use, transport and storage of radioactive sources</td>
<td>Data not instantaneously available Usually provided by irrigation consultants</td>
<td>Provides volumetric water contents and data are easy to interpret</td>
<td>Need to be licensed to use radioactive equipment</td>
</tr>
<tr>
<td>Combined water, EC, and temperature sensor</td>
<td>2660-3220 €</td>
<td>No</td>
<td>Knowledge of electronics Moderate level of computer skills Each sensor must be calibrated Careful placement of probes in stony soils</td>
<td>Easy use and data interpretation Calibrations available for many soils and growing media</td>
<td>Effect of soil salinity and texture on measurements</td>
<td></td>
</tr>
<tr>
<td>Auger method</td>
<td>50-250 €</td>
<td>No</td>
<td>Nothing relevant</td>
<td>Manual method</td>
<td>Simplicity</td>
<td>In some type of soils, extraction can be difficult</td>
</tr>
<tr>
<td>Wetting front detector</td>
<td>Yes</td>
<td>No</td>
<td>Frequent readings</td>
<td>Hard installation</td>
<td>Very simple and intuitive system. Suitable for farmers without experience with sensors</td>
<td>It should be installed when the soil is dry to avoid excessive compacting The obtained solution is drainage, not soil solution</td>
</tr>
<tr>
<td>Tensiometers</td>
<td>300-3000 €</td>
<td>Yes</td>
<td>Moderate level of computer skills Technical training</td>
<td>Fragile during installation and cultural practices Maintenance required</td>
<td>User-friendly. It indicates well the thresholds in which it is necessary to irrigate for different crops and soils</td>
<td>Coarse soils, good contact between the soil matrix and the ceramic cup is required</td>
</tr>
</tbody>
</table>

### Transfer of INNOvative techniques for sustainable WAter use in FERtigated crops

<table>
<thead>
<tr>
<th>Technology</th>
<th>Cost</th>
<th>Maintenance</th>
<th>Required</th>
<th>Weaknesses</th>
<th>Strengths</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Granular matrix sensors</td>
<td>40-200 €</td>
<td>Not relevant</td>
<td>Moderate level of computer skills</td>
<td>The short lifespan of sensors. Maintenance and support required</td>
<td>User-friendly software</td>
<td>Relatively slow responding to soil moisture changes</td>
</tr>
<tr>
<td>Time domain reflectometry</td>
<td>1200-1900 €</td>
<td>40-200 €</td>
<td>High level of computer skills</td>
<td>Technical assessment during the first periods of use and interpretation help needed in many cases</td>
<td>Accurate</td>
<td>Limited applicability in saline soils. Good contact is required between soil and probe</td>
</tr>
<tr>
<td>Capacitance probe</td>
<td>2000 €</td>
<td>100 €</td>
<td>Technical advice and data logging</td>
<td>Salinity can influence the measurements</td>
<td>Response time is instantaneous</td>
<td>Effect of temperature on moisture measurements should be considered especially in soilless systems</td>
</tr>
<tr>
<td>Digital penetrating radar</td>
<td>15000-20000 €</td>
<td>None</td>
<td>Interpretation of radar grams needs experience</td>
<td>Large and complex, costly, normally used for soil surface Technical support required</td>
<td>Fast High resolution Measurement of large areas overcomes the limitation of point sampling techniques</td>
<td>Large and complex system</td>
</tr>
<tr>
<td>Slab balances</td>
<td>3600 €</td>
<td>Not applicable</td>
<td>Computer skills (moderate) Technical knowledge of equipment Training</td>
<td>Cannot shift position after installed at the beginning of the season</td>
<td>Real-time monitoring</td>
<td>Accurate information on crop water needs</td>
</tr>
<tr>
<td>Drain sensor</td>
<td>2345 €</td>
<td>No</td>
<td>Moderate level of computer skills</td>
<td>Expensive compared to manual measurement High maintenance required</td>
<td>Transferable to all soilless systems with drain collection system</td>
<td>Connection with the controller is required</td>
</tr>
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## Technology

<table>
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<th>Strengths</th>
<th>Limitations</th>
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<td>Demand tray system</td>
<td>800 €</td>
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<td>Weather sensor</td>
<td>2500-6000 €</td>
<td>Moderated - high level of computer skills</td>
<td>Periodic maintenance and calibration is important to assure reliable results</td>
<td>Prediction of disease and pest outbreaks</td>
<td>Automatic weather stations save human labour and enable availability of data from remote areas</td>
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10.3. Water balance methods

(Authors: Marisa Gallardo\textsuperscript{23}, Jadwiga Treder\textsuperscript{12})

10.3.1. Used for
- More efficient use of water
- Minimising the impact to the environment by nutrient discharge

10.3.2. Region
All EU regions.

10.3.3. Crop(s) in which it is used
- All vegetables
- Fruit trees
- Ornamentals

10.3.4. Cropping type
- Soil-bound
- Protected
- Open air

10.3.5. Description of the technology

10.3.5.1 Purpose/aim of the technology
The water balance is a well-established method used for crop irrigation scheduling. Using this method, users can obtain recommendations of the volume and frequency of irrigation for a given crop in given climatic and soil conditions.

10.3.5.2 Working Principle of operation
The water balance method calculates daily variations of soil water content (SWC) in the root zone as the difference between gains and losses of water. The objective is to maintain the SWC above a threshold value below which the plants experience water stress. The water content is generally expressed in terms of water depth (that is mm of water) of depletion in relation to Field Capacity. The amount of permitted depletion (from Field Capacity), is also known as “permissible depletion” or “allowable depletion”. In the water balance calculation, rainfall and irrigation add water to the root zone. Crop evapotranspiration (ETc) removes water from the root zone, thereby increasing depletion. The daily water balance, expressed as the increment in depletion, at the end of day $i$, is:

$$D_i = D_{i-1} + ETc - NI - Re$$

Where $D_i$ and $D_{i-1}$ are the water depletion at the end of days $i$ and $i-1$, respectively, ETc is the crop evapotranspiration of day $i$, and NI is the net irrigation and Re the effective rainfall during day $i$. ETc is estimated from climate and crop data. Re is the amount of rainfall that remains in the root zone after subtracting water lost by percolation and runoff; there are simplified procedures to estimate Re from rainfall data. To initiate the water balance, the
initial depletion can be measured with a sensor. Generally, users start the water balance after heavy rain or following the first irrigation, and assume Field Capacity conditions and an initial depletion of zero. Each irrigation should be applied shortly before the readily available soil water (RAW) is depleted \((D_i \leq \text{RAW})\) (see Figure 10-1). The RAW is the threshold soil water content below which the amount of soil water is insufficient to meet the evapotranspiration demand and the crop commences to experience water stress. The day when the accumulated water depletion becomes close to RAW, an irrigation is scheduled with a volume equal to the RAW so that the soil is restored to Field Capacity, and consequently, the deficit returns to zero i.e. \(D_i = 0\) (Figure 10-1). Other options are to apply an irrigation volume smaller than RAW and increase the irrigation frequency or to apply a larger irrigation volume if leaching of salts from the root zone is required. For more information on the calculation of the different components of the water balance equation, see the FAO56 Manual of the United Nations Food and Agriculture Organisation (http://www.fao.org/docrep/X0490E/X0490E00.htm).

When using high-frequency irrigation systems such as drip irrigation, it is possible to simplify the water balance by ignoring the soil component and assume that the soil is constantly maintained close to Field Capacity. Consequently, the applied volume of a single irrigation is equivalent to the cumulative ETc (or the ETc divided by the application efficiency) for the period between subsequent irrigations. This applies to irrigation scheduling, using the water balance method, with crops grown in soil in Mediterranean greenhouses.

![Figure 10-1. Example of the use of the water balance to determine the irrigation schedule of a tomato crop grown in soil. \(D_i\) is the soil water deficit (in relation to Field Capacity) at day \(i\), and \(\text{RAW}\) is the amount of Readily Available Water in the root zone of the expected rooting depth. The expected rooting depth increases as the crop grows.](image)

### 10.3.5.3 Operational conditions

The water balance method for irrigation scheduling can be used at a very small scale (e.g. greenhouse), at farm level (several crops in a farm) or for an irrigation district.
10.3.5.4 Cost data
The use of the water balance method requires the use of a personal computer, and internet access to download climatic data. In some cases, such as in greenhouses or when there are no nearby official climate stations, ETc can be calculated from real-time climatic data measured in-situ in the growers’ crop or greenhouse; for this, a low-cost meteorological station provided with a logger is required. Generally, the software needed to compute the water balance method is free and provided by local irrigation or extension services. The time required to implement this technique will depend on whether historical (2h/week) or real-time climatic data (4 h/week) are used.

10.3.5.5 Technological bottlenecks
The technical bottlenecks that can influence the adoption of the water balance method are the availability of suitable software to make the calculations of ETc and of the soil water balance, the availability of suitable climatic data for the calculation of ETc, and the availability technical support to assist using the software and implementing the water balance method.

10.3.5.6 Benefit for the grower

**Advantages**
It provides growers with a tool that assists in making decisions about the volume and timing of irrigation based on the crop demand. It results in reduced water use and reduces the environmental impacts associated with excessive irrigation. Optimal irrigation will also enhance crop performance by avoiding reduced growth associated with deficient and excessive irrigation, and the risks of pathological issues associated with excessive irrigation.

**Disadvantages**
In case of using real-time climatic data, the time involved in collecting climatic data and inputting them into the irrigation scheduling software; the initial difficulty of learning the system.

10.3.5.7 Supporting systems needed
It is essential that there is a technical support to assist growers to implement the water balance method. It is likely that assistance will initially be required when commencing to use a relevant software package when learning how to download meteorological data from the nearest climatic station or from an on-farm station, and in data interpretation during the cropping season when first using this approach.

10.3.5.8 Development phase
- Research: Research is continually being conducted to developed new DSSs for irrigation scheduling based on the water balance method, adapted to specific crops and systems
- Experimental phase: As with research, applied experimental work is on-going
- Field tests: Field testing is often conducted to adapt the technique to particular crops and cropping systems

Transfer of INNOvative techniques for sustainable WAter use in FERtigated crops

- Commercialised: There is software available for irrigation scheduling based on the water balance method at international level and at regional or local level

10.3.5.9 Who provides the technology
At the international scale, the software CROPWAT version 8.0 is provided by FAO (http://www.fao.org/nr/water/infores_databases_cropwat.html). This software has provision to make water balance calculations for many cropping situations. Commonly, at the local level, the software has been developed to deal with specific cropping situations. For example, in Andalusia (Spain), the regional government offers online advice for irrigation scheduling, using the water balance for olive trees and strawberries.

10.3.5.10 Patented or not
Generally, public authorities freely provide the software and relevant information. While software may be registered, generally, the associated information is publicly available.

10.3.6. Which technologies are in competition with this one
Alternative approaches, to irrigation scheduling with the water balance method, are the use of soil and plant sensors. Soil sensors measure the soil water content or the soil matric potential and can be used to schedule the volume and frequency of irrigation. Alternatively, soil sensors can be used as a complement to the water balance method, to verify the recommendations. Plant sensors that measure the plant water status are still in a research phase and there appears to be little practical application.

10.3.7. Is the technology transferable to other crops/climates/cropping systems?
The use of the water balance method for irrigation scheduling with adaptations can be applicable to all crop types, climates, and cropping regions. The FAO publications of the Irrigation and Drainage Series, No. 56 “Crop Evapotranspiration - Guidelines for computing crop water requirements” contains information about the application of this method for different situations.

10.3.8. Description of the regulatory bottlenecks
There are no regulatory bottlenecks at European, country, or regional level.

10.3.9. Brief description of the socio-economic bottlenecks
The socio-economic bottlenecks relate to the time requirement. Time is required to download the climatic data and input them into the software. Additionally, there is the general reticence of growers, particularly older growers to adopt new approaches and to change their habitual ways of doing things.

10.3.10. Techniques resulting from this technology
1) FAO provides the free software CROPWAT 8.0 for irrigation scheduling based on the water balance that can be downloaded at: http://www.fao.org/nr/water/infores_databases_cropwat.html
2) CROPWAT 8.0 for Windows is a computer program for the calculation of crop water requirements and irrigation requirements based on soil, climate and crop data and using the water balance method. In addition, the program allows the development of irrigation schedules for different management conditions. CROPWAT 8.0 can also be used to evaluate farmers’ irrigation practices and to estimate crop performance under both rain-fed and irrigated conditions. This software can be used in combination with the climatic database CLIMWAT also from FAO which can be downloaded at: http://www.fao.org/nr/water/infores_databases_climwat.html. CLIMWAT 2.0 offers agro climatic data from 5000 meteorological stations worldwide.
3) FAO also provided the tool ETo calculator that allows the calculations of reference evapotranspiration using the Penman-Monteith equation.
4) The crop model AQUACROP by FAO (http://www.fao.org/nr/water/aquacrop.html) also has applications for irrigation scheduling using the water balance approach.
5) In California, the CropManage is a web application for managing irrigation and nitrogen in lettuce (http://ucanr.edu/blogs/blogcore/postdetail.cfm?postnum=8501).
6) In Italy, IRRINET in a web service freely available developed by the CER (a consortium of canal irrigation) that provides irrigation advice for several crops using the water balance.
7) In Spain, the ISS-ITAP (Albacete) is an irrigation scheduling service that was created in 1988 and provides recommendations on 33500 ha, about 30% of the irrigable area.
8) In Australia, the IrriSAT is a weather-based irrigation management technology that use remote sensing to provide site-specific crop water management recommendations across large spatial areas.

10.3.11. References for more information
10.4. Irrigation management with soil moisture sensors
(Author: María Dolores Fernández, Rodney Thompson)

10.4.1. Used for
More efficient use of water.

10.4.2. Region
All EU regions.

10.4.3. Crop(s) in which it is used
Irrigated crops.

10.4.4. Cropping type
- Soil-bound
- Protected
- Open air

10.4.5. Description of the technology

10.4.5.1 Purpose/aim of the technology
The use of sensors to monitor soil water status offers the potential to irrigate in accordance with the characteristics of individual crops. Additionally, these sensors offer the potential for a fine degree of crop management such as applying controlled stresses for product quality considerations and accurate control of drainage for salinity management.

10.4.5.2 Working Principle of operation
The most widespread irrigation scheduling method is based on the determination of the soil-water balance, which implies the estimation of a crop’s evapotranspiration (ETc). The other approach to irrigation scheduling entails the use of sensors to obtain soil moisture status and to replenish the water in a growing medium to a pre-set level. The use of soil water sensors for irrigation management requires maintaining soil water content within upper and lower limits (Figure 10-2).

The maximum permitted amount of soil moisture is referred to as the Full Point or Upper Limit and is defined as the moisture content at which water movement beyond the root zone drops to an acceptably low rate. The minimum permitted amount of soil moisture is referred to as the Refill Point or Lower Limit and is defined as the moisture content at which mild drought stress first becomes apparent. The Refill Point identifies when to commence irrigation, and Full Point identifies when to stop; the distance between the two limits indicates the maximum amount that can be applied. Maintaining soil water within this range ensures that the crop maintains an adequate water status and appreciable drainage is avoided.
For practical purposes, the SWC in drying soil can be separated into three distinct phases (Figure 10-2), based on the rate at which the soil water content changes.

In phase 1, the change in volumetric soil water content is relatively fast due to the processes of drainage and evapotranspiration. In phase 2, the rate of change is predominantly due to evapotranspiration and the drainage component has ceased, SWC reduces in a step-like manner with sharp reductions during daylight periods because of crop water uptake and relatively constant SWC during overnight periods when little or no drainage occurs. In this phase, the soil moisture is readily available to the crop. In phase 3, the declining slope of the continuous soil water dynamics changes (Figure 10-3). As soil progressively dries, day-time reductions in SWC get progressively smaller. The daily reduction in SWC is less and is also has a steeper slope because ETc is progressively reduced because there is insufficient readily available soil water to meet crop requirements. Such data indicate to the irrigation manager that there is insufficient readily available water in the soil.

10.4.5.3 Operational conditions

The location of soil sensors and the Full and Refill values for each crop are important when using sensors for irrigation scheduling. The sensor must be located spatially and depth-wise within the maximum concentration of active roots. The depth of the sensor will depend on the rooting depth of the species and soil characteristics. Another sensor can be located at a depth at the bottom of the root zone. This deeper sensor enables the depth of wetting to be controlled ensuring that the full depth of the root zone is adequately wetted and also that drainage is controlled.

The setting of the limits may be done through: 1) using recommended numerical threshold values (Fixed values) or 2) visual interpretation of data. Fixed values are generally suitable for soil matric potential sensors, but they should be used with care with volumetric soil water content sensors. Fixed values or threshold values may not be available and laboratory-determined values may not reflect field conditions. An alternative is the in-situ determination of upper and lower limits based on the interpretation of soil water dynamics.
A suggested approach for defining lower limit SWC values is first to identify the SWC at which “commencement of stress” occurs, and then to select a slightly higher value. The transition from adequate to insufficient soil water supply for crop growth occurs during the progressive reduction in the rate of daily water loss. A decline in SWC in drying soil occurs in two phases: 1) a relatively rapid phase and 2) a subsequent slower phase when soil water is strongly limiting crop water uptake. The transition between the two phases is the “breaking point” and can be used to identify the beginning of crop water stress (Figure 10-3).

**Figure 10-3. Example of estimating the Refill Point. The straight broken lines represent periods of relatively fast and slower soil drying; the intersection between the two is the “breaking point” (Thompson et al., 2007b)**

In-situ determination of the upper limit of SWC can be made using the cessation of drainage from the root zone after irrigation or precipitation event; data of drainage beneath the root zone can assist in these assessments.

**Figure 10-4. Example of Upper Limit or Full Point estimation using soil moisture data (www.decagon.com)**

In the example shown in Figure 10-4, Decagon STE water content sensors were installed in silt loam at 0.5 m and 1 m in a vineyard. On November 13th and 17th, two significant precipitation events increased the water content at both depths. After the second event on November 17th, it is possible to see the soil water decrease, which is mainly determined by
drainage as evapotranspiration is minimal in this period of the year. From the beginning of December, the water content levels stop changing, suggesting that drainage had ceased and that SWC at that time corresponded to the upper limit.

10.4.5.4 Cost data
The cost of the sensors is variable (= 100-1000 €). The more sophisticated sensors include a data logger for capturing and transmission of data, and it is also necessary to additionally buy software which handles multiple sensors (400-500 €). Access to the data logger via mobile requires contracting a mobile phone line and costs approximately 10 €/month. The grower has to view the data daily for decision-making (approx. 0.5 hours/day).

10.4.5.5 Technological bottlenecks
For all sensors, it is essential that the recommended procedures for preparation, installation and maintenance be followed. The user will require technical support and assistance for sensor installation, determination of SWC thresholds (Full and Refill Points) and data interpretation. In addition, he/she must learn how to manage software, download data and communicate with the logger.

Full and Refill values can vary for each point of installation, particularly for volumetric soil water content sensors. In-situ determination of Full and Refill values is often necessary with volumetric soil water content sensors. Where the soil is not very homogeneous, it may be necessary to determine these in-situ for all locations.

The measurements of some capacitance sensors are affected by salinity and changes in salinity. Some sensors have a useful life of less than 4 years. Sensors and wires can interfere with or be damaged by farm operations.

10.4.5.6 Benefit for the grower
Adantages
- Automated readings
- Changes during short duration events can be observed
- Continuously recorded data from sensors provide a detailed history
- Helps to identify problems in irrigation water management (excessive intervals between irrigations, inadequate wetting, too frequent irrigations, and differences in soil moisture extraction patterns, broken pipes)
- Improved water use efficiency

Disadvantages
- Restricted extrapolation of SWC limits when using volumetric SWC sensors
- Close contact with the soil matrix required
- Large volumes of data are generated
- Difficult data management
10.4.5.7 Supporting systems needed
The use of sensors for irrigation scheduling requires at least, apart from the sensors, a data logger, a computer, and software for information display. It is recommended that climate data such as solar radiation, temperature, wind speed, also be obtained to assist with data interpretation.

10.4.5.8 Development phase
Commercially available: Sensor providers usually supply software for displaying information collected from sensors. Storage and display systems of sensor data in the Cloud are available for users. These systems may allow the incorporation of alarms, limits, comfort zones, predictions, and the possibility of adding indices and models, and information display for different electronic devices.

10.4.5.9 Who provides the technology
There are different companies supplying soil water sensors, such as Sentek (www.sentek.com.au), Delta-T (www.delta-t.co.uk), Decagon Devices (https://www.decagon.com), etc. These companies usually supply the software for information display.

10.4.5.10 Patented or not
Sensors and software are usually patented.

10.4.6. Which technologies are in competition with this one
Irrigation scheduling based on the estimation of crop evapotranspiration. However, both methods can be used together.

10.4.7. Is the technology transferable to other crops/climates/cropping systems?
Yes.

10.4.8. Description of the regulatory bottlenecks
Not applicable.

10.4.9. Brief description of the socio-economic bottlenecks
In general, many growers are interested in this technology; however, they consider that many of the currently available sensors are too expensive. This perception is a barrier to their adoption.

The main obstacles to the adoption of soil moisture technology at farm level appear to be the overall costs of the technology and the lack of effective dissemination and technology transfer activity including grower training. On-going progress in the field of electronics and information technology suggests there will be on-going reductions in prices and a more incorporation of these technologies into intensive horticulture.

For on-farm use, there are several general practical issues to be considered by potential users:
- Training in the use, installation, and maintenance of the sensor system
• Continued support for data interpretation, and use and maintenance of equipment
• Software must be user-friendly and easy to use
• Clear guidelines provided for interpretation of data

10.4.10. Techniques resulting from this technology

Different types of SWC sensors can be used for irrigation management such as time domain reflectometry (TDR) or capacitance sensors. The approaches described for the determination of the soil moisture limits for irrigation management be applied independently of the sensor used.

10.4.11. References for more information

10.5. Partial Root Drying
(Authors: Eleftheria Stavridou, Carlos Campillo)

10.5.1. Used for
- More efficient use of water
- Minimising the impact to the environment by nutrient discharge

10.5.2. Region
All EU regions.

10.5.3. Crop(s) in which it is used
All crops.

10.5.4. Cropping type
All cropping types.

10.5.5. Description of the technology

10.5.5.1 Purpose/aim of the technology
Partial root drying (PRD) is an irrigation technique that aims to:
- Reduce the use of irrigation water
- Control vegetative growth
- Increase the contents of antioxidants in the plant

10.5.5.2 Working Principle of operation
PRD is an irrigation technique by which two different parts of a plant root system are alternated from wet to dry state, so shoots and leaves are simultaneously supplied with water and water stress signalling compounds. PRD is also described in the scientific literature as controlled alternate partial root-zone irrigation and alternate partial root-zone irrigation.

PRD requires that dual dripper lines serve every row of trees or grapevines and that each dripper line can be used independently of the other. To achieve such independence, there must be a duplication of sub-mains and the valves regulating water flow to the sub-mains. Direct measurement of root zone soil water content is required so as to control the duration of irrigation events and the timing of the switch from drying to re-wetting. Soil profiles need to be well monitored to ensure that the alternating wet/dry sides are re-wetted to the full depth (i.e. root depth).

The frequency of wetting will vary with seasonal conditions, but irrigation volumes generally are fixed. The frequency of re-wetting is adjusted according to variation in crop evapotranspiration (ETc) as the cropping season progresses. Reference has already been made to “duty cycles” of drying and re-wetting that range to 10-14 days under mild conditions to 3-5 days under hot conditions.
10.5.5.3 Operational conditions

In strawberry, when supplying 80% of ETc with PRD management, ascorbic and ellagic acid contents, and the total antioxidant capacity increased, whereas yields were maintained. However, when irrigation was 60% of that needed to maintain the soil at full capacity, yields decreased compared fully irrigated plants.

Deep porous sandy loam soils offer best prospects for successful partial root zone drying. Orchards and vineyards that have been established with a drip irrigation system will most likely already have restricted root zones, and are thus more immediately suited to a partial rootzone drying irrigation regime.

10.5.5.4 Cost data

It depends on the irrigation system in use. In the case of drip irrigation, doubling the number of driplines etc., will double the cost of the drip irrigation system.

Managing this technique requires an increased labour input.

10.5.5.5 Technological bottlenecks

Determining the time at which to switch irrigation between dry and wet zones is difficult. The decision on the farm may be based on experience or on soil moisture readings, if available.

10.5.5.6 Benefit for the grower

Advantages

- Increased fruit quality and shelf-life
- Reduction of vegetative growth

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Potential savings in water and possibly fertilisers

Disadvantages

- Potential increase in labour and irrigation system costs
- Challenging management, high management skills required

10.5.5.7 Supporting systems needed

The irrigation system may need to be adapted to facilitate the application of this technology.

10.5.5.8 Development phase

Commercialised: in viticulture and fruit production in Australia, New Zealand, Spain, Israel, the United States, and South Africa. To date, most installations use a second drip line either above or below ground. Several irrigation-equipment manufacturers are working to eliminate the need to install two separate drip lines. PRD is now an active area of research in various vegetable crops including strawberry, raspberry, basil, coriander, or processing tomato.

10.5.5.9 Who provides the technology

PRD is a management strategy, that is applied by growers, often with the assistance of advisors or consultants.

10.5.5.10 Patented or not

Not patented.

10.5.6. Which technologies are in competition with this one

Other water saving techniques such as regulated deficit irrigation (see relevant technology description in this chapter) or transient deficit irrigation which triggers similar effects on the plant but requires different management.

10.5.7. Is the technology transferable to other crops/climates/cropping systems?

Yes.

10.5.8. Description of the regulatory bottlenecks

There are no relevant directives or regulatory bottlenecks at European, country or regional level.

10.5.9. Brief description of the socio-economic bottlenecks

- Potential increase in labour costs
- Challenging management, high management skills required

10.5.10. Techniques resulting from this technology

Fixed partial root-zone drying is a variation of PRD by which the wet and dry zones are not alternated PRD treatments and can be applied at different levels of stress.
10.5.11. References for more information


10.6. Deficit irrigation
(Authors: Carlos Campillo\textsuperscript{5}, Bozena Matysiak\textsuperscript{12})

10.6.1. Used for
More efficient use of water.

10.6.2. Region
Mediterranean.

10.6.3. Crop(s) in which it is used
- Fruit trees and vines
- Vegetables

10.6.4. Cropping type
- Soil-bound
- Protected
- Open air

10.6.5. Description of the technology

10.6.5.1 Purpose/aim of the technology
This is an irrigation strategy that imposes water stress on crops at key stages of vegetative and fruit development to limit water consumption without impacting yield.

10.6.5.2 Working Principle of operation
Deficit Irrigation (DI) is the application of less water than full crop water requirements based on full crop evapotranspiration (ETc). DI is a watering strategy that can be applied to different types of irrigation application methods. The correct application of DI requires a thorough understanding of the yield response to water (crop sensitivity to drought stress) and the economic impact of reductions in harvest. In DI, the entire root-zone is irrigated (different with partial root irrigation, see Technology 10.4). It’s necessary to determine ETc for each crop (generally known for herbaceous crops, but is more complicated for tree crops and vines). For deficit irrigation, there may be two situations. Either the reduction of volume irrigation is compensated by water stored in the soil reservoir or the soil water supply is insufficient, and ETc is reduced because of a limited supply of available soil water.

Two main techniques are based on the knowledge of crops response to water stress: Regulated deficit irrigation (RDI) and partial deficit irrigation also called partial root-zone drying (PRD) where only half of the root system is watered. The mechanism is that roots detect drought and generate abscisic acid, an anti-stress root chemical signal that is transported in the xylem to the shoots. In the shoots, increasing abscisic acid reduces the stomatal opening and transpiration.

In the scientific literature, there is substantial variation in the definition of “water deficit” for agricultural crops. To facilitate analysis and the summary of published research findings, we define water deficit at the following five levels:

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1) Severe water deficit: Soil water is less than 50% of the field capacity
2) Moderate water deficit: Soil water is maintained at 50-60% of the field capacity
3) Mild water deficit: Soil water is maintained at 60-70% of the field capacity
4) No deficit or full irrigation: Soil water is generally greater than 70% of the field capacity during the key plant growth period
5) Over-irrigation: The amount of water irrigated may be greater than what plants would require for optimal growth

Stage-based deficit irrigation is defined as RDI applied at different stages of plant development, with water applied to meet full plant evapotranspiration (ET) at the critical growth stages, and with less water applied at non-critical growth stages. The principle behind this approach is that the response of plants to RDI-induced water stress varies with growth stages and that less irrigation applied to plants at non-critical stages does not cause a significant negative impact on crop yield even though it may reduce crop growth. To apply this approach effectively, one must predetermine the critical growth stages for a specific crop species and cultivar and evaluate the relative sensitivity of crop plants to water deficit at various stages in their life cycle.

The application of RDI improves yield per unit of irrigation (yield per unit of irrigation is commonly known as water use efficiency). An increase from 4.9 to 8.0 t/ha has been observed under RDI in peach that yielded 48 t/ha (Figure 10-6). The increase in water use efficiency is largely due to a reduction in transpiration, which can be as much as 50%.

![Figure 10-6. Typical shoot and fruit growth pattern for (a) peach and (b) European pear](http://www.fertinnowa.com/wp-content/uploads/2017/11/FERTINNOWA-website-terms-and-conditions.pdf)

10.6.5.3 Operational conditions

Deficit irrigation strategies have been developed for high-density orchards (apple, pear, peach) and to balance vegetative and reproductive growth. Plant tolerance to drought is different at different growth stages. Therefore, deficit irrigation is based on plant growth stages, and full irrigation is applied during establishment and flowering to avoid negative impact on yield potential. To predict the re-irrigation timing, predictive models can be used. Models are based on abscisic acid root production and the simulation of soil-plant-atmosphere water dynamics. However, these models (e.g. DAISY) need to be improved to be used in commercial practice. It is also possible to use Soil Vegetation Atmosphere Transfer models, such as AquaCrop.

DI has been investigated mainly with perennial crops, but some annual crops may also benefit. RDI has been tested in many tree crops and with grape vines with generally good results, particularly with respect to product quality. RDI has been found to control...
vegetative growth, increase fruiting, advance fruit maturity, and to increase precocity and soluble solids in fruits. The key to successful RDI is good control of all water (irrigation or rain) to limit soil water volumes, which in turn limits vegetative growth. However sufficient water must be available for the entire growing season. Soil water volume control is made possible by two factors, the practical ability to achieve high-frequency irrigation regimes and the capacity to carefully restrict soil water by controlling the amount applied and the size of the wetted volume of soil. In practice, it can be difficult to implement these strategies in many areas because commonly the water savings are mostly early in the season when water is usually most abundant.

10.6.5.4 Cost data
This can be more expensive for PRD because of the cost of doubling the watering installation (see Technology Description of Partial Root Drying).

10.6.5.5 Technological bottlenecks
In a hot and dry environment such as the coastal Mediterranean region, it is not rare to have extremely high temperatures. For vegetables, plants under deficit irrigation are significantly stressed during the short periods of heat waves. In this case, it is necessary to suspend temporary the deficit irrigation and replace by full irrigation. In practice, set up regulated deficit irrigation is difficult because it requires maintaining a plant water status within narrow limits.

10.6.5.6 Benefit for the grower
**Advantages**
- Save water during irrigation (evapotranspiration losses from the soil and the culture and water losses from the distribution to the land)
- Improve nitrate use efficiency
- Minimise leaching of nutrients
- Improve the fruit quality (increasing the fruit dry weight, total soluble solids, colour intensity, sugar content, total acidity, and total antioxidant contents)

**Disadvantages**
- Risk of a decrease of the yield of fruits (an increase of non-marketable fruits and small-sized fruits)
- Risk of flower abortion and difficulty with fruit setting
- Risk of an increase in soil salinity
- Cost of double installation for PRD

10.6.5.7 Supporting systems needed
Models are needed to better determine the re-irrigation period. Calibration has been done only for a few soils. Strong technical support is needed to setup the technic.

10.6.5.8 Development phase
- Field tests

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- Commercialised

10.6.5.9 Who provides the technology
Not applicable.

10.6.5.10 Patented or not
Not patented, these technics were developed in research centres.

10.6.6. Which technologies are in competition with this one
None.

10.6.7. Is the technology transferable to other crops/climates/cropping systems?
To transfer deficit irrigation, it is recommended to do more studies on different kind of crops in different environmental conditions.

10.6.8. Description of the regulatory bottlenecks
Not applicable.

10.6.9. Brief description of the socio-economic bottlenecks
High risk of potential yield loss. Adapted only for areas suffering from water availability. There is still a lack of data and procedures on determining the optimum timing for irrigation in deficit irrigation.

10.6.10. Techniques resulting from this technology
Partial rootzone irrigation (EU SAFIR Project http://www.safir4eu.org/).

10.6.11. References for more information

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Transfer of INNOvative techniques for sustainable WAter use in FERTigated crops

10.7. Decision Support Systems to estimate crop requirements
(Authors: José Miguel de Paz\textsuperscript{14}, Carlos Campillo\textsuperscript{5})

10.7.1. Used for
- Preparation of irrigation water
- More efficient use of water
- Minimising the impact to the environment by nutrient discharge

10.7.2. Region
All EU regions.

10.7.3. Crop(s) in which it is used
- Woody crops
- Annual crops: high economic value crops as vegetables and flowers

10.7.4. Cropping type
All cropping types.

10.7.5. Description of the technology

10.7.5.1 Purpose/aim of the technology
Provide recommendations for irrigation, and in some cases also for nutrient management.

10.7.5.2 Working Principle of operation

![Diagram of Decision Support System scheme (Visconti & de Paz, 2016)](image)

10.7.5.3 Operational conditions
This technology is suitable for irrigation and fertilisation recommendations. Decision Support Systems generally contain simulation models of varying complexity. To obtain more accurate recommendations, these models parameters should be calibrated for local conditions. Sometimes these systems are used by a farmer, and a period of training is

required to understand and manage the system. To make them easier to use, many of these systems now work from platforms such as web-systems, smartphones, tablets etc. DSSs are often developed for specific crops in particular conditions, although some generic DSSs have been developed. Those developed for specific conditions should be calibrated and adapted when used in new conditions.

10.7.5.4 Cost data
Most of the DSSs are freely available on the Internet. It just needs a computer or other suitable platform to operate them.

10.7.5.5 Technological bottlenecks
- High costs (money, time) to develop them
- Often not sufficiently user-friendly
- Robustness of software
- Calibration of model parameters
- Often are too complex for farm users
- Training and on-going support required

10.7.5.6 Benefit for the grower

Advantages
- Water savings
- Increase irrigation efficiency
- Reduce nitrate pollution problems
- Help to develop plans for the crop

Disadvantages
- Many require that users are computer literate
- Can be excessively time-consuming
- Requires support in many cases
- Need to be maintained

10.7.5.7 Supporting systems needed
Technical assistance is needed, particularly during the first period of use.

10.7.5.8 Development phase
Commercialised: poor.
Generally, they are developed by research intuitions for local use.
Generic DSSs have been developed by FAO.

10.7.5.9 Who provides the technology
Public institutions and some private initiatives.
10.7.5.10 Patented or not
Unknown.

10.7.6. Which technologies are in competition with this one
Recommendations made by commercials, cooperatives and advisors.

10.7.7. Is the technology transferable to other crops/climates/cropping systems?
Yes. Generally, this technology is welcome in all growing areas, in which the DSS could be adapted to local crops, conditions, soil, climate, crop management etc.

10.7.8. Description of the regulatory bottlenecks
None

10.7.9. Brief description of the socio-economic bottlenecks
A major bottleneck is the user-friendliness of the DSS.
Other bottlenecks are the amount of information to be entered to operate these systems. Complex DSS with high data requirements tend to have few growers using them.

10.7.10. Techniques resulting from this technology
1) VegSyst: Is a DSS for water and N requirements of vegetable crops. More details at: http://www.ual.es/GruposInv/nitrogeno/VegSyst-DSS.shtml
2) SigAgroasesor: Is a Geographic Information System (GIS) platform to optimise crop management specific for each field included in the GIS-PAC. More details at: http://agroasesor.es/en/
3) EU-ROTATE_N. This DSS was developed by several European research groups to provide nitrogen recommendations for vegetable crops. It can also estimate crop irrigation requirements. More details at: http://www2.warwick.ac.uk/fac/sci/lifesci/wcc/research/nutrition/eurotaten/
4) FIGARO: “Flexible and Precision Irrigation Platform to Improve Farm Scale Water Productivity”, is a precision agriculture DSS based on remote sensing and soil sensors measurements to provide significant water and energy savings while leading to increased production and yield. More details at: http://www.figaro-irrigation.net/outputs/the-figaro-platform/en/
5) WATER-BEE: “Smart Irrigation and Water Management system”. This system recommends irrigation management based on soil water content measurements by sensors and crop modelling. http://waterbee.iris.cat/
6) FAO-AQUACROP: AquaCrop is the FAO crop-model to simulate yield response to water of several herbaceous crops. More details and download at: http://www.fao.org/nr/water/aquacrop.html
7) DSS-SALTIRSOIL. This DSS recommend irrigation management depending on the soil salinity and crop tolerance. More details at: www.agrosal.ivia.es or in the article:
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8) DSSAT: Decision Support System for Agrotechnology Transfer is a software application program that comprises crop simulation models for over 42 crops. More details at: http://dssat.net/downloads/dssat-v46

10.7.11. References for more information


10.8. Integrated sensor in decision support system for irrigation water management

(Authors: Carlos Campillo, Dolors Roca)

10.8.1. Used for
More efficient use of water.

10.8.2. Region
- Central-East Europe
- Mediterranean

10.8.3. Crop(s) in which it is used
All crops.

10.8.4. Cropping type
All cropping types.

10.8.5. Description of the technology

10.8.5.1 Purpose/aim of the technology
This technology aims to support growers and irrigation manager make decisions about when and how much to irrigate in specific farm conditions, based on estimates of crop growth and water availability measurements of from measurements of soil water and environmental conditions.

10.8.5.2 Working Principle of operation
A DSS is a computer-based information system that supports organisational decision-making activities, typically resulting in ranking, sorting, or choosing from among alternatives. A properly designed DSS is an interactive software-based system intended to help decision makers compile useful information from a combination of raw data, documents, and personal knowledge to identify and solve problems and make decisions.

Figure 10-8. Diagram of the inputs and outputs in an integrated support irrigation system
Generally, the DSS incorporated a simulation model. The models are based on the measurement of different sensor types (soil moisture measurement and plant water sensors) that allow real-time corrections to the initial estimation obtained by the model. The system works first with the development and implementation of a crop needs model, calculating the water needs of the crop based on agrometeorological historical data or taken from a nearby agrometeorological station and adjusted with a crop coefficient of each crop, estimated of crop development curves, or measured in the field with digital images.

There are some models that allow the determination of these parameters in a very precise form, allowing the incorporation of water strategies at certain moments of the crop cycle. These systems automatically or manually incorporate values obtained in the field that allow modifications of the irrigation schedules, generated by the water needs model. The model is connected to a series of sensors installed in the field that send the information through a logger to a central computer that analyses the data obtained by eliminating the erroneous or out of range values and providing the model with a certain value. This value is used by the model from a series of algorithms to modify the initial conditions of irrigation and to modify these to adjust the irrigation doses.

### 10.8.5.3 OPERATIONAL CONDITIONS

It depends on the manufacturer but ranges from one to 60 inputs and 1-35 outputs with or without remote control and access. The system is scalable by adding loggers in numbers dependent on a) the area to cover and b) the maximum distance to the inputs and outputs. Most of the models that incorporate sensors for decision support can simply provide growers with advice on irrigation, when and how much. More recent models command the head irrigation system and trigger the automatic opening and closing of electrovalves. Threshold set points are assigned to the inputs values (water needs, water contents, etc.). Sensor readings produce a signal that could be opening or closing of the valve. The systems can also incorporate systems for automatically closing the electrovalves from the amount of water that has passed through the flow meter when this is higher than calculated by the system.

### 10.8.5.4 COST DATA

- For installation: 2000 € for the basic equipment plus labour
- Yearly maintenance or inputs needed: 200 €

### 10.8.5.5 TECHNOLOGICAL BOTTLENECKS

- Internet access is required
- The instruments need a power source
- Installation and use requires a certain degree of expertise
10.8.5.6 Benefit for the grower

Advantages
- Automated
- Precise water management
- Reduction of irrigation management errors
- Improvement of harvesting in cases of irrigation support
- Reduction of dedication time to schedule and supervise irrigation
- Reliable
- Easy and fast detection of problems
- Better control feels (repeatability, reliability, etc.)

Disadvantages
- Challenging to adapt to certain growing conditions
- Can vary substantially in extensive crops
- Settings must be adapted to varying soil conditions
- Effective water delivery is also dependent on the reliability of the irrigation system: pipes, drippers, sprinkles etc. all must work within manufacturer specification

10.8.5.7 Supporting systems needed
- Internet connection although some systems can work independently
- Some source of electricity: solar panels or batteries that need to be regularly replaced

10.8.5.8 Development phase
Commercialised.

10.8.5.9 Who provides the technology
- Smartfield
- Waterbee system (MAC Ltd. company) http://www.mac.ie/

10.8.5.10 Patented or not
Yes.

10.8.6. Which technologies are in competition with this one
None.

10.8.7. Is the technology transferable to other crops/climates/cropping systems?
Yes, but require specific installation settings and input thresholds.

10.8.8. Description of the regulatory bottlenecks
There are no relevant regulatory bottlenecks for the use of sensors in DSS.
10.8.9. Brief description of the socio-economic bottlenecks

The high cost of the system can hold back growers from using it. It also requires some training to use the software and instruments, which is not very attempting.

10.8.10. Techniques resulting from this technology

Most irrigation strategies can be complemented and controlled by using these devices, such as Controlled Deficit Irrigation, Partial Root Drying, precision irrigation.

Some examples of irrigation modelling and scheduling systems:

The WaterBee system (http://waterbee-da.iris.cat) incorporates a Soil-Moisture Model for optimal water use, continuously self-adapting to each user’s situation and business objectives, using machine learning approaches. This system incorporates granular water sensors to determine when it is necessary to irrigate (Figure 10-9).

Another similar case is the DSS Figaro (http://www.figaro-irrigation.net), which allows the integration of sensors with the information provided by the system. FarmConnect software (http://www.rubiconwater.com/catalogue/farmconnect-software-usa) is web-based, connected devices such as soil moisture sensors, weather stations and rain gauges can be remotely monitored.

Most systems use soil moisture sensors to adjust irrigation needs. There are some systems that use plant sensors to establish the water needs of the crop, so the Smartfield™ System (http://www.smartfield.com) has been used in many different environments across the U.S. and many countries around the world. Smartfield™ provides users with many crop monitoring tools and analytical services that allow the user to make better informed and timely management decisions. The Smartfield ™ Base Station is a product that seamlessly collects data from multiple products and bundles the data into one package that is then sent via a cellular network to CropInsight™ for further analysis. The Smartfield™ Base Station also measures ambient temperature, relative humidity, and rainfall. This product is the backbone of the SmartCrop® system which is used to measure infrared canopy temperature in order
to determine the stress of a crop (Figure 10-10). These stress calculations have the ability to manage the crop for maximum return on investment.

Other systems can be developed for specific crops that can integrate different plant measure obtained in the field, for example, the irrigation DSS for processing tomato developed by Campillo and colleagues in 2016, measures the percentage of ground cover (Figure 10-11a) and leaf water potential (Figure 10-11b) are used for crop coefficient adjustment. All information allows the user to do an adjustment to the FAO56 recommendation and water balance (Figure 10-11b).

EFFIDRIP (http://effidrip.eu) is an ICT-based tool for supporting the management and supervision of irrigation and fertigation. It has been conceived for localised irrigation systems in tree crops, although its use could be extended to other scenarios (Figure 10-12). Its overall objective is to offer a cost-effective tool that provides the end-users (farmers or technicians) effortless irrigation and fertilisation help, as well as easy and reliable supervision of the state of the irrigation system. The EFFIDRIP system complements the functionalities of current irrigation and fertigation control equipment by making them part of a higher-level system based on Information and communications technology (ICT).
The role of that high-level system is the integration of data and information from multiple sources for their usage in automated scheduling decisions and supervision. It can also facilitate user interaction with the system and communication between people involved in the process. The irrigation controller remains as a key component for the execution of irrigation and fertigation schedules with some autonomy. What really makes the difference is that those schedules will be updated remotely once a day for each irrigation sector. For each subsequent application, the precise crop water and fertiliser needs will be estimated as a function of weather conditions, the soil and crop water status assessed by sensors, as well as the productive and environmental goals by the farmer. For this purpose, weather data and sensor measurements are combined in a base of state-of-the-art agronomic knowledge.

The IRRIX system (Figure 10-13) works from collected data through sensors installed in the field that cross with reference meteorological data and available water resources in the plot. With this information, the platform plans the irrigation campaign efficiently and adjusted to each case, without requiring practical dedication by operators. Each day, the system automatically adjusts itself according to the indications of the sensors, within the margins that allow the planning established at the beginning of the campaign. Each day data is collected through sensors and the system adjusts irrigation needs autonomously. The IRRIX web platform for automated irrigation monitoring and control developed by the Institute of Agrifood Research and Technology in Catalonia, Spain (IRTA) will be applied in several areas of Lleida, Badajoz and Almería, in Spain, within a project “Integrating soil water sensors on a seasonal strategy for automated re-scheduling of drip irrigation” funded by the National Institute of Agricultural and Food Research and Technology (INIA) RTA2013-00045-C04.
10.8.11. References for more information

10.9. Weather forecast related tools
(Authors: María Dolores Fernández, Carlos Campillo)

10.9.1. Used for
More efficient use of water.

10.9.2. Region
All EU regions.

10.9.3. Crop(s) in which it is used
Irrigated crops.

10.9.4. Cropping type
- Soil-bound
- Protected
- Open air

10.9.5. Description of the technology

10.9.5.1 Purpose/aim of the technology
Crop water requirements depend on climatic conditions and crop characteristics (type, development stage, planting distance, etc.) and can be estimated by multiplying the reference evapotranspiration (ETo) by the crop coefficient (Kc) value. ETo forecasting is valuable in planning irrigation or in areas with limited or deficient weather data.

10.9.5.2 Working Principle of operation
ETo varies with weather and is usually estimated using observed weather data from the nearest weather station.

The most widely used method to estimate ETo is the FAO Penman-Monteith equation, which has shown good performance in different climatic zones. This method requires data of solar radiation, temperature, relative humidity, and wind. Networks of agrometeorological stations have been installed in many irrigated areas throughout the world, allowing the measurement of the climatic variables needed for ETo calculation. However, the high cost of these stations and data downloading has limited its expansion; consequently, there are areas where no data is available or where the data do not have the necessary quality to estimate ETo with precision. In these cases, the alternative is the use of expected ETo values.

ETo forecasting procedures can be categorised into direct and indirect methods, depending on the methodology used and the input data. In the direct methods, current and historical data are used to forecast ETo, using time series methods or using artificial or computational neuronal networks, allowing ETo predictions in the medium and long-term. The oldest and simplest way to predict the daily ETo is from average values of a historical series of ETo data. The use of historical values enables irrigation planning for the whole growing season (up to one year) and is an easy tool. However, periods of crop water stress leading to yield
reductions may be occasionally induced in a number of years (3 out of 15) when the current climatic conditions determine a crop water demand higher than the corresponding to the mean microclimatic year. For that reason, time series models and artificial or computational neuronal networks have been subsequently developed, enabling better weekly and monthly ETo predictions than the historical average data.

In the indirect method, weather variables needed to calculate ETo are forecasted by numerical weather prediction (NWP). Several public and private institutions provide online daily weather forecast that usually includes numerical daily maximum and minimum air temperatures, wind speed and relative humidity estimations and daily non-numerical forecasts of sky cover. In Europe, the two main consortiums providing daily weather forecast data are HIRLAM and ALADIN. In 2006, both European consortiums collaborated in the development of high-resolution systems (HARMONIE).

10.9.5.3 Operational conditions

Farmers and technical advisors in different parts of the world can obtain free online data of real-time or historical ETo from public advisory services, as well as climatic data measured in agrometeorological stations installed in irrigable areas. The most known public advisory services is the California irrigation management information system, which has served as a model for other services. In Spain, for example, the Agroclimatic Information System for Irrigation (SIAR) is responsible for capturing, recording and reporting the agro-climatic data of 468 stations distributed throughout the country.

Predicted ETo values from NWP are being supplied in the recent years. National Weather Service’s, Weather Forecast Offices of USA are providing ETo predictions for that country from 2014 (Figure 10-14).

ETo can be also calculated from NWP provided by National Weather Services. Usually, NWP forecasts numerical daily air temperature, relative humidity and wind speed and daily non-numerical sky cover. However, these variables have to be processed before being used for ETo estimation. Thus, in meteorology wind speed values refer to a standard height of 10 m, so that the wind values provided have to be converted into 2 m (u2; reference for agrometeorological studies) using the procedure described by Allen et al. (1998):

\[ u_2 = u_z \frac{4.87}{\ln(67.8 \ z - 5.42)} \]

where \( u_z \) is wind speed (m/s) at height \( z \) (m) above the ground.
10.9.5.4 Cost data

Growers can download the weather forecast with different electronic devices (PC, Smartphone, tablet, etc.) by consulting internet services of National Weather Agencies. Access to internet and time are necessary to download weather forecast from services of National Weather Agency. Some companies are providing weather forecast via e-mail or App.

10.9.5.5 Technological bottlenecks

Institutions presently providing ETo forecast are very scarce. However, in many parts of the world, it is possible to obtain estimated climatic data provided by public and private institutions. These data can be used to estimate ETo, but pre-processing of data and calculation of ETo with FAO Penman-Monteith model is complex. Other simpler methods for ETo estimation showing good results in different climatic conditions, such as Hargreaves model, have been proposed. Forecast performance for weather data and ETo gradually declines with increasing lead time.

10.9.5.6 Benefit for the grower

Advantages

- Public institutions provide online, mostly free, weather forecasts
- The use of ETo forecast allows anticipating irrigation to water requirements, thus making an efficient use of water and energy
- It is possible to have meteorological data in areas where measured data are not available
Disadvantages

- Not all growers have access to these methodologies
- Requires in-depth knowledge of data acquisition and processing, calibration and evaluation
- NWP provides weather forecasts with a short lead time (1-7 days)
- Forecast performance varies depending on NWP model, lead time, location and climate
- Quantification of ETo forecast using outputs from NWP models has been limited to a small number of studies in certain geographical areas such as United States, Europe, China, Australia and Chile and to relatively short lead times

Figure 10-15: Watering recommendations for strawberry based on weather forecast provided by IFAPA in Andalusia (Spain) (from http://www.juntadeandalucia.es/agriculturaypesca/ifapa/servifapa)

10.9.5.7 Supporting systems needed
Internet access and an electronic device for data capture.

10.9.5.8 Development phase
Applied in some commercial farms but new developments are in progress.

10.9.5.9 Who provides the technology
Public and private institutions supply weather forecasts.

10.9.5.10 Patented or not
No.
10.9.6. Which technologies are in competition with this one
Data of ETo estimated from historical or real-time climatic data.

10.9.7. Is the technology transferable to other crops/climates/cropping systems? 
Yes.

10.9.8. Description of the regulatory bottlenecks 
There are no regulatory bottlenecks.

10.9.9. Brief description of the socio-economic bottlenecks
The user must have the knowledge, spend time and be persevering to consult or download weather forecasts, perform calculations and vary the irrigation scheduling on a daily basis. The use of ETo forecast is useful when the irrigation scheduling is carried out in a very short-term (1-3 days). For programming in the medium term, up to 7 days, it must be considered that ETo forecast is less precise than real-time ETo.

10.9.10. Techniques resulting from this technology
There are public institutions giving free available recommendations for irrigation based on weather forecast (California irrigation management information system in the USA (http://www.weather.gov/cae/fretinfo.html), IFAPA in Andalusia (Spain) (http://www.juntadeandalucia.es/agriculturaypesca/ifapa/servifapa)) Irristrat is commercial software (http://www.hidrosoph.com/ES/irristrat.html) able to give such recommendations for different crops.

10.9.11. References for more information
Transfer of INNOvative techniques for sustainable WAter use in FERtigated crops


10.10. Remote sensing
(Authors: Juan del Castillo\textsuperscript{13}, Carlos Campillo\textsuperscript{5})

10.10.1. Used for
More efficient use of water.

10.10.2. Region
All EU regions.

10.10.3. Crop(s) in which it is used
- All vegetables
- Fruit

10.10.4. Cropping type
- Soil-bound
- Open air

10.10.5. Description of the technology

10.10.5.1 Purpose/aim of the technology
Remote sensing provides information capable of improving the use of water balance, integrated into a DSS to estimate evapotranspiration based on meteorological stations and monitoring and characterisation of actions in plots.

10.10.5.2 Working Principle of operation
Remote sensing uses multispectral vegetation indexes to assist the estimation of plant transpiration through the computation of the basal crop coefficient, both sensitive to plant ground cover fraction. The multispectral vegetation indexes are obtained from remote sensing collected by different platforms: satellite, aircraft or unmanned aerial vehicle (UAV). The main multispectral indexes used in this technology are the Soil Adjusted Vegetation Index (SAVI) and the Normalised Difference Vegetation Index (NDVI).

The advances in the spectral, spatial, and temporal resolution of the remote sensing allow detecting properties of crops related to the growth. The Copernicus program developed by ESA agency provides accurate, timely and easily accessible information about earth observing. The satellite Sentinel-2, with its 13 bands covering the visible to the shortwave infrared spectrum will allow an efficient mapping of vegetation at 10-20 m resolution, suitable for instance for pan-European high-resolution products.

The FAO-56 methodology calculates reference evapotranspiration (ET\textsubscript{o}) representing the evaporative energy of the atmosphere and a crop coefficient that is related to the state of development of the vegetation. Irrigation management systems in DSS, use dual K\textsubscript{c} by separating soil evaporation and plant transpiration, using the evaporation coefficient (Ke) and the basal crop (K\textsubscript{cb}), respectively.
DSS use theoretical Kcb curves, depending on the crop and the phenological state. This technology estimates the Kcb of each crop plot from multispectral vegetation index (VI), such as SAVI or NDVI. These data should be compared with the theoretical curve, to provide the farmer with accurate information for correction.

Satellites provide multispectral images due to the reflectance of each crop in incident sunlight (Table 10-1). These images collect information of different wavelengths of the visible and infrared spectrum and are used to calculate vegetative indexes by means of mathematical equations. These indexes correlate well with the relative photosynthetic size of the crop cover and show how vegetative canopy absorbs photosynthetically active solar radiation.

The relationship between vegetation index (SAVI or NDVI) and coverage fraction 1) is used to estimate the Kcb plot level. In each pixel of the plot, a value of fc derived from the image will be calculated and entered the formula of Kcb 2) where the value of the VI will come from a satellite image and the rest of the parameters will be tabulated for each crop.

Table 10-1. Different satellite platforms

<table>
<thead>
<tr>
<th>Platform</th>
<th>Multispectral resolution (m/pixel)</th>
<th>Frequency images (days)</th>
<th>Minimum image size</th>
<th>Cost (€/km²)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geoeye 1</td>
<td>2,00</td>
<td>3</td>
<td>25 km²</td>
<td>15,25</td>
</tr>
<tr>
<td>WorldView 3*</td>
<td>1,24</td>
<td>1</td>
<td>25 km²</td>
<td>27,87 (0,2788 €/ha 697 €/image)</td>
</tr>
<tr>
<td>Pléiades</td>
<td>2,80</td>
<td>1</td>
<td>25 km²</td>
<td>11,33</td>
</tr>
<tr>
<td>Quickbird</td>
<td>2,40</td>
<td>3</td>
<td>25 km²</td>
<td>15,25</td>
</tr>
<tr>
<td>Kompasat 3A</td>
<td>2,20</td>
<td>4</td>
<td>25 km²</td>
<td>6,97</td>
</tr>
<tr>
<td>Sentinel 2A</td>
<td>10,00</td>
<td>3 when Sentinel 2B is available</td>
<td>Free</td>
<td></td>
</tr>
<tr>
<td>LANDSAT 7 and 8</td>
<td>20-30</td>
<td>15</td>
<td>Free</td>
<td></td>
</tr>
<tr>
<td>UAV</td>
<td>&lt;0,5</td>
<td>According to demand</td>
<td>According to demand</td>
<td>400 €/10-20 ha depending on company and service</td>
</tr>
</tbody>
</table>

10.10.5.3 Operational conditions

Limits:

- Spatial resolution according to the size of the operative irrigation unit
- Uncontrolled conditions in the agricultural plot, or a combination of factors (nutrient deficiency, failures in irrigation equipment, diseases, pests, etc.)
- Factors like clouds, pixel errors, etc. that affect the quantitative values derived from the image
- Temporary resolution not sufficient for decision-making

10.10.5.4 Cost data

It is necessary to differentiate the raw cost of the images from the cost of the final product after manipulated by specialised service companies. These will finally be used by growers.

10.10.5.5 Technological bottlenecks
Use of technology since it is necessary to have a deep knowledge of Geographic Information Systems (GIS).

10.10.5.6 Benefit for the grower

Advantages
- Easy crop tracking display
- Detection of problems or heterogeneity in crops
- Provides information to compare strategies

Disadvantages
High experience in computer needed.

10.10.5.7 Supporting systems needed
DSS (Decision Support System) uses remote sensing indexes to provide irrigation recommendations.

10.10.5.8 Development phase
Commercialised.

10.10.5.9 Who provides the technology
In relation to image services, both public and private companies.

10.10.5.10 Patented or not
Satellite technology is not patented, but image access platforms or analysis software are.

10.10.6. Which technologies are in competition with this one
Companies that base irrigation recommendations on proximal crop and soil sensing.

10.10.7. Is the technology transferable to other crops/climates/cropping systems?
Yes.

10.10.8. Description of the regulatory bottlenecks
There are no regulatory bottlenecks.

10.10.8.1 Brief description of the European directive and implications for growers at European level

10.10.8.2 Implementation at the country level
All the European legislation is implemented at country level.

10.10.9. Brief description of the socio-economic bottlenecks
• Need of good knowledge of geographic information systems. The need to incorporate crop tracking data when using remote sensing data for irrigation conditions growers' involvement through ICT technologies. Therefore, services should be adapted to the level of growers in terms of usability. However, the impact of ICT in this sector is slow, being limited to support the operation of machinery.
• Some satellites, as Sentinel (free use), do not work with all wavelengths required for certain tasks, for example, thermal wavelength.
• The platforms that are used for irrigation and fertilisation are not adapted for all crops, local adaptations must be conducted for each crop.
• The reflectance values given by the satellite do not say much, they must be related to plant parameters.

10.10.10. Techniques resulting from this technology
Find below some companies that provide irrigation recommendations based on canopy reflectance measurements from combined platforms (satellite, plane, drone):
• sigAGROasesor (http://agroasesor.es/es/plataforma-sigagroasesor/integracion-de-conocimiento-suelos-clima-riesgos.html)
• Farmstar: http://www.farmstar-conseil.fr/web/fr/7-la-technologie.php
• http://maps.spiderwebgis.org/login/?custom=
• Agrisat: http://www.agrisat.es/
• http://www.esa.int/Our_Activities/Observing_the_Earth/Copernicus/Land_services

10.10.11. References for more information
10.11. Plant growth balance analysis system
(Author: Eleftheria Stavridou)\(^{15}\)

10.11.1. Used for
More efficient use of water.

10.11.2. Region
North-West Europe.

10.11.3. Crop(s) in which it is used
Tomato.

10.11.4. Cropping type
- Soilless
- Protected

10.11.5. Description of the technology

10.11.5.1 Purpose/aim of the technology
Enables the monitoring and analysis of the daily weight accumulation processes.

10.11.5.2 Working Principle of operation
The system weighs individual plants in the greenhouse using a weighing unit. Data are transferred every 20 minutes by radio to a computer and then to the server to process data, using software that was developed especially for this purpose. Processed data are transferred to the grower via the Internet website on the following day. Climate and irrigation data are collected from the grower’s climate and irrigation control system. They enable the grower to:

- Monitor the daily growth of plants in the greenhouse
- Observe growth patterns
- Analyse the correlation between growth patterns with the climate and irrigation data
- Compare performances of:
  - Various varieties
  - Different compartments
  - New techniques or technologies used
  - Different crop management strategies (rootstocks, fertilisers, irrigation, etc.)

The system is not only able to compare compartments (different areas of a crop), but also differences between “Weighing Units”. With this information, crops can be tracked at a detailed level.
10.11.5.3 Operational conditions
The number and distribution of the weighing units are decided according to the conditions at the site: size and structure of the greenhouse, uniformity factors, sensor location etc. Using the Paskal system, as an example, a typical unit consists of 100 Weighing Units for 8 ha with 1 type of crop. For smaller areas, the number can be less. The minimum is 32 units for 1 system and at least 16 units per compartment.

10.11.5.4 Cost data
For installation: the minimum units per system costs 25000 €.
Yearly maintenance or inputs needed: subscription to the service and the software for the data analysis 1490 €/year.

10.11.5.5 Technological bottlenecks
There no real-time data. The data need time to be processed and the grower has access to the data 24h later.

10.11.5.6 Benefit for the grower
Advantages
- Automated
- The computer processes the data
- Constant monitoring

Disadvantages
- Expensive
- No real-time data access
- Interpretation of the data is difficult if no other monitoring systems (EC, pH, slab weight) are used

10.11.5.7 Supporting systems needed
To be able to interpret the growth analysis data they need to be combined with other data such as radiation, water, EC, and pH values etc.

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Figure 10-16. System Components Scheme (http://www.hortidaily.com/article/11380/Special-series-of-articles-on-Hortidaily-featuring-Paskals-Plant-Growth-Analysis)
The computer that receives the data from the greenhouse must be continuously connected to a stable internet network.

10.11.5.8 Development phase
Commercialised.

10.11.5.9 Who provides the technology
Paskal-tech.

10.11.5.10 Patented or not
This technology is patented.

10.11.6. Which technologies are in competition with this one
Turtina Hydro by Gremon systems.

10.11.7. Is the technology transferable to other crops/climates/cropping systems?
Yes, it can possibly also be used in soilless, covered crops other than tomato. However, an adaption of the software might be needed for that.

10.11.8. Description of the regulatory bottlenecks
There are no relevant regulatory bottlenecks at European, country, or regional level.

10.11.9. Brief description of the socio-economic bottlenecks
The high costs associated with buying the equipment and the yearly license of the software will hold back a lot of growers.

10.11.10. Techniques resulting from this technology
None.

10.11.11. References for more information
[2] Plant Growth Analysis - System structure and capabilities brochure
10.12. Thermal Infrared Sensor

(Author: Carlos Campillo, Elisa Suárez-Rey)

10.12.1. Used for
- More efficient use of water
- Determining water needs

10.12.2. Region
- Central-East Europe
- Mediterranean

10.12.3. Crop(s) in which it is used
- Woody crops
- Annual crops

10.12.4. Cropping type
All cropping types.

10.12.5. Description of the technology

10.12.5.1 Purpose/aim of the technology
Thermal infrared sensors can provide information on plant water status and the amount of water to apply to an orchard during a certain period, the distribution of irrigation water, evaluation of moisture parameters and analysis of plant stress.

10.12.5.2 Working Principle of operation
Thermal images or thermograms are visual displays of the amount of infrared energy emitted, transmitted, and reflected by an object. Because there are multiple sources of the infrared energy, it is difficult to get an accurate temperature of an object using this method. A thermal imaging camera can perform algorithms to interpret that data and build an image. Although the image shows the viewer an approximation of the temperature of an object, the camera uses multiple sources of data based on the areas surrounding the object to determine that value rather than detecting the actual temperature. Thermographic cameras usually detect radiation in the long-infrared range of the electromagnetic spectrum (roughly 9-14 µm) and produce images of that radiation. This technology can be used in agriculture to determine plant water status.

The instrument’s optics pick up the sample of infrared radiation from the warm object to be measured, focusing it on the small infrared radiation sensor that converts it into a proportional electrical signal analogous to incoming infrared radiation (hence the temperature of the object). This signal is amplified and linearised by changing the radiation ratio into a perfectly linear voltage-temperature relationship. The temperature appears in the display.

In plants, the canopy temperature increases when solar radiation is absorbed but is cooled when that energy is used for evaporating water (latent energy or transpiration) rather than...
heating plant surfaces (Figure 10-17). Canopy temperature commonly follows a diurnal curve, with day-time temperatures rising due to increases in solar radiation and temperature. A water-stressed plant will reduce transpiration and will typically have a higher temperature than the non-stressed crop. This effect has also been explored as a response to nutrient stress and disease stress. Canopy temperature-based algorithms are strongly correlated to important quantifiable crop outputs such as yield, water use efficiency, seasonal ET, midday leaf water potential, irrigation rates, and herbicide damage. Variability of canopy temperature has been used to indicate water stress. Canopy temperature depends on the aerial temperature. The more water is transpired, the more the canopy temperature is below the temperature of the surrounding air.

Figure 10-17. Factors affecting Canopy Temperature Depression (CTD) in plants (Reynolds et al., 2001)

The Crop Water Stress Index (CWSI), developed by the U.S. Water Conservation Laboratory in Arizona depends on this. The main criterion of the CWSI, therefore, is the temperature difference between the canopy leaves and the air. If a crop has water stress and therefore cannot transpire, there is hardly any difference between leaf and air temperature. The red upper baseline in Figure 10-18 stands for this situation. For the not water stressed crop, the transpiration depends on the relative humidity of the air. The lower the relative humidity is, the more the crop transpires. And the more the crop transpires, the lower the temperatures of the leaves. The green lower baseline (Figure 10-18) represents the case of the fully transpiring, non-water stressed crop. The vertical distances between the upper and lower baseline define the differences of the temperature span between leaves and air that occur when non-transpiring crops on the one hand with fully transpiring plants, on the other hand, are compared.
The crop temperature is measured using an infra-red thermometer or thermal camera, while the air temperature and vapour pressure deficit are measured using dry and wet bulb thermometers, or using formulae to convert relative humidity measurements.

The CWSI value is a measurement of the reduction in transpiration, expressed as a decimal in CWSI units. The CWSI has values ranging from 0 (no stress) up to 1 (maximum stress). A CWSI value of 0.25-0.35 would occur when the irrigation is due. The baselines are different for various phenological stages in certain crops. For winter wheat, different baselines should be developed for pre- and post-head stages. Baselines are strongly location dependent and perhaps species and variety dependent. To determine a non-water stressed baseline, it is a matter of measuring a non-stressed crop canopy temperature over a range of vapour pressure deficits (VPDs). This can be done by monitoring it as it changes over one day or by taking measurements on different days when the VPD is different around solar noon.

### 10.12.5.3 Operational conditions

Infrared thermometers are sufficiently reliable for continuous use over the period of a growing season and require only minimal in-field maintenance. The placement of the Infrared thermometers (IRTs) is an important consideration in the implementation of the protocol. A typical installation for a drip irrigation system utilises two IRTs viewing the canopy in a nadir view that produces a viewing area with a diameter of 10 cm. The IRTs are in the field in a manner that provides canopy temperatures that are representative of the field. When used with a centre pivot or linear drive irrigation system, IRTs have been mounted on the system in a forward-looking orientation. In this installation, the IRTs view the driest portion of the field. The IRTs are periodically checked for height adjustment and the lenses are cleaned. Temperature is typically monitored every six seconds and 15 minutes averages are used for irrigation decisions.

A thermal camera is installed in UAV before the flight. Images and flight data (position) are recorded in a memory card. The images are saved as mosaics by specialised software. Temperature value of each pixel is calibrated with a field local measurement during the flight. Yearly maintenance or inputs are needed.
Infrared thermometers are accurate and have a wide range of action (from -30 °C to 100 °C). There are different distance / size relationships of the measurement object (e.g. 50: 1, 60: 1, 12: 1). Measurements at long distances will measure larger area. This is something that sometimes is not desired, hence a higher distance/size ratio is preferred. In some catalogues, this characteristic is expressed as field of view and it is measured with the angle of the cone whose apex coincides with the sensor. The field of view angles vary between 0,1° and 50° for the different models. For measurements in plants, thermometers with field of view angles between 4° and 15° are used. There are models with selective and fixed emissivities (0,95).

10.12.5.4 Cost data
Infrared thermometers cost 500-1000 € depending on the accuracy or the commercial company. A logger is necessary to save the data. Thermal cameras are more expensive (10000-20000 €). Different companies do technical works with UAV and thermal images of the farm. Processing images and crop water status on the farm costs 20-30 €/ha.

10.12.5.5 Technological bottlenecks
Variability, correct installation, interpretation of information, easy-to-use friendly software, the threshold for different crops and different crop phase. It’s also necessary to know the air temperature.

10.12.5.6 Benefit for the grower

**Advantages**

- Water savings
- A non-destructive method to determine crop’s water content
- Continuous monitoring
- Allows for irrigation scheduling
- Relatively cheaper wireless technology
- Automation possible
- Provides a picture of a whole field or farm
- Using cameras or remote sensors, many fields can be measured with a single instrument

**Disadvantages**

- Help needed for installation
- Difficult data interpretation and management
- Cost
- In aerial images, image-processing is necessary: Mosaic, Orthorectification, Elimination of soil (reduce errors in the calculation of the temperature of the plant)
- In aerial images, images must be calibrated with data taken from the plot
• The temperature value does not indicate directly whether there are stresses or not, the values obtained must be compared with measurements in the field made with other sensors. Vapour pressure deficit, water potential, soil moisture, etc.
• Variations in temperature depending on the part of canopy and angle of measurement
• Thermographs are expensive

10.12.5.7 Supporting systems needed
A technical assessment during the first periods of use is required.

10.12.5.8 Development phase
Commercialised.

10.12.5.9 Who provides the technology
Infrared Sensor
Apogee: http://www.apogeeinstruments.co.uk/infraredradiometer/
Smartfield http://www.smartfield.com/smartfield-products/equipment/smartcrop-system/

Thermal Camera (used with drone or manual)
FLIR: TAU Thermal camera
Sensefly: thermoMAP

10.12.5.10 Patented or not
Yes, this technology is patented.

10.12.6 Which technologies are in competition with this one
Plant Sensors and Remote sensing.

10.12.7 Is the technology transferable to other crops/climates/cropping systems?
Yes.

10.12.8 Description of the regulatory bottlenecks
For aerial images UAV legislation:
The legislation on the use of drones is different in each country of the European Union, the commission is working on a common legislation. In some countries, there are fewer legal restrictions on how people can use drones, type of drones, flight height, where they can fly, no-fly zones, what types of jobs can be done, what flight permits they need, national database, etc.

In Spain to fly a drone you need a special license and an official course of drones handling, the company must have a permit from the air agency, drones cannot be used in public places or with people, the works must be for professional use, there are areas of special air protection that cannot be flown in any way (http://www.icarusrpa.info/mapa.php?opt=all), in addition the drone must always be visible by the pilot.
10.12.9. Brief description of the socio-economic bottlenecks

- In many places in Spain, water saving is still not an objective of farmers
- Orchards are often too small to afford the costs of sensors and remote sensing technologies

10.12.10. Techniques resulting from this technology

Most irrigation strategies such as Controlled Deficit Irrigation, Partial Root Drying, etc., can be complemented and controlled using these devices.

There are different sensors based on this principle that permit to measure the canopy temperature:

Infrared thermometer: This sensor measures the canopy temperature with a point measurement over the canopy. The ratio of measure (target area) depends on the distance between sensor and crop and the measurement angle. The temperature will be average of the measured area, with a unique value. This sensor can be connected to a logger and take a continuous measurement (with a defined time interval). The GPS technology permits the use of sensors and loggers to carry measurements of all farm holding parts if the sensor is placed on a tractor.

Thermal camera: This camera permits to take images with pixels expressing the temperature of the crop area. This allows knowing the temperature of a specific area of the crop canopy. This sensor can be used with local images of a specific point of the farm or be installed in a UAV to take measurements of a large zone or even all plots in the farm holding. The UAV system allows to obtain different images and with the mosaic techniques a continuous image of the farm with information on the temperature in each pixel of the image.
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The aerial inspection of a crop with an UAV is another example of its application and the result could determine areas with possible leakage of irrigation, as well as zones with lack of water and/or with poor fertility to help to change water scheduling in specific parts of the farm holding.

10.12.11. References for more information

10.13. **Dendrometers**  
*(Authors: Marisa Gallardo, Benjamin Gard)*

**10.13.1. Used for**  
More efficient use of water.

**10.13.2. Region**  
All EU regions.

**10.13.3. Crop(s) in which it is used**  
- All vegetables  
- Fruit trees  
- Ornamentals

**10.13.4. Cropping type**  
All cropping types.

**10.13.5. Description of the technology**

**10.13.5.1 Purpose/aim of the technology**  
Dendrometers, which are also known as linear variable displacement transducers, measure Stem (or trunk) Diameter Variations (SDVs) with a very high resolution and are a very sensitive indicator of plant water status.

Using suitable protocols, dendrometers can be used for determining the timing of irrigation. They appear to be most suited for use with grapevines and fruit trees.

**10.13.5.2 Working Principle of operation**  
The stems or trunks of plants experience shrinkage and swelling within 24-hour periods because of a dis-phase between transpiration and plant water uptake. As the evaporative demand increases in the morning, plants begin to transpire using water stored in tissues including stems/trunks; this results in the contraction of the stem and within daily 24-hour periods, stem diameters have minimum values around midday (Figure 10-21). In the afternoon and evening, root water uptake has progressively more influence on stem diameter than transpiration and complete re-hydration of all tissues progressively occurs reaching a maximum value just before sunrise (Figure 10-21). A water-stressed plant has a larger contraction during the day and a lower recovery at night than a well-watered plant. These differences between water-stressed and well-watered plants form the basis of the use of dendrometers. Dendrometers continuously measure stem diameter and consequently stem diameter variations. The dendrometers are connected to data-loggers to enable automatic data collection.

Among the SDV-derived parameters that are used in irrigation scheduling in trees with slow trunk growth, the most sensitive parameter is often the maximum daily shrinkage, i.e. the difference between the maximum stem diameter value before sunrise and the minimum value at approximately midday. For young trees, stem growth rate, the difference of the
maximum trunk diameter over two consecutive days (Figure 10-21), is the most sensitive parameter because decreases in trunk growth occur rapidly in response to water stress.

Irrigation protocols have been developed for some mature fruit trees that involve: 1) selecting the derived parameter most suitable for an individual species, particular growth stage and crop load, and 2) relating the derived parameters to reference values of well-watered crops and normalising them for climatic conditions such as VPD, which is a measure of the humidity of air in relation to saturation. In the case of maximum daily shrinkage, equations to predict reference values from meteorological data are available for several woody crops.

![Graph showing trunk diameter fluctuations over two days](image)

**Figure 10-21.** Parameters that can be derived from trunk-diameter measurements, including maximum daily trunk contraction, and trunk growth expressed as daily differences in maximum and minimum daily trunk diameters (MXTD and MNTD, respectively) (Adapted from Goldhamer and Fereres, 2001)

### 10.13.5.3 Operational conditions

Absolute stem diameter variation (SDV) values, without consideration of evaporative demand, can be difficult to interpret. For that reason, SDV values are generally normalised with respect to those in non-limiting soil water conditions with the same evaporative demand, which is they are divided by values from well-watered plants. Other considerations when using this method are the number of replicate measurements required to account for a high between-plant variability and other biological stresses (e.g. diseases, nutritional issues) and abiotic stresses (e.g. high and low temperature) can affect SDV measurements. Normally, the scale of operation is implemented at field level within an orchard. In large orchards with high variability in crop water status, SDV measurements can be combined with aerial or satellite imaging.

### 10.13.5.4 Cost data

Online, a dendrometer can be bought for 475 €. But, lower cost alternatives are possible, for example, the BEI 9605 sensor is relatively inexpensive (21 €), in which case the total cost for an automatic dendrometer (point and band) will be below 34 € (see reference 9).
The additional costs of data loggers to collect and store data, climate stations and software to analyse data add to the cost.

New users require training and on-going assistance when commencing with this technology. Generally, it is recommended that growers contract the services of consultancy companies that offer sensor installation and data interpretation; data interpretation with dendrometers is challenging for inexperienced users. Some considerations regarding the use of dendrometers are care during installation and good protection of the sensor with insulating reflecting material to minimise heating and the effects of rain both of which can cause unacceptable noise. Unintended contact of the sensor by farm workers can also cause data errors. It is strongly recommended that experienced technicians conduct or assist with sensor installation and data interpretation for new users. The cost of these services adds to the overall cost.

10.13.5.5 Technological bottlenecks

Absolute SDV values must be normalised with respect to those in non-limiting soil water conditions at the same evaporative demand.

SDV data are influenced by climate, crop development stage, fruit load and other factors that must be considered when using them for irrigation scheduling (IS). This can limit their potential for automatic irrigation because of the requirement to consider other data and growers’ impressions of these factors when making irrigation scheduling decisions.

SDV data can be difficult to interpret when there are foggy, rainy, and overcast weather conditions and when there has been physical contact with the sensors or cables from farming activities, birds, insect etc. These effects can be reduced with the use of adequate sheltering of the sensors.

SDV derived indices such as maximum daily shrinkage and stem growth rate are affected not only by plant water status but by other factors such as crop nutritional stress, salinity etc. Care must be taken to ensure that no factors, other than crop water status, are influencing the dendrometer data.

In fast-growing plants such as vegetables or young trees, dendrometers may have to be repositioned several times during the growing season.

A limitation is a high variability between plants in the derived indices. Consequently, many replicated sensors are required.

10.13.5.6 Benefit for the grower

Advantages

- Reliable and robust
- Provides an integration of the crop’s response to both the soil water supply water and the atmospheric evaporative demand
- Automatic measuring
- Very early detection of crop water stress, even when the stress is mild
- Very suitable for trees

Disadvantages
• Difficult data interpretation and decision making
• Several other factors affect data apart from plant water status
• Normalisation of data required
• Correct installation is fundamental
• Need for calibration before use
• High variability between plants/trees

10.13.5.7 Supporting systems needed
Dendrometers require supplementary equipment for data collection, storage, and transmission, which are suitable for field operation. It is also recommended to have climatic data from the same crop as where the sensors are located; these climatic data help with data interpretation and implementation of irrigation protocols.

For untrained people with little knowledge of the technology, it is essential to contract the services of a specialised consulting service to instruct the user with installation, data management and particularly with data interpretation for irrigation scheduling.

10.13.5.8 Development phase
• Research: A large amount of research has been conducted in the last 15 years regarding the development of new sensors, data transmission systems and determination of the sensitivity of various SDV derived-indices to water stress for a range of species. Also, there has been appreciable research conducted during this period to develop Irrigation scheduling protocols based on SDV measurements
• Commercialised: There are several companies that produce different types of dendrometers. There are other companies that provide services in which dendrometers are used for Irrigation scheduling

10.13.5.9 Who provides the technology
Several companies provide services in which dendrometers are used for Irrigation scheduling. These include the French company Agro-Technologie (http://www.agrotechnologies.com/) that markets the Pepista system, the Spanish company Verdtech (http://www.verdtech.es/), the Israeli Phytech company (http://www.phytech.com/), and the Belgium company Phyto-sense (http://www.phytosense.net/forgrowers.html) which has developed automatic monitoring systems with several plant, soil, and climatic sensors, including dendrometers. These companies provide complete systems that provide continuous records of soil, plant and weather variables which are provided in a user-friendly format for early detection of water stress and more rational irrigation scheduling. These companies offer services and consultancy for the sale of sensors, sensor installation, calibration, and data interpretation. Some publicly-funded researchers are also involved in the development of companies (spin-off companies) such as the Spanish CEBAS research centre (of CSIC, the Spanish National Research Council) and the Laboratory of Plant Ecology of Ghent University, Belgium.

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10.13.5.10 Patented or not
Presumably, some of the technology is patented and the software used for data analysis is registered.

10.13.6. Which technologies are in competition with this one
This technology could be used instead of or in combination with other irrigation scheduling procedures such as the use of the water balance method, the use of soil moisture sensors (tensiometers, Watermark, capacitance sensors) or other plant monitoring approaches such as the use of infrared sensors.

10.13.7. Is the technology transferable to other crops/climates/cropping systems?
The technology is commercially in orchards of grapevines and fruit trees. In some cases, in Israel and Belgium dendrometers in combination with other sensors are being used in commercial applications for irrigation scheduling and climate control of greenhouse-grown crops.

10.13.8. Description of the regulatory bottlenecks
No regulatory bottlenecks at this level.

10.13.9. Brief description of the socio-economic bottlenecks
The main socio-economic bottlenecks are the costs of purchasing or renting sensors and associated equipment and of contracting the services of a consulting company to help with sensor installation, calibration, and data interpretation. Additionally, these sensors will be perceived as a high technology approach. The costs and perception of advanced technology will restrict their use to growers with an interest in high technology and with high-value crops for which sensitive information is required on crop water status.

10.13.10. Techniques resulting from this technology
1) Agro-Technologie (www.agro-technologie.com) manufactures Pepista 4000 that measures and evaluates automatically the demand for water in tree trunks, through a sensor fixed in the plant. The company has certification from INRA
2) The Spanish Verdtech (http://www.verdtech.es/) offers an automatic monitoring system with several plant, soil and climatic sensors including dendrometers for optimal irrigation scheduling
3) The Israeli Phytech (http://www.phytech.com/) offer an automatic monitoring system with several plant, soil and climatic sensors including dendrometers for optimal irrigation scheduling
4) The Belgium Phyto-sense (http://www.phytosense.net/forgrowers.html) offers automatic monitoring systems with several plant, soil and climatic sensors including dendrometers for optimal irrigation scheduling. Data interpretation is based on the use of crop models

10.13.11. References for more information

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Transfer of INNOvative techniques for sustainable WAter use in FERTigated crops


10.14. Leaf turgor sensor

(Authors: Sandra Millán, Carlos Campillo, Luis Bonet)

10.14.1. Used for
More efficient use of water.

10.14.2. Region
All regions, the most likely use is in the Mediterranean region

10.14.3. Crop(s) in which it is used
Fruit trees and olives, it could be used with vegetable crops

10.14.4. Cropping type
- Soil-bound
- Open air

10.14.5. Description of the technology

10.14.5.1 Purpose/aim of the technology
A leaf turgor sensor is used to assess the water status of the plant. In some cases, the readings can indicate when to irrigate.

10.14.5.2 Working Principle of operation
The leaf sensor technology indicates water deficit stress by measuring the turgor pressure of a leaf, which decreases dramatically at the onset of leaf dehydration. Early detection of impending water deficit stress in plants can be used as an input parameter for precision irrigation control. For example, a base system utilising the wirelessly transmitted information of several sensors appropriately distributed over various sectors of a round field irrigated by a centre-pivot irrigation system could tell the irrigation operator exactly when and which sector of the field needs to be irrigated.

The sensor measures the relative changes in the leaf’s turgor pressure. Turgor pressure is the pressure caused by fluid pushing against the cell wall of plant cells. It is needed to keep the plant’s rigid in order to stand straight and continue normal cellular functions. Turgor is related to the hydration status as cell and bulk leaf turgor pressure decline when leaves dehydrate during transpiration and in response to drought. As the stress level in the tree increases, the turgor potential of its leaves decreases.

10.14.5.3 Operational conditions
The probes show the relative changes in leaf hydration. If the more detailed information is needed, such as predicting absolute turgor pressure values, calibration would be needed. The volumetric elasticity of leaves is temperature dependent, but it is also dependent on the hydration of cell walls and cell turgor pressure.
10.14.5.4 Cost data
The prices of the components are:
Yara Water-Sensor = 290 €.
Transmitter (for connection of up to three 3 Yara Water-Sensors or microclimate sensors) = 535 €.
Base Station (including antennas and Installation Device; excl. SIM-card) = 2750 €.
User data centre (1 year) = 100 €.
The total cost will depend on how many probes are used on a farm. In a field of 20-30 ha, at least six are needed, which would involve a total cost of almost 6200 €.

10.14.5.5 Technological bottlenecks
The devices need frequent maintenance, relocation, and calibration (wind, leaf necrosis, quality of signal) and even then, a high variability of the measurements is possible. Additionally, thresholds are not always available.
Internet access is required for remote access to the data.
Under severe water stress conditions, the information given turgor sensor can be limited by an increase of air in the spongy mesophyll tissue of the leaf, which attenuates the pressure transfer through the leaf tissue.

10.14.5.6 Benefit for the grower
Advantages
- Sensitive sensor
- Versatile
- Non-destructive measurements
- Easy to handle sensor
- Results are immediately available
- Savings in energy and water consumption up to 20%
- Reductions in tree maintenance
- Boosts yield up to 15%

Disadvantages
- Close contact of the probe with the leaf surface is required for reliable measurements
- Unsuitable for plants showing isohydric behaviour
- User requires certain degree of expertise
- Advice required in the first phases, on the interpretation of the information

10.14.5.7 Supporting systems needed
Internet connection.
10.14.5.8 Development phase
Commercialised.

10.14.5.9 Who provides the technology
Yara.

10.14.5.10 Patented or not
Yes.

10.14.6. Which technologies are in competition with this one

10.14.7. Is the technology transferable to other crops/climates/cropping systems?
Many methods have been used previously to measure plant water use or water balance. One of the most standard techniques is the determination of leaf water potential using a pressure chamber. However, this method is destructive. Stomatal conductance and transpiration are commonly measured using porometry and gas exchange equipment and although these measurements can be carried out on intact leaves, they are disruptive and suffer from the same temporal and spatial resolution problems as leaf water potential measurements.

Thermal imaging using infrared technology to measure leaf and canopy temperatures, as a surrogate for stomatal conductance. While thermal imaging has obvious advantages in scaling from leaves to whole fields, turgor can provide the extra information needed to understand the effect of stomatal behaviour on plant adaptation and growth rate.

10.14.8. Description of the regulatory bottlenecks
Not applicable.

There are no socio-economic bottlenecks known at this time.

10.14.10. Techniques resulting from this technology
Magnetic patch-clamp pressure sensors serve to monitor the leaf hydration. These sensors enable application of water on demand which assists to optimise water use while maintaining production quality and quantity.
The technology of the leaf turgor sensors is that miniature pressure sensors are clamped to leaves via magnets. The magnets apply a constant clamp pressure to the leaf so that the pressure sensors detect relative changes in leaf turgidity.

Installation: An intact leaf is positioned between the two pads of the probe (diameter 10 mm), each of which is connected with magnets. The probe measures the pressure transfer exerted by the two magnets through the leaf patch. The leaf patch is assumed to be in hydraulic contact with the surrounding unclamped leaf tissue. The output pressure signal (i.e. the so-called patch pressure \(P_p\)) is sensed by a pressure sensor that is integrated into one of the pads. The clamp pressure \(P_{\text{clamp}}\) that is exerted by the two magnets onto the leaf patch can be adjusted to the rigidity of the leaf by varying the distance between the two magnets and is constant during the measurements. Essentially, leaf turgor opposes the clamp pressure and the pressure sensor detects changes in turgor by monitoring the change in pressure opposing the magnetic force (i.e. turgor). Therefore, \(P_p\) is inversely correlated with leaf turgor pressure, such that when the leaf dehydrates during stomatal opening and in response to water deficit \(P_p\) increases and conversely, decreases again when the leaf rehydrates.

Figure 10-23. The water sensor measures changes in the leaf turgor pressure in real time (Zimmermann et al. 2013)
10.14.11. References for more information


10.15. Pressure chamber for plant water potential measurement

(Authors: Henar Prieto*, Benjamin Gard*)

10.15.1. Used for
More efficient use of water.

10.15.2. Region
All EU regions.

10.15.3. Crop(s) in which it is used
All crops.

10.15.4. Cropping type
All cropping types.

10.15.5. Description of the technology

10.15.5.1 Purpose/aim of the technology
Pressure chambers are used to assess plant water status. The numeric value provided informs not only on the existence of a stress situation but also makes it possible to quantify the intensity of the stress.

10.15.5.2 Working Principle of operation
The principle behind the pressure chamber is simple. If you cut a cross-section of a twig or petiole, it reveals a central core of xylem transport vessels, through which nutrient-laden water goes up from the roots. Surrounding the xylem are the phloem transport vessels, through which sugars and carbohydrates travel down to the roots.

Water within the plant mainly moves through very small inter-connected cells, collectively called xylem, which is essentially a network of pipes carrying water from the roots to the leaves. The water in the xylem is under tension, pulled with a suction force as water evaporates from the leaves. As the soil dries or humidity, wind or heat load increases, it becomes increasingly difficult for the roots to keep pace with evaporation from the leaves. This causes the tension to increase. This tension can be measured; negative values are typically reported. An easy way to remember this is to think of water stress as a "deficit". The larger the stress, the more the plant is experiencing a deficit of water. The scientific name given to this deficit is the "water potential" of the plant.

The pressure chamber is just a device for applying air pressure to a leaf (or small shoot or any other plant portion), where most of the leaf is inside the chamber but a small part of the leaf stem (the petiole) is exposed to the outside of the chamber through a seal. The amount of pressure that it takes to cause water to appear at the cut surface of the petiole tells you how much tension the leaf is experiencing on its water: a high value of pressure means a high value of tension and a high degree of water stress. The unit of pressure most commonly used is Bar. (1 Bar = 14,5 PSI = 0,1 MPa)). The actual physics of how the water
moves from the leaf is more complex than just “squeezing” water out of a leaf, or just bringing water back to where it was when the leaf was cut. However, in practice, the only important factor is for the operator to recognise when water just begins to appear at the cut end of the petiole.

The basic elements of the equipment are, a closed chamber able to withstanding pressure, with a movable head where to place the sample (support by the petiole); an air source to generate pressure inside the chamber and a manometer where carry out the readings. A small twig is snipped, trimmed neatly, and then inserted into the lid of the pressure cylinder, which is filled with compressed air or nitrogen gas under pressure. A gauge registers the pressure under which water begins to flow up the xylem, revealing whether the plant needs water.

There are different models available, differing in the source of air for the pressure, that can be a tank with compressed nitrogen or a simple pumping system that makes the equipment lighter and portable (Figure 10-24). Others differences are related to the design of the instrument as a console or a briefcase or the characteristics of the different components.

![Diagram](https://www.pmsinstrument.com/)

Figure 10-24. Pump-up pressure chamber [https://www.pmsinstrument.com/]

10.15.5.3 Operational conditions

The precision of the measurements depends on the selected model, the most precise being the console type or briefcase. In the “pump-up” (pumping) type (Figure 10-25a), each stroke of the pump increases the pressure in the chamber by 0,5 bar, which is the limit of the precision of this instrument. Moreover, this instrument is limited to 20 bar. Therefore, in order to carry out measurements under conditions of very severe stress that require high precision, another instrument model (Figure 10-25b) is necessary. The use of pressure tanks increases the cost of the measurements and/or makes necessary an investment in infrastructure in addition to the risks to the operators associated with the manipulation of a source with high pressure. The second aspect in relation with the precision is the skill of the worker. Because the measurement depends on visual perception, there is an element of subjectivity. Therefore, trained operators improve the accuracy of the measurements.
10.15.5.4 Cost data

It is a portable system, so only a fixed installation is required to fill the pressure tanks (if this is the chosen option). The time of measurement depends on the number of leaves/plants measured and the size of the field/greenhouse being assessed. Each measurement takes about one minute; however, the time required to select the most appropriate plants and leaves also has to be considered. In large fields and when there is large variability between plants, the time required to obtain a representative measurement may become an issue.

The cost could be between 1500-6000 € depending on the model and the supplier.

Yearly maintenance or inputs needed to depend on the use, but are low. There is no fixed maintenance or input needed on a yearly basis.

10.15.5.5 Technological bottlenecks

In order to obtain useful information for decision support, it is necessary to have established the sampling procedure and have trained personnel, since the choice of the plant and the leaf (or other part of the plant) are important, as well as the time of day and the meteorological conditions at the moment of measurement. Otherwise, the data must be contrasted with appropriate reference values for the particular crop and sometimes also variety and phenological status. When relative humidity varies during the growing season, it may be necessary to make corrections taking into account the vapour pressure deficit.

10.15.5.6 Benefit for the grower

Advantages

- Enhances efficient use of water
- Valuable information about the crop water status
- Simple technique
- Portable meter

Disadvantages

- Time-consuming to set-up the sampling and measuring procedure
- Dedication of qualified staff time to carry out monitoring checks, interpret measures and take agronomic decisions

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• Need of reference values for the particular crop

10.15.5.7 Supporting systems needed
None.

10.15.5.8 Development phase
Commercialised.

10.15.5.9 Who provides the technology
Several manufacturing companies sell different models of pressure chambers.

10.15.5.10 Patented or not
Each company has developed its models, the technology is probably not patented, although some designs are likely to.

10.15.6. Which technologies are in competition with this one
There are several technologies that also pursue the same objective: to quantify the water status of the plant. Some of them measure indirectly the water potential in some parts of the plant but important differences exist between them. Canopy or plant temperature, stomatal conductance, trunk or fruit shrinkage, non-invasive leaf turgor sensor, sap flow, among others, are an example of such technologies.

10.15.7. Is the technology transferable to other crops/climates/cropping systems?
Yes.

10.15.8. Description of the regulatory bottlenecks
There are no relevant directives or regulatory bottlenecks at European, country or regional level.

10.15.9. Brief description of the socio-economic bottlenecks
The socio-economic bottlenecks refer to the training, set-up and time needed to start the instrument and the cost of the equipment. There is no information available on the specific economic improvements that can be derived from the use of this technology, making it difficult to assess the return on investment.

10.15.10. Techniques resulting from this technology
Deficit Irrigation Strategies for water saving, to increase water use efficiency and/or to improve crop quality (This technique allows to control the duration and intensity of the hydric stress supported by the plants).

10.15.11. References for more information
Transfer of INNOvative techniques for sustainable WAter use in FERTigated crops

10.16. Neutron probe

(Authors: Eleftheria Stavridou\textsuperscript{15}, Mike Davies\textsuperscript{15}, Carlos Campillo\textsuperscript{5}, Javier Carrasco\textsuperscript{5})

10.16.1. Used for

- Preparation of irrigation water
- More efficient use of water
- Minimising the impact to the environment by nutrient discharge

10.16.2. Region

All EU regions.

10.16.3. Crop(s) in which it is used

- Fruit
- Vegetables

10.16.4. Cropping type

- Soil-bound
- Protected
- Open air

10.16.5. Description of the technology

10.16.5.1 Purpose/aim of the technology

A neutron probe is used to determine the volumetric moisture content and the water content in a soil profile. It aids the grower to make irrigation decisions for the crop.

10.16.5.2 Working Principle of operation

The neutron probe consists of a radioactive source (pellet of americium and beryllium), producing fast neutrons, a slow neutron detector and a pulse counter. The neutron probe works by emitting fast neutrons into the surrounding soil, which collide with hydrogen atoms in the soil water, resulting in these neutrons to lose energy and slow down, the slow neutrons are detected by a slow neutron detector which is converted to a count rate. The greater the count rate, the greater the number of neutrons that have been slowed down and therefore the higher the soil moisture.

To measure soil moisture content, aluminium access tubes are inserted vertically into the soil via pre-augured holes, which have a slightly smaller diameter than the access tubes to avoid air gaps. The depth that the access tubes are inserted will depend on the depth of the soil and/or the rooting zone, but access tubes of 1,2 m depth are commonly installed but deeper or shallower tubes can be used. Each access tube needs a plug at the base to stop entry of water and a cap to place on the top to stop rainwater entering the tube.
Once the access tubes are installed in a crop, readings are taken in the same location throughout the life of the crop. To measure the soil moisture content, the neutron probe is positioned over the access tube and the probe is lowered to the first required depth, the count detector is activated and the neutron “count” is displayed. The time for each measurement can be set by the user, commonly 16 seconds is used to give reasonably accurate results, although for greater accuracy a larger time interval can be used. These readings need to be calibrated against samples of soils with known moisture contents to enable the count rate to be converted to soil moisture content. To convert readings to volumetric water content a calibration curve for each soil type is applied. The probe is then lowered further into the access tube for readings at subsequent depths. The depths that measures are taken are determined by the user but commonly readings are taken every 10 - 20 cm. The measurements at each depth are used to determine the total water content of the soil over the measured depth and to determine from which depths of soil the crops are extracting water and ultimately the water deficit from field capacity can be calculated.

Crop daily water use can be estimated. The water deficit (in mm) from soil field capacity can be determined and the amount of irrigation needed to be applied to bring the soil back to field capacity or a specific deficit can be calculated.

A measurement is required when the soil is at field capacity (e.g. in the UK, towards the end of the winter, is a good time provided there has been adequate rainfall) to enable a deficit to be calculated.

10.16.5.3 Operational conditions

Requires the use of a radioactive source.

Only licensed operators, who comply with the rules and regulations for use, transport and storage of the radioactive source can use the equipment.

Neutron meters require little maintenance beyond checking to ensure proper operation. Access tubes should be checked for water or foreign materials in them. The most common failure is a broken or worn cable, which connects the source tube to the electronic readout device. A repaired instrument may also require recalibration. Operator recertification is required every two years.

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10.16.5.4 Cost data
Device 10755 €, training and documentation development 2440 €, signs 200 €, radiation monitors 400 € or more per bunker, according to the construction company.
Yearly maintenance; national taxes 2500 €, 900 € medical examinations to check radiation levels.
Installation of the access tubes.
Measurements carried out and data interpreted on at least a weekly basis through the growing season, usually by specialist irrigation advisors.

10.16.5.5 Technological bottlenecks
Probes cannot be left in-situ to measure continuously, therefore data cannot be logged.
Cannot be used in an automatic irrigation system.
Accurate readings in the top 10-15 cm of soil are more challenging to obtain as some neutrons leave the soil at the soil/air interface. Soil-specific calibration at 10 cm may improve the accuracy.
Only licensed operators can use this device, usually, it is provided by irrigation consultants who provide the neutron probe technology.

10.16.5.6 Benefit for the grower
**Advantages**
- Increases water and nutrient use efficiency
- Easy data interpretation
- Total soil water content can be calculated along with the water deficit
- Daily/weekly crop water use can be calculated
- Volumetric moisture content and the changes over time at different depths can be determined
- Accurate readings, soil surface measured is relatively large. The greatest in relation to others soil moisture sensor

**Disadvantages**
- Expensive
- Limited use
- Need of a license for use of radioactive substances
- Data from a couple of neutron probe readings per week are not sufficient to optimise water use efficiency
- Data are not instantaneously available.
- Accuracy in top 10-15 cm of the soil profile is difficult
- The neutron probe cannot measure reliably irrigation and rainfall input, with or without a field-specific calibration on temperate climates, which has major implication on irrigation scheduling

10.16.5.7 Supporting systems needed
None.

10.16.5.8 Development phase
Commercialised.

10.16.5.9 Who provides the technology
Neutron probe devices provided by e.g. CPN (a Instro Tek company) providing rh 503 Elite Hydroprobe; Troxler who provide the Troxler moisture monitoring gauges. Irrigation consultants are often the ones to provide a service to growers (e.g. in UK 0 Agri-tech services the UK provide a Neutron probe service).

10.16.5.10 Patented or not
Not known.

10.16.6. Which technologies are in competition with this one
Various soil water sensors, profile probes, matric potential sensors.

10.16.7. Is the technology transferable to other crops/climates/cropping systems?
Yes.

10.16.8. Description of the regulatory bottlenecks
Various legislation governing the use, transport, and storage of radioactive substances e.g. The Ionising Radiation Regulations 1999 (abbreviated IRR99), European Agreement Concerning the Carriage of Dangerous Goods by Road 2009 (ADR).

10.16.9. Brief description of the socio-economic bottlenecks
Expensive technique and the need to be licensed for use of radioactive substances with, transporting and storage of radioactive material to use make it economically less interesting for growers. Risk of exposure to the radioactive source, requires film badge monitoring to detect any exposure to the operator are social bottlenecks.

10.16.10. Techniques resulting from this technology
None

10.16.11. References for more information
10.17. *Combined water, EC and temperature sensor*  
*Authors: Eleftheria Stavridou\(^{15}\), Mike Davies\(^{15}\), Carlos Campillo\(^{5}\)*

10.17.1. **Used for**
More efficient use of water.

10.17.2. **Region**
- Nordic
- North-West Europe
- Mediterranean

10.17.3. **Crop(s) in which it is used**
- Soft fruit
- Vegetables

10.17.4. **Cropping type**
All cropping types.

10.17.5. **Description of the technology**

10.17.5.1 **Purpose/aim of the technology**
The combined sensor is used to measure three of the most important indications of root zone health:

- Water content (%)  
- Pore water conductivity (\(\text{EC}_p\)), which is the EC of the water available to plant roots  
- Temperature (\(^\circ\)C)

This sensor is particularly useful in horticulture for monitoring and correcting variation when applying fertigation, control released fertilisers or organic treatments.

10.17.5.2 **Working Principle of operation**
The WET sensor of Delta-T Devices uses three pins to maintain an electromagnetic field at a frequency of 20 MHz. Like other capacitance sensors, the combined sensor measures changes in the electromagnetic field, which are related to the dielectric constant. The raw measurements taken are soil permittivity, conductivity, and temperature, and these are converted to soil water content and bulk EC using calibration tables. The sensor pins are 7 cm long and, with a measurement radius of 2 cm, this gives a measurement volume of about 220 \(\text{cm}^3\).

Generalised calibrations are provided for most common soil types and specialised calibrations are available as separate cost options for several artificial substrates.

The pore water conductivity calculation is based on a unique formula that minimises the effects of probe contact and soil moisture on the readings. Temperature is measured using a miniature sensor built into the central rod.
The combined sensor is designed to be used with the HH2 Moisture Meter, but can also be interfaced to control systems for fertigation control.

Figure 10-27. WET sensor used to take measurements on rockwool and soil in open air (https://www.delta-t.co.uk)

10.17.5.3 Operational conditions
The combined sensor was originally designed to be used in soil, where normally the EC is lower than 2 dS/m. In horticultural growing media, however, the EC may be as high as 10 dS/m. Delta-T Devices Ltd. supplies extended calibration curves up to 5 dS/m. In high-saline soils, the accuracy of the standard WET is not warranted.

10.17.5.4 Cost data
The combined sensor probe costs about 1200 € and handheld meter 620 €. The sensor can be connected to a logger for continuous measurement such GP1 or GP2 data loggers which cost 840-1400 €
You need approximately 30 seconds to take each measurement; there is no financial cost apart from that of the time and sensor doesn’t need any maintenance.

10.17.5.5 Technological bottlenecks
- The relatively low oscillation frequency in the combined sensor (20 MHz) makes the measurements much too dependent on soil salinity and therefore, impairs the estimations of θ, and thus ECp
- Only one sensor can be practically handled per handheld reader
- Each sensor must be calibrated
- Calibration tables do not exist for mixtures of media and measurements are not accurate in such situations
- Careful application of probe in stony soils
- Underestimating of permittivity in media with low permittivity (ε > 40, clay and organic soils)
- Inaccurate values in saturated media

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10.17.5.6 Benefit for the grower

Advantages

- Water and fertiliser savings
- Rapid measurements (~5 seconds) of all 3 parameters
- Easy use and data interpretation
- Calibrations available for many soils and growing media (peat, coir, mineral wool)
- Lightweight ergonomic design, rugged

Disadvantages

- High cost
- Automatic logging of the sensor needs a high level of electronic knowledge

10.17.5.7 Supporting systems needed

HH2 meter for handheld measurements or GP2 data loggers for continuous recording.

10.17.5.8 Development phase

Commercialised.

10.17.5.9 Who provides the technology

Several companies sell these sensors, among others WET sensors (see 10.20.6).

10.17.5.10 Patented or not

This technology is patented.

10.17.6. Which technologies are in competition with this one

Alternative approaches to combined sensors are various soil/substrate water monitoring sensors. These are TDR, neutron probe, water potential sensor etc. (see relevant TDs).

10.17.7. Is the technology transferable to other crops/climates/cropping systems?

The combined sensor can be used in various crops, climates, different cropping systems, such as crops in soil or substrate and crops in the open field or in greenhouses. However, for each application, it is necessary to calibrate the sensor for the substrate that is being used.

10.17.8. Description of the regulatory bottlenecks

There are no relevant European directives or regulatory bottlenecks at European, country or regional level.

10.17.9. Brief description of the socio-economic bottlenecks

- When using a manual device, the time required to take the samples should be accounted for
- The costs associated with buying the equipment
10.17.10. Techniques resulting from this technology

- Grodan B.V. has modified the original design of the WET sensor and calibrates their WCM up to 10 dS m$^{-1}$ for use on stone wool production systems. The WCM control (a handheld meter) the WCM Continu (connected to a climate control computer) and the GroSens were developed especially for measuring the water content, the conductivity and the temperature in stone wool substrates used in greenhouse production.
- 5TE (Decagon Devices Inc.)
- Hydraprobe (Stevens Inc.)

10.17.11. References for more information

10.18. Auger method

(Authors: Claire Goillon\textsuperscript{2}, Carlos Campillo\textsuperscript{5}, Rodney Thompson\textsuperscript{23}, Benjamin Gard*)

10.18.1. Used for
More efficient use of water.

10.18.2. Region
All EU regions.

10.18.3. Crop(s) in which it is used
All vegetable and fruit crops.

10.18.4. Cropping type
- Soil-bound
- Protected
- Open air

10.18.5. Description of the technology

10.18.5.1 Purpose/aim of the technology
Sampling with an auger enables the soil to be sampled at different locations and different depths to assess soil type and to estimate soil moisture. With this method, it is possible to estimate water retention properties of the soil and soil available water capacity (AWC). The estimation is empirically based on the appearance and feel of the soil.

10.18.5.2 Working Principle of operation

Soil samples are taken with a metallic auger at several depths and locations of the field. Depth depends on the crop’s root zone but, generally, samples are taken between 10 and 40 cm. At least 15-20 soil samples for 1 ha are needed to have an accurate view of the soil moisture. It is important to select plots representative of the field. Choose a homogeneous area and avoid the areas adjacent to the field, areas compacted by passages of tractor and agricultural machinery, low points and mounds.

The soil sample taken with the auger is then analysed according to the feel and appearance. With practice, this method can provide a good indication of the moisture content that can assist in irrigation management decisions.
Transfer of INNOvative techniques for sustainable WAter use in FERtigated crops

Table 10-2. Guidelines for estimating soil texture and approximate percentage of the available water capacity of soil samples, by the feel of the sample during manual manipulation.

<table>
<thead>
<tr>
<th>Soil appearance</th>
<th>Coarse</th>
<th>Moderately Coarse</th>
<th>Medium</th>
<th>Moderately Fine and Fine</th>
<th>% of Available Water Capacity (AWC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Free water appears when the soil is bounced in hand</td>
<td>Free water is released by kneading</td>
<td>Free water can be squeezed out</td>
<td>Puddles and free water forms on the surface</td>
<td>Exceeds field capacity – runoff &amp; deep percolation</td>
<td></td>
</tr>
<tr>
<td>Upon squeezing, no free water appears on soil, but wet outline of ball is left on hand</td>
<td>Tends to stick together, forms a weak crumbly ball under pressure</td>
<td>Forms a weak ball that breaks easily; does not stick</td>
<td>Forms a ball and is very pliable; sticks readily if relatively high in clay</td>
<td>Ribbons out between thumb and finger; has a slick feeling</td>
<td></td>
</tr>
<tr>
<td>100% – At field capacity</td>
<td>70-80% of AWC</td>
<td>25-50% of AWC</td>
<td>0-25% of AWC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dry, loose, single-grained flow through fingers</td>
<td>Dry, loose, flows through fingers</td>
<td>Powdery dry, sometimes slightly crusted but easily breaks down into powder</td>
<td>Hard, baked, cracked; sometimes has loose crumbs on the surface</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

10.18.5.3 Operational conditions
In some soil types, the extraction of soil can be difficult, for instance when the soil contains a lot of stones or when the soil is packed.

10.18.5.4 Cost data
- For installation: Augers are inexpensive tools; the price ranges at 50-100 €, for a manual auger. Besides, it can be easily handmade for a price below 30 €. The part of the auger used for soil sampling must be round to penetrate easily in the soil. For soils with a high percentage of stones, it is possible to use mechanical augers, but prices rise from 150-250 €
- Yearly maintenance or inputs needed: None, the auger is a very resistant tool

10.18.5.5 Technological bottlenecks
There is no technological bottleneck. The auger method does not need any complex device. The grower just has to think to take its auger when he goes to the field. It is often forgotten.
10.18.5.6 Benefit for the grower

Advantages
Easy, cheap.

Disadvantages
Not automatic, it takes time and you need to be familiar with soil appearance and feeling method.

10.18.5.7 Supporting systems needed
None.

10.18.5.8 Development phase
Commercialised.

10.18.5.9 Who provides the technology
Retailers or handmade.

10.18.5.10 Patented or not
Not patented.

10.18.6. Which technologies are in competition with this one
All the method for measuring soil moisture (tensiometer, capacitance probe, etc.).

10.18.7. Is the technology transferable to other crops/climates/cropping systems?
Yes, except soilless crops.

10.18.8. Description of the regulatory bottlenecks
There are no regulatory bottlenecks.

10.18.9. Brief description of the socio-economic bottlenecks
None.

10.18.10. Techniques resulting from this technology
None.

10.18.11. References for more information

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10.19. Wetting Front Detector

(Authors: Juan José Magán, Benjamin Gard*)

10.19.1. Used for
More efficient use of water.

10.19.2. Region
Mediterranean.

10.19.3. Crop(s) in which it is used
Vegetables.

10.19.4. Cropping type
- Soil-bound
- Protected
- Open air

10.19.5. Description of the technology

10.19.5.1 Purpose/aim of the technology
The Wetting Front Detector is a type of equipment that can help growers with irrigation scheduling in soil crops by detecting if watering is insufficient or excessive, as well as the presence of waterlogging. Furthermore, it can be used for assisting in the management of fertilisers and salts.

10.19.5.2 Working Principle of operation
Knowing the position of the wetting front is useful information to improve irrigation management. This equipment is a buried funnel-shaped container (Figure 10-29) able to detect the position of the wetting front in the soil. When the wetting front reaches the device, the unsaturated flow lines converge towards the base of the funnel, where soil water content reaches saturation and free water appears. This water flows through filtered sand and accumulates in a small reservoir, activating a float which raises a visual indicator placed at the top of the tube emerging from the soil when the wetting front has reached a certain depth of soil. The indicator float rises when 20 mL of water has been collected. If the float is up, then a wetting front passed the buried funnel but if the float is down, then not enough water was applied to produce a wetting front which the equipment could detect. When the soil around it is drier than the soil inside the funnel, the first will act as a “wick” to draw the water out of the funnel after irrigation end. An indicator allows the grower to detect the activation of the device at any moment, so it is not compulsory to visit it just after irrigation. However, if the indicator has popped up, it needs to be reset before the next irrigation. If the indicator immediately pops up again it means that the soil around the device is still very wet (http://www.fullstop.com.au/).

It is possible to extract the water accumulated with a syringe via a 4 mm flexible pipe which connects the reservoir to the soil surface. This water can be analysed to determine salt or...
nutrient concentration. The solution obtained contains the ions which are moving from one soil horizon to another.

![Diagram](image)

**Figure 10-29. Schemes (indicating components and dimensions) and picture of a FullStop before being installed (from [http://www.fullstop.com.au/](http://www.fullstop.com.au/))**

### 10.19.5.3 Operational conditions

The manufacturer recommends installing the wetting front detectors in pairs so that one of them is buried about one-third of the way down the active root-zone and the other about two thirds.

The optimum depth of placement depends on the irrigation method and the frequency of irrigation, as well as the type of crop and soil. A guide given by the manufacturer is shown in Table 10-3 but these recommendations must be adjusted for local conditions and management styles. Placement depths are measured from the soil surface to the locking ring (0 cm level in Figure 10-29).

The different situations of activation of the wetting front detectors are shown in Figure 10-30. If neither indicator is triggered (left), then watering is generally too shallow. If the higher indicator is triggered and the lower is down (centre), then water has moved past the shallow detector to the lower part of the root zone; this is usually the best situation. Finally, if both indicators are triggered (right), then the wetting front is at the low part or under the root-zone. However, if this happens frequently, irrigation can be excessive. Some additional details about this are shown in Table 10-4.
Table 10-3. FullStop installation depths recommended by the manufacturer based on the irrigation system used (http://www.fullstop.com.au/)

<table>
<thead>
<tr>
<th>Type of irrigation</th>
<th>Notes</th>
<th>Shallow detector (cm)</th>
<th>Deep detector (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drip</td>
<td>Amount applied per dripper usually less than 6 litres at one time (e.g. row crops, pulsing)</td>
<td>30</td>
<td>45</td>
</tr>
<tr>
<td>Drip</td>
<td>Amount applied per dripper usually more than 6 litres at one time (perennial crops)</td>
<td>30</td>
<td>50</td>
</tr>
<tr>
<td>Sprinkler</td>
<td>Irrigation is usually less than 20 mm at one time (e.g. centre pivot, micro-jets)</td>
<td>15</td>
<td>30</td>
</tr>
<tr>
<td>Sprinkler</td>
<td>Irrigation is usually more than 20 mm at one time (e.g. sprinklers and draglines)</td>
<td>20</td>
<td>30</td>
</tr>
<tr>
<td>Flood</td>
<td>Deeper placements than shown needed for infrequent irrigations or very long furrow</td>
<td>20</td>
<td>40</td>
</tr>
</tbody>
</table>

Figure 10-30. Different situations of activation of the wetting front detectors after watering (from http://www.fullstop.com.au/)

On the other hand, the system can detect waterlogging. Since the vertical distance from the base of the funnel to the rim is greater than 20 cm, a suction greater than 20 cm (> 2 kPa) will be needed to wick the water out. When the soil dries beyond 2 kPa suction, the soil outside can start withdrawing water from the funnel. The time it takes to empty the funnel depends on the soil type and amount of water in the funnel. If the indicator cannot be reset for several days, the soil is waterlogged.

The solution obtained can be analysed in order to assist in nutrient management but it is necessary to take into account that this device collects freely draining soil solution whereas a suction cup can sample soil solution from soil pores with longer residence times, especially under unsaturated flow conditions, and might represent better the available element.

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concentrations for plant nutrition studies. In a study carried out in Almería (Spain), Cabrera et al. (2016) found the same average relationship between the electric conductivity (EC) obtained from 0.25 m depth funnels and that measured from suction cups (81%) in two different tomato growing cycles. Furthermore, the relationship corresponding to sodium and chloride concentration was around 85% in both crops and that corresponding to calcium and magnesium was around 73 and 77% respectively. However, the relationship between nitrate and potassium was more variable, what makes this system non recommendable for nutrient monitoring.

Table 10-4. Recommendations for different situations of device activation (http://www.fullstop.com.au/)

<table>
<thead>
<tr>
<th>Shallow detector</th>
<th>Deep detector</th>
<th>What it means</th>
<th>What you should do</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Shallow detector" /></td>
<td><img src="image2.png" alt="Deep detector" /></td>
<td>Not enough water for established crops</td>
<td>Satisfactory for young crops or after fertigation when it is important to eliminate leaching. Apply more water to established crops at each irrigation or shorten the interval between two irrigations.</td>
</tr>
<tr>
<td><img src="image3.png" alt="Deep detector" /></td>
<td><img src="image2.png" alt="Deep detector" /></td>
<td>The wetting front has penetrated into the lower part of the root zone</td>
<td>Mostly, this is the desired result. However, during hot weather or when the crop is at a sensitive growth stage irrigation should be increased. The deep detector should respond from time to time, showing that the entire root zone is wet.</td>
</tr>
<tr>
<td><img src="image3.png" alt="Deep detector" /></td>
<td><img src="image2.png" alt="Deep detector" /></td>
<td>The wetting front has moved toward the bottom or below the root zone</td>
<td>Both detectors should respond when irrigating to satisfy the high demand for water. However, if this happens on a regular basis, particularly in the case of sprinkler irrigation, over-watering is likely. Reduce irrigation amounts or increase the time interval between irrigations.</td>
</tr>
<tr>
<td><img src="image1.png" alt="Shallow detector" /></td>
<td><img src="image2.png" alt="Deep detector" /></td>
<td>Soil or irrigation is not uniform or the soil surface is uneven</td>
<td>Ensure the soil level is over the detectors and water is not running towards or away from the installation site. Check uniformity of irrigation or location of drippers.</td>
</tr>
</tbody>
</table>

10.19.5.4 Cost data

Installation time is around 1-2 hours/unit. The cost of a couple of detectors is 150 €.

It is convenient to check the activation of the system after each irrigation for a better adjustment of watering.

The device has to be removed at the end of the growing season if the soil is going to be ploughed but it can be maintained in the soil between crops in the opposite case.
Nevertheless, it is convenient to remove the tube emerging from the soil for avoiding its deterioration by sun radiation or an accidental breakage and to cap the hole of coupling for avoiding soil entrance to the device.

10.19.5.5 Technological bottlenecks
The installation of the device is critical for a good functioning. It is better to do it when the soil is dry by avoiding excessive compacting, which can impede water to enter into the funnel. In drip irrigation, the dripper must be placed above the rim of the funnel.

10.19.5.6 Benefit for the grower

Advantages
- Very simple and intuitive system. It can be suitable for farmers without experience with sensors
- Low initial investment
- Low maintenance costs
- Technology readily available

Disadvantages
- It does not give numerical information about the water status of the soil
- It is necessary to spend time for device checking after irrigation
- The installation of the device can be a quite hard work
- The soil inside the device is more humid than the rest
- There are sometimes problems to recover water
- The solution recovered is not soil solution but drainage, which are not the same

10.19.5.7 Supporting systems needed
None.

10.19.5.8 Development phase
Commercialised.

10.19.5.9 Who provides the technology
FullStop is a technology developed and owned by the company CSIRO Land and Water.

10.19.5.10 Patented or not
Yes.

10.19.6. Which technologies are in competition with this one
- Sensors measuring water status of the soil (tensiometers, capacitance sensors)
- Lysimeters
- Suction cups
10.19.7. Is the technology transferable to other crops/climates/cropping systems?
Yes, this technology may be used in any crop grown in soil.

10.19.8. Description of the regulatory bottlenecks
None.

10.19.9. Brief description of the socio-economic bottlenecks
A problem with this technology is that the grower can feel tired of checking the activation of the device.

10.19.10. Techniques resulting from this technology (add as many needed)
In Almería (Spain) some growers have eliminated the magnets of the device in order to estimate how much water is accumulated in the deposit, based on the height reached by the visual indicator. Moreover, in this way, the grower does not have to take down the indicator after water re-absorption. On the other hand, in Almería greenhouses, the installation depth is generally lower than usual for drip irrigation because the sand mulching typically used (“enarenado”) induces the development of a more superficial root system. Furthermore, there is frequently a layer of supplied soil (cultivable layer) of only 30 cm on the original soil (usually too rocky).

10.19.11. References for more information
10.20. Tensiometer
(Authors: Claire Goillon\textsuperscript{2}, Carlos Campillo\textsuperscript{5}, María Dolores Fernández\textsuperscript{9}, Benjamin Gard*)

10.20.1. Used for
More efficient use of water.

10.20.2. Region
All EU regions.

10.20.3. Crop(s) in which it is used
Tensiometers are used in a large variety of fruit and vegetable crops.

10.20.4. Cropping type
- Soil-bound
- Protected
- Open air

10.20.5. Description of the technology

10.20.5.1 Purpose/aim of the technology
The purpose of a tensiometer is to directly measure the soil water matric potential, the force that root systems must develop to extract water from the soil. This is a reliable measure of the water availability for the plants.

10.20.5.2 Working Principle of operation
A tensiometer is a sealed water-filled tube with a porous ceramic cup in contact with soil in one extremity (Figure 10-31). Water in the tube is equilibrated with the soil solution. When plants and environment remove water from the soil, water is drawn from the ceramic cup, creating a depression in the tube. This depression can be measured with a manometer or a pressure gauge linked to a data logger. It is directly linked to the soil water matric potential (SMP) and expressed in centibar (cbar) or kPa.

Figure 10-31. Description of the parts of a tensiometer
(https://wiki.metropolia.fi/display/sensor/Soil+moisture+sensors)

10.20.5.3 Operational conditions

Soil tensiometers provide a measure of the soil water matrix tension from 0 to 85 cbar. Tensiometers measure the water tension at one point of the agricultural parcel (few centimetres around the porous probe). Several tensiometers must be located, at different soil depth (e.g. 20, 40 and 60 cm) and repeated in different locations, to have a good measure of water availability in the soil. For managing irrigation, the location of the tensiometers must consider the soil heterogeneity. Generally, SMP provides a useful measure of the availability of soil water to plants. Irrigation management with tensiometers is based on irrigating when the soil water matric tension reaches a lower limit (drier value) or threshold value. Thresholds are available for vegetable crops in open field and greenhouse (Table 10-5). These limits vary with crop species, crop developmental stage, soil texture and the evaporative conditions.

Table 10-5. Thresholds values of soil water matric potential (in cbar) for vegetable crops in open field and greenhouse (Thompson et al., 2007)

<table>
<thead>
<tr>
<th>Crop</th>
<th>Open field</th>
<th>Greenhouse¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pepper</td>
<td>40-50</td>
<td>58</td>
</tr>
<tr>
<td>Melon</td>
<td>30-40</td>
<td>35</td>
</tr>
<tr>
<td>Tomato</td>
<td>40-60</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td></td>
<td>40 (under low evaporative conditions: ETo ≈ 0,8 mm/day)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>40 (under higher evaporative conditions: ETo ≈ 2-3 mm/day)</td>
</tr>
</tbody>
</table>

10.20.5.4 Cost data

For installation: for 6 tensiometers with
- manual data collection 300-400 €
- automated data collection 600-1000€
- automated data collection and remote data transmission 1400-3000 €

yearly maintenance or inputs needed: weekly or daily maintenance is needed to check the water level in the tube, to check good contact between soil and the porous cup and to maintain water within the water column free of dissolved air.

10.20.5.5 Technological bottlenecks

Tensiometers are sustainable tools and need to be removed after use. When the ceramic tip is immersed in water, it could indicate 0 cbar (saturation) but after several installations, a derive is notified and tensiometers have to be changed. The electric connections often break or the data logger becomes deficient and a new investment is necessary. There is a risk of water discharge in not high frequently irrigated crops when the evaporative demand is high. Consequently, it is not a useful tool to manage irrigation if crop water requirements are not covered (e.g. application of deficit irrigation to favour crop rooting or the reproductive development of the crop, to increase the fruit sugar content, etc.).
10.20.5.6 Benefit for the grower

**Advantages**
- Good price-quality
- Continuous measurements
- Remote data transmission available
- Thresholds for irrigation triggering for numerous crops and types of soil
- Easy to install

**Disadvantages**
- Require preparation in order to work effectively
- Maintenance required
- Can break during installation and crop cultural practices

10.20.5.7 Supporting systems needed
Advice from suppliers or extension services may help growers to better use the technology, and to know the threshold values for crops. Data logging and remote transmission can facilitate the use of the tensiometer, if compatible with computer systems.

10.20.5.8 Development phase
Commercialised.

10.20.5.9 Who provides the technology
Several suppliers.

10.20.5.10 Patented or not
Not patented.

10.20.6. Which technologies are in competition with this one
Granular matrix sensors, capacitive probe, Gypsum blocks.

10.20.7. Is the technology transferable to other crops/climates/cropping systems?
Yes, the technology is easily transferable.

10.20.8. Description of the regulatory bottlenecks
None.

10.20.9. Brief description of the socio-economic bottlenecks
Knowledge of the technology and costs and lack of advice for a good use may be the main socio-economic bottlenecks. Further, the constraint of measuring in the case of systems without a data logger can be a bottleneck.

10.20.10. Techniques resulting from this technology
Irrigation scheduling.

10.20.11. References for more information


10.21. Granular Matrix Sensors
(Authors: Rafael Granell\textsuperscript{14}, Luis Bonet\textsuperscript{14}, Mike Davies\textsuperscript{15}, Eleftheria Stavridou\textsuperscript{15})

10.21.1. Used for
- More efficient use of water
- Minimising the impact to the environment by nutrient discharge

10.21.2. Region
Mediterranean.

10.21.3. Crop(s) in which it is used
- Woody crops
- Annual crops

10.21.4. Cropping type
All cropping types.

10.21.5. Description of the technology

10.21.5.1 Purpose/aim of the technology
A granular matrix sensor (GMS) provides information on the amount of water to apply to an orchard during a certain period.

10.21.5.2 Working Principle of operation
Granular matrix sensor technology reduces the problems inherent in gypsum blocks (i.e. loss of contact with the soil by dissolving, and inconsistent pore size distribution) by use of a granular matrix confined in a metal case. Granular matrix sensors operate on the same electrical resistance principle as gypsum blocks and contain a wafer of gypsum embedded in the granular matrix. The electrodes inside the GMS are embedded in the granular fill

Figure 10-32. Watermark sensor (http://cropwatch.unl.edu/measuring-soil-water-status-using-watermark-sensors)
material above the gypsum wafer. The gypsum wafer slowly dissolves, to buffer the effect of salinity of the soil solution on electrical resistance between the electrodes.

GMS is similar to tensiometers as they are made of a porous material that reaches equilibrium with the soil moisture. The electrical resistance between electrodes embedded in a porous medium is proportional to its water content, which is related to the soil water matric potential of the surrounding soil. Electrical resistance increases as the soil and the block lose water.

### 10.21.5.3 Operational conditions

Proper preparation and installation of the GMS are vital to their operation. Sensors should be soaked overnight and installed wet. If time permits, condition the sensor with multiple wet/dry cycles: soak the sensor in irrigation water overnight, allow it to air dry for a day or two, then re-soak overnight. To install the sensor, an access hole should be made to the desired depth using a length of ½ or ¾” PVC pipe. Fill the access hole with water, then seat the sensor firmly in the bottom of the access hole using the PVC pipe. Fill the hole with soil again and tamp firmly, but avoid compacting the soil.

Suitable for dry soil conditions or clay soils, where usually soil matric potential is high. The GMS is convenient for sensing soil water potential to automatically start an irrigation because they do not require periodic maintenance during the growing season. The GMS have limitations in reading soil water potential in soils wetter than -10 cbar and in responding in coarse-textured soils.

Regarding the thresholds and reference values for irrigation, it depends on the type of crop, the type of soil (textures and structure) and even irrigation system, so that the following values could be taken as a general reference guideline:

- 0-10 cbar = Saturated soil (field capacity)
- 10-20 cbar = Soil is adequately wet (except coarse sands, which are beginning to lose water)
- 30-60 cbar = Usual range for irrigation (except heavy clay soils)
- 60-100 cbar = Usual range for irrigation in heavy clay soils
- 100-200 cbar = Soil is becoming dangerously dry for maximum production.

In commercial applications of these sensors, the simplest procedure is based on determining the relative values of field capacity from a saturation episode, like a heavy rain. With these values and taking into account the trends in soil moisture content during the previous 4-5 days, appropriate irrigation schedules are established.

### 10.21.5.4 Cost data

Granular matrix sensors have advantages of low unit cost and simple installation procedures, similar to those used for tensiometers. Annual costs are 40-200 €, depending on the company and the uploading frequency.

### 10.21.5.5 Technological bottlenecks

Variability, correct installation, interpretation of information, easy-to-use software, the relatively short life of sensors.

10.21.5.6 Benefit for the grower

Advantages

- Water/Fertiliser savings
- Low cost of equipment
- Very little preparation required
- Easy maintenance
- Intuitive information provided

Disadvantages

- Installation and interpretation help needed in many cases
- The short life of sensors
- Relative slowness in their response to soil moisture changes

10.21.5.7 Supporting systems needed

Technical assessment during the first periods of use.

10.21.5.8 Development phase

Commercialised.

10.21.5.9 Who provides the technology

Irrometer.

10.21.5.10 Patented or not

A Granular matrix sensor for electronically measuring soil water has been patented (Larson, 1985: Hawkins, 1993) and is marketed as the Watermark soil moisture sensor (Irrometer Co., Riverside, CA).

10.21.6. Which technologies are in competition with this one

Plant Sensors, Remote sensing, Soil moisture sensors.

10.21.7. Is the technology transferable to other crops/climates/cropping systems?

Yes.

10.21.8. Description of the regulatory bottlenecks

None.

10.21.9. Brief description of the socio-economic bottlenecks

Saving water is still not an encouragement for farmers in many places of Spain. Orchards are economically too small to cover the costs of the sensors.

10.21.10. Techniques resulting from this technology

Most irrigation strategies can be complemented and controlled by using these devices, such as Controlled Deficit Irrigation, Partial Root Drying, etc.
10.21.11. References for more information

[1] Chard, J. (2002). Watermark soil moisture sensors: characteristics and operating instructions, Utah State University


10.22. Time Domain Reflectometry
(Author: Luis Bonet, Dolors Roca, María Dolores Fernández)

10.22.1. Used for
- More efficient use of water
- Minimising the impact to the environment by nutrient discharge

10.22.2. Region
Mediterranean.

10.22.3. Crop(s) in which it is used
- Woody crops
- Annual crops

10.22.4. Cropping type
All soil-bound cropping types.

10.22.5. Description of the technology

10.22.5.1 Purpose/aim of the technology
To provide information about soil water content, which can then be used for determining the amount of water to be applied to an irrigated crop during a certain period.

10.22.5.2 Working Principle of operation
Time domain reflectometry technique is based on the measurement of the displacement time of an electromagnetic wave through a transmission line. The velocity of the wave depends on the dielectric permittivity ($\varepsilon_a$) of the material in contact and surrounding the line, that parameter being proportional to the square of the transit time out and back along the transmission line. The soil is composed of air, minerals, organic matter, and water. $\varepsilon_a$ of these materials widely varies from 1 for air to 80 for water, with values of 2 to 3 for the mineral particles. Due to the large difference between water $\varepsilon_a$ and that of the rest of the soil components, electromagnetic wave velocity will depend mainly on soil water content, which may be determined by knowing $\varepsilon_a$. Toppet et al. (1980) established an empirical relationship between $\varepsilon_a$ and volumetric soil moisture (VWC) for a range of frequencies between 1 MHz and 1 GHz:

$$VWC = -5.5 \times 10^{-2} + 2.92 \times 10^{-2} \varepsilon_a - 5.5 \times 10^{-4} \varepsilon_a^2 + 4.3 \times 10^{-6} \varepsilon_a^3$$

The pulse from the oscilloscope moves towards the stainless-steel rod of the probe to its ends and is reflected (Figure 10-33). The TDR could be made with different lengths of rod, from 4-50 cm. The number of rods used to be 2, but there are other designs with 3 or even more.

The rods have to be inserted into the soil, vertically or horizontally, taking into account that the measure is obtained as the average along the rod.
10.22.5.3 Operational conditions
This technique gives accurate results within an error limit of ±1% and allows continuous measurements over the full soil moisture range, along with measurements of the electrical conductivity of the soil. These sensors are especially suitable for short root crops. TDR, for non-permanent installations or shallow samples, is a non-destructive and relatively less labour-intensive technique, in relation with other soil moisture techniques as can be gravimetric soil moisture or other soil moisture sensors that it need permanent installation; the instrument used could be portable, probes are easy to install and safe to operate. This technique allows reliable measurements of volumetric water content to be made within a short time. No soil-specific calibrations are required.

10.22.5.4 Cost data
A single probe costs around 400 € plus the portable display that costs 500 €. In case of a permanent logger, the prices could vary from 300 € with a manual discharge to 1000 € with GPRS transmission and multiple channels.
Annual transmission data costs 40-200 €, depending on the company and the uploading frequency.

10.22.5.5 Technological bottlenecks
High price, the variability of the measure for small sensing volumes, correct installation is essential, interpretation of information help is needed in many cases, not easy-to-use software, cable length limitations. TDR probes are environmentally sensitive and the probe length influences the accuracy of the moisture. Consequently, the measurements could be erroneous due to gaps between the soil and probe. Further, it has limited applicability in highly saline soils.

10.22.5.6 Benefit for the grower
Advantages
Water/Fertiliser savings.

Disadvantages
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Transfer of INNOvative techniques for sustainable WAter use in FERtigated crops

- Expensive
- Installation (especially in stony soils) and interpretation help needed in many cases

10.22.5.7 Supporting systems needed
Technical assessment during the first periods of use.

10.22.5.8 Development phase
Commercialised.

10.22.5.9 Who provides the technology
- Specialised Companies that provide on crop management

10.22.5.10 Patented or not
Unknown.

10.22.6. Which technologies are in competition with this one
Plant sensors, remote sensing, other soil moisture sensors (capacitance sensors).

10.22.7. Is the technology transferable to other crops/climates/cropping systems?
Yes.

10.22.8. Description of the regulatory bottlenecks
There are no regulatory bottlenecks.

10.22.9. Brief description of the socio-economic bottlenecks
In countries such as Spain, the optimisation of irrigation is not a high priority for many growers.
TDR systems are relatively expensive as far as soil moisture sensors are concerned. Capacitance sensors are being presently used for irrigation management rather than TDR sensors because of their lower cost.

10.22.10. Techniques resulting from this technology
Deficit irrigation strategies, such as Controlled Deficit Irrigation, Partial Root Drying, etc., can be complemented and controlled by using these devices.

10.22.11. References for more information


10.23. Capacitance probe
(Authors: Krzysztof Klakowski\textsuperscript{1,2}, Benjamin Gard\textsuperscript{*})

10.23.1. Used for
More efficient use of water.

10.23.2. Region
All EU regions.

10.23.3. Crop(s) in which it is used
- Annual vegetable crops
- Fruit crops (orchards and berry plantations)
- Ornamental plants

10.23.4. Cropping type
All cropping types.

10.23.5. Description of the technology

10.23.5.1 Purpose/aim of the technology
The purpose of capacitance probe is to measure the volumetric soil water content in order to indicate when and how much to irrigate.

10.23.5.2 Working Principle of operation
This probe measures the dielectric permittivity of soil/growing medium, which is highly dependent on water content (moisture). The dielectric constant in a dry material consisting of soil particles is relatively small (2-5) whereas the dielectric water constant is \( \sim 80 \) (room temperature). Dielectric permittivity is determined by measuring the capacitance between two electrodes implanted in the soil. The probe is subjected to excitation at a frequency (10-100MHz) to permit measurement of the dielectric constant (Figure 10-34).
10.23.5.3 Operational conditions

Measurements are influenced by several factors: soil structure, soil texture, temperature, specific salinity and the contact between the soil and the sensor. The probe requires calibration and can provide the absolute value of the soil moisture at any depth as well as the moisture profile with several sensors, distributed on the probe. The choice of a proper sensor is determined by many factors such as the type of soil/growing medium, the required accuracy, cost and ease of use. The way of installing a probe depends on its design and cropping system. Small size sensors can be inserted directly into the soil at a different depth (e.g. 20, 40, 60 cm) and connected to a logger unit. This method can be used for trees and shallow rooting plants (e.g. berry crops, vegetables). A probe that measures the moisture automatically at the desired levels (e.g. every 10 cm) can also be used. An access tube is installed in the soil and readings are taken through the wall of the tube. There are different probe lengths available.

It is recommended to place probes/access tubes close to the active root area, within the irrigated area (if applied), however not directly under a drip emitter (if used).

In containerised plants, a sensor is installed directly in soil/growing medium a few centimetres from the container walls due to the sensor’s zone of influence.

Results can be presented in percent (volumetric), m$^3$/m$^3$, mm (per depth range – soil profile sensors) or imperial units (depends on the type of sensor).

10.23.5.4 Cost data

Sensors are expensive and long-term sustainability is questionable because of the calibration requirement. For instance, a capacitance probe with 4 sensors, 60 cm long, costs 1000 €. With data logging and remote transmission 2000 €. In Central-East Europe (Poland) the cost of a single (simple) capacitance sensor is about 150 €, multiparameter sensors (moisture, temperature, EC) – 340 €, handheld sensor read-out units – 700 €, a data logger – 700 € (standard) - 1400 € (with GPRS modem).

Figure 10-34. Schematic diagram of a capacitance probe in an access tube (White & Zegelin, 1994)
The purchase costs of sensors can vary appreciably between different manufacturers.

Yearly maintenance or inputs needed: calibration according to the soil characteristics, ensuring a good contact between probe and soil. Costs of data transfer (if wireless transmission is used) – 100 €/year//logger (5 channels).

10.23.5.5 Technological bottlenecks
The effect of temperature on the quality of moisture measurements conducted with the capacitance method should be considered, especially in soilless cultivation systems due to the limited volume of substrate (temperature fluctuations over time) and altered microclimate (if cultivated under protected conditions). Changes in soil salinity can influence the readings of some sensors.

10.23.5.6 Benefit for the grower

**Advantages**

- Response time is instantaneous
- High level of precision
- Can be read continuously by remote methods
- Sufficiently accurate for irrigation scheduling
- Applicable in soilless cultivation under protected conditions
- Calibration supplied by a manufacturer is often sufficient for monitoring changes in mineral soil water status
- Multi-parameter probes are available (they measure water content, temperature and, for some sensors, EC)
- Applicable for direct control of irrigation valves (under development)
- More reliable than tensiometer
- Responds over a much larger range of soil moisture contents (15-180 cbar) than a tensiometer

**Disadvantages**

- Expensive
- Less precise than TDR probe
- Calibration is recommended
- Influence of salinity (in modern sensors less pronounced) and temperature (important especially in container production systems)
- Careful site selection is critical to get good representative information (because of the costs, often only one probe is used to monitor a field)
- Specific (for a given medium) calibration may be necessary
10.23.5.7 Supporting systems needed
Advice from suppliers or extension services may help growers to better use the technology and to determine threshold values for crops. Data logging and remote transmission can facilitate the use of capacitance probes.

10.23.5.8 Development phase
- Research: see below
- Experimental phase: see below
- Field test: system controllers, control algorithms which use capacitance probes for direct controlling irrigation valves are being examined and developed
- Commercialised: a variety of capacitance sensors/loggers are available on the market

10.23.5.9 Who provides the technology
Several retailers (Sentek, John Deere, Aquacheck, Buddy, Gopher, Decagon Devices, Spectrum Technologies, etc.).

10.23.5.10 Patented or not
Generic technology. Suppliers build own constructions. Some construction solutions may be patented.

10.23.6. Which technologies are in competition with this
All technologies to measure soil water status: tensiometers (measures soil water potential), electrical resistance sensors, digital ground-penetrating radars, TDR probes, neutron scattering (currently rarely used), gravimetric analysis (sample destructive, laboratory method used for calibration of other methods).

10.23.7. Is the technology transferable to other crops/climates/cropping systems?
Capacitance probes are being used with a wide range of crops, climate and cropping systems

10.23.8. Description of the regulatory bottlenecks
There are no relevant European directives or regulatory bottlenecks at European, country and regional level.

10.23.9. Brief description of the socio-economic bottlenecks
The main socio-economic bottlenecks are the high costs, knowledge of the technology, proper interpretation of the obtained results, basic knowledge about plant-soil-water relations, need for calibration in some situations, probes are often hardly available in the market (in Poland, in most cases irrigation companies do not have this type of equipment in basic offer) and lack of advice for the good use.
These sensors are commonly used by commercial growers in countries such as Australia and the USA. There are often local suppliers who also provide on-going technical support.
Generally, most growers learn how to use this technology so that they can work independently with it.

10.23.10. Techniques resulting from this technology
Irrigation scheduling with capacitance probe.

10.23.11. References for more information
10.24. Digital penetrating radar
(Authors: Claire Goillon², Carlos Campillo⁵, Benjamin Gard*, Javier Carrasco⁵)

10.24.1. Used for
More efficient use of water.

10.24.2. Region
All EU regions.

10.24.3. Crop(s) in which it is used
All soil bound vegetable and fruit crops.

10.24.4. Cropping type
- Soil-bound
- Protected
- Open air

10.24.5. Description of the technology

10.24.5.1 Purpose/aim of the technology
Measuring of the soil moisture through the measurement of electromagnetic energy.

10.24.5.2 Working Principle of operation

![Figure 10-35. The operating modes of the ground-penetrating radar. Transmitter and receiver are shown as black boxes.](image-url)

Measurements are based on the transmission and reflection of an electromagnetic wave in the soil. The transmitter antenna of the radar system generates radio-waves propagating in a broad beam. The receiver detects variations in the electrical properties of the sub-surface by detecting the part of the transmitted signal that is reflected. The electrical properties are mainly due to the water content in natural soils, thus the difference between the transmission and the reflection of the electromagnetic wave matches to the soil moisture. The less the difference, the more water is present in the soil. There are two systems of measurements: the first has the antenna on the soil surface (ground mode) and the second
has the antenna in the air (airborne mode). The system must be calibrated on a large surface of which the measured reflections are known.

10.24.5.3 Operational conditions
This is a method well suited for acquisition of soil moisture across large areas. But the use of this technology is limited because many soil types are radar opaque and dissipate radar energy (they have a high electrical conductivity - EC). It is necessary that there isn’t a shallow water table or a stratigraphic transition because the electromagnetic wave would be reflected. On a crop with a large canopy, the measurements are erroneous because trees behave as reflectors. For the ground mode, the equipment needs to be moved for the radar to examine the specified area by looking for differences in material composition.

10.24.5.4 Cost data
Complete systems: transmitter antenna, receiver antenna, control unit, a display unit, power unit and software and GPS, depends on the manufacturer cost varies between 15000 and 20000 €.

10.24.5.5 Technological bottlenecks
The choice of the good wave (Hz). Low frequencies (a few MHz) give good depth penetration but low resolution, we will move between 200 MHz and 1 GHz, depending on the type of soil and its moisture.

10.24.5.6 Benefit for the grower

Advantages
- Fast
- Non-destructive technique
- High resolution
- Remote measurements
- Measurement on a large area which overcomes the limitation of point sampling techniques

Disadvantages
- Large and complex system
- Expensive
- Usually used for soil surface
- Interpretation of data needs experience
- Strong expertise is needed to design, conduct, and interpret ground penetrating radar (GPR) surveys
- Not possible an automatic measurement in soil with high clay and salinity
10.24.5.7 Supporting systems needed
It’s necessary to have the equipment to measure electromagnetic waves (transmitter antenna and receptor antenna and a control unit, for example, Pulse EKKO IV GPR). Interpretation of the results can be done solely by someone trained in GPR analysis.

10.24.5.8 Development phase
Commercialised.

10.24.5.9 Who provides the technology
Companies like Mala, Leica, Radio detection provide this technology. Several companies specialised in GPR analysis offer services for soil analysis and hydrologic investigations.

10.24.5.10 Patented or not
The technology is not patented but the different devices are patented.

10.24.6. Which technologies are in competition with this one
Time domain reflectometry, capacitance probe.

10.24.7. Is the technology transferable to other crops/climates/cropping systems?
Yes.

10.24.8. Description of the regulatory bottlenecks
None.

10.24.8.1 Brief description of the European directive and implications for growers at European level

The European Commission (EC) decided to include GPR/WPR within the scope of the Radio and Telecommunications Terminal Equipment (R&TTE) Directive 1999/5/EC.

Protection of the health and safety of the user and any other person, including the objectives, set out in with respect to the safety requirement in the low voltage directive 73/23/EEC, but with no voltage limit applying.

The protection requirement with respect to electromagnetic compatibility (EMC) contained in the Directive 89/336/EEC.

10.24.9. Brief description of the socio-economic bottlenecks
This technology is expensive. A strong experience is needed to conduct such GPR analysis. GPR analysis may be interesting for a hydrologic investigation on soil, to have a clear image of soil water content or soil layers but it is not suitable for irrigation management. This
technology seems currently to be more suitable for research studies and experiments rather than for on-farm irrigation management.

10.24.10. Techniques resulting from this technology
Soil Cartography at the farm scale.

10.24.11. References for more information
10.25. Slab balances

(Authors: Alain Guillou⁴, Esther Lechevallier⁴, Jadwiga Treder¹², Waldemar Treder¹²)

10.25.1. Used for
More efficient use of water.

10.25.2. Region
All EU regions.

10.25.3. Crop(s) in which it is used
Tomato, cucumber, leafy vegetable, strawberry.

10.25.4. Cropping type
- Protected
- Soilless

10.25.5. Description of the technology

10.25.5.1 Purpose/aim of the technology
Automatic balance systems can be used to continuously measure the weight of substrate slabs or containers with plants. Real-time monitoring of changes in the weight of slabs or containers with plants is used to trigger irrigation when threshold weight values are reached. The decrease in weight over time is an indication of the amount of water lost through transpiration, evaporation, and leaching (if applicable). This decrease in weight can then be used to determine how much water needs to be applied to replenish the soil/substrate, thus providing a simple and direct method for irrigation control. Balances can be used to quantify the daily water loss and after calibration can be used to estimate the soil moisture of the growing media. The balance helps to determine the number of irrigation events and the amounts applied during the day.

10.25.5.2 Working Principle of operation
The basic concept behind this technique is simple: the substrate and crops are considered as having a relatively constant weight. The variation in measured weight is the variation in available water in the substrate. A slab or container is heaviest when it has just been irrigated but loses weight over time as water is lost by evaporation and transpiration. When the container weight reaches a predetermined weight (threshold value), it is time to irrigate.

The simplest balance consists of a load cell mounted, on a base, with a weighing platform or a platform hanging from the load cell (Figure 10-36 and Figure 10-37). Standing platforms are used for tomato, cucumber, pepper in soilless systems and in container nurseries. Hanging platforms are used in the cultivation of strawberries and ornamental plants.

A balance generally holds two substrate slabs (8-12 crops for a tomato crop). Direct and continuous in-situ measurements (~ every 5 minutes) are recorded by software and can be displayed on the control computer.
The balance can be equipped with a device that enables measurement of the drainage volume from the substrate. In doing so, the measurement of volumes supplied and drained, and the continuous weighing of the substrate helps to optimise irrigation through specialised software.

The software determines when to irrigate according to a transpiration calculation in combination with measurement of the substrate weight and drainage volume. The balance can also be used as a simple control and adjustment tool without acting directly on irrigation programming.

![Figure 10-36. Balance that accurately monitors the weight of substrate and/or plants (Source: Waldemar Treder)](image)

![Figure 10-37. Substrate weighing under a tomato crop (Source: CATE)](image)

10.25.5.3 Operational conditions

It is the plants themselves that determine the amount and timing of irrigation with high accuracy based on calculations that consider the amount of water absorbed by the plant, the water content in the substrate and the drainage volume. These weight and drainage measurement are continuously performed. This enables optimal irrigation which ensures optimal crop water status, good aeration of roots, and avoids unnecessary costs through the excessive application of water and nutrients.

It is used in soilless greenhouses, with vegetable crops, with aromatic and ornamental species.

The size of the slab balances depends on the manufacturer, for example, PRIVA slab balance: drain measurement with capacity 10 L/h and drain gutter lengths of 2 m and 2,8 m and maximum load up to 100-200 kg.
10.25.5.4 Cost data
Installation: 1 balance, with the software program: 3600 €.

10.25.5.5 Technological bottlenecks
Site selection is important. It is necessary to avoid locating the balance in unrepresentative parts of the greenhouse. Once the balance is placed, it is not possible to move it to another place. If plants on the balance die, that can be a problem.

10.25.5.6 Benefit for the grower

**Advantages**
- Accurate information about plant water needs, irrigation fine-tuning is possible
- Direct on-time monitoring
- Automatic irrigation control based on transpiration rate

**Disadvantages**
- The device cannot be moved once it is installed at the beginning of the season
- High costs
- Basic technical knowledge is necessary to interpret the results
- Requires regular monitoring of the accuracy of operation

10.25.5.7 Supporting systems needed
A data collection and support system related to the control computer is required. It requires initial training and support. The balance can be coupled to a device measuring the drainage volume.

10.25.5.8 Development phase
Commercialised.

10.25.5.9 Who provides the technology
PRIVA (Groscale), HORTIMAX (Prodrain, Newton), Hoogendoorn (HGM Balance/Aquabalance).

10.25.5.10 Patented or not
Patented.

10.25.6. Which technologies are in competition with this one
Irrigation controllers equipped with moisture sensors. Irrigation controllers calculating the dose and frequency of irrigation based on evapotranspiration.

10.25.7. Is the technology transferable to other crops/climates/cropping systems?
Yes. Transferable to soilless systems using substrate slabs/pots.
10.25.8. Description of the regulatory bottlenecks
None.

10.25.9. Brief description of the socio-economic bottlenecks
The equipment and supporting software are costly. The grower should be trained to use it.

10.25.10. Techniques resulting from this technology
Crop monitoring: The balance helps determine the number and the doses of irrigation events to bring the substrate to its pre-defined maximum weight in the morning. The balance helps the grower to determine the start and end times of these irrigation events depending on the weight loss wanted during the night (e.g. for a tomato crop on coir substrates, a 10-15% loss of substrate weight from the last irrigation on day D to the first irrigation on day D+1) (Figure 10-38). The balance helps to verify that the irrigations maintain the substrate moisture within the optimal range. The balance also helps the grower to observe the behaviour of the substrate regarding water retention and to plan either fewer irrigation events with bigger doses or more irrigation events with less water provided.

![Figure 10-38 Evolution of the substrates’ weight in 4 glasshouses in a soilless tomato crop (Source: CATE)](image_url)

10.25.11. References for more information
10.26. Drain sensor
(Authors: Alain Guillou, Esther Lechevalier)

10.26.1. Used for
More efficient use of water.

10.26.2. Region
All EU regions.

10.26.3. Crop(s) in which it is used
All crops.

10.26.4. Cropping type
All cropping types.

10.26.5. Description of the technology

10.26.5.1 Purpose/aim of the technology
The aim of the technology is to measure the quantity of drainage under one or several substrate slabs, or of the total greenhouse area.

10.26.5.2 Working Principle of operation
The quantitative measurement of drainage volume is done using a device which collects the drainage on a collection tray, usually containing one or two substrate slabs (2-3 m) or the whole gutter. The tray is installed with a slight slope so that the drain water flows to a drain trough and the volume is then measured by a measurement unit (Figure 10-39). The measuring unit consists of a mechanical volume sensor: a previously calibrated tipping ladle measures the drain water quantity so that each tip of the ladle represents a specific volume. The data are then sent to a computer and are continuously updated. Using appropriate software, the computer calculates the percentage of applied water that has drained, based on the volume of water supplied to the sector and the drainage measured from the same sector. Every morning before irrigation commences, the device is reset to zero. Usually, this device also measures the water temperature and electric conductivity, in order to have more information for the control of irrigation and nutrient solution composition.

The drainage volume collected from the whole cropping area can be measured by a water meter at the entrance of the storage container for drain water.
10.26.5.3 Operational conditions
The device should be connected to the process computer to centralise the measure and compare it to the water supplied to the crop. Usually, it is coupled to a slab balance so that the grower is able to link the weight variations with the drainage quantity measurement. The device usually has a maximum measuring capacity. Beyond this capacity (in L/h), the tipping ladle is continuously loaded, and some drainage may not be measured.

10.26.5.4 Cost data
For installation: 2345 € (DSS from PRIVA, France).
Yearly maintenance or inputs needed: usual maintenance, no input needed.

10.26.5.5 Technological bottlenecks
No bottlenecks are known (at least in France).

10.26.5.6 Benefit for the grower

Advantages
- Allows a comparison between provided water and drained water, to see if the crop is stressed, over-irrigated, etc.
- Allows prevision of the quantity of drain water that needs to be managed (disinfection, treatment, discharge)

Disadvantages
- The devices (tipping ladle) are often placed on only one or a few sites in the greenhouse so the data might not be representative for the whole greenhouse and the monitoring objectives can be biased (same problem with the slab balances)
- The drainage gauge can be blocked by coir or leaf material which can results in inaccurate measurements. This can result in excessive irrigation and fertiliser application.

Figure 10-39. A substrate slab balance equipped with a drainage quantity measurement system (PRIVA drain water sensor) (Source: CATE)
10.26.5.7 Supporting systems needed
Computer and software.

10.26.5.8 Development phase
Commercialised.

10.26.5.9 Who provides the technology
PRIVA, Hoogendoorn Aquabalance, Hortimax.

10.26.5.10 Patented or not
The technology is not patented but the specific sensors might be.

10.26.6. Which technologies are in competition with this one
- Integrated solutions that take into consideration both drainage volume and plant growth (e.g. Hortimax, Prodrain, Priva Root Optimizer)
- Manually drainage measurement: Some growers collect daily the drainage for individual slabs and measure the drainage with a measuring jug, but this method is less precise and not continuous

10.26.7. Is the technology transferable to other crops/climates/cropping systems?
Transferable to all soilless systems with drain collection system.

10.26.8. Description of the regulatory bottlenecks
There are no regulatory bottlenecks.

The device is costly compared to a manual measurement.

10.26.10. Techniques resulting from this technology
Monitoring the irrigations depending on the drainage target: The grower sets up a drainage objective depending on the crop type, growth stage, the weather, etc. The instant measure of the drainage will help him to adjust the irrigation dose desired for the next irrigation events.

10.26.11. References for more information
10.27. Demand tray system

(Authors: Juan José Magán\(^9\), Rodney Thompson\(^3\))

10.27.1. Used for

More efficient use of water.

10.27.2. Region

Mediterranean.

10.27.3. Crop(s) in which it is used

Vegetables.

10.27.4. Cropping type

- Soilless
- Protected

10.27.5. Description of the technology

10.27.5.1 Purpose/aim of the technology

The demand tray is a simple method for automatic activation of the irrigation in soilless cultures.

10.27.5.2 Working Principle of operation

This technology consists of a tray made from fibreglass or from metal that contains one or usually two crop units (substrate bags). The drainage from the substrate accumulates in a channel inside the tray, where there are two vertically-installed adjustable screws at different heights that serve as electrodes for the activation of irrigation (Figure 10-40). This water reservoir is hydraulically connected to the substrate by an absorbent blanket (Figure 10-41), so that water consumption within the substrate causes a water potential difference with respect to the reservoir, thereby promoting water movement towards the substrate and a reduction of the water level in the channel. When water is not in contact with the upper screw, the electrical circuit is open and the resultant electrical signal is detected by the irrigation controller that automatically activates a new irrigation for a fixed time period. The height of the upper screw is regulated to optimise the frequency of irrigation; the irrigation frequency will be excessive if the upper screw is too high, and insufficient if it is too low. To empirically obtain information to assist with the regulation of the screw height, another tray is used, where the drainage volume is measured, and also the electrical conductivity and pH of the drainage are determined.
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10.27.5.3 Operational conditions

One tray is required per irrigation sector. It is not recommended to connect more than four demand trays to the same fertigation controller because having too many sectors may make it difficult to irrigate the individual sectors with sufficient frequency during high water demand periods.

This system requires that the plants located in the tray are representative of the entire crop, or at least the sector, and have a uniform development.

10.27.5.4 Cost data

The cost varies depending on the material used to make the tray and the distance to the fertigation controller. The cost ranges at 500-800 €, including tray, screws, wire, accessories, and labour.

- Installation of a new absorbent blanket at the beginning of the crop: 5 €
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- Periodical adjustment of the screw height during the crop, especially during the vegetative phase, when there is a progressive increase of leaf area and hence of crop transpiration
- Replacement of the screw if necessary (some models can be affected by an excessively high voltage which can occur during electrical storms): ≈ 125 €
- Cleaning of the screw if necessary to ensure a good electric contact (yearly)

10.27.5.5 Technological bottlenecks

When automating irrigation with this system, the matric potential of the substrate at the start of the irrigation event is not always the same, this value can increase with high water demand (Figure 10-42). (Editor’s note: Please note that matric potential is actually negative but commonly is referred to, as here, as being positive. In this case, the real measurements are in units of negative hPa, and when there is high evaporative demand, matric potential values at the start of the may be lower). This effect could be related to the response speed of the system, which is conditioned by the hydraulic conductivity of the absorbent blanket. If water consumption is high, the water flow through the blanket may be too slow to rapidly equilibrate substrate and reservoir water potentials causing a delay in the response of the demand tray and, hence, in activating irrigation. On the other hand, the plants in the demand tray have an additional reservoir of water compared to the rest of the crop; this can also influence the water supply in the substrate bags on the demand tray.

![Figure 10-42. Evolution of the substrate matrix potential in rockwool-grown tomato on a sunny day. Watering activation was automated by a demand tray and matrix potential was measured by a tensiometer (Terés et al., 2000)](image)

10.27.5.6 Benefit for the grower

**Advantages**
- Very simple
- High reliability
- Low initial investment
- Low maintenance costs
- Technology widely developed and readily available

Disadvantages

- It cannot be used soon after transplanting because there is not sufficient root development
- It does not give information about the water status of the substrate
- There is a problem if plants growing in the tray die during the cropping cycle. It is not possible to change the substrate units if plants are too big.

10.27.5.7 Supporting systems needed
The demand tray has to be connected to a fertigation controller for automatic activation of irrigation.

10.27.5.8 Development phase
Commercialised.

10.27.5.9 Who provides the technology
Different companies installing irrigation and fertigation systems.

10.27.5.10 Patented or not
This technology is not patented.

10.27.6. Which technologies are in competition with this one
Sensors measuring water status of the substrate (tensiometers, capacitance sensors)
- Irrigation control system based on radiation measurement (usually combined with automatic measurement of drain volume)
- Crop evapotranspiration models
- Weighing scales

10.27.7. Is the technology transferable to other crops/climates/cropping systems?
Yes.

10.27.8. Description of the regulatory bottlenecks
There are no regulatory bottlenecks.

10.27.9. Brief description of the socio-economic bottlenecks
There are no socio-economic bottlenecks.

10.27.10. Techniques resulting from this technology
Irrigation control by programmed irrigations during the beginning of the crop, followed by use of the demand tray once there is good root development. The demand period is usually from 1-2 hours after sun rise to 1-3 hours before sunset. The demand tray can be associated with programmed irrigations during the night in high water demand periods.
10.27.11. References for more information


10.28. Weather sensors

(Authors: Carlos Campillo\textsuperscript{5}, Javier Carrasco\textsuperscript{5}, Krzysztof Klamkowski\textsuperscript{12}, Waldemar Treder\textsuperscript{12})

10.28.1. Used for
- More efficient use of water
- Minimising the impact to the environment by nutrient discharge

10.28.2. Region
All EU regions.

10.28.3. Crop(s) in which it is used
It may be used in many crop types: fruit crops, vegetables, ornamentals, agricultural crops.

10.28.4. Cropping type
All cropping types.

10.28.5. Description of the technology

10.28.5.1 Purpose/aim of the technology
Weather sensors are used for measurement of basic climatic parameters (temperature, humidity, atmospheric pressure, precipitation, solar radiation, wind speed and wind direction). Access to the weather data is crucial for estimating water needs for open air and greenhouse crops. The weather data are used to calculate reference evapotranspiration (ET\textsubscript{o}). This is an important weather parameter to calculate crop water needs and to determinate different water needs between different irrigation zones in the same crop. The correct estimation of the ET\textsubscript{o} will permit a more efficient water use. Knowledge of local rainfall helps to reduce irrigation.

Parameters such as VPD (relation between temperature and relative humidity) can affect threshold values of different sensors. For example, threshold values of plant water potential can vary with VPD for the same plant water status.

Different crop water relation parameters such as crop water stress index need air temperature and VPD to establish if the crop is in a water stress situation.

Data obtained from weather sensors are used for simulation models that predict the risk of disease and insect pest outbreaks, and the risk of physiological disorders during storage. Temperature monitoring plays a key role in preventing spring frost damage. Sensors are also used in greenhouse climate control systems. Light, temperature, air humidity need to be effectively adjusted to optimise conditions for crop growth in greenhouses. Moreover, monitoring the influence of the external conditions (wind, precipitation) on the internal greenhouse climate is crucial for optimal greenhouse climate management.

10.28.5.2 Working Principle of operation
Evapotranspiration refers to the combined loss of water from soil (evaporation) and plant (transpiration) surfaces. It can be estimated from weather data. This “reference” ET\textsubscript{o} can be used to determine the irrigation required to replace the water used by a crop. To calculate
crop evapotranspiration (ETc) (crop water requirements), it is necessary to multiply ETo by a “crop coefficient” value. These coefficient values are provided for various crops, and change during the growing season to reflect changes in the size of the crop canopy. A wide range of equations has been developed for the estimation of ETo. Simple equations require only measurements of one meteorological parameter (air temperature) as an input (e.g. Hargreaves equation) or two parameters (air temperature, humidity) as inputs (e.g. Grabarczyk equation). The Penman-Monteith equation is considered to be most consistent over a wide range of climatic conditions. It is used as the international standard equation for calculating ETo. The Penman-Monteith equation requires a significant amount of meteorological data input, including radiation, air temperature, air humidity and wind speed data, which creates complexity in data collection and computation. This equation is most often implemented in weather station software calculating ETo.

Figure 10-43 shows a type of station used to obtain data to enable calculation of ETo, with the different equations previously described for open-air crops. These data of the local conditions will be used by computer-based DSS to calculate crop ETc or crop water needs, as a product between ETo and the crop coefficient (Kc).

In the case of greenhouses, the calculation of ETo require solar radiation data that is obtained from a solarimeter or pyranometer that is often placed outside, and transmissivity values (percentage of solar radiation transmitted by the cover material) are used to estimate solar radiation inside the greenhouse. Accumulated solar radiation can be used to trigger irrigation. When the accumulated solar radiation reaches a certain value, chosen by
the user, a control order is transmitted to an irrigation controller. The chosen value is the “trigger point”, expressed in J/cm².

10.28.5.3 Operational conditions

There are many types of commercially available sensors. Depending on their construction they might have the different methods of operation, durability, operating range and sensitivity (e.g. spectral sensitivity for solar radiation sensors).

In some countries, agrometeorological data can be downloaded from the Internet. e.g. the SiAR network of agricultural weather stations (http://www.magrama.gob.es/siar/), created in 1998 by the Spanish Ministry of Agriculture in cooperation with regional governments. A web page publishes daily-updated agrometeorological information for each agricultural weather station of the SiAR network (Figure 10-44). Published information includes standardised reference evapotranspiration values estimated by the FAO Penman-Monteith method (Allen et al., 1998).

10.28.5.4 Cost data

Installation

Cost of the weather station depends on the manufacturer: 2500 € – simple data logger with basic sensors, 6000 €– automatic station with weather sensors and GPRS data transmission to the computer. Decagon weather station costs 3500-5000 € and Imetos® station (Fieldscan) € 4500-5000 €.
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**Yearly maintenance or inputs needed**

Costs of data transmission (GPRS card) and maintenance (calibration of the sensors) should be considered. The pyranometer should be cleaned from time to time to ensure reliability of the data. Annual calibration is advised.

**10.28.5.5 Technological bottlenecks**

Sensors available on the market have a different operating range, sensitivity, response time and accuracy. Proper sensor exposure, levelling and orientation are key to obtain accurate weather data.

Sensor performance should be regularly verified. Appropriate calibrations and adjustments should be performed to eliminate errors of sensors. Incorrect data inputs result in erroneous ETo calculations.

**10.28.5.6 Benefit for the grower**

**Advantages**

- Improving water use efficiency in crop production systems, predicting disease and pest outbreaks, monitoring and controlling greenhouse climate
- Automatic weather stations (with an autonomous power source) save human labour and enable measurements from remote areas (wireless communication) assuring quick access to the weather data

**Disadvantages**

- Substantial start-up expenses (costs of sensors, station siting)
- Periodic maintenance and calibration is important to assure reliable results and to maximise the lifespan of the sensors

**10.28.5.7 Supporting systems needed**

Access to the Internet if wireless transmission of data (GSM/GPRS network) is considered (in most cases the data are available on the supplier’s website).

Access to reference instruments and methods (calibration service is often offered by the sensors supplier or independent laboratories).

**10.28.5.8 Development phase**

- Research: comparisons, validations and improvements of different evapotranspiration models in different climatic regions (to increase their accuracy)
- Experimental phase: climate monitoring and management systems are developed and tested
- Field tests: climate monitoring and management systems are developed and tested.
- Commercialised: many types of sensors are available for use in agricultural and horticultural production systems

**10.28.5.9 Who provides the technology**

Many suppliers. 

**10.28.5.10 Patented or not**
Not patented.

**10.28.6. Which technologies are in competition with this one**
The irrigation requirements can be also estimated by monitoring soil water status (water content/potential). Sensors measuring water content and potential are commercially available. The best solution is to combine these two approaches – use weather data for calculating plant water needs (evapotranspiration) and control effectiveness of the irrigation with soil moisture sensors.

Evapotranspiration (plant water requirements) can also be estimated with lysimeters.

**10.28.7. Is the technology transferable to other crops/climates/cropping systems?**
Yes. The technology is broadly applicable to many climates/cropping systems.

**10.28.8. Description of the regulatory bottlenecks**
There are no specific regulatory bottlenecks related to the technology use. It is safe and produces no wastes.

**10.28.9. Brief description of the socio-economic bottlenecks**
There are no specific socio-economic bottlenecks. In many countries, the problem of meteorological data availability exists. Due to this data limitation, simpler (less accurate) models are used for ETo calculation.

**10.28.10. Techniques resulting from this technology**
There are many suppliers offering weather sensors of different construction and operation principles.

In the open air: Different decision support systems use an ETo calculation to manage irrigation scheduling. These systems normally use an ETo calculation of Penman-Monteith equations and Kc to calculate the water needs for application in the determinate day and determinate irrigation zone. In Spain, there are DDS models available in all regions to calculate an ETc of the most important crops, through SiAR. In Figure 10-45, the irrigation scheduling recommended in the web of Extremadura Advisory network to the irrigator (REDAREX) from SiAR are showed.

**Figure 10-45. Processing tomato Irrigation scheduling recommended by Extremadura Advisory network to the irrigator web** ([http://redarexplus.gobex.es](http://redarexplus.gobex.es))

In greenhouses: Decision support systems to manage irrigation scheduling based on solar radiation accumulation have been developed. Irrigation scheduling is often triggered by solar radiation accumulation after mid to late morning, while earlier irrigations are often triggered on a timer, to fill up the substrate with water. The irrigation scheduling programs integrate parameters like crop type, growing stage, substrate type, target drainage rate, to adjust irrigation dose and trigger value to trigger the irrigation.

10.28.11. References for more information


