

University of Warwick institutional repository

This paper is made available online in accordance with publisher policies. Please scroll down to view the document itself. Please refer to the repository record for this item and our policy information available from the repository home page for further information.

To see the final version of this paper please visit the publisher's website. Access to the published version may require a subscription.

Authors:	D. J. GREENWOOD, K. ZHANG, H. W. HILTON and A. J. THOMPSON
Article title:	Opportunities for improving irrigation efficiency with quantitative models, soil water sensors and wireless technology
Year of publication:	2009
Link to published version:	http://dx.doi.org/10.1017/S0021859609990487
Publisher statement:	None

1 | Agriscsci [29 10 08-09](#)

2 | **Opportunities for improving of irrigation efficiency with quantitative models, soil**

3 | **water sensors and wireless technology are reviewed**

4 | By

5 |

6 | Short title: Irrigation with sensors and wireless technology

7 |

8 | Word processor: Word

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21

SUMMARY

Increasingly serious shortages of water make it imperative to improve the efficiency of irrigation in agriculture, horticulture and in the maintenance of urban landscapes. The main aim of this review is to identify ways of meeting this objective. After reviewing current irrigation practices, discussion is centred on the sensitivity of crops to water stress, the finding that growth of many crops is unaffected by considerable lowering of soil water content and on this basis the creation of improved means of irrigation scheduling. Next, attention is focussed on irrigation problems associated with spatial variability in soil water and the often slow infiltration of water into soil, especially the subsoil. As monitoring of soil water is important for estimating irrigation requirements, the attributes of the two main types of soil water sensors and their most appropriate uses are described. Attention is also drawn to the contribution of wireless technology to the transmission of sensor outputs. Rapid progress is being made in transmitting sensor data, obtained from different depths down the soil profile across irrigated areas, to a PC that processes the data and on this basis automatically commands irrigation equipment to deliver amounts of water, according to need, across the field. To help interpret sensor outputs, and for many other reasons, principles of water processes in the soil-plant system are incorporated into simulation models that are calibrated and tested in field experiments. Finally it is emphasised that the relative importance of the factors discussed in this review to any particular situation varies enormously.

INTRODUCTION

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23

Water shortage severely depresses yields in many parts of the world. Increasing populations and diminishing supplies of geological water exacerbate the problem. Indeed, FAO (2008) considers that by 2025, 800 million people could be living under conditions of absolute water scarcity. The scale of these problems is illustrated by the fact that world agriculture wastes 1,500 trillion litres of water, 0.6 of the 2,500 trillion litres of water it uses each year- which is 0.7 of the world's accessible water (Clay 2004). In southern Europe, irrigation accounts for over 0.6 of the water use in most countries (European Commission 2000). The problems are enormous and require immediate remedies.

The comprehensive monograph (Stewart & Nielsen 1990) gives an excellent account of the various factors influencing irrigation and how to improve irrigation efficiency of many crops. Recent attention has been given to improved cultural practices including subsurface irrigation (Banedjschafie *et al.* 2008), and partial root zone drying irrigation (i.e. irrigating one side of a row crop whilst leaving the other side dry and then at the next irrigation irrigating the dry side and leaving the previously irrigated side dry) (Saeed *et al.* 2008). Considerable effort has also been devoted to developing drought resistant cultivars by conventional and GM techniques (e.g. Farooq *et al.* 2009), and in the long-term this could result in improved water use efficiency. Yet there is still considerable uncertainty about how to adjust timing and rates of irrigation in different cropping systems. Practical advances in predicting irrigation requirements that are of wide applicability are needed. They could be applied immediately over wide could be of immense benefit.

1 assessment but are based on experience on what seems to have given good results in the
2 past. Nevertheless, science-based methods of assessing irrigation needs have had an
3 impact on practice. An early and most important contribution was the introduction of a
4 formula (Penman 1948), derived from considerations of energy and aerodynamics, for
5 calculating evaporative loss from well-watered turf. The formula has been modified to
6 the widely used Penman-Monteith equation (Monteith 1973; McNaughton & Jarvis 1984)
7 but the main principles remain and evapotranspiration calculated in this way for turf is
8 usually referred to as a reference evapotranspiration and is designated by ET (Hatfield
9 1990); the meteorological inputs to the model are measured routinely in most
10 meteorological stations. Pan evaporation (evaporation from a large pan of water) usually
11 designated as E_o is similar to that for well-watered turf and is also measured routinely
12 (Hatfield 1990). However, the percentage crop cover and the “surface roughness” vary
13 with crop species and development stage and are generally different from those of turf.
14 To correct for these differences, ET is multiplied by a crop specific coefficient K_c , the
15 values of which for different crops during their growth have been tabulated (Allen *et al.*
16 1998; Savaa & Frenken 2002). So if the aim of irrigation is to add sufficient water to
17 compensate for that lost by evapotranspiration then this can be achieved approximately
18 by adding an amount of water equal to that lost by the calculated evapotranspiration
19 ($K_c \times ET$) less rainfall. A weakness of using this approach for estimating water loss over
20 substantial periods is that errors are cumulative and so added irrigation water can become
21 out of step with requirement (Jones 2004). These methods have been used for estimating
22 irrigation requirement by both full irrigation and deficit irrigation practices. In full
23 irrigation, sufficient irrigation is applied to maintain the root zone soil near field capacity,

1 a practice that results in excessive waste of water from drainage and from evaporation
2 from the soil surface. In deficit irrigation less water is applied than is needed to meet total
3 losses from evapotranspiration (Costa *et al.* 2007; Fereres & Soriano 2007). **Soil**
4 **moisture deficit is important and can be defined as the volume of water needed to bring**
5 **the soil to field capacity (i.e. the minimum water content at which free drainage can**
6 **occur).** The extent to which the soil moisture deficit can be allowed to fall without
7 reducing crop growth varies depending on the crop species and its stage of development
8 and on the environmental conditions: topics which are discussed in detail in this review.
9 Increased use of deficit irrigation promises to bring about considerable increases in water
10 use efficiency.

11 Irrigation scheduling using plant-based methods has been comprehensively
12 reviewed by Jones (2004). Several procedures for measuring plant water stress have been
13 devised but they generally require a good deal of expertise to operate and, in any event,
14 they do not indicate the water requirement. The most promising approach is thermal
15 imaging. It is based on measuring the drop in temperature resulting from the evaporation
16 of water. As loss of water from stomata is greater when they are open than when they are
17 closed, temperatures are lower. The temperature difference of course also depends on the
18 evaporative conditions in the surrounding atmosphere. Thus the techniques have been a
19 useful tool for irrigation scheduling in arid regions but less so in humid regions (Jones
20 2004).

21 On the other hand, irrigation scheduling-based on soil water has been widely
22 reported. The distributions of water down soil profiles have long been measured
23 gravimetrically and by neutron and capacitance probes. Soil water sensors that are

1 inexpensive, convenient to operate and require little labour are being developed and are
2 increasingly used commercially. Some of them are described later in this review. Soil
3 water has also been monitored remotely by microwave radar techniques (Ragab 1995;
4 *Clark et al. 2005*; Jadoon *et al.* 2008; Lambot *et al.* 2008) generally for research and
5 specialized purposes.

6

7 PLANT AND SOIL PROCESSES AFFECTING IRRIGATION REQUIREMENTS

8

9 Opportunities for reducing the wastage of irrigation water include:

- 10 (1) reducing loss of water through evaporation from the soil surface;
- 11 (2) reducing leaching below the depth of rooting;
- 12 (3) allowing crops to exploit the water stored within the soil profile to the full depth
13 of rooting; in many parts of the world, winter rain or monsoons bring the soil to
14 field capacity and it is essential to make full use of this stored water;
- 15 (4) reducing the accumulation of salts within the soil profile that arise from excessive
16 irrigation.

17 All four objectives can be met, at least partially, by reducing the total application of
18 irrigation water. For example, if the frequency of irrigation is kept to a minimum then the
19 surface soil will dry out and less water will be lost by evaporation from the soil surface.

20 *Plant factors influencing irrigation need*

21 *Static maximum allowable soil moisture deficits*

22 The key to minimizing irrigation without inhibition of growth is the often repeated
23 finding that soils can lose considerable quantities of water without suppressing growth

1 rate (Bailey 1990; Hills *et al.* 1990; Krieg & Lascano 1990; Musick & Porter 1990; Bacci
2 *et al.* 2003; Panda *et al.* 2003). Much effort has therefore been devoted to quantifying
3 this phenomenon (Denmeade & Shaw 1962; Ritchie 1973; Meyer & Green 1980;
4 Rosenthal *et al.* 1987; Muchow & Sinclair 1991; Sadras *et al.* 1993; Sadras & Milroy
5 1996; Thompson *et al.* 2007). A summary of this work is given in the FAO irrigation
6 manual (Allen *et al.* 1998; Savva & Frenken 2002). It considers that water stress does not
7 inhibit growth unless it also inhibits evapotranspiration. It is based on the assumption
8 that crop evapotranspiration remains constant with a decrease in available water until a
9 value is reached after which evapotranspiration declines linearly with a further decrease
10 in available water until the wilting point is reached when evapotranspiration ceases. It
11 summarizes existing knowledge in terms of a maximum allowable soil moisture deficit
12 expressed as a **proportion** of the available water to the depth of rooting (MADP). The
13 concept is illustrated by the diagram given in Fig. 1.

14

$$15 \quad \text{MADP} = \text{RAW}/\text{TAW} \quad (1)$$

16

17 where TAW is the total available water in the root zone, i.e. between field capacity and
18 the permanent wilting point. RAW, the readily plant available water, is the proportion of
19 TAW that can be removed before transpiration and growth rate start to decline. MADP
20 depends on plant species and the evaporative conditions. Values of MADP standardized
21 to a value of $\text{ET} = 5 \text{ mm d}^{-1}$ (the reference evapotranspiration) and referred to as MADP
22 (5), have been provided by Allen *et al.* (1998) for 92 different crops. Examples are given
23 in Table 1. Standardization to an ET of 5 mm d^{-1} was by an equation that enabled values

1 of MADP to be adjusted for differences in ET, over the range $0.1 \leq \text{MADP(ET)} \leq 0.8$. It
2 is

3

$$4 \quad \text{MADP(ET)} = \text{MADP(5)} + 0.04(5-\text{ET}) \quad (2)$$

5

6 MADP(ET) is the value of MADP for a given value of ET in mm d^{-1} . Perhaps the
7 equation should be treated with some caution as there has been a long standing
8 controversy about the dependence of MADP on ET (e.g. Denmeade & Shaw 1962;
9 Ritchie 1973). These estimates of the MADP's for different crops can only be
10 approximate as Eqns (1) and (2) are assumed to hold for all soils and environments.

11 *Dynamic maximum allowable soil moisture deficits*

12 Implicit in the FAO tables of MADP(5) (Allen *et al.* 1998) is that MADP(5) for each
13 species is considered to remain constant throughout growth, even though it has long been
14 established that the sensitivity of crop growth to water stress varies during the growing
15 season (Salter & Goode 1975). Recent work summarizing the more sensitive stages of
16 growth over a range of crops is illustrated in Table 2, and emphasizes that crops are
17 particularly sensitive to water stress at flowering and seed development. Also, the method
18 does not take account of the short-term changes in evaporative demand, plant water stress
19 and growth rate during the growth period. The reason for the omission of these aspects
20 from the FAO tables could be that the bulk of experiments on which they are based only
21 reported the net effects of the soil average water deficit during growth on crop yields and
22 provided little information on the short-term changes during the growing period.
23 Typically in an irrigation experiment (Bailey 1990, p.30) treatments consisted of

1 applying irrigation whenever the soil moisture deficit fell to each of different extents
2 during growth. It enabled the minimum soil moisture deficit for maximum final yield to
3 be estimated, which together with the depth of rooting gave the MADP.

4 One possible way of obtaining better information about changes during growth of
5 allowable soil water deficits is to base it on the finding that, although growth increases
6 almost asymptotically with increase in transpiration, growth and transpiration over a wide
7 range of conditions are almost proportional to one another with a gradient that depends
8 on evaporative conditions (Guitjens 1990; Steduto *et al.* 2007). Thus in some lysimeter
9 experiments, once there is complete crop cover of the soil the rate of loss of water is
10 assumed to be proportional to growth rate. Also from the daily loss of water the average
11 soil water content can be estimated. Non-destructive measurements of transpiration and
12 soil water content as in some lysimeter experiments can provide a good indication of
13 changes in the sensitivity of growth to soil water stress over much of the growing period.

14 Another approach to the problem is to relate surrogate measures of plant growth
15 rate, such as the rate of leaf expansion, to plant available soil water (PAW) (Sadras &
16 Milroy 1996). Essentially plant measurements are made at intervals over a period during
17 which the soil water content to the depth of soil containing most roots declines. The rate
18 of the surrogate process measured on the stressed plant relative to that on the unstressed
19 plant is considered to be unaffected by fall in water content until a threshold value is
20 reached when the rate starts to fall. This threshold value and the corresponding apparent
21 maximum allowable deficit expressed as a fraction of the total available water are
22 determined. They are analogous to MADP and they are broadly consistent (Sadras &
23 Milroy 1996) with values of MADP referred to previously (Allen *et al.* 1998).

1 *The rooting depth problem*

2 All the above methods suffer from the drawback that the amount of crop available
3 water is critically dependent on the depth of rooting which is often very difficult to
4 estimate. A major problem in generalizing the results at one site to others is that rooting
5 depths are very sensitive to soil conditions (Taylor & Gardner 1963; Stalham *et al.* 2007)
6 as is illustrated by Fig. 2 which shows that root penetration can vary by four fold over the
7 normal range of soil resistances induced by compaction and by reduced soil water content.
8 Field experiments and surveys on 602 UK commercial fields of potatoes demonstrated
9 that compaction resulted in shallower rooting than is desirable for efficient use of water
10 and nutrients (Stalham *et al.* 2007). Practically useful models are needed to predict the
11 effects of soil conditions throughout growth. A possible way forward is suggested by the
12 finding that penetrometer measurements can give a good measure of the effect of soil
13 conditions on root growth at a point in time (Clark *et al.* 2005). It may be possible to
14 develop models for the dependence of penetrometer readings and thus root penetration on
15 soil texture, soil organic matter content and soil water content and thus provide a means
16 of estimating the effects of changes in soil conditions on root penetration over long
17 periods..

18 A new procedure for measuring the maximum allowable deficits without any
19 explicit requirement of rooting depth was introduced by Thompson *et al.* 2007 for crops
20 in a 40 cm deep soil. Measurements are made of volumetric water content to this depth
21 every 30 minutes. The loss of water is partitioned into drainage and transpiration losses
22 by considering that only drainage loss occurred at night. It is considered that when
23 transpiration loss divided ET starts to fall, growth is inhibited by water stress and thus

1 the MADP can be calculated from the corresponding soil water content. The idea that the
2 net changes in soil water content from drainage (and also from evaporation) can be
3 assessed from measurements during the night might have wider applications. They may
4 be relevant to estimating the depth of rooting from sensor measurements of soil water
5 down the soil profile. The depth of rooting is sometimes taken as the maximum depth at
6 which soil water content declines according to measurements at a given time of day. This
7 could be due to a combination of transpiration, drainage, and other soil processes
8 affecting water movement. Ideally what is required is the depth from which transpiration
9 removes water. By taking account of changes in soil water during the night, it should be
10 possible to separate the changes due to soil processes from those due to transpiration and
11 thus obtain a more reliable measure of rooting depth.

12

13 *Soil factors affecting irrigation need*

14 *Soil variability across the field*

15 A major limitation to irrigation efficiency of many arable crops can be differences in
16 irrigation requirement across fields which are associated with variations in soil hydraulic
17 properties (Ahuja & Nielson 1990). Ideally measurements of hydraulic properties over
18 the irrigated area need to be made and interpreted with kriging techniques to produce
19 contour diagrams of the variation in hydraulic conductivity. These measurements are,
20 however, too costly and there is a need for short-cut cheaper procedures. Soil surveys
21 provide data on soil properties to depth which is important as deep rooted crops can
22 extract much water from the subsoil. Information gained in this way, or even better by
23 direct measurement, about particle size distributions, bulk density and soil organic matter

1 content can be used to infer soil hydraulic properties by means of pedo-transfer functions
2 (PTFs). Several PTFs have been proposed including those based on the HYPRES
3 database (Lilly *et al.* 1998), which covers different European soils (Wösten *et al.* 1999).
4 Thermal imaging (Jones 2004), airborne radiometric surveys (Rawlins *et al.* 2009) and
5 grain yields which are often measured routinely across fields by farmers, can also provide
6 useful information.

7 Water use efficiency could be improved by monitoring soil water contents down
8 the soil profile, at different locations, and adjusting irrigation practice accordingly. In
9 practice it seems too time consuming and costly to do this manually, with a neutron probe
10 or similar device, but as will be shown later it should be possible to do so, relatively
11 cheaply, using soil water sensors combined with wireless technology.

12 *Distribution of irrigation water*

13 Another cause of variation is that most irrigation equipment does not distribute water
14 uniformly (Losada *et al.* 1990) and in consequence application of the amount of water
15 required to meet the average soil moisture deficit results in too little water being applied
16 at some locations and too much in others with consequent leaching and waste of water.
17 Poor water use efficiency can also be caused by irrigation failing to intercept plant roots.
18 While this is not a problem with drip irrigation, it is a problem especially with boom
19 irrigation of wide spaced crops and of pot and container plants because a large proportion
20 of the irrigation misses the plants.

21 *Infiltration of water into soil*

22 Effective irrigation requires that water penetrates soil rapidly. It is particularly important
23 for deep rooted crops. The strategy for conserving water in deep rooted soils consists of

1 applying heavy applications of water albeit occasionally. It is thus essential that the soil
2 permits rapid infiltration of water over long periods as occurs in well structured soils.
3 Rates of infiltration into some soils, however, fall very sharply to a low value shortly
4 after the start of irrigation (Kruse *et al.* 1990). Slow rates can usually be attributed to
5 compaction and small water filled pores through which water can pass only slowly but it
6 can result from the soil surfaces being water repellent (Bryant *et al.* 2007). Water
7 repellency occurs worldwide (Dekker *et al.* 2005) probably because of the deposition of
8 hydrophobic organic materials on soil surfaces (Debano 1971; Nannipieri & Badalucco
9 2003). Also some bacteria can produce extracellular polymeric substances in soil that can
10 bring about a four fold reduction in hydraulic conductivity (Or 2007).

11 Irrigation and rain can lead to surface sealing in some soils (e.g. Silva 2007); the
12 process results from disintegration of soil crumbs, swelling of soil colloids and
13 entrapment of air (Payne 1988 p.315). It has long been recognized as a major problem
14 and it has been alleviated in soils by application of soil conditioners (Ben-Hur *et al.* 1989)
15 and by various soil management practices (Abrisqueta *et al.* 2007). Barriers to water
16 penetration can of course also occur within the body of the soil profile. Well known
17 examples are plough and iron pans (Avery 1990). But such restrictions can also occur for
18 less well understood reasons; thus when a limited volume of water is added to some soils
19 the water content is brought to a uniform water content to a given depth but there is a
20 sharp boundary between this wetted soil and the unwetted soil beneath it (Russell 1973, p
21 435). The sharp transition could result from the hysteresis of the soil moisture release
22 curve (Warrick 1990) where the relation between water content and water potential
23 differs depending on whether the dry soil is wetted or whether the wet soil is dried. Water

1 moving from the wet soil to the dry soil beneath consists of desorped water moving to
2 sorped water. Owing to hysteresis the water content on the wet side could be much
3 greater than on the dry side but they both have the same water potential and thus there is
4 no transfer of water. Inducing some soils to accept substantial volumes of water can be
5 difficult but a procedure which consisted of drilling holes to a depth of 60 cm, filling
6 them with sand and then irrigating (Abu-Awwad 1998) has resulted in deep penetration
7 of water and good crops on an impermeable soil.

8 Models for infiltration are of two types. One consists of empirical relationships
9 between various measurements for a particular area. The other is derived mechanistically
10 from the Richards' equation and some of these models take account of hysteresis (Hanks
11 & Cardon 2003). As far as we are aware, however, none take account of soil water
12 repellency.

13

14

SENSORS

Required characteristics

16 Soil water sensors need to measure soil water content or the corresponding soil
17 water potential over the ranges that are found in practice. A recent survey of MADP(5)
18 on 22 different crop species gave 72 values that ranged from 0.05 to 0.81 with 26 values
19 being greater than 0.5. The majority of MADP(5) were therefore less than 0.5 (D. J.
20 Greenwood, personal communication). A proportion of 0.5 of the maximum available
21 water corresponds to a water potential of approximately -20 kPa for a loamy sand soil
22 and -200 kPa for a clay soil. A different survey gives 33 values of the soil water
23 potentials that had been found to be necessary for good growth of 16 species but only 6

1 were less than -200 kPa (D. J. Greenwood, personal communication). The results from
2 the two surveys are broadly consistent with one another and suggest that water potential
3 sensors over the range 0 to -200 kPa should cover most requirements. These values are,
4 however, averages, and water is unevenly distributed down the soil profile so the water
5 potential in a specific position, say at the uppermost sensor, could be much lower than -
6 200 kPa. Variations between sensors of the same type in their responsiveness to soil
7 water should be small otherwise the cost of calibration could be considerable. Ideally
8 sensors should need no calibration by the user, and it is notable that according to
9 Decagon Devices (2009) one of their sensors meets this requirement.

10 There is no advantage of using sensors that measure water content over those that
11 measure water potential because the ability of a given soil to supply water to plant roots
12 is governed by both water potential and water content. Irrigation requirement is
13 dependent on soil water content at field capacity and the threshold value. So whichever
14 type of sensor is used the soil moisture release curve is required to calculate the missing
15 parameter and thus the irrigation requirement.

16 *Available sensors*

17 Numerous sensors for monitoring soil water are presently on the market; there are two
18 main types; those that measure soil water content and those that measure soil water
19 potential. The majority of the former actually measure the dielectric constant of soil,
20 which is largely determined by its water content. One type of dielectric sensor, frequency
21 domain reflectometer (FDR), also referred to as a capacitance sensor, adjusts the
22 frequency of an oscillating voltage until it identifies the strongest resonating frequency,
23 which is a measure of the dielectric constant and thus the water content of the soil.

1 Another type of dielectric sensor uses the technology ‘time domain reflectometry’ (TDR)
2 to measure the dielectric constant, as the time taken for an electromagnetic pulse,
3 traveling down a rod to be reflected along its precise length. Both types of sensor,
4 although expensive, measure a wide range of bulk soil water contents. They can also
5 respond quickly to changes in soil water content (Campbell & Anderson 1998; Evett &
6 Parkin 2005; Nemali & Iersel 2006). However there is evidence that the performance of
7 some sensors may vary with the soil conditions; one commercially available capacitance
8 probe did not give reliable absolute measurements of soil water content although it
9 enabled relative changes in soil water content over time to be estimated (Mwale *et al.*
10 2005). Although they do not always give reliable measurements of soil water content,
11 dielectric sensors are generally chosen where there is a requirement to measure small but
12 rapid changes in soil water contents needed for precise control of water addition to soil.
13 For example, in container cropping where volumes of soil are small and it is essential to
14 maintain soil water contents close to a constant value, despite sudden variations in
15 evaporative conditions that in the absence of irrigation would cause rapid changes in soil
16 water content.

17 Moisture sensors that measure water potential are numerous. However, prominent
18 among sensors that have been used to measure water potential in field soils are granular
19 matrix sensors. Essentially, they consist of two concentric electrodes embedded in a
20 reference matrix material, which is surrounded by a synthetic membrane for protection
21 against deterioration (Chard 2005). When a sensor is put into moist soil, the matrix water
22 equilibrates with that in soil. Absorption of water increases the electrical conductivity of
23 the matrix and from this, the water potential of the soil can be calculated. Such sensors

1 are comparatively inexpensive, have a range of 0 to -240 kPa, can measure water
2 potentials in small volumes of soil, and have functioned satisfactorily in soil for 3.5 years
3 after installation (Qualls *et al.* 2001). They are, however, slow to respond to changes in
4 soil water content, especially in drier soils. Granular matrix sensors are usually chosen
5 when soil water changes are gradual, where many sensors are required to monitor soil
6 water to depth over considerable areas, and where satisfactory sensor performance over a
7 long period is required.

8 A novel and, probably more accurate sensor for measuring soil water potential
9 consists of porous material that equilibrates with the soil water and a dielectric device
10 that measures the water content of the porous material. A closed-form of hysteresis loop
11 is used to convert the measured water content of the porous material into water potential.
12 The use of two ceramic materials instead of one enables the sensor to measure matric soil
13 water potentials over the approximate range -10 kPa to -200 kPa. (Whalley *et al.* 2001;
14 Whalley *et al.* 2007; Whalley *et al.*, in press).

15 *Practical experience in the use of sensors*

16 Much experience has been gained on the use of soil water sensors from which the
17 following practical advice on their use has emerged.

18 (a) Sensors must be calibrated for the given soil before use. **Problems can arise,**
19 **however, because of failure to recognize that soil water potential sensors can only**
20 **operate over a limited range of water potentials and that equilibration times can be**
21 **considerable. Manufacturers of some types of sensors provide experimental**
22 **protocols for deriving calibration equations and others are published in the**
23 **scientific literature (for example, Geesing *et al.* 2004; Groves & Rose 2004). In**

1 Typical examples are container crops, lawns and urban landscapes as the rooting depths
2 are often no more than about 20 cm, often because they overlay a very compact soil layer,
3 or an extremely stony horizon that is a barrier to root penetration. The water contents in
4 such soils change very quickly and water needs to be added frequently so as to ensure
5 that the plant is never restricted by temporary water stress and yet ensure there is only
6 minimal drainage. Soil water sensors at only one depth are required for these cropping
7 systems.

8 Horticultural plants, such as ornamentals for the retail market are grown in
9 containers under evaporative conditions that are often high and vary during the day and
10 from day to day. Efficient irrigation practice has included taking readings at a specific
11 time of day and adjusting irrigation practice for the evaporative conditions (Klein 2004).
12 The amount of water that can be held in the rooting medium for container crops is small
13 so the water content can change quickly. What is required is a way of maintaining the soil
14 water at a constant value irrespective of changes in weather conditions, an objective that
15 has been achieved by Nemali & Iersel (2006). They devised a system in which a
16 controller uses dielectric substrate moisture sensors interfaced with a datalogger and
17 solenoid valves that supply irrigation. Measurements of substrate water were made every
18 20 minutes which enabled the substrate water content to be maintained within 2-3 % of
19 the target value over 40 days. The key to the success was the use of a very rapidly
20 responding dielectric sensor.

21 Sensor driven irrigation systems for urban landscapes in China and the USA are
22 described in a number of papers (e.g. Qualls *et al.* 2001; Guo *et al.* 2005). Scheduled
23 irrigations have been based on applying sufficient water to compensate for estimates of

1 water loss from evaporative demand. However, in one system (Qualls *et al.* 2001)
2 granular matrix sensors (Watermark) were embedded in soil at different points within the
3 area and transmitted their readings by wire to an electronic module that either allows or
4 prevents a scheduled irrigation cycle depending on the soil moisture condition. The
5 system was adopted on 22 sites and the average area of each site was 2177 m², resulting
6 in an average saving of 27% of water and of 331 \$US yr⁻¹ per sensor.

7 Irrigation of lawns has, as for urban landscapes, been based on supplying
8 sufficient water to compensate for estimated evaporative demand. It can result in
9 excessive drainage losses. To prevent such losses, sensors that detect free water are
10 embedded in soil at a suitable depth, and when they indicate the presence of free water
11 they send a signal that cuts off the irrigation supply (Stirzaker & Hutchinson 2005). A
12 rather more sophisticated system has been reported, using a simulation model to estimate
13 water requirement together with a subsurface time domain sensor to monitor soil water
14 content (Blonquist *et al.* 2006). Its use resulted in 53% less irrigation than the currently
15 recommended fixed rate of 50 mm water per week and also resulted in no detectable
16 drainage below 30 cm from the surface.

17 Few papers in the literature are on sensor controlled irrigation of field crops that
18 penetrate to only a shallow depth. One such paper (Kang & Wan 2005) related the growth
19 and quality of radish (*Raphanus sativus* L.) to sensor measured water potentials at 20 cm
20 from the surface. It reported that although maintaining water potentials at each of
21 different values over the range -15 to -65 kPa had no affect on yield, they affected root
22 cracking which is an important quality attribute. A literature review of irrigation
23 scheduling controlled by soil water sensors at a depth of approximately 25 cm also

1 indicated that good growth of a variety of crops required a water potential greater than -
2 65 kPa (Boote & Ketring 1990; Stanley & Maynard 1990; Wright & Stark 1990; Munoz-
3 Carpena *et al.* 2005; Wang *et al.* 2007). It is possible that at least some of these crops are
4 deep rooted.

5 As mentioned earlier, sub-surface drip irrigation (Banedjschaffe *et al.* 2008), can,
6 by minimizing evaporation from the soil surface, improve water use efficiency. It is
7 notable that water sensors at only 5 cm depth have been effectively used to control
8 decisions by irrigation from drip tapes installed 25-30 cm from the soil surface
9 (Noguerira *et al.* 2003). Sensors at shallow depths within the soil profile can therefore
10 provide useful information for irrigation scheduling.

11 *Deep rooted agricultural crops*

12 Limited support for the view that sensor determinations at about 25 cm depth may
13 provide a useful indication of irrigation need of some deeper rooted crops is provided by
14 Steiber & Shock (1995). These authors concluded that irrigation of potatoes could best be
15 determined by maintaining soil water potential above -59 kPa with sensors at a single
16 depth of between 0.1 and 0.2 m offset from the centre of the ridge.

17 Crops with roots that penetrate to a depth of 1 to 2 m can, if the soil conditions are
18 satisfactory, extract water to that depth. Many such soils are at near field capacity
19 immediately before planting, often as a result of winter rainfall or monsoon rains.
20 Considerable soil water deficits can occur on such soils without growth being inhibited.
21 Irrigating according to the distribution of soil water down the profile so as to make
22 maximum use of the stored water could therefore enable substantial saving of irrigation
23 water. As irrigation would be infrequent, the surface of the soil would be dry for long

1 periods which would reduce evaporation from it. For these reasons, some growers have
2 been using sensors to monitor soil water at different depths down the profile and using
3 the information obtained to schedule irrigation as described by free advice from extension
4 services (Thomson & Ross 1996; Werner 2002).

5 **Estimation of when and how much irrigation is required for deep rooted crops can**
6 **be based on MADP using the information and sequence of decisions summarized in Fig.3.**
7 **Determinations of the rooting depth and volumetric water content to that depth require**
8 **further explanation.** Thomson & Ross (1996) inferred the rooting depth from soil water
9 distribution measured by sensors. Other workers deduced the time course of the depth of
10 rooting from mean daily temperatures (Pedersen *et al.* 2009) or an algorithm that enables
11 the rooting depth to be calculated from plant dry weight (excluding fibrous roots), depth
12 of rooting at final harvest and an equation that defines the increase in plant dry weight
13 with time (e.g. Greenwood *et al.* 1977; Greenwood *et al.* 1982; Zhang *et al.* 2007). **The**
14 **average volumetric water content to the depth of rooting can be calculated from the**
15 **measured soil water potentials down the profile and the soil water release curves. These**
16 **calculations can be aided by models that are subsequently described.**

17

18

WIRELESS TECHNOLOGY

19

20 Wireless data acquisition and control systems (WDAC) will have an increasing impact on
21 many aspects of crop production. They enable data obtained from sensors or data loggers
22 to be received and facilitate remote control of a device through standard telephone lines,
23 computers or other communication systems. Wireless technology is widely used in spatial

1 data collection, variable rate technology and in disseminating information (Wang *et al.*
2 2006). Using WDAC systems to control irrigation should enable

3 (i) equipment to be remotely, and possibly automatically operated, for example
4 from control centre on the basis of the sensor data (Damas *et al.* 2001),

5 (ii) sensor readings at different depths and in different locations within a field to
6 be transmitted at predetermined times to a control centre where they are
7 processed, and possibly used to control equipment,

8 (iii) real time data to be made available over the Internet (Shulka *et al.* 2006) .

9

10 Much less work has been published on the use of WDAC systems for the control of
11 equipment than for the acquisition of data. Remote wireless controls of a central pivot
12 irrigation system (Pocknee *et al.* 2004) and of drip line irrigation (Coates *et al.* 2006) are
13 examples of the few publications of wireless control systems. By contrast, a literature
14 search (D.J Greenwood, personal communication) revealed 16 papers describing
15 successful wireless data acquisition systems (e.g. Bratton *et al.* 2000; Cao *et al.* 2005;
16 Kim *et al.* 2007; Vellidis *et al.* 2008). It seems that problems of installing effective
17 wireless acquisition systems have been largely solved but there are still technical
18 problems in wireless control of remote equipment. An encouraging development is that a
19 USDA group is studying wireless based irrigation control of self propelled linear-move
20 and centre-pivot irrigation equipment (Wang *et al.* 2006).

21 Recent advances for field crops include a wireless sensor means of scheduling
22 irrigation for field crops described by Vellidis *et al.* (2008). It also has the merit of being
23 inexpensive. There are three major components: nodes that are distributed throughout the

1 field and a base station that consists of a receiver to accept wireless signals from the
2 nodes and a laptop to process the signals. At each node, sensors monitor soil water
3 potential at depths of 0.2, 0.4 and 0.6 m from the soil surface. They are connected by wire
4 to a specially-designed smart circuit board, mounted on top of a flexible rod, which at
5 predetermined times obtains readings from each of the sensors, activates a radio
6 frequency identification tag (RFID) and transmits the data to the base station; during the
7 remaining periods the node 'sleeps', does not use power, and over the entire growing
8 period only requires a single 9V lithium battery. The transmitter has a range of 0.8 km
9 provided there are no obstructions in the line of site to the base station. The procedure
10 was tested in a cotton field in which there were four different soil types. It appeared to
11 give excellent measurements of the distributions of soil water potential down the profiles
12 in each of them. In addition, outputs from the laptop have been linked to a variable rate
13 central pivot irrigation system so as to supply water at rates according to the needs of
14 individual areas within fields. Complete systems of sensors, wireless transmitters and
15 receivers are now available commercially (Decagon Devices 2009) and integrated
16 wireless communication and data logger systems are also on the market (Shukla *et al.*
17 2006).

18 Improvements in commercial wine production have been achieved by controlling
19 irrigation with high density multiple depth soil moisture sensors and transmitting the
20 outputs by wireless communication at 10 minute intervals to a central PC for processing
21 and storage on a database and estimating irrigation requirements. It was also transmitted
22 to the internet via satellite where it is available on line (Holler 2008; Ulrich 2008).

1 A major opportunity for advance in sensor controlled irrigation is provided by
2 recent research in wireless sensor networks which are impacting on many subjects.
3 Essentially it is concerned with the design of networks in which some of the nodes can
4 communicate with each other so that information can travel over short distances
5 (requiring little battery power) from node to node until it reaches the base station. This
6 enables low cost sensors to be distributed over a wide area and results in long battery
7 lives at the nodes and therefore little maintenance (Hart & Martinez 2006).

8 Wireless technology has recently been introduced into glasshouse
9 cropping to facilitate the retrieval of sensor information. Prior to this innovation, sensor
10 driven irrigation has involved extensive wiring that degrades under these conditions,
11 requires substantial maintenance and is quite impracticable in modern large glasshouse
12 systems. In consequence, current work is focused on devising combined wireless-
13 transmitter-sensor modules that are distributed throughout the glasshouse and that
14 transmit to a computer controlled irrigation system (Cayanan *et al.* 2008). Such wireless-
15 soil water sensor systems for glasshouses are now marketed commercially (Hoogendoorn
16 2008).

17

18

QUANTITATIVE MODELS

19 *Simulation models for soil water and its effect on crop growth*

20 Principles about water dynamics in the soil-crop system, such as those described above,
21 have been encapsulated into simulation models that calculate changes in soil water and
22 plant growth over time. The models are of varying complexities and include SWATRE

1 (Belmans *et al.* 1983), CROPWAT (Clarke 1998), IRSIS (Raes *et al.* 1988) and SWAP
2 (Kroes *et al.* 2008) . They aim to provide a widely applicable means of estimating water
3 distributions down the soil profile and their effects on plant growth. SWAP is one of the
4 most sophisticated models of its kind. The model simulates transport of water, solutes
5 and heat in the vadose zone interactively with the development of vegetation. The
6 governing equation for soil water flow is solved using an implicit finite difference
7 method. The model has been widely tested and has given promising results. However,
8 such a complex model requires many data inputs, which could cause difficulties for any
9 user who has not got an excellent knowledge of soil and plant sciences. Furthermore, the
10 adopted chosen numerical scheme is associated with instability. The most recent model,
11 AquaCrop, developed by FAO (Steduto *et al.* 2009; Raes *et al.* 2009a, b; Hsiao *et al.*
12 2009), simulates the effects of the aerial environment and soil water on plant processes.
13 The model updates for each day a range of variables. It calculates canopy cover, root
14 distribution, stomata opening, the roots ability to meet transpiration demand and
15 transpiration. Each of these variables depends to different extents on thermal time,
16 potential evapotranspiration and soil water stress which is calculated from the fraction of
17 available soil water to the depth of rooting. Plant biomass is calculated from transpiration
18 and is modified for atmospheric CO₂ and soil fertility. Water evaporates from the soil
19 surface that is not covered by crop canopy. Water movement throughout the body of soil
20 is calculated by a cascade method using semi-empirical algorithms. The model has been
21 calibrated and tested against field experimental data for some crops with promising
22 results (e.g. Farahani *et al.* 2009; Hsiao *et al.* 2009). In the model, soil water is central to
23 controlling crop growth, but the treatment of soil movement using a cascade method

1 appears to be questionable for some circumstances such as where there is a relatively
2 high groundwater table and upward capillary flow makes an important contribution
3 towards meeting evapotranspiration. Further, the model requires a large number of inputs
4 which are often difficult to obtain such as those associated with soil water movement.
5 Cascade methods, though easy to implement, are associated with unsatisfactory
6 simulations of capillary flow and poor predictions of daily soil water changes (Gandolfi
7 *et al.* 2006; Cannavo *et al.* 2008; Yang *et al.* 2009). If a way could be found of replacing
8 the cascade method in the AquaCrop model with ones based on the fundamental theory of
9 soil water movement then the resulting model might be more widely applicable than the
10 current version.

11 *Application of classical theory of soil water movement*

12 Application of this theory, besides improving existing models for water dynamics in the
13 soil-crop system, is also important for interpreting soil water sensor data. Although there
14 are many situations where soil water content increases with depth and the total soil
15 moisture deficit can be readily obtained from the integral of a fitted empirical equation
16 between sensor measured soil water content and depth, there are other situations where
17 the patterns are complex and the fitting procedure is unsatisfactory, especially when soil
18 sensors are few. Also it is always difficult, from soil sensor measurements, to distinguish
19 between evaporative and drainage losses and crop transpiration.

20 The key to solving these problems probably lies in applying classical theory of
21 soil water transport, despite complications associated with the dependence of the soil
22 water release curve on changes in bulk density after cultivation and on whether the soil

1 water content is rising or falling (Warrick 1990). Classical theory is encapsulated in the
2 Richards' equation (Bastiaanssen *et al.* 2007; Yang *et al.* 2009). The equation is
3 differential and highly non linear and until recently complex procedures were required to
4 solve it. Often their use requires specialized expertise that many potential users lack,
5 which could explain why the cascade method for soil water movement is still favored in
6 many crop models used to solve practical problems.

7 The extremely rapid rate of computing by PCs provides an alternative and easy-
8 to-use means of solving the Richards' equation (Lee & Abriola 1999). The essential idea
9 behind the advance can best be understood by simulating water movement down a
10 column consisting of sequential soil layers with uniform thickness. It is assumed that at
11 any instant although the average water contents in each layer may differ, the water within
12 each individual layer is uniformly distributed. Water flows between adjacent layers are
13 according to the flow equation. The calculations are repeated for a very small time step in
14 the order of 0.001 day, and give estimates of water distribution that are similar to those
15 obtained by solving the Richards equation using the finite element method.

16 A new model, by extending the work by Lee and Abriola (1999), has recently
17 been constructed for simulating water dynamics in the soil-crop system (Yang *et al.*
18 2009). The model treats infiltration of water into the surface layer and evaporation from it;
19 it also includes algorithms for root growth and the associated transpiration. Potential
20 evaporation and transpiration are estimated from Allen *et al.* (1998). Soil hydraulic
21 functions are those defined by Van Genuchten (1980) and Mualem (1976). Simulations
22 with the model of the distributions of water down the soil profile in different cropped
23 soils at time intervals during growth were in excellent agreement with measurements

1 (Yang *et al.* 2009). The model as such could be used to predict irrigation requirements as
2 shown in Fig. 3.

3 In the sensor based irrigation system, a model of this kind can be calibrated
4 against the sensor data and then used to calculate the daily distributions of water down
5 the profile and the evaporative and drainage losses. To calibrate the model, inverse
6 modeling techniques, based on optimization theory to obtain the best fit between
7 simulation and measurement could be used to estimate uncertain parameter values. One
8 possible set of parameters for such estimation are those defining soil hydraulic properties
9 which are often determined by pedofunctions (PTFs) in terms of percentages of clay, silt,
10 and soil organic matter and bulk densities as proposed by Wösten *et al.* (1999) and
11 Cresswell *et al.* (2006). Estimating soil hydraulic properties using PTFs is widely applied,
12 but has proved to be not accurate enough on many occasions. Also, inverse modeling
13 techniques can be employed to deduce root development and root distribution for the
14 given soil.

15

16

FUTURE DEVELOPMENTS

17

18 The developments so far discussed will lead to improvements in water use
19 efficiency for crop production and amenity horticulture. The pressing need is to introduce
20 better means of adjusting irrigation for differences in soil and weather
21 conditions. Irrigation is often applied in amounts sufficient to compensate for predicted
22 water losses without proper consideration of soil water. Inevitably the plants do not make

1 full use of the water stored in the soil. Irrigation practice needs to take account of the
2 ability of crops to sustain near maximum growth rate even when the soil water content is
3 well below that at field capacity and also of the ability of deep rooted crops to satisfy
4 much of their needs for water from the subsoil. Several advances provide ways of
5 quantitatively meeting these requirements, especially the development of soil water
6 sensors, improved understanding crop-soil water relationships and the development of
7 mechanistic models for soil water dynamics. Serious consideration should be given to
8 developing a combined strategy for using the sensor measurements and model predictions
9 to improve irrigation practice.

10 Full use needs to be made of the rapid progress of wireless networking for
11 collecting and disseminating data. Research is also required to improve soil water
12 sensors. They need to be less expensive, to cover a wider range of soil water potentials
13 and to respond more rapidly to change in water contents. Methods of assessing irrigation
14 requirement should be sought that do not involve estimates of water content at field
15 capacity as its determination is rather subjective and inaccurate. Inexpensive but rapid
16 means of assessing soil texture or hydraulic properties down the soil profile are required
17 to estimate their variation across fields and to allow accurate calculations of the
18 distribution of soil water down the soil profile from sensor measurements at specific
19 points.

20 Within the foreseeable future many irrigation systems will have soil water and
21 temperature sensors at pre-determined positions and depths throughout the irrigation
22 area. Data from them will be wireless-transmitted to a base station, processed and used
23 to adjust irrigation across the area according to need. It is also likely that the latter

1 process will become fully automated and that all the information will be placed on the
2 internet so that, amongst other things, a remote operator could, if the need arises,
3 overwrite the automatic system. This will result in less waste of water and more efficient
4 use of operator's time.

5

6

CONCLUSIONS

- 7 • High yields of many crops can be obtained even when the soil moisture content to the
8 depth of rooting is maintained far below that at field capacity. This means that
9 irrigation practice can be better adapted so that water loss from drainage and from
10 evaporation from moist soil surfaces is minimized and transpiration requirements can
11 be largely met from water stored in the subsoil. Other crops, however, are much more
12 sensitive to water stress, and more generally there are stages of growth at which crops
13 are particularly sensitive to water stress
- 14 • Simulation models of varying complexity have been introduced for predicting the
15 effects of soil water on crops and their validity tested in field experiments. The
16 models, however, need to incorporate algorithms for classical soil water theory for
17 improving the predictions and widening their application since the computational
18 difficulties of doing so have now been largely overcome. They should, amongst other
19 things, improve the estimation of irrigation requirements from soil sensor
20 measurements of soil water down the profile.
- 21 • Spatial differences in soil hydraulic properties and thus various irrigation needs
22 across a field mean that a uniform application of water results in some areas receiving

1 too much water and others too little. Water can only penetrate some soils extremely
2 slowly either because of their physical properties or because of their water repellency.
3 Greater spatial and temporal control of irrigation may address these problems.

- 4 • Commercially available soil water sensors range from high performance expensive
5 sensors that are required for precise monitoring in some intensive horticulture, to
6 poorer performance sensors that are sufficiently inexpensive for large numbers to be
7 used in monitoring soil water to depth across a substantial area.
- 8 • Sensors have been installed at a given depth throughout large glasshouses and also
9 over urban landscapes and their outputs used to automatically control irrigation. They
10 have also been installed at different depths in deep soils beneath field crops at
11 representative stations throughout the irrigated area and the outputs from the sensors
12 collected by a central PC.
- 13 • Wireless technology is greatly extending the use that can be made of soil water
14 sensors in improving irrigation practice. Key features include nodes consisting of
15 smart circuit boards at different positions within a field to collect local sensor data
16 and transmit it to a central PC for processing. Installation of nodes that can ‘talk’ to
17 one another enable low cost sensors to be distributed and collect information over a
18 wide area and require little maintenance. Progress is being made in deducing from
19 such sensor information how applications of water should be varied across fields and
20 how this information can be implemented by wireless controlled remote equipment.

21

22

23

ACKNOWLEDGEMENTS

1

2 The work was partially funded by the EU project Grant Agreement Number: 222440. The
3 Project is funded by the Seventh Framework Programme of the European Community for
4 research, technological development and demonstration activities (2007-2013) under the
5 Specific Programme “Capacities” (Research for the Benefit of SMEs).

6

7

REFERENCES

8

9 ABRISQUETA, J. M., PLANA, V., MOUNZER, O. H., MENDEZ, J. & RUIZ-
10 SANCHEZ, M. C. (2007). Effects of soil tillage on runoff generation in a Mediterranean
11 apricot orchard. *Agricultural Water Management* **93**, 11-18.

12

13 ABU-AWWAD, A. M. (1998). Influence of vertical sand column and supplemental
14 irrigation on barley yield in arid soils affected by surface crust. *Irrigation Science* **18**,
15 101-107.

16

17 AHUJA, L. R. & NIELSEN, D. R. (1990). Field soil-water relations, In *Irrigation of*
18 *Agricultural Crops*. (Eds B. A Stewart & D. R Nielsen), pp. 143-190. Madison USA:
19 ASA CSSA SSSA.

20

21 ALLEN, R. G., PERIERA, L. S., RAES, D. & SMITH M. (1998). Crop
22 evapotranspiration. Guidelines for computing crop water requirements. *FAO Irrigation*
23 *and Drainage Paper 56*. Rome: FAO.

1

2 AL-KAISI, M. M. & BRONER, I. (2005). *Irrigation: crop water use and growth stages*,
3 *No 4. 715 Colorado State University Cooperative Extension.*

4

5 **AVERY, B.W. (1990). *Soils of the British Isles*. Wallingford, UK: C.A.B. International.**

6

7 BACCI, L., BATTISTA , P., RAPI, B., SABATINI, F. & CHECCACCI, E. (2003).
8 Irrigation control of container crops by means of tensiometers. *Acta Horticulturae* **609**,
9 467-474.

10

11 BAILEY, R. (1990). *Irrigated Crops and Their Management*. Ipswich, UK: Farming
12 Press Books.

13

14 BANEDJSCHAFIE, S, BASTANI, S, WIDMOSER, P. & MENGEL, K. (2008).
15 Improvement of water use efficiency and N-fertilizer efficiency by subsoil irrigation of
16 winter wheat. *European Journal of Agronomy* **28**, 1-7.

17

18 BASTIAANSEN, W. G. M., ALLEN, R. G., DROOGERS, P., D'URSO, G. &
19 STEDUTO, P. (2007). Twenty-five years modeling irrigated and drained soils: State of
20 the art. *Agricultural Water Management* **92**, 111-125.

21

22 BELMANS, C., WESSELING, J. G. & FEDDES, R. A. (1983). Simulation model of the
23 water balance of cropped soil: SWATRE. *Journal of Hydrology* **63**, 271-286.

24

- 1 BEN-HUR, M., FARIS, J., MALIK, M. & LETEY, J. (1989). Polymers as soil
2 conditioners under consecutive irrigations and rainfall. *Soil Science Society of America*
3 *Journal* **53**, 1173-1177.
- 4
- 5 BLONQUIST, J. M. Jr., JONES, S. B. & ROBINSON, D. A. (2006). Precise irrigation
6 scheduling for turfgrass using a subsurface electromagnetic soil moisture sensor.
7 *Agricultural Water Management* **84**, 153-165.
- 8
- 9 BOOTE, K. J. & KETRING, D. L. (1990). Peanut. In *Irrigation of Agricultural Crops*.
10 (Eds B. A Stewart & D. R Nielsen), pp. 675-717. Madison, USA: ASA CSSA SSSA.
- 11
- 12 BRATTON, W. L., SHINN, J. D., FARRINGTON, S. P. & BIANCHI, J. C. (2000).
13 Water management using soil moisture sensor networks to determine irrigation
14 requirements. (ASAE Publication 701P0004). In: *Proceedings of the 4th Decennial*
15 *Symposium*. pp. 485-490. Phoenix, Arizona, USA: American Society of Agricultural
16 Engineers.
- 17 BRYANT, R., DOERR, S. H., HUNT, G. & CONAN, S. (2007). Effects of compaction
18 on soil surface water repellency. *Soil Use and Management* **23**, 238-244.
- 19
- 20 CAMPBELL, G. S. & ANDERSON, R. Y. (1998). Evaluation of simple transmission
21 line oscillators for soil moisture measurement. *Computers and Electronics in Agriculture*
22 **20**, 31-44.
- 23

- 1 CANNAVO, P., RECOUS, S., PARNAUDEAU, V. & REAU, R. (2008). Modelling N
2 dynamics to assess environmental impacts of cropped soils. *Advances in Agronomy* **97**,
3 131-174.
4
- 5 CAYANAN, D. F., DIXON, M. & ZHENG, Y. (2008). Development of an automated
6 irrigation system using wireless technology and root zone environmental sensors. *Acta*
7 *Horticulturae* **797**, 167-171.
8
- 9 CAO, C. M., XIA, P. & ZHU, Z. Q.. (2005). Application of wireless data transmission to
10 the automatic control of water saving irrigation. *Transactions of the Chinese Society of*
11 *Agricultural Engineering* **21**, 127-130.
12
- 13 CHARD, J. (2005). Watermark soil moisture characteristics and operating instructions
14 **Utah: Utah State University.**
15
- 16 CLARK, L. J., GOWING, D. J. G., LARK, R. M., LEEDS-HARRISON, P. B.,
17 MILLER, A. J., WELLS, D. M., WHALLEY, W. R. & WHITMORE, A. P.
18 (2005). Sensing the physical and nutritional status of the root environment in the field: a
19 review of progress and opportunities. *Journal of Agricultural Science* **143**, 347-358.
20
- 21 CLARKE, D. (1998). *Cropwat for windows: user guide*. Rome: FAO.
22
- 23 CLAY, J. (2004). World Agriculture and the Environment: A Commodity-by-
24 Commodity Guide to Impacts and Practices. 570pp. Washington D. C: Island Press,

1

2 COATES, R. W., DELWICHE, M. J. & BROWN, P. H. (2006). Design of a system for
3 individual sprinkler control. *Transactions of the American Society of Agricultural and*
4 *Biological Engineers* **49**, 1963-1970.

5

6 COSTA, J. M., ORTUÑO, M. F. & CHAVES M. M. (2007). Deficit irrigation as a
7 strategy to save water: physiology and potential application to horticulture. *Journal of*
8 *Integrative Plant Biology* **49**, 1421-1434.

9

10 CRESSWELL, H. P., COQUET, Y, BRUAND, A. & MCKENZIE, N. J. (2006). The
11 transferability of Australian pedotransfer functions for predicting water retention
12 characteristics of French soils. *Soil Use and Management* **22**, 62-70.

13

14 DAMAS, M., PRADOS, A. M., GÓMEZ, F. & OLIVARES, G. (2001). HidroBus system:
15 fieldbus for integrated management of extensive areas of irrigated land. *Microprocessors*
16 *and Microsystems* **25**, 177-184.

17

18 DEBAEKE, P. & ABOUDRARE, A. (2004). Adaptation of crop management to water-
19 limited environments. *European Journal of Agronomy* **21**, 433-446.

20

21 DEBANO, L. F. (1971). The effect of hydrophobic substances on water movement in soil
22 during infiltration. *Soil Science Society of America Proceedings* **35**, 340- 343.

23

- 1 DECAGON DEVICES. (2009). Soil moisture systems. <http://www.decagon.com>
2 (accessed 31.07.09).
3
- 4 DEKKER, L. W., OOSTINFIE, K. & RITSWIA, C. J. (2005). Exponential increase of
5 publications related to soil water repellency. *Australian Journal of Soil Research* **43**, 403-
6 441.
7
- 8 DENMEADE, O. T. & SHAW, R. H. (1962). Availability of soil water to plants as
9 affected by soil moisture content and meteorological conditions. *Agronomy Journal* **54**,
10 385-390.
11
- 12 EUROPEAN COMMISSION. (2000). The environmental impacts of irrigation in the
13 European Union. 147pp. <http://ec.europa.eu/environment/agriculture/pdf/irrigation.pdf>.
14 (accessed 31.07.09).
- 15 EVETT, S. R. & PARKIN, G. W. (2005). Advances in soil water content sensing: the
16 continuing maturation of technology and theory. *Vadose Zone Journal* **4**, 986-991.
17
- 18 FAO. (2008). <http://www.fao.org/nr/water/issues/scarcity.html> (accessed 31.07.09).
19
- 20 FARAHANI, H. J., IZZI, G. & OWEIS, T. Y. (2009). Parameterization and evaluation of
21 the AquaCrop model for full and deficit irrigated cotton. *Agronomy Journal* **101**, 469-476.
22

- 1 FAROOQ, M., KOBAYASHI, N., WAHID, A., ITO, O. & BASRA, S.M.A. (2009).
2 Strategies for producing more rice with less water. *Advances in Agronomy* **101**: 351-388
3
- 4 FERERES, E. & SORIANO, M. A. (2007). Deficit irrigation for reducing agricultural
5 water use. *Journal of Experimental Botany* **58**, 147-159.
6
- 7 GANDOLFI, C., FACCHI, A. & MAGGI, D. (2006). Comparison of 1D models of water
8 flow in unsaturated soils. *Environmental Modelling & Software* **21**, 1759-1764.
9
- 10 GEESING, D., BACHMAIER, M. & SCHMIDHALTER, U. (2004). Field calibration of
11 a capacitance soil water probe in heterogeneous fields. *Australian Journal of Soil*
12 *Research* **42**, 289-299.
13
- 14 GREENWOOD, D. J., CLEAVER, T. J., LOQUENS, S. M. H. & NIENDORF, K. B.
15 (1977). Relationship between plant weight and growing period for vegetable crops in the
16 United Kingdom. *Annals of Botany* **41**, 987-97.
17
- 18 GREENWOOD, D. J., GERWITZ, A., STONE, D. A. & BARNES, A. (1982). Root
19 development of vegetable crops. *Plant and Soil* **68**, 75-96.
20
- 21 GROVES, S. J. & ROSE, S. C. (2004). Calibration equations for Diviner 2000
22 capacitance measurements of volumetric soil water content of six soils. *Soil Use and*
23 *Management* **20**, 96-97.
24

1

2 GUO, J., ZHENG, W., ZHAO, C., LI, K. & WANG, J. (2005). Design and
3 implementation of supervision and control system based on SMS for irrigation system in
4 middle of isolated grassland of highway. *Water Saving Irrigation* **3**, 21-23.

5

6 HANKS, R. J & CARDON, G. E. (2003). Soil water dynamics . In *Handbook of*
7 *processes and modelling in the soil plant system* (Eds D.K. Benbi & R Neider), pp. 261-
8 278. Binghampton, New York: The Haworth Reference Press.

9

10 HART, J. K. & MARTINEZ, K. (2006). Environmental sensor networks: a revolution in
11 the earth system science? *Earth-Science Reviews* **78**, 177-191.

12

13 HATFIELD, J. L. (1990). Methods of estimating evapotranspiration In *Irrigation of*
14 *Agricultural Crops*. (Eds B. A Stewart & D. R Nielsen), pp. 435-474. Madison USA:
15 ASA CSSA SSSA.

16

17 HILLS, F. J., WINTER, S. R. & HENDERSON D. W. (1990). Sugarbeet. In *Irrigation*
18 *of Agricultural Crops*. (Eds B. A Stewart & D. R Nielsen), pp 796-810. Madison USA:
19 ASA CSSA SSSA.

20

21 HOLLER, M. (2008). High density multiple depth soil moisture tension measurements
22 for irrigation management

1 <http://www.xbow.com/Eko/Images/High%20Density,%20Multiple%20Depth,%20Wireless%20Soil%20Moisture.pdf> (accessed 31.07.09)

3

4 HOOGENDOORN, (2008). Sensiplant: the easy wireless solution for pot plant
5 cultivation. http://www.hoogendoorn-uk.com/sensiplant_uk.htm. (accessed 31.07.09)

6

7 HSIAO, T. C., HENG, L., STEDUTO, P., ROJAS-LARA, B., RAES, D. & FERERES, E.
8 (2009). AquaCrop—The FAO Crop Model to Simulate Yield Response to Water: III.
9 Parameterization and testing for maize. *Agronomy Journal* **101**, 448-459.

10

11 JADOON, K. Z., SLOB, E., VANCLOOSTER, M., VEREECKEN, H. & LAMBOT, S.
12 (2008). Uniqueness and stability analysis of hydrogeophysical inversion for time-lapse
13 ground-penetrating radar estimates of shallow soil hydraulic properties. *Water Resources*
14 *Research* **44**, W09421.

15

16 JENSEN, M. E., RANGELEY, W. R. & DIELEMAN, P. J. (1990). Irrigation trends in
17 world agriculture. In *Irrigation of Agricultural Crops*. (Eds B. A Stewart & D. R Nielsen),
18 pp. 31-67. Madison USA: ASA CSSA SSSA.

19

20 JONES, H. G. (2004). Irrigation scheduling: advantages and pitfalls of plant-based
21 methods. *Journal of Experimental Botany* **55**, 2427-2436.

22

- 1 JONES, C. A., SANTO, L. T., KINGSTON, G. & GASHO, G. J. (1990). Sugarcane. In
2 *Irrigation of Agricultural Crops*. (Eds B.A. Stewart & D. R. Nielsen), pp. 837-858.
3 Madison USA: ASA CSSA SSSA.
4
- 5 KANG, Y. & WAN, S. (2005). Effect of soil water potential on radish (*Raphanus sativus*
6 *L.*) growth and water use under drip irrigation. *Scientia Horticulturae* **106**, 275 – 292.
7
- 8 KIM, Y., EVANS, R. G. & IVERSEN, W. M. (2007). The future of intelligent
9 agriculture: wireless site-specific irrigation. *Resource Engineering & Technology for a*
10 *Sustainable World*. **14**: 12-13.
11
- 12 KLEIN, I. (2004). Scheduling automatic irrigation by threshold-set soil matric potential
13 increases irrigation efficiency while minimizing plant stress. *Acta Horticulturae* **664**,
14 361-368.
15
- 16 KRIEG, D. R. & LASCANO, R. J. (1990). Sorghum. In *Irrigation of Agricultural Crops*.
17 (Eds B.A. Stewart & D. R. Nielsen). pp. 719-739. Madison USA: ASA CSSA SSSA.
18
- 19 KROES, J. G., VAN DAM, J. C., GROENENDIJK, P., HENDRIKS, R. F. A. &
20 JACOBS, C. M. J. (2008). *SWAP version 3.2: Theory description and user manual*.
21 *Alterra Report 1649*, 262 pp. Wageningen: . Alterra.
22

- 1 KRUSE, E. G., BUCKS, D. A., & VON BERNUTH, R. D. (1990). Comparison of
2 irrigation systems In *Irrigation of Agricultural Crops*. (Eds B.A. Stewart & D. R.
3 Nielsen), pp. 475- 508. Madison USA: ASA CSSA SSSA.
4
- 5 LAMBOT, S., BINLEY, A., SLOB, E. & HUBBARD, S. (2008). Ground penetrating
6 radar in hydrogeophysics. *Vadose Zone Journal* **7**, 137-283.
7
- 8 LEE, D. H. & ABRIOLA, L. M. (1999). Use of the Richards equation in land surface
9 parameterizations. *Journal of Geophysical Research* **104**, 27519-27526.
10
- 11 LILLY, A., WÖSTEN, J.H.M., NEMES, A. & LE BAS, C., (1998). The development
12 and use of the HYPRES Database in Europe. In: *Proceedings of the International*
13 *Workshop on Characterisation and Measurement of the Hydraulic Properties of*
14 *Unsaturated Porous Media*. (Eds M. Th. van Genuchten, F. J. Leij & L. Wu), pp1283-
15 1294. Riverside USA: University of California
16
- 17 LOSADA, A., JUANA, L. & ROLDÁN, J. (1990). Operation diagrams for irrigation
18 management. *Agricultural Water Management* **18**, 289-300.
19
- 20 MCNAUGHTON, K. G. & JARVIS, P. G. (1984). Using the Penman-Monteith equation
21 predictively. *Agriculture Water Management* **8**, 263-278.
22

- 1 MEYER, W. S. & GREEN, G. C. (1980). Water use in wheat and plant indicators of
2 available soil water. *Agronomy Journal* **72**, 253-257.
3
- 4 MONTEITH, J. L. (1973). *Principles of environmental soil physics*. London: Edward
5 Arnold.
6
- 7 MUALEM, Y. (1976). A new model for predicting the hydraulic conductivity of
8 unsaturated porous media. *Water Resource Research* **12**, 513-522.
9
- 10 MUCHOW, R. C. & SINCLAIR, T. R. (1991). Water deficit effects on maize yields
11 modelled under current and greenhouse climates. *Agronomy Journal* **83**, 1052-1059.
12
- 13 MUNOZ-CARPENA, R., DUKES, M. D., LI, Y. C. & KLASSEN, W. (2005). Field
14 comparison of tensiometer and granular matrix sensor automatic drip irrigation on tomato.
15 *Horttechnology* **15**, 584-590.
16
- 17 MUSICK, J. T. & PORTER, K. B. (1990). Wheat. In *Irrigation of Agricultural Crops*.
18 (Eds B. A Stewart & D. R Nielsen), pp. 597-638. Madison USA: ASA CSSA SSSA.
19
- 20 MWALE, S.S., AZAM-ALI, S. N. & SPARKES, D. L. (2005). Can the PR1 capacitance
21 probe replace the neutron probe for routine soil-water measurement? *Soil Use and*
22 *Management* **21**, 340-347
23

- 1 NANNIPIERI, P. & BADALUCCO, L. (2003). Biological processes. In: *Handbook of*
2 *processes and modeling in the soil-plant system*. (Eds D K Benbi & R Nieder), pp. 57-82.
3 Binghampton, New York: The Haworth Reference Press.
4
- 5 NEMALI, K. S. & IERSEL, M. W. (2006). An automated system for controlling drought
6 stress and irrigation in potted plants. *Scientia Horticulturae* **110**, 292-297.
7
- 8 NOGUEIRA, L. C., DUKES, M. D., HAMAN D. Z., SCHOLBERG, J. M. & CORNEJO,
9 C. (2003). Data acquisition system and irrigation controller based on CR10X Datalogger
10 and TDR sensor. *Soil Crop Science Society of Florida Proceedings* **62**, 38-46.
11
- 12 OR, D., PHUTANE, S. & DECHESNE, A. (2007). Extracellular polymeric substances
13 affecting pore-scale hydrologic conditions for bacterial activity in unsaturated soils.
14 *Vadose Zone Journal* **6**, 298-305.
15
- 16 PANDA, R. K., BEHERA, S. K. & KASHYAP, P.S. (2003). Effective management of
17 irrigation water for wheat under stressed conditions. *Agricultural Water Management* **63**,
18 37-56.
19
- 20 PAYNE, D. (1988). The behaviour of water in soil. In: *Russell's soil conditions and plant*
21 *growth* (Ed A Wild). London: Longman Scientific and Technical.
22

- 1 PEDERSEN, A., ZHANG, K., THORUP-KRISTENSEN, K. & JENSEN, L. S. (2009).
2 Modelling diverse root density dynamics and deep nitrogen uptake – A simple approach.
3 *Plant and Soil*. [doi:10.1007/s11104-009-0028-8](https://doi.org/10.1007/s11104-009-0028-8).
4
- 5 PENMAN, H. L. (1948). Natural evaporation from open water, bare soil and grass.
6 *Proceedings of the Royal Society A, London* **193**, 120-145.
7
- 8 POCKNEE, S., GARRICK, V. & KVIEN, C. (2004). Wireless local area network
9 technology for on-farm monitoring and control. In: *Proceedings of the 7th International*
10 *conference on precision agriculture and other precision resource management*. St Paul,
11 USA: University of Minnesota.
12
- 13 QUALLS, R. J., SCOTT, J. M. & DEOREO, W. B. (2001). Soil moisture sensors for
14 urban landscape irrigation: Effectiveness and reliability. *Journal of the American Water*
15 *Resources Association* **37**, 547-559.
16
- 17 RAES, D., LEMMENS, H., VAN AELST, P., VANDEN BULCKE, M. & SMITH, M.
18 (1988). IRSIS- Irrigation scheduling information system. *Volume 1. Manual., Reference*
19 *Manual 3. Department of Land Management, K.U. Leuven University*. Leuven Belgium:
20 Leuven University
21
- 22 RAES, D., STEDUTO, P., HSIAO, T.C. & FERERES, E. (2009a). AquaCrop Reference
23 Manual. Rome: FAO

1

2 RAES, D., STEDUTO, P., HSIAO, T. C. & FERERES, E. (2009b). AquaCrop—The
3 FAO Crop Model to Simulate Yield Response to Water: II. Main algorithms and software
4 description. *Agronomy Journal* **101**, 438-447.

5

6 RAGAB, R. (1995). Towards a continuous operational system to estimate the root zones
7 soil moisture from intermittent remotely sensed surface moisture. *Journal of Hydrology*
8 **173**, 1-25.

9

10 RAWLINS, B. G., MARCHANT, B. P., SMYTH, D., SCHEIB, C., LARK, R. M &
11 JORDAN, C. (2009). Airborne radiometric survey data and a DTM as covariates for
12 regional scale mapping of soil organic carbon across Northern Ireland. *European Journal*
13 *of Soil Science* **60**, 44-54.

14

15 RITCHIE, J. T. (1973). Influence of soil water status and meteorological conditions on
16 evaporation from a corn canopy. *Agronomy Journal* **65**, 893-897.

17

18 ROSENTHAL, W. D., ARKIN, G. F., SHOUSE, P. J. & JORDAN, W. P. (1987). Water
19 deficit effects on transpiration and leaf growth. *Agronomy Journal* **79**, 1019-1026.

20

21 RUSSELL, E. J. (1973). *Soil conditions and plant growth*. 10th edn. London: Longman.

22

- 1 SADRAS, V. O. & MILROY, S. P. (1996). Soil-water thresholds for the responses of
2 leaf expansion and gas exchange: A review. *Field Crops Research* **47**, 253-266.
3
- 4 SADRAS, V. O., VILLALOBOS, F. J. & FERERES, E. (1993). Leaf expansion in field
5 grown sunflower in response to soil and leaf water status. *Agronomy Journal* **85**, 564-570.
6
- 7 SAEED, H., GROVE, I. G., KETTLEWELL, P. S. & HALL, N. W. (2008). Potential of
8 partial rootzone drying as an alternative irrigation technique for potatoes. *Annals of*
9 *Applied Biology* **152**, 71-80.
10
- 11 SALTER, P. J. & GOODE, J. E. (1967). Crop responses to water at different stages of
12 growth. Farnham Royal, UK: Commonwealth Agricultural Bureaux.
13
- 14 SAVVA, A. P. & FRENKEN, K., (2002). Crop water requirements and irrigation
15 scheduling. *Irrigation Manual Module 4, FAO*. Harare: FAO.
16
- 17 SHUKLA, S., YU, C. Y., HARDIN, J. D. & JABER, F. H. (2006). Wireless data
18 acquisition and control systems for agricultural water management projects.
19 *HortTechnology* **16**, 595-604.
20
- 21 SILVA, L. L. (2007). Fitting infiltration equations to centre-pivot irrigation data in a
22 Mediterranean soil. *Agricultural Water Management* **94**, 83-92.
23

- 1 STALHAM, M. A., ALLEN, E. J., ROSENFELD, A. B. & HERRY, F. X. (2007). Effects
2 of soil compaction in potato (*Solanum tuberosum*) crops. *Journal of Agricultural Science*
3 *Cambridge* **145**, 295-312.
- 4
- 5 STANLEY, C. D. & MAYNARD, D. N. (1990). Vegetables. In *Irrigation of Agricultural*
6 *Crops*. (Eds B. A Stewart & D. R Nielsen), pp 921-950. Madison USA: ASA CSSA
7 SSSA.
- 8
- 9 STEDUTO, P., HSIAO, T. C. & FERERES, E. (2007). On the conservative behaviour
10 of biomass mass productivity. *Irrigation Science* **25**, 189-207.
- 11
- 12 STEDUTO, P., HSIAO, T. C., RAES, D. & FERERES, E. (2009). AquaCrop—The FAO
13 Crop Model to Simulate Yield Response to Water: I. Concepts and underlying principles.
14 *Agronomy Journal* **101**, 426–437.
- 15
- 16 STEWART, B. A. & NIELSEN, D. R. (eds) (1990). *Irrigation of Agricultural Crops*.
17 *Agronomy No 30*. pp. 1218. Madison USA: ASA CSSA SSSA.
- 18
- 19 STIEBER, T. D. & SHOCK, C. C. (1995). Placement of soil moisture sensors in
20 sprinkler irrigated potatoes. *American Potato Journal* **72**, 533-543.
- 21

- 1 STIRZAKER, R. J. & HUTCHINSON, R. A. (2005). Irrigation controlled by a wetting
2 front detector: field evaluation under sprinkler irrigation. *Australian Journal of Soil*
3 *Research* **43**, 935-943.
- 4
- 5 TAYLOR, H. M. & GARDNER, H. R. (1963). Penetration of cotton seedling tap roots as
6 influenced by bulk density, moisture content, and strengths of soil. *Soil Science* **96**, 153-
7 156.
- 8
- 9 THOMSON, S. J. & ROSS, B. B. (1996). Using soil moisture sensors for making
10 irrigation management decisions in Virginia. Virginia Co-operative Extension: Biological
11 Systems Engineering Publication 442-024.
- 12
- 13 THOMPSON, R. B., GALLARDO, M., VALDEZ, L. C. & FERNANDEZ, M. D. (2007).
14 Determination of lower limits for irrigation management using in situ assessments of
15 apparent crop water uptake made with volumetric soil water content sensors. *Agricultural*
16 *Water Management* **92**, 13-28.
- 17
- 18 ULRICH, T. (2008). Wireless Network monitors H₂O system saves resources, increases
19 yield in Cabaret vineyard. *Wines & Vines Magazine*. July issue.
- 20
- 21 VAN GENUCHTEN, M. TH. (1980). A closed-form equation for predicting the
22 hydraulic conductivity of unsaturated soils. *Soil Science Society of America Journal* **44**,
23 892-898.

1

2 VELLIDIS, G., TUCKER, M., PERRY, C., KVIEN, C. & BEDNARZ, C. (2008). A real-
3 time wireless smart sensor array for scheduling irrigation. *Computers and Electronics in*
4 *Agriculture* **61**, 44-50.

5

6 WANG, F., KANG, Y., LIU, S. & HOU, X. (2007). Effects of soil matric potential on
7 potato growth under drip irrigation in the North China Plain. *Agriculture Water*
8 *Management* **88**, 34-42.

9

10 WANG, N., ZHANG, N. & WANG, M. (2006). Wireless sensors in agriculture and food
11 industry – recent development and future perspective. *Computers and Electronics in*
12 *Agriculture* **50**, 1-14.

13

14 WARRICK, A. W. (1990). Nature and dynamics of soil water. In *Irrigation of*
15 *Agricultural Crops*. (Eds B. A Stewart & D. R Nielsen), pp 69-92. Madison USA: ASA
16 CSSA SSSA.

17

18 WERNER, H. (2002). *Measuring soil water for irrigation management. Publication FS*
19 *876. Dakota: College of Agriculture and Biological Sciences, South Dakota State*
20 *University.*

21

- 1 WHALLEY, W.R., WATTS, C.W., HILHORST, M.A., BIRD, N.R.A., BALENDONCK,
2 J. & LONGSTAFF, D. J. (2001). The design of porous material sensors to measure
3 matric potential of water in soil. *European Journal of Soil Science* **52**, 511-519.
4
- 5 WHALLEY, W.R., CLARK, L.J., TAKE, W.A, BIRD, N.R.A., LEECH, P.K., COPE,
6 R.E. & WATTS, C.W. (2007). A porous-matrix sensor to measure the matric potential of
7 soil water in the field. *European Journal of Soil Science* **58**, 18–25.
8
- 9 WHALLEY, W. R., LOCK, G., JENKINS, M., PELOE, T., BUREK, K.,
10 BALENDONCK, J., TAKEI, W. A., TUZEL, H. & TUZEL, Y. (in press). Measurement
11 of low matric potentials with porous matrix sensors and water filled tensiometers. *Soil*
12 *Science Society of America Journal*.
13
- 14 WÖSTEN, J. H. M., LILLY, A., NEMES, A. & LE BAS, C. (1999). Development and
15 use of a database of hydraulic properties of European soils. *Geoderma* **90**, 169-185.
16
- 17 WRIGHT, J. L. & STARK, J. C. (1990). Potato. In *Irrigation of Agricultural Crops*. (Eds
18 B. A Stewart & D. R Nielsen), pp 859-888. Madison USA: ASA CSSA SSSA.
19
- 20 YANG, D., ZHANG, T., ZHANG, K., GREENWOOD, D. J., HAMMOND, J. P. &
21 WHITE, P. J. (2009). An easily implemented agro-hydrological procedure with dynamic
22 root simulation for water transfer in the crop–soil system: Validation and application.
23 *Journal of Hydrology* **370**, 177-190.

1

2 ZHANG, K., GREENWOOD, D. J., WHITE, P. J. & BURNS, I. G. (2007). A dynamic
3 model for the combined effects of N, P and K fertilizers on yield and mineral
4 composition: description and experimental test. *Plant and Soil* **298**, 81-98.

5

Table 1. *Some values of the maximum allowable deficit expressed as a proportion of the available water to the depth of rooting (MADP(5)) and standardized to an ET of 5 mm d⁻¹ (after Allen et al. 1998).*

Crop	Maximum rooting depth (m)	MADP(5)
Small vegetables		
Brussels sprouts	0.4-0.6	0.45
Spinach	0.3-0.5	0.2
Vegetables Solanum family		
Tomato	0.7-1.6	0.4
Vegetables cucumber family		
Sweet melons	0.8-1.6	0.4
Roots		
Potato	0.4-0.6	0.35
Legumes		
Soybeans	0.6-1.3	0.5
Cereals		
Spring wheat	1.0-1.5	0.55
Maize	1.0-1.7	0.55
Sorghum	1.0-2.0	0.55
Forages		
Alfalfa	1.0-2.0	0.55

Table 2. *Stages of growth that are particularly sensitive to water stress*

Crop	Growth stage
All crops	Crop establishment – during this period the soil needs to be maintained near field capacity
Beans	Pollination and pod development
Carrot	Root enlargement
Corn	Silking, tasseling and ear development
Onions	Bulb enlargement
Peas	Flowering and pod fill
Potato	Tuber set and enlargement
Squash	Bud development and flowering
Tomato	Flowering, fruit set and enlargement
Turnip and radish	Root enlargement
Wheat, barley and oats	Flowering and grain fill

Derived from Stanley & Maynard (1990), Muaick & Porter (1990), Al-Kaisi & Broner (2005), (D. J. Greenwood, personal communication).

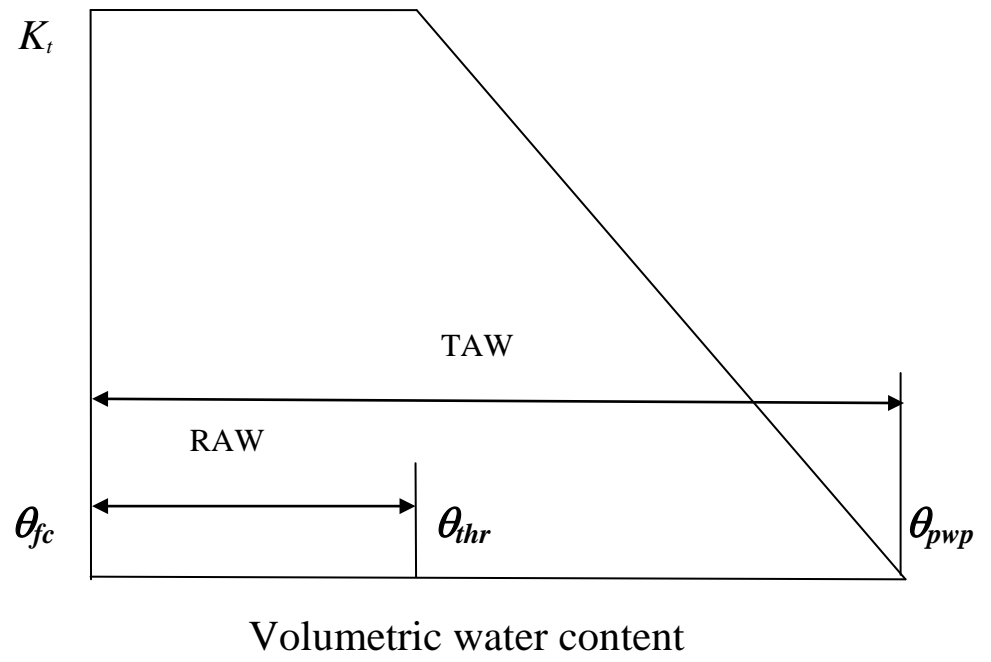


Fig. 1. Schematic diagram of the effect of soil water content on crop transpiration. K_t is the ratio of the transpiration rate (or growth rate) at the given water content expressed as a fraction of the rate when water is not limiting. θ_{fc} , θ_{thr} and θ_{pwp} are the water contents at field capacity, threshold and the permanent wilting point.

Fig.2

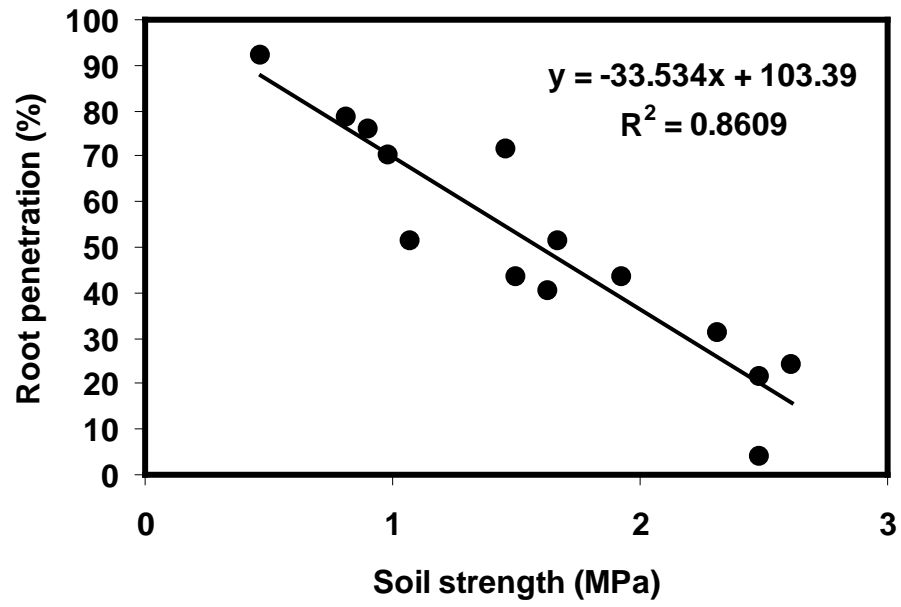


Fig. 2. Effect of soil strength on root penetration of cotton seedling tap roots. Different soil strengths were created by modifying bulk density and soil water content; both variables affected the dependence of root penetration on soil strength similarly. (The figure is derived from Taylor & Gardner 1963)

Fig.3

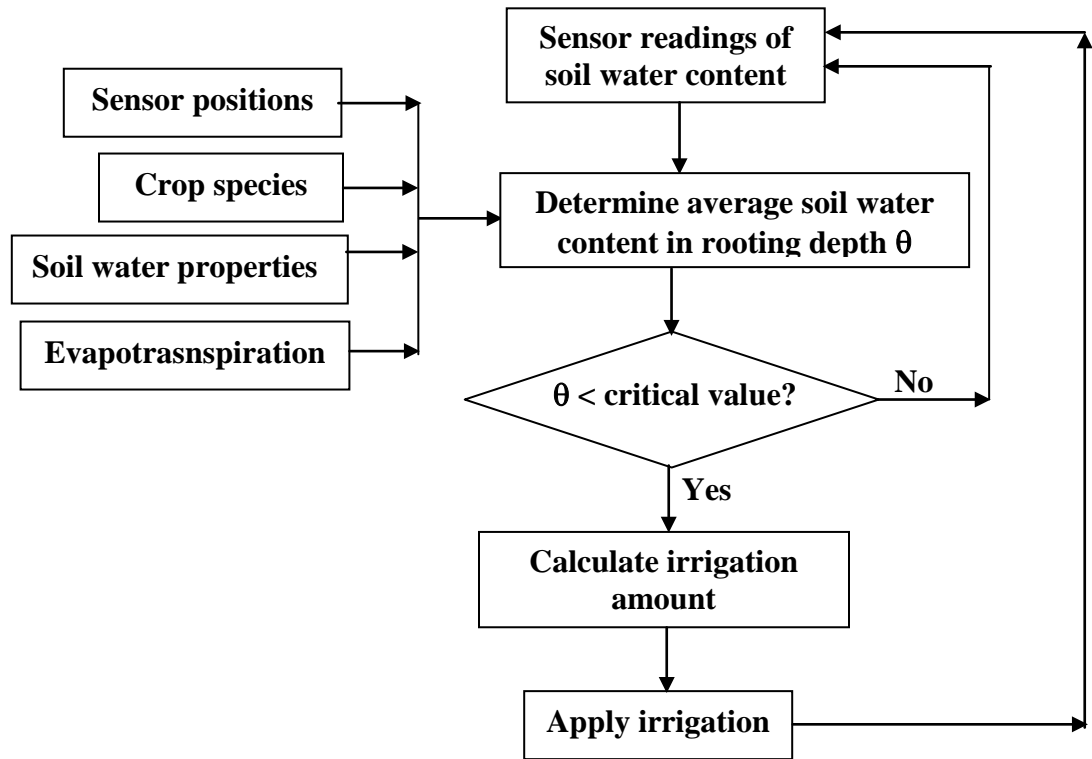


Fig.3. Flow chart of irrigation scheme based on sensor readings and model predictions