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Evaluation of the Watermark sensor for use with drip irrigated vegetable crops

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Abstract The Watermark 200SS sensor was evaluated for the measurement of soil matric potential (SMP) with drip-irrigated vegetable crops. Pepper and melon crops were grown sequentially during autumn-winter and spring-summer, in a sandy loam soil in a greenhouse. Ranges of SMP were generated by applying three different irrigation treatments — 100, 50 and 0% of crop water requirements, during two treatment periods (16 December 2002–7 January 2003; 20 January–10 February 2003) in pepper and one treatment period (26 May–6 June 2003) in melon. Watermark sensors and tensiometers were positioned, at identical distances from irrigation emitters, at 10 cm soil depth, with four replicate sensors for each measurement. Electrical resistance from Watermark sensors and SMP from tensiometers were recorded at 30-min intervals. An in-situ calibration equation was derived using data from the first pepper treatment period. For data in the three treatment periods, SMP was calculated from Watermark electrical resistance using the in-situ, Thomson and Armstrong (in Appl Eng Agric 3:186–189 1987), Shock et al. (1998) and Allen (2000) calibration equations. Additionally, the Thomson and Armstrong (in Appl Eng Agric 3:186–189 1987) and Shock et al. (1998) equations were re-parameterised with the SOLVER® function of Microsoft Excel 2000® using data from the first pepper treatment period. Watermark-derived SMP, for each equation, were compared with tensiometer-measured SMP, for <-10, -10 to -30, -30 to -50 and -50 to -80 kPa ranges, using visual analysis, and relative root mean square error (RRMSE) and mean difference (Md) values. In rapidly drying soil, the Watermark-derived SMP responded considerably more slowly to continual drying and to drying between irrigations, regardless of the calibration equation used. Otherwise, the Watermark sensor was able to provide an accurate indication of SMP, depending on the calibration equation. The in-situ and re-parameterised equations were accurate for the conditions in which they were derived/re-parameterised. However, as the growing conditions increasingly differed from those original conditions, these equations lost their advantage compared to the two published equations, suggesting that they are not robust approaches. The Thomson and Armstrong (in Appl Eng Agric 3:186–189 1987) equation generally provided an accurate indication of SMP at >-30 kPa, measuring to -2.5 kPa. Where the soil was not drying rapidly, the Shock et al. (1998) equation generally provided an accurate indication of SMP at -30 to -80 kPa. The use of dynamic data (collected every 30 min) compared to static data (collected only at 6 a.m.) did not influence the evaluation of calibration equations. This study suggested that the Watermark sensor can provide an accurate indication of SMP provided that a suitable calibration equation is derived/verified for the specific cropping conditions, and that the performance characteristics of the sensor are considered.

Introduction

Irrigation scheduling in intensive vegetable production systems ensures optimal water use while maintaining high levels of production and product quality. Irrigation scheduling generally is based on calculation of crop water requirements (Allen et al. 1998), or monitoring of soil water status (Campbell and Campbell 1982; Campbell

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and Mulla 1990; Hanson et al. 1999). The use of sensors to monitor the soil water status enables irrigation scheduling to be adapted to the particular requirements of individual crops and fields. For on-farm use, soil matric potential (SMP) is a more practical parameter than volumetric soil water content (VSWC). This is because the lower and upper limits of soil water status, as SMP, that are used to, respectively, initiate and stop irrigation (Campbell and Campbell 1982) are generally readily available from extension sources or equipment distributors. For VSWC, standard values for these limits cannot generally be used; commonly, these values have to be defined for individual cropping situations.

For many years, tensiometers have been widely used to measure SMP for irrigation scheduling in commercial farming, and in research studies (Campbell and Mulla 1990; Young and Sisson 2002). However, tensiometers have a number of practical limitations. To be accurate, they require preparation and regular maintenance (Cassel and Klute 1986; Young and Sisson 2002), and their restricted working range of 0 to -80 kPa can be a limitation. The Watermark 200SS sensor (Irrometer Co. Riverside, CA, USA) is a granular matrix sensor that measures SMP indirectly using electrical resistance (Eldredge et al. 1993; Scanlon et al. 2002; Shock 2004). It has several characteristics that make it potentially attractive for irrigation scheduling use on commercial farms, and for research applications. It is inexpensive, simple to use and install, has simple preparation and minimal maintenance requirements (Scanlon et al. 2002), and is claimed to have a relatively wide working range of -10 to -200 kPa (Thomson and Armstrong 1987; Spaans and Baker 1992). Watermark sensors can either be used for "spot" measurements using a hand-held reader, or can be automatically and continuously logged using data loggers.

Calibration equations are required to convert electrical resistance, measured with the Watermark sensor, to SMP values. Thomson and Armstrong (1987) developed a calibration equation for an earlier model, the Watermark 200 sensor. Subsequently, Thomson et al. (1996) verified that the Thomson and Armstrong (1987) calibration equation was accurate with the current model, the Watermark 200SS. Shock et al. (1998) developed a calibration equation for the Watermark 200SS sensor, for the range of -10 to -75 kPa, which is used by the manufacturer as a default calibration (T. Penning, Irrometer Co., personal communication). Allen (2000) developed a composite equation consisting of the Shock et al. (1998) equation and two other equations to extend the wet and dry ranges of measurement. The two additional equations developed by Allen (2000) were derived from a standard calibration table (Watermark calibration chart ver. 3; Irrometer Co. Riverside, CA, USA). Irmak and Haman (2001) used a re-parameterisation procedure to enhance the accuracy of published calibration equations.

The available calibration equations and data sets have been derived under controlled conditions, using either pressure plates (Thomson and Armstrong 1987; Thomson et al. 1996; Watermark calibration chart ver. 3) or tensiometers in pot studies (Shock et al. 1998). Evaluations of calibration equations have generally been done in controlled conditions (e.g. Spaans and Baker 1992; Irmak and Haman 2001) or under field conditions using small number of irrigation cycles (Bausch and Bernard 1996). The data sets that have been used to develop and to evaluate calibration equations have generally consisted of data collected manually once a day (Eldredge et al. 1993; Irmak and Haman 2001; Leib et al. 2003) or were 6 a.m. data points selected from continuously recorded data (Bausch and Bernard 1996; Shock et al. 1998). The selection of 6 a.m. data in these studies was done because SMP is most stable in the period shortly before sunrise. In summary, much of the available calibration data for the Watermark sensor have not been obtained under realistic field conditions, and much of the data used have been "static" data i.e. single daily measurements collected under stable conditions. In contrast, practical measurement of SMP on both commercial farms and in research studies is done in the field under dynamic conditions in which SMP is changing constantly with soil wetting and drying cycles. Therefore, evaluations of calibration equations, and assessments of sensor performance should be conducted under realistic field conditions using continuously collected data. Additionally, there is a need to assess whether there are differences between calibration equations derived from data sets consisting of "static" 6 a.m. data, and those derived from "dynamic" data sets consisting of data collected throughout entire 24-h periods.

Drip irrigation enables high frequency irrigation of vegetable crops; with correct irrigation scheduling, soil water can be maintained in the vicinity of field capacity (Dasberg and Or 1999). Additionally, drier soil conditions can occur when moderate water stresses are intentionally applied to enhance product quality (Sanders et al. 1989; Mitchell et al. 1991), or simply because crop evapotranspiration was more than anticipated. To be effective for irrigation scheduling with drip-irrigated vegetable crops, soil water sensors must be able to provide accurate data in (a) relatively moist soil e.g. -10 to -30 kPa under dynamic conditions of frequent wetting and drying cycles, and (b) in drier soil e.g < -30 kPa.

This work was conducted with the overall objective of evaluating the performance of the Watermark sensor for field measurement of SMP in high frequency, drip irrigated, vegetable production. Sequential pepper and melon crops were grown in a sandy loam soil, and three different irrigation treatments were periodically applied to create a 0 to -80 kPa range of SMP. For this SMP range, the following specific objectives were assessed: (1) development and evaluation of a calibration equation developed in-situ, (2) evaluation of the Thomson and Armstrong (1987), Shock et al. (1998) and Allen (2000) calibration equations, (3) evaluation of the use of a re-parameterisation procedure with published calibration equations, (4) comparison of the use of dynamic (continuous data) and static (6 a.m.) data sets for evaluating calibration equations, and (5) identification of general characteristics of the Watermark sensor under practical working conditions.

Material and methods

Location and cropping details

The experiments were conducted within a greenhouse at the field research station "Las Palmerillas" of Cajamar in El Ejido, Almería province, in southeastern Spain, (2°43'W, 36°48'N and 151 m elevation). The plastic greenhouse measured 58 m long by 24 m wide; it was unheated, and passively ventilated. It was aligned with an east-west orientation.

The soil within the greenhouse was an artificial layered soil, typical of the region (Wittwer and Castilla 1995), which was formed by placing a 20 cm layer of sandy loam soil, imported from a quarry, over the naturally occurring, stony, loam soil. A 10 cm layer of coarse river sand was placed over the imported sandy loam soil as a mulch. The original soil had 46% sand, 32% silt, and 22% clay, soil bulk density of 1.6 Mg m^{-3}, and upper and lower soil water limit of 0.35 and 0.15 m^3 m^{-3} respectively. The imported sandy loam soil had 55% sand, 28% silt, and 17% clay, with soil bulk density of 1.5 Mg m^{-3}, and upper and lower soil water limit of 0.34 and 0.13 m^3 m^{-3}, respectively.

Drip irrigation tape was placed on the surface of the sand mulch; emitters with a discharge rate of 2 L h^{-1} were positioned every 0.5 m. The irrigation water had an electrical conductivity of 0.4 dS m^{-1}. Nutrients were applied through the irrigation system. Nutrient management was in accordance with local practice.

Sweet pepper (*Capsicum annum*, L.; cv. Vergasa) was grown from 18 July 2002 to 14 February 2003, and melon (*Cucumis melo* L. cv. Sirio) from 21 February to 25 June 2003. Pepper plants were grown in double rows, with 0.5 m spacing between adjacent plants within each row, and 0.4 m between rows in each double row, and 1.1 m between the closest rows of adjacent double rows, giving a plant population of 2.6 plants m^{-2}. Drip tape was positioned midway between the two rows of each double row, with one emitter located centrally, 20 cm from each of two parallel plants. Melon plants were grown in single rows 1.5 m apart with 0.5 m spacing between plants giving a plant population of 1.33 plants m^{-2}. A drip irrigation emitter was located adjacent to and 16 cm from each melon plant. In both crops, plants were vertically supported by nylon cord guides, and pruned and managed following local practice.

The greenhouse was divided into 12 experimental plots, with six plots on either side of a central passage. There were three drip lines in each plot; all measurements were made in the middle drip line. Plots on the southern side of the greenhouse measured 10.5 by 4.5 m, and plots on the northern side measured 8.5 by 4.5 m. Adjacent plots were partially hydraulically separated by vertically placing plastic sheeting to a depth of 30 cm from the surface of the imported soil.

Irrigation treatments and experimental design

Three periods of varied irrigation treatments were applied — two in pepper, and one in melon. Each of these treatment periods consisted of three irrigation treatments: T_{100} — irrigated with 100% of estimated crop water requirements, T_{50} — irrigated with 50% of the water applied to T_{100}, and T_0 — no irrigation during the period. Irrigation frequencies were identical in T_{100} and T_{50}. The three different irrigation treatments provided different ranges of SMP during each treatment period. The varied irrigation periods were — for pepper: 16 December 2002 – 7 January 2003 and 20 January 2003 – 10 February 2003, and for melon: 26 May 2003 – 6 June 2003. Hereafter, these three varied irrigation periods are referred to, respectively, as pepper treatment period 1, pepper treatment period 2, and the melon treatment period. In the melon treatment period, treatment T_{100} was generally maintained at SMP of > -10 kPa in order to evaluate the performance of the Watermark sensor under very moist soil conditions; in this period, two daily irrigations were applied to treatments T_{100} and T_{50}. Before and after the varied irrigation periods, the crops were optimally irrigated using a computer programme to calculate crop water requirements (Fernández et al. 2001) and manual tensiometers (Irrometer Co., Riverside, CA, USA) to determine irrigation frequency (threshold of -30 kPa). The experimental design for each treatment period was a randomised block design within four blocks (two in the northern side, and two in the southern side of the greenhouse), with the three irrigation treatments randomly allocated to each block.

Measurements

Soil matric potential was measured with electric tensiometers, equipped with pressure transducers, (Model SKT 600/IE, Skye Instruments, Llandrindod Wells, Wales, UK); measurements were made every 5 min, which were then averaged and recorded every 30 min on a Data Hog 2 data logger (Skye Instruments). Each tensiometer had been individually calibrated by the manufacturer. The Watermark 200SS sensors (Irrometer Co., Riverside, CA, USA) were read every 30 s, with the data averaged and then recorded every 30 min with a Campbell CR10X data logger (Campbell Scientific International, Logan, Utah, USA) used in combination with a Campbell AM416 multiplexer (Campbell Scientific International). The tensiometers and Watermark sensors were positioned so that the mid-point of the tensiometer ceramic capsule and the Watermark sensor body were at 10 cm soil depth relative to the surface of the imported soil. In each replicated plot, one tensiometer and one Watermark sensor were symmetrically located on either side of the same irrigation emitter and plant, which were both aligned. In pepper, each tensiometer and Watermark sensor was 14 cm from the emitter (perpendicular to the drip line), and 11 cm from emitter and plant in the direction parallel to the drip line. In melon, the corresponding distances were 8 and 11 cm. All tensiometer and Watermark sensor data are the means of four replicate sensors for individual irrigation treatments during the periods of varied irrigation.

The Watermark sensors were attached to 2 cm diameter by 42 cm long PVC pipe to facilitate installation and removal. Prior to installation, Watermark sensors were subjected to three wetting and drying cycles, and were moist when installed. To install tensiometers and Watermark sensors, the sand mulch was removed, and holes the same diameter as the tensiometer shaft or Watermark sensor were made to the appropriate depth in the imported soil layer. Soil slurry was added to ensure good contact between sensor and soil. After installing the sensors, the soil at the surface was raised slightly and firmed on the tensiometer shaft or Watermark support pipe.

Climatic parameters were continuously monitored within the greenhouse. Air temperature and relative humidity were measured inside the greenhouse with a ventilated psychrometer located immediately above the crop. Solar radiation was measured with a pyranometer installed at 2 m height. Soil temperature was measured with a soil thermistor installed at the same depth and distance from emitter and plants as the Watermark sensors and tensiometers. Climatic data were recorded at the same 30-min intervals as the Watermark and tensiometer data.

Calibration of the Watermark sensor

1) In-situ calibration using static data analysis

An in-situ calibration equation was developed using data from the three irrigation treatments in the first pepper treatment period (16 December 2002 – 7 January 2003). Soil electrical resistance values obtained with Watermark sensors were compared with SMP values measured with the tensiometers, for data collected at 6 a.m. These data were selected because SMP is most stable at this time of the day. Soil electrical resistance was corrected to a reference temperature of 21°C following the recommendation of Campbell Scientific:

$$R_{21} = \frac{R_s}{1 - (0.018\Delta T)} \tag{1}$$

where R_{21} = resistance at 21°C (reference temperature) R_s = measured sensor resistance (kΩ) $\Delta T = T_s - 21$(°C), where T_s is the soil temperature (°C).

In the zero irrigation treatment (T_0), measurements began when the soil was close to saturation and continued until air entered the tensiometer, which occurred at approximately −80 kPa, ensuring that the entire range of SMP measured by tensiometers was examined.

To test the repeatability of the in-situ calibration,

(1) a second calibration equation was developed, in the same way, for the second pepper treatment period (20 January to 10 February 2003), and
(2) the in-situ calibration developed in the first pepper treatment period was evaluated for its accuracy in measuring SMP in the second pepper treatment period.

The latter was done by calculating the absolute differences between SMP values measured with tensiometers and those estimated from electrical resistance data using the in-situ calibration; these absolute differences were tested for being statistically significantly different ($P < 0.05$) from zero with the Student's *t*-test procedure. All conventional statistical analyses were conducted using Statgraphics Plus ver. 4.1®. (Manugistics, Inc., Maryland, USA).

2) Evaluation of published calibration equations

Complete data sets (all data recorded at 30 minute intervals) from the two treatment periods in pepper and the treatment period in melon, were used to evaluate the Thomson and Armstrong (1987), Shock et al. (1998) and Allen (2000) calibration equations for calculating SMP from soil electrical resistance, obtained with the Watermark sensor.

The calibration equation of Thomson and Armstrong (1987) is:

$$\mathrm{SMP} = -\frac{R_s}{0.01306\left[1.062\left(34.21 - T_s + 0.01060T_s^2\right) - R_s\right]} \tag{2}$$

where all variables are as previously defined.

The calibration equation of Shock et al. (1998) is:

$$\mathrm{SMP} = \frac{-(4.093 + 3.213R_s)}{1 - 0.009733R_s - 0.01205T_s} \tag{3}$$

where all variables are as previously defined.

Allen (2000) developed a composite equation consisting of the Shock et al. (1998) equation complemented with two additional equations derived from a standard calibration table (Watermark calibration chart ver. 3; Irrometer Co. USA). Resistance was considered as three distinct ranges, using a linear function for $0 \leq R_s \leq 1$ kΩ, the Shock et al. (1998) equation for $1 < R_s \leq 8$ kΩ, and a quadratic equation for $R_s > 8$ kΩ. Because the Shock et al. (1998) and Allen (2000) calibration equations provided generally very similar SMP values, only data from the Shock et al. (1998) will be presented. Wherever there were notable differences between these two calibration equations, these will be presented in the text.

To compare SMP values derived from Watermark electrical resistance values, using the previously mentioned equations, with SMP values measured using tensiometers, for each treatment period, the data were filtered into four different ranges of SMP, being > -10, -10 to -30, -30 to -50 and -50 to -80 kPa. For each SMP range, the relative root mean square error (RRMSE) and mean difference (Md) were calculated as described by Leib et al. (2003). RRMSE and Md values were also calculated for the full 0 to -80 kPa SMP range for each treatment period. RRMSE and Md calculations were made using Microsoft Excel 2000®.

The RRMSE parameter (measured in percentage) provides an assessment of the magnitude of the relative difference between Watermark derived SMP and tensiometer-measured SMP values; it is a similar relative parameter to the coefficient of variation (CV). RRMSE analysis enables:

(1) comparison of different calibration equations within particular SMP ranges, and
(2) comparison between different SMP ranges for a given calibration equation.

The Md parameter provides the averaged absolute difference (measured in kPa) between SMP values determined with Watermark sensors and measured with tensiometers, for given SMP ranges. Positive or negative Md values, respectively, indicate over- and under-estimation. The Md values were tested for being statistically significant ($P < 0.05$) with the Students *t*-test procedure.

3) Evaluation of re-parameterisation procedure

A re-parameterisation procedure was evaluated to assess whether it enhanced the accuracy of the published equations. The SOLVER® procedure in Microsoft Excel 2000® was used to estimate new parameters for the Thomson and Armstrong (1987) and Shock et al. (1998) calibration equations, by minimising the RRMSE between SMP measured with tensiometers and estimated using the calibration equation, using the complete data set from the first pepper treatment period. The RRMSE and Md procedures, described in the preceding section, were used to evaluate the re-parameterised forms of the Thomson and Armstrong (1987) and Shock et al. (1998) calibration equations.

4) Assessment of variability

The variability associated with SMP measurements made with the Watermark sensor was assessed by calculating CV for the four replicate measurements, for mean SMP values of -10 ± 1, -30 ± 1, and -50 ± 1 kPa for each of the two pepper treatment periods, and the melon treatment period. The Watermark SMP data used were calculated from electrical resistance values using the Shock et al. (1998) calibration equation. CV's were also calculated for equivalent SMP values measured with tensiometers in each of the three treatment periods. Data were filtered to obtain all mean SMP values in each selected range for each treatment period; the four replicate values for each mean value were then used to calculate the standard deviation. The standard deviation was divided by the corresponding mean to obtain the CV.

5) Comparison of static and dynamic approaches for evaluation of calibration equations

A comparison was made of the use of static and dynamic data sets for the evaluation of calibration equations. The static data set consisted of the combined 6 a.m. data collected from the T_0 irrigation treatments, during the two treatment periods in the pepper crop. The dynamic data set contained the equivalent complete data set, i.e. all data collected at 30-min intervals, from the T_0 irrigation treatments during the two treatment periods of the pepper crop. The reasons for combining data from the two separate time periods was to ensure that the 0 to -80 kPa range of SMP was fully covered with an adequate number of data points for performing linear regression analysis.

The Thomson and Armstrong (1987) and Shock et al. (1998) calibration equations, and the in-situ calibration developed for the site (Eqn. 4), were used to calculate SMP values for both the static and dynamic data sets. Linear regression analyses of SMP values derived from Watermark electrical resistance data against tensiometer SMP data were conducted with the static and dynamic data sets. For each of the three calibration equations evaluated, the linear regression equations derived from the static and dynamic data sets were compared for statistically significant differences ($P < 0.05$) in slope and intercept values.

Results

Climatic conditions

There were large differences between the climatic conditions of the melon treatment period and the two pepper treatment periods (Table 1) due to the spring-summer growing season of the melon crop compared with the autumn-winter growing season of the pepper. Average daily mean, maximum and minimum air temperatures and average daily soil temperature were 6–10°C higher during the melon treatment period than during the two pepper treatment periods. Comparing the melon treatment period to the two pepper treatment periods, the average daily mean vapour pressure deficit (VPD) was 2–3 times higher, and the average daily integral of solar radiation was almost double.

Table 1 Climatic data averaged for each of the three treatment periods for daily maximum, daily mean, and daily minimum air temperatures (°C), daily mean vapour pressure deficit (VPD, kPa), integral of daily solar radiation (MJ m^{-2} d^{-1}), and daily mean soil temperature (10 cm depth, °C)

Climatic parameter	Pepper treatment		Melon treatment period
	Period 1	Period 2	
Maximum daily air temperature (°C)	20.6	20.7	29.3
Mean daily air temperature (°C)	14.1	12.5	22.0
Minimum daily air temperature (°C)	9.9	7.3	16.2
Daily mean VPD (kPa)	0.23	0.37	0.73
Daily integral solar radiation (MJ m^{-2} d^{-1})	6.2	8.8	18.5
Daily mean soil temperature (°C)	16.6	15.0	23.3

In-situ calibration of the Watermark sensor

Using 6 a.m. data from the combined data set from the three irrigation treatments, from the first treatment period of the pepper crop, a second order polynomial equation ($SMP = -0.34R_s^2 - 1.94R_s - 3.10$; Eqn. (4)) provided the best fit ($r^2 = 0.99$) between SMP in kPa, measured with tensiometers, and electrical resistance (R_s) in kΩ, measured with the Watermark sensor, for the sandy loam soil used in this study (Fig. 1a). In the second treatment period of pepper, a very similar second order polynomial equation was obtained, with an r^2 of 0.96 (Fig. 1b).

In the second pepper treatment period, the absolute differences between SMP values measured with tensiometers and those estimated from electrical resistance data using Eqn. (4) were not statistically significant ($P < 0.05$, Student's *t*-test) indicating that Eqn. (4) described the relationship between tensiometer-measured SMP and electrical resistance in both treatment periods of the pepper crop.

Evaluation of published and in-situ calibration equations

Visual analysis

SMP values calculated from Watermark sensor resistance data using the calibration equations of Thomson and Armstrong (1987) [Eqn.(2)] and Shock et al. (1998) [Eqn.(3)] for the first pepper treatment period are presented in Fig. 2, with treatments T_{100} i.e 100% of ETc, T_{50} i.e 50% of ETc, and T_0 i.e no irrigation in Fig. 2a, b and c, respectively. SMP calculated from Watermark sensor electrical resistance data using the in-situ calibration equation, developed for this soil [Eqn.(4)], are presented in Fig. 2d, e and f. SMP measured with tensiometers is included in each panel for comparison. In the second pepper treatment period, the relationships between SMP derived from the Watermark sensor, using each of these three calibration equations, and SMP measured with tensiometers (data not presented) were very similar to those in the first pepper treatment period.

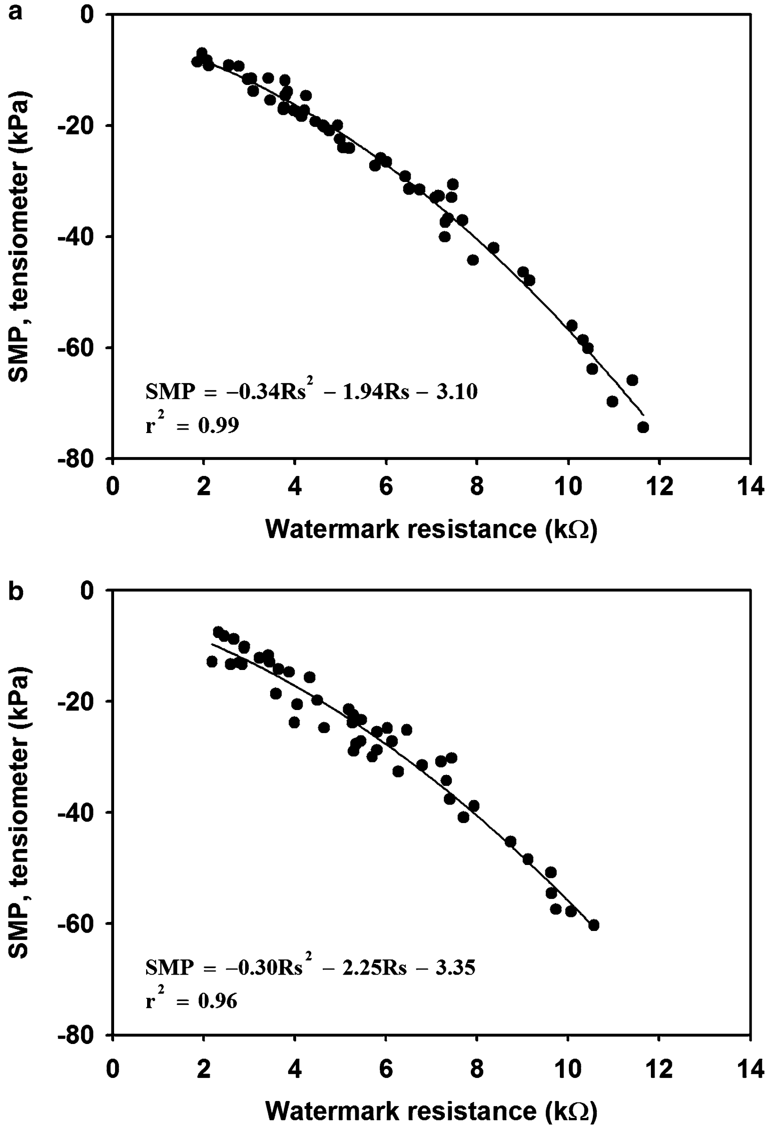
During the two pepper treatment periods, SMP values derived from Watermark electrical resistance readings, using the two published calibration equations and the in-situ calibration equation [Eqn.(4)], qualitatively tracked relative changes in SMP in a similar manner to the tensiometers. SMP determined with the Watermark sensor, using the three calibration equations, clearly showed:

(1) each irrigation event in treatments T_{100} and T_{50} (Fig. 2a, b), and
(2) subsequent soil drying caused by crop water uptake and drainage.Where irrigation was withheld (treatment T_0), SMP determined using the Watermark sensor qualitatively followed the same drying trends as the tensiometer SMP data (Fig. 2c, f).

During the pepper treatment periods, there were quantitative differences between SMP values obtained using the Thomson and Armstrong (1987) and Shock et al. (1998) calibration equations. In the −5 to −25 kPa range (moist soil conditions), the Thomson and Armstrong (1987) equation generally provided similar SMP values to the tensiometers (Fig. 2a, b), whereas the Shock et al. (1998) equation provided consistently lower (drier) SMP values. Under drier conditions (< −30 kPa), the Shock et al. (1998) equation provided generally more accurate SMP values than the Thomson and Armstrong (1987) equation, which was most apparent at −50 to −80 kPa when the Thomson and Armstrong (1987) equation appreciably under-estimated SMP (giving drier values) (Fig. 2b, c). In the first pepper treatment period, at SMP of approx. < −60 kPa there was clearly a large error with SMP calculated using the Thomson and Armstrong (1987) equation (Fig. 2c). In both pepper treatment periods, the in-situ calibration equation (Eqn. 4) provided SMP values that were generally similar to those of the tensiometers, being more accurate in treatment period 1 (Fig. 2d–f).

In the melon treatment period, there were larger differences between Watermark-derived and tensiometer-measured SMP than in the pepper treatment periods, regardless of the calibration used (Fig. 3 c.f. Fig. 2). Under the rapidly drying conditions of treatment T_0 in the melon treatment period (Fig. 3c, f), Watermark-derived SMP responded very slowly to soil drying resulting in considerable over-estimation of SMP. In treatments T_{100} and T_{50}, Watermark-derived SMP also responded slowly to soil drying between irrigations (Fig. 3a–e). The slow response to soil drying was apparent in smaller daily fluctuations in Watermark-derived SMP (Fig. 3 all

Fig. 1 Relationship between soil matric potential (SMP), measured with tensiometers, and electrical resistance (Rs) measured with the Watermark sensor for (**a**) the first pepper treatment period and (**b**) the second pepper treatment period 2. In each pepper treatment period, 6 a.m. data from the three irrigation treatments were used. The best-fit equations and their regression coefficients are presented for each pepper treatment period



panels), and in increasing divergence between Watermark-derived and tensiometer-measured SMP, as the soil increasingly dried (Fig. 3b, c, e, f).

Under the very moist conditions (0 to -12 kPa) of treatment T_{100} in the melon treatment period, there were clear differences between the Thomson and Armstrong (1987), Shock et al. (1998) and in-situ calibration equations (Fig. 3a, d). The Thomson and Armstrong (1987) equation effectively tracked changes in SMP and was generally within 2 kPa of tensiometer SMP values; it was unable to measure SMP > -2.5 kPa, and the magnitude of drying-wetting fluctuations was somewhat less than measured with tensiometers. The Shock et al. (1998) equation was unable to measure SMP of > -8 kPa, and the fluctuations were much smaller than those measured with tensiometers. The Allen (2000) equation measured to 0 kPa, and generally provided "wetter" values than the tensiometers; some of the fluctuations were larger and others smaller than those measured with the tensiometers (data not presented).

Statistical evaluation

Considering the two published equations (Thomson and Armstrong 1987 and Shock et al. 1998) in the two pepper treatment periods, the Thomson and Armstrong (1987) equation was more accurate (lower RRMSE) in moist soil conditions at SMP of > -30 kPa (Table 2), and the Shock et al. (1998) equation was more accurate (lower RRMSE; Table 2) in drier soil water conditions, at SMP of < -30 kPa. The RRMSE data suggested that the Shock et al. (1998) equation was most accurate within the -30 to -80 kPa range, appreciably less accurate within the -10 to -30 kPa range, and very inaccurate at SMP of > -10 kPa where it had RRMSE values of $> 100\%$. The smallest RRMSE values with the

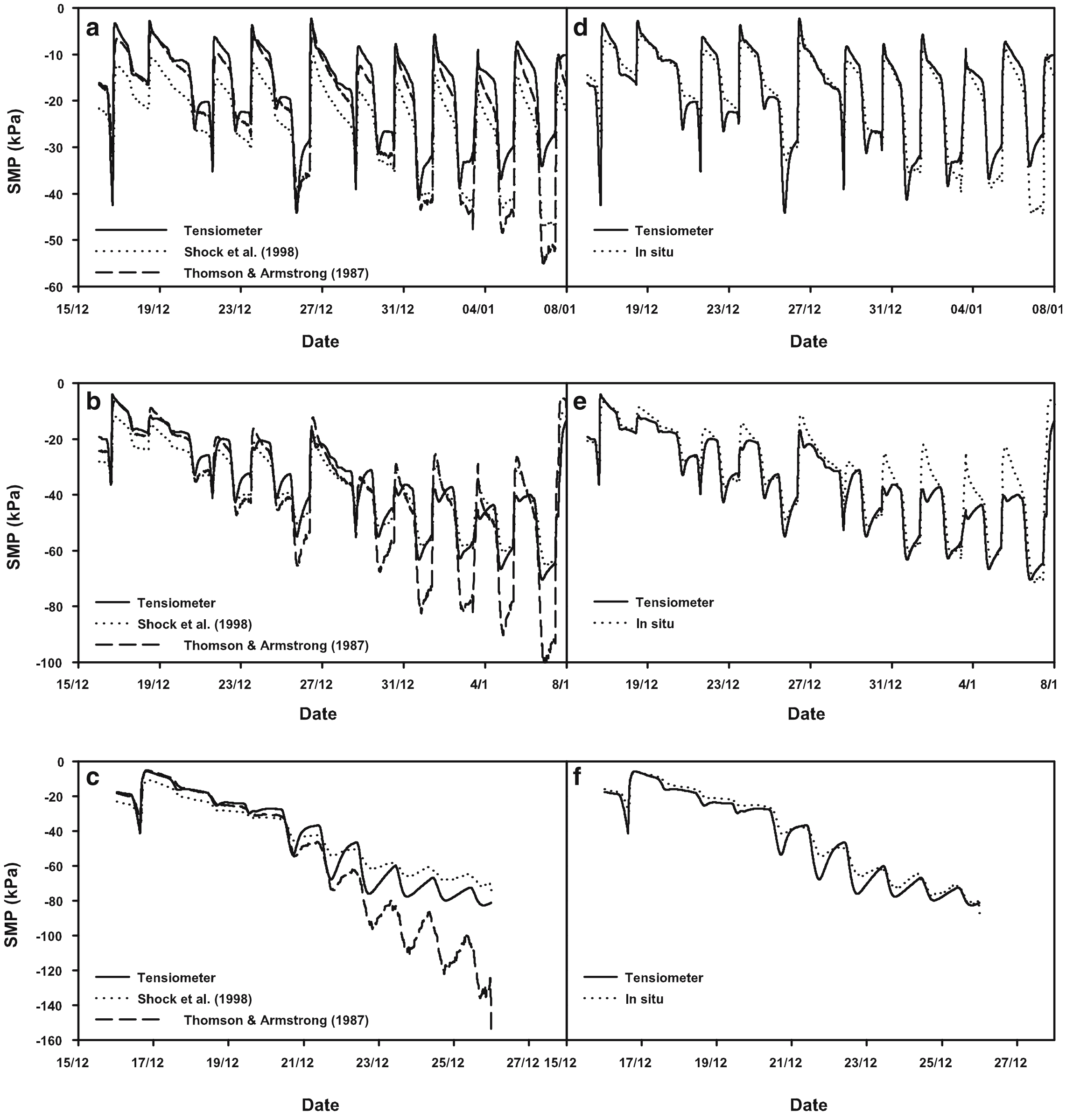


Fig. 2 For the first pepper treatment period, SMP calculated from the Watermark sensor using three calibration equations and measured with tensiometers. In panels (a–c), SMP derived using the Shock et al. (1998) and Thomson and Armstrong (1987) calibration equations, and measured with tensiometers; in panels (d–f), SMP derived using the in-situ calibration equation, and measured with tensiometers. In panels (a) and (d), SMP data from irrigation treatment T_{100}; in panels (b) and (e), SMP data from treatment T_{50}, and in panels (c) and (f), SMP data from irrigation treatment T_0. Continuous data collected every 30 min are presented

Thomson and Armstrong (1987) equation were for the −10 to −30 and −30 to −50 kPa ranges; the highest values were for the > −10 kPa range, although these values were much less than obtained for the Shock et al. (1998) equation in this range. Relatively high RRMSE and Md values were obtained for the Thomson and Armstrong (1987) equation in pepper treatment period 1, in the −50 to −80 kPa range on account of the large error at < −60 kPa, referred to previously (see Fig. 2c).

For each range of SMP values examined with the Shock et al. (1998), Thomson and Armstrong (1987) and in-situ calibration equations, RRMSE values were generally appreciably larger in the melon treatment period than in the two pepper treatment periods, indicating a much larger error for Watermark-derived SMP values in the melon treatment period. The differences in RRMSE values, between the melon treatment period and the pepper treatment periods were largest at lower (drier) SMP values (Table 2).

In pepper treatment period 1, the in-situ calibration equation (Eqn. 4) had generally lower RRMSE values than the Thomson and Armstrong (1987) and Shock et al. (1998) equations, indicating that it was the most accurate of these three calibration equations (Table 2). However,

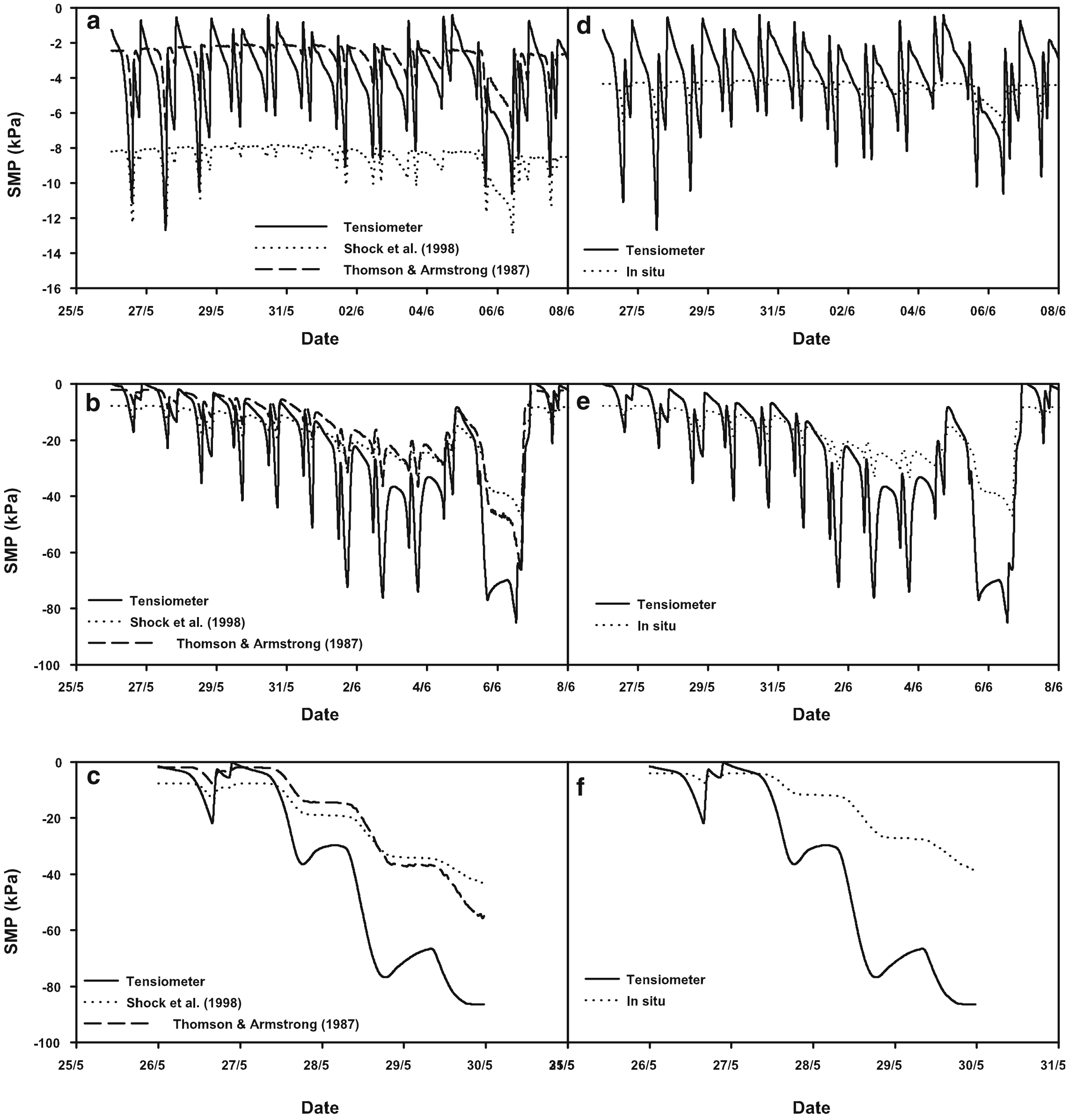


Fig. 3 For the melon treatment period, SMP calculated from the Watermark sensor using three calibration equations measured with tensiometers. In panels (a–c), SMP derived using the Shock et al. (1998) and Thomson and Armstrong (1987) calibration equations, and measured with tensiometers; in panels (d–f), SMP derived using the in-situ calibration equation, and measured with tensiometers. In panels (**a**) and (d), SMP data from irrigation treatment T_{100}; in panels (b) and (e), SMP data from treatment T_{50}, and in panels (c) and (f), SMP data from irrigation treatment T_0. Continuous data collected every 30 min are presented

in pepper treatment period 2, the RRMSE values of the in-situ equation were generally similar to that of the published equations; and in the melon treatment period they were generally higher, suggesting that in the melon it was the least accurate of these three equations.

The Allen (2000) equation compared with the Shock et al. (1998) equation had slightly smaller RRMSE values for the −50 to −80 kPa range for the two pepper treatment periods, being 9.2 and 15.0, respectively, for the first and second pepper treatment periods. In the >−10 kPa range of the melon treatment period, the Allen (2000) equation had a RRMSE value of 81.7 which was much smaller than that of the equivalent Shock et al. (1998) value, but still appreciably larger than the equivalent RRMSE value for the Thomson and Armstrong (1987) equation (Table 2). Otherwise, RRMSE values from the Allen (2000) equation were equal to or very similar to those for the Shock et al. (1998) equation for each SMP range in each of the three treatment periods.

Considering the Md values for the Thomson and Armstrong (1987) equation in the two pepper treatment periods, the mean differences (Md) from the tensiometer-measured SMP values were approximately 2 kPa for both the >−10 and −10 to −30 kPa ranges, and only slightly larger for the −30 to −50 kPa range (Table 3).

Table 2 Values of relative root mean square error (RRMSE) comparing SMP measured with the Watermark sensor, using different calibration equations, to SMP measured with tensiometers

			Calibration Equation				
			In-situ	Shock et al. (1998)		Thomson and Armstrong (1987)	
				Original	Re-parameterised	Original	Re-parameterised
Crop	Range (kPa)	*n*	RRMSE (%)	RRMSE (%)	RRMSE (%)	RRMSE (%)	RRMSE (%)
Pepper treatment period 1							
	> -10	321	29.5	100.7	33.7	35.9	37.5
	-10 to -30	1,235	19.9	36.5	20.4	25.4	20.2
	-30 to -50	704	18.9	15.3	16.5	23.0	16.4
	-50 to -80	410	8.1	11.3	5.6	36.9	5.9
	0 to -80	2,670	16.9	28.8	15.1	37.0	15.2
Pepper treatment period 2							
	> -10	307	48.6	127.8	49.6	53.5	54.7
	-10 to -30	1,227	25.1	31.3	23.9	25.1	23.2
	-30 to -50	511	20.3	14.7	17.7	21.6	17.6
	-50 to -80	301	16.8	16.1	14.6	19.9	14.7
	0 to -80	2,346	23.3	25.7	21.1	25.3	20.9
Melon treatment period							
	> -10	1,009	51.5	130.9	67.7	49.3	46.4
	-10 to -30	263	55.6	28	49.6	49	47.3
	-30 to -50	152	59.4	40	46.6	48.1	48.1
	-50 to -80	160	60.4	51.3	46.6	45.6	49.8
	0 to -80	1,584	97.7	81.8	77.2	75.9	80.6

The calibration equations used are two published equations in their original form, and after re-parameterisation, and an in-situ calibration. RRMSE values were calculated for the given SMP ranges during the two treatment periods in pepper and one treatment period in melon. Continuous data collected every 30 min were used. *n* denotes the number of observations

These data demonstrate that this calibration equation was quantitatively accurate at > -50 kPa in both pepper treatment periods. The Shock et al. (1998) equation had appreciable negative Md values of -7 to -8 kPa and -5 to -6 kPa, in the > -10 and -10 to -30 kPa ranges (Table 3), respectively, indicating a relatively large under-estimation at > -30 kPa. The Md values of 1–2 kPa for the Shock et al. (1998) equation at -30 to -50 kPa demonstrated its accuracy within this range. At -50 to -80 kPa, Md values for the Shock et al. (1998) equation were 6–7 kPa, indicating a relatively moderate over-estimation.

For both the Thomson and Armstrong (1987) and Shock et al. (1998) equations in the melon treatment period, Md values in the -30 to -50 and -50 to -80 kPa ranges were much larger than for the two pepper treatment periods (Table 3). The large size and positive nature of these Md values indicated that considerable over-estimation occurred under the rapidly drying soil conditions of the melon treatment period.

The in-situ calibration equation (Eqn. 4) had very small Md values in the first pepper treatment period, which were lower than those of the two published calibration equations (Table 3). However, in the second pepper treatment and melon treatment periods, the Md values from the in-situ calibration were, respectively, generally similar and generally higher than those of the two published equations. An identical tendency was observed for the RRMSE values for the in-situ equation compared to the two published equations (Table 2). These data suggest that whilst the most accurate of the three calibration equations, in the treatment period in which it was derived, the in-situ equation progressively and then completely lost its advantage, relative to the two published equations, as the growing conditions increasingly differed from those in which the derivation was conducted.

For the Thomson and Armstrong (1987), Shock et al. (1998) and in-situ calibration equations in each SMP range in the three treatment periods, the only Md value that was not statistically significantly different ($P < 0.05$) from zero was the Thomson and Armstrong (1987) equation in the -10 to -30 kPa range of pepper treatment period 2 (Table 3).

Re-parameterisation of existing equations

Visual analysis

Soil matric potential data obtained using the forms of the Shock et al. (1998) and Thomson and Armstrong (1987) calibration equations that were re-parameterised using the SOLVER® procedure of Microsoft Excel 2000®, with data from the first pepper treatment period, are presented in Fig. 4 for the first pepper treatment period, and in Fig. 5 for the melon treatment period. The re-parameterised Thomson and Armstrong (1987)

Table 3 Values of mean difference (Md) comparing soil matric potential (SMP) measured with the Watermark sensor, using different calibration equations, to SMP measured with tensiometers

			Calibration Equation				
			In-situ	Shock et al. (1998)		Thomson and Armstrong (1987)	
				Original	Re-parameterised	Original	Re-parameterised
Crop	Range (kPa)	*n*	Md (kPa)	Md (kPa)	Md (kPa)	Md (kPa)	Md (kPa)
Pepper treatment period 1							
	> −10	321	−1.3	−7.2	−1.1	−1.6	−1.8
	−10 to −30	1235	1.2	−6.0	−1.1	−1.9	−1.3
	−30 to −50	704	3.5	−1.6	0.3[a]	−4.0	0.6[a]
	−50 to −80	410	3.1	6.1	0.1[b]	−21.1	0.1[b]
	0 to −80	2670	1.7	−3.1	−0.5	−5.4	−0.6
Pepper treatment period 2							
	> −10	307	−2.4	−8.2	−2.0	−2.4	−2.6
	−10 to −30	1227	2.4	−4.5	1.0	0.2[b]	0.8
	−30 to −50	511	4.2	−1.0	2.4	−1.6	2.5
	−50 to −80	301	6.8	6.9	5.6	−7.5	5.7
	0 to −80	2346	2.7	−2.8	1.5	−1.5	1.4
Melon treatment period							
	> −10	1009	−0.7	−4.8	2.1	0.9	0.7
	−10 to −30	263	9.0	2.7	7.9	7.8	7.4
	−30 to −50	152	21.7	14.1	16.5	17.1	17.2
	−50 to −80	160	42.2	35.8	32.1	31.2	34.5
	0 to −80	1584	7.4	2.4	7.4	6.7	6.8

[a] Md is not significantly different from zero at the 0.05 probability level using a *t*-test

[b] Md is not significantly different from zero at the 0.01 probability level using a *t*-test

The calibration equations used are two published equations in their original form, and after re-parameterisation, and an in-situ calibration. Md values were calculated for the given SMP ranges during two treatment periods in pepper and one treatment period in melon. Continuous data collected every 30 minutes were used. *n* denotes the number of observations

and Shock et al. (1998) equations provided very similar data, consequently only data obtained using the re-parameterised Shock et al. (1998) equation are presented in Fig. 4.

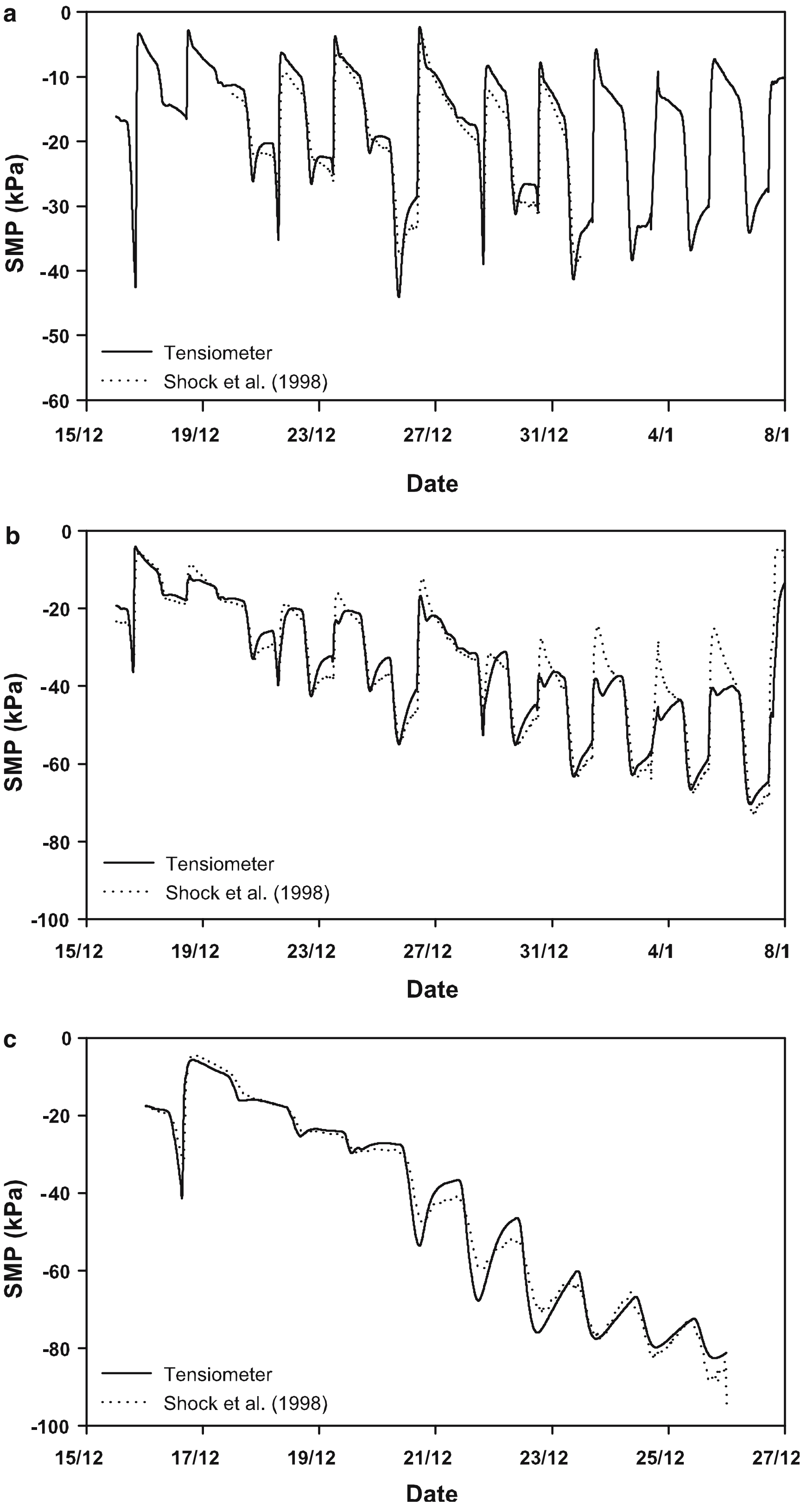
Re-parameterisation clearly improved the overall accuracy of the Shock et al. (1998) equation in the first pepper treatment period (Fig. 2 c.f. Fig. 4), particularly at > −40 kPa (Fig. 4), where the original Shock et al. (1998) was notably inaccurate (Fig. 2a). Re-parameterisation had little effect on the Thomson and Armstrong (1987) equation at > −50 kPa, but considerably improved its accuracy at < −50 kPa where the original equation was most inaccurate (Fig. 2c). In the melon treatment period, re-parameterisation improved the accuracy of the Shock et al. (1998) equation in very moist soil (> −10 kPa) in treatment T_{100} (Fig. 5a c.f Fig. 3a), but had little effect on the Thomson and Armstrong (1987) equation. As with the original forms of these two published equations, the re-parameterised forms were clearly unable to accurately measure SMP under the rapid drying conditions of treatments T_{50} and T_0 in the melon treatment period (Fig. 5b, c). Under rapidly drying conditions, the re-parameterised equations could not track overall changes in SMP nor the magnitude of short-term fluctuations in SMP resulting from drying between irrigations, moderate irrigations or soil water re-distribution.

Statistical evaluation

Re-parameterisation of the Shock et al. (1998) equation resulted in considerable overall improvement in accuracy, as indicated by smaller RRMSE values, in the first pepper treatment period, most notably in the > −30 kPa and −50 k to −80 kPa SMP ranges (Table 2). In the second pepper treatment period, re-parameterisation of the Shock et al. (1998) equation resulted in a relatively smaller improvement in accuracy; in the melon treatment period, there was no overall improvement in accuracy. Re-parameterisation reduced the overall error of the Thomson and Armstrong (1987) equation in the first pepper treatment period (Table 2), mostly by considerably reducing the RRMSE associated with the large measurement error at < −60 kPa (Fig. 2c). Otherwise, re-parameterisation of the Thomson and Armstrong (1987) equation resulted in only slight improvements in overall accuracy of the two pepper treatment periods, and had no effect in the melon treatment period.

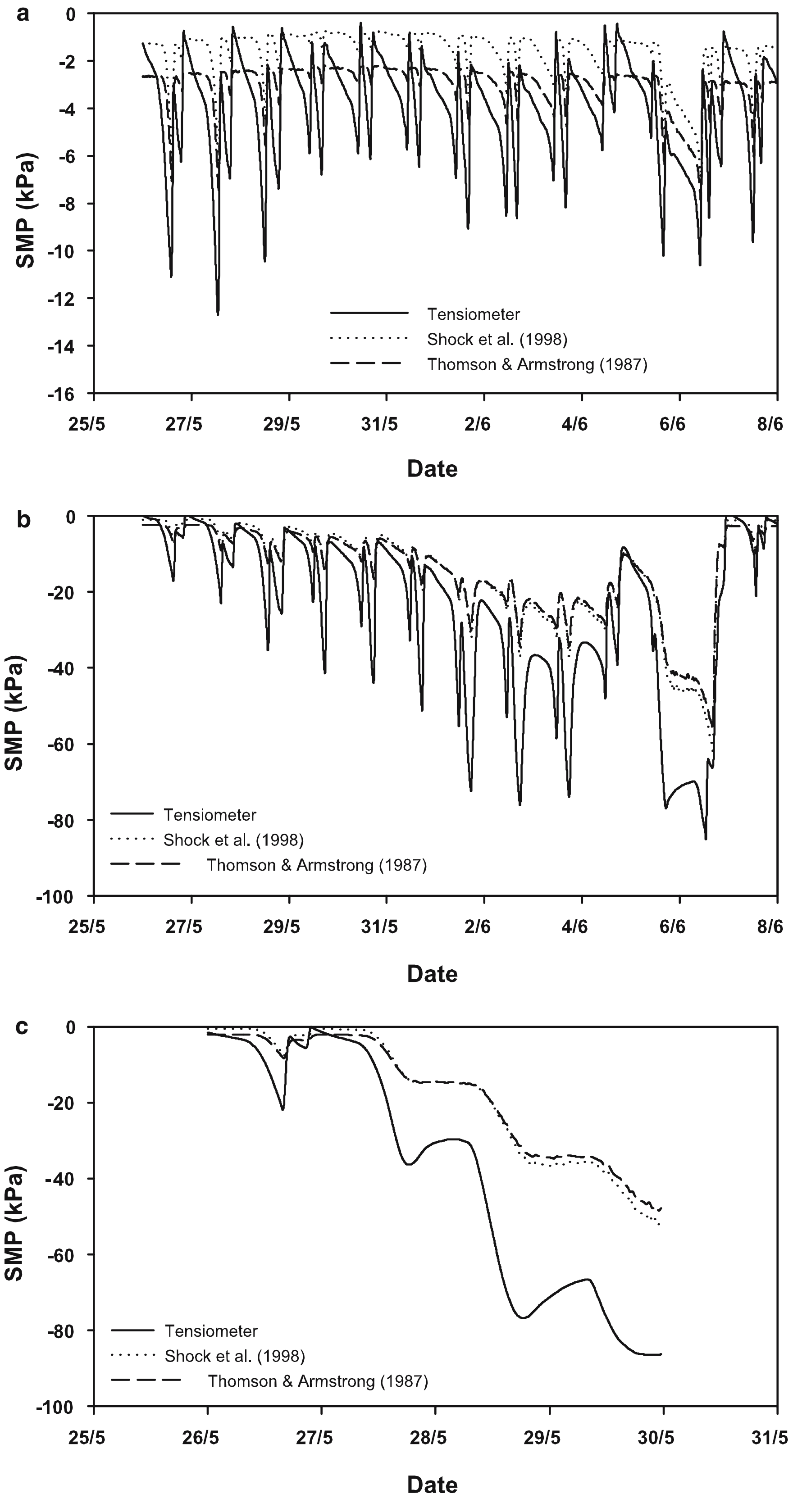
The re-parameterised forms of the Shock et al. (1998) and Thomson and Armstrong (1987) equations were more accurate than the original forms of these two equations and than the in-situ calibration equation (Eqn. 4), in the two pepper treatment periods, when considering the lowest overall RRMSE and lowest overall Md values for 0 to −80 kPa (Tables 2, 3). The

Fig. 4 For the first pepper crop treatment period, SMP calculated from the Watermark sensor using the re-parameterised Shock et al. (1998) and measured with tensiometers. In panels (a), (b) and (c), SMP data from irrigation treatments T_{100}, T_{50}, and T_0, respectively. Continuous data collected every 30 min are presented



largest overall improvements, obtained with re-parameterisation, were in the first pepper treatment period, the data of which were used to conduct the re-parameterisation procedure. The overall improvement was noticeably smaller in the second pepper treatment period, and there were no overall improvements, through re-parameterisation to the two published equations in the melon treatment period.

Fig. 5 For the melon treatment period, SMP calculated from the Watermark sensor using the re-parameterised Shock et al. (1998) and Thomson and Armstrong (1987) calibration equations and measured with tensiometers. In panels (a–c), SMP data from irrigation treatments T_{100}, T_{50}, and T_0, respectively. Continuous data collected every 30 min are presented



Assessment of variability

Coefficients of variation (CV) for SMP values of -10 ± 1, -30 ± 1, and -50 ± 1 kPa measured with tensiometers and with the Watermark sensor, using the Shock et al. (1998) equation, are presented in Table 4. CVs for the Watermark SMP values were between 12 and 24%, compared to between 12 and 38% for tensiometer SMP values. In general, there was consistently slightly less variation associated with SMP determined with the Watermark sensor than those determined with tensiometers.

Comparative evaluation of static and dynamic analyses

The approach of using dynamic data (data recorded every 30 min) to evaluate calibration equations, as done in the previous sections, was compared to the commonly used approach of using static data (6 a.m. data). These analyses were conducted with combined data from treatment T_0 in the two pepper treatment periods. SMP calculated from Watermark electrical resistance data was compared to the corresponding tensiometer SMP data using linear regression analysis. The Thomson and Armstrong (1987), Shock et al. (1998) and in-situ [Eqn.(4)] calibration equations were used to calculate SMP. An example of the two approaches is presented in Fig. 6 for data of T_0 from pepper treatment period 1 only, using the Shock et al. (1998) equation; the dynamic (30 min) data are presented in Fig. 6a, and the static (6 a.m.) data in Fig. 6b. In this case, the linear regression equations were very similar, with similarly high r^2 values.

Linear regressions with high r^2 values described the relationship between the SMP calculated from Watermark electrical resistance data and SMP measured with tensiometers for each of the six cases examined, namely the application of each of the Thomson and Armstrong (1987), Shock et al. (1998) and in-situ (Eqn. 4) calibration equations to the dynamic and static data sets (Table 5). For each of these three calibration equations, there were no statistically significant differences ($P > 0.05$) between slopes and intercepts of the linear regression equations obtained for the dynamic and static data sets (Table 5), indicating that using dynamic or static approaches for the evaluation of the three calibration equations provided very similar results.

Table 4 Values of the coefficient of variation (CV) for SMP measured with tensiometers and calculated with Shock et al. (1998) calibration equation from electrical resistance measured with the Watermark sensor

		Tensiometer		Shock et al. (1998)	
Crop	SMP (kPa)	*n*	CV (%)	*n*	CV (%)
Pepper treatment period 1					
	−10	138	23	51	20
	−30	82	25	74	24
	−50	23	24	53	18
Pepper treatment period 2					
	−10	127	23	39	13
	−30	129	38	201	18
	−50	21	29	44	18
Melon treatment period					
	−10	52	27	182	22
	−30	28	41	15	18
	−50	4	14	55	12

Values were calculated for the given values of SMP (+/− 1 kPa) for two treatment periods in pepper and one treatment period in melon. *n* denotes the number of observations

Discussion

In the three treatment periods examined, each with three different irrigation treatments, the Watermark sensor was generally able to detect changes in SMP associated with irrigation and soil drying. The accuracy of the SMP values derived from the Watermark sensor electrical resistance readings were a function of:

(a) the calibration equation used and its performance within a particular range of authentic SMP, and

(b) the general performance of the Watermark sensor under the given environmental and soil water conditions.In rapidly drying soil and in very moist soil (> -10 kPa), the Watermark sensor displayed limitations which will be discussed subsequently. The best performance of the Watermark sensor was obtained under conditions of moderate evaporative demand in moist soil (−10 to −50 kPa).

Under conditions of moderate evaporative demand during the two treatment periods of the pepper crop grown in a mild winter climate in a greenhouse, the Watermark sensor, depending on the calibration equation used, provided an accurate indication of SMP between −5 and −80 kPa. However, none of the three published equations evaluated, the Thomson and Armstrong (1987), Shock et al. (1998) and Allen (2000) equations in their original forms, was accurate for the complete −5 to −80 kPa SMP range. The Thomson and Armstrong (1987) equation provided an accurate indication of SMP for −5 to −50 kPa, and the Shock et al. (1998) for −30 to −80 kPa. The Allen (2000) equation was generally very similar to the Shock et al. (1998) equation. The in-situ calibration equation, derived under these conditions, and the re-parameterised forms of the Thomson and Armstrong (1987) and Shock et al. (1998) equations, which were re-parameterised under these conditions, all provided an accurate indication of SMP for the complete −5 to −80 kPa range, under conditions of moderate evaporative demand. The limitations of the in-situ calibration equation, and of the re-parameterised equations will be discussed subsequently.

In rapidly drying soil induced by the high evaporative demand during the melon treatment period, the Water-

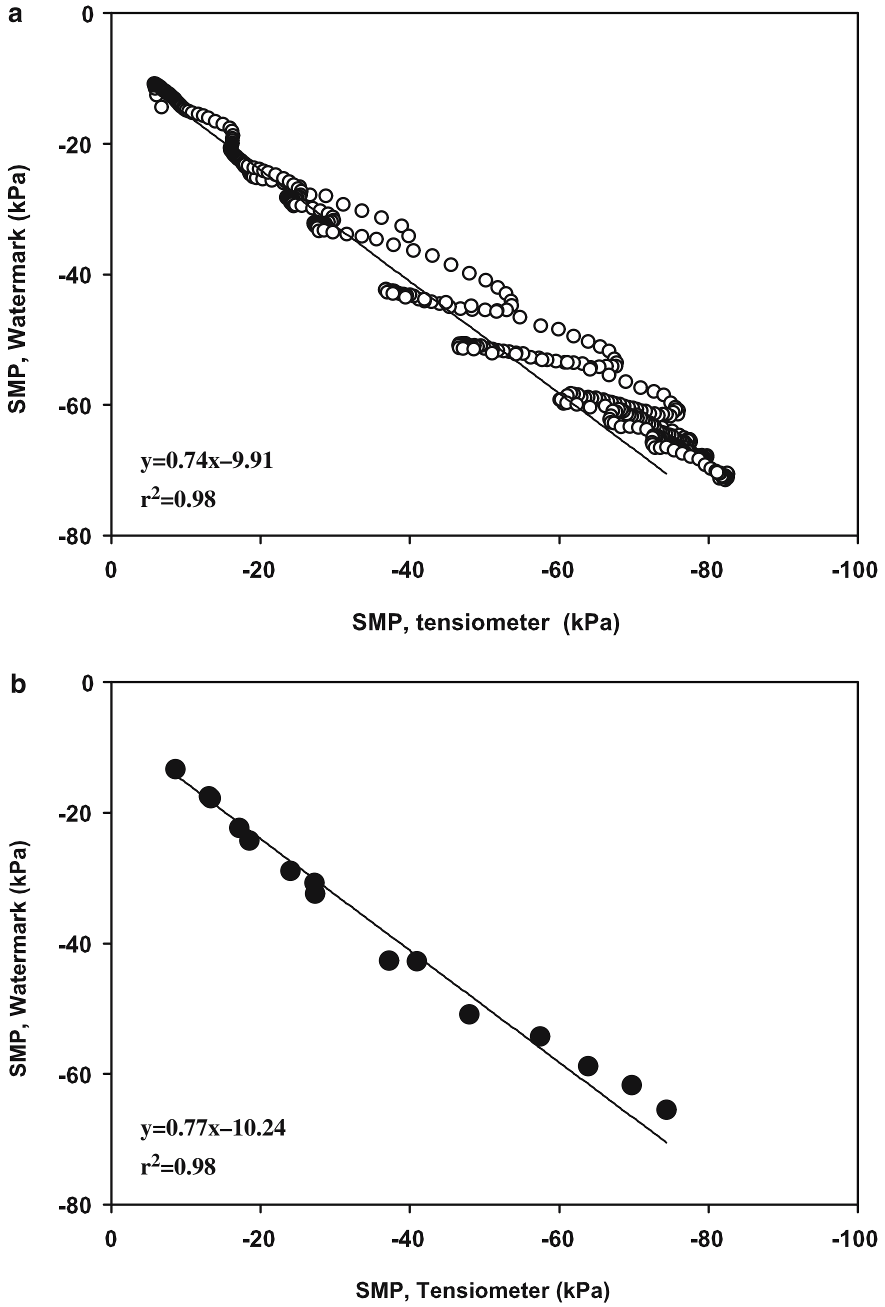


Fig. 6 Relationship between SMP as calculated, from the Watermark sensor using the Shock et al. (1998) calibration equation and measured with tensiometers in the treatment T_0 of the first pepper treatment period. In panel (a) continuous data collected every 30 min are presented and in panel (b) only data collected at 6 a.m. each day during the same period are presented

mark sensor responded much more slowly than tensiometers, regardless of the calibration equation used. This occurred both for continuous drying when irrigation was withheld, and between irrigations. Other studies have reported that the Watermark sensor responded appreciably more slowly to rapid soil drying than tensiometers (Meron et al. 1996; Hanson et al. 2000; Taber et al. 2002). Taber et al. (2002) suggested that this was due to the Watermark sensor having a smaller exposed surface area and a matrix with slower transmission. The available data suggest that there may be considerable uncertainty when using the Watermark to measure SMP under rapidly drying soil conditions, when using standard published calibration equations or calibration equations developed under conditions of moderate evaporative demand.

The conditions of moderate evaporative demand in the present study, in which the Watermark sensor provided the most accurate SMP data, are not representative of the most common cropping situations on account of cool season (winter) growth and the reduced evaporative demand inside greenhouses compared to open fields (FAO 1991). Most irrigated crops are grown in open field conditions with spring-summer growing cycles where rapid soil drying is likely to occur. It is suggested that care be taken when using the Watermark sensor to

Table 5 Linear regression analyses relating SMP measured with Watermark sensor, using different calibration equations, to SMP measured with tensiometers, for a pepper crop during two treatment periods in which irrigation was withheld

Equation	Analysis	Intercept	Slope	r^2	SE
Shock et al. (1998)					
	Dynamic	11.17	1.33	0.96	4.99
	Static	10.97	1.24	0.98	2.83
	Statistical comparison	n.s.	n.s.		
Thomson and Armstrong (1987)					
	Dynamic	−9.15	0.66	0.92	6.76
	Static	−5.71	0.69	0.99	2.28
	Statistical comparison	n.s.	n.s.		
In-situ					
	Dynamic	−3.07	1.04	0.96	5.18
	Static	−1.59	1.00	0.99	1.53
	Statistical comparison	n.s.	n.s.		

n.s. indicates not statistically significantly different ($P > 0.05$)

The dynamic analysis used continuous data collected every 30 minutes (716 data points), and the static analysis used only 6 a.m. data (15 data points). Statistical comparison refers to the statistical comparison of the linear regressions based on dynamic and static data for significant differences ($P < 0.05$) in slope and intercept values. SE is the standard error of the estimation

determine when the soil has reached threshold SMP values for irrigation management, particularly under open field conditions. Site-specific in-situ calibration for such conditions may be the most accurate option. Given that the limited working range of tensiometers (< -80 kPa) restricts their use as a calibration reference, laboratory calibrations that simulate rapid drying, may be a suitable approach for such calibration equations.

Under the more moderate soil drying conditions of the pepper treatment periods, the accuracy of the Watermark sensor at SMP of −50 to −80 kPa depended on the calibration equation. A large error was associated with the Thomson and Armstrong (1987) equation in the first pepper treatment period at < -60 kPa, and there was a suggestion of a similarly large error with this equation in second pepper treatment at < -75 kPa. Bausch and Bernard (1996) reported substantial errors when applying the Thomson and Armstrong (1987) equation at SMP values close to the minimum tensiometer limit. This calibration equation appears to be unreliable at SMP of < -60 kPa; whereas the Shock et al. (1998) equation provided a good indication of SMP within the −50 to −80 kPa range, under these conditions.

The Watermark sensor is reported to have the capacity to measure SMP in much drier soils than tensiometers (Thomson and Armstrong 1987; Spaans and Baker 1992). However, given that the rate of soil drying and the choice of calibration equation influence the accuracy of the sensor in moderately dry soil (−50 to −80 kPa), there may be appreciable uncertainty associated with results from drier soil. An additional consideration is how to verify/calibrate the Watermark sensor at SMP of < -80 kPa when tensiometers cannot be used.

In very moist soil (> -10 kPa), the ability of the Watermark sensor to track changes in SMP and the maximum SMP value determined were both dependent on the calibration equation used. The Thomson and Armstrong (1987) equation measured SMP up to −2.5 kPa with a moderate degree of accuracy indicated by Md values of 1–3 kPa. The Shock et al. (1998) equation, which was developed for a −10 to −75 kPa range, was ineffective at > -8 kPa. The adaptations of the Allen (2000) equation to the Shock et al (1998) equation improved performance in these moist conditions, but it was still inferior to the Thomson and Armstrong (1987) equation at < -10 kPa. The in-situ calibration equation provided SMP measurement up to −4 kPa, with similar Md values to the Thomson and Armstong (1987) equation. Following re-parameterisation, the Shock et al. (1998) equation performed similarly to the original Thomson and Armstrong (1987) equation in very moist soil conditions. Previous studies (Thomson and Armstrong 1987; Spaans and Baker 1992) have reported that the maximum SMP limit for the Watermark sensor as −10 kPa. In the current study, depending on the calibration equation, moderately accurate data was obtained up to −2.5 kPa.

The in-situ calibration equation (Eq. 4) was the most accurate equation for the data set from which it was derived (pepper treatment period 1). However, relative to the Thomson and Armstrong (1987) and Shock et al. (1998) calibration equations, it became increasingly inaccurate as the growing conditions became more different from those in which it was derived. In the melon treatment period, it was less accurate than the Thomson and Armstrong (1987) and Shock et al. (1998) equations. These data indicate that the in-situ calibration equation developed in the present study was highly specific to the conditions under which it was developed i.e. winter-grown greenhouse crop. However, it was not sufficiently robust to be adapted to other growing conditions e.g. spring-summer crops, in the same soil. This suggests that in-situ calibrations may be accurate in the specific growing conditions in which they are developed, but that care should be used when applying them in different growing conditions.

The re-parameterisation procedure using the SOLVER® function of Microsoft Excel 2000® appreciably enhanced the accuracy of both the Thomson and Armstrong (1987) and Shock et al. (1998) equations, for the data set with which the re-parameterisation was conducted (the first pepper treatment period). However, with increasing divergence of the growing conditions from those in which the re-parameterisation was conducted, the improved accuracy of the re-parameterised calibration equations was progressively reduced. In the melon treatment period, the re-parameterised forms of the Thomson and Armstrong (1987) and Shock et al. (1998) were no more accurate than the original forms. It was concluded that the re-parameterisation procedure is most suitable for optimising calibration equations for specific growing conditions (e.g. specific combinations of soil and climatic conditions), but that re-parameterised calibration equations do not appear to be sufficiently robust to be used as standard calibration equations for a range of growing conditions for a given site or soil type. Irmak and Hamman (2001) used the same re-parameterisation procedure, with several published equations, to improve their accuracy in a sandy soil. However, they did not evaluate the re-parameterised equations, in the same soil, under different growing conditions. They reported that the re-parameterised calibration equations were soil-specific and could not be applied to soils different from those in which the re-parameterisation had been conducted.

Given that the in-situ and re-parameterised calibration equations appeared to be very specific to the conditions in which they were derived, the published calibration equations of Thomson and Armstrong (1987), Shock et al. (1998) and Allen (2000) were considered to be more robust in terms of applicability to different growing conditions. Considering the overall performance of these published equations throughout this study, the Thomson and Armstrong (1987) equation was more accurate than the Shock et al. (1998) equation in the -2.5 to -30 kPa range, and the Shock et al. (1998) equation was comparatively more accurate in the range -30 to -80 kPa. Whilst the Shock et al. (1998) equation gave a relatively small error in the -10 to -30 kPa range, it was clearly less accurate in this range than the Thomson and Armstrong (1987) equation. The Allen (2000) equation made only relatively minor improvements to the overall accuracy of the Shock et al. (1998) equation in the SMP range examined; however, it did notably improve accuracy at < -10 kPa. The Shock et al. (1998) equation is the default calibration equation used by the manufacturer. In the current study, its use would have resulted in appreciable under-estimation of SMP at > -30 kPa.

For high frequency drip irrigation in a moderately textured soil, where the target SMP range is likely to be approximately -10 to -30 kPa, the data from the current study suggest that the Thomson and Armstrong (1987) equation provides a good indication of SMP; this equation also has the advantage of being able to provide a moderately accurate indication of SMP at > -10 kPa. For drier soil conditions, the data from the current study suggested that the Shock et al. (1998) or Allen (2000) equations were more suitable.

The comparison of the use of dynamic (continuous data) versus static (6 a.m. data points) data, for evaluating Watermark sensor performance, indicated that no clear advantage was obtained by using continuously collected data (at 30 min intervals) compared to using single daily data points. Nevertheless, we suggest that as a general procedure, the use of dynamic data sets is preferable because it more closely resembles the constantly changing field conditions under which the sensors would be used in commercial farming and in research studies.

The presence of the mulch layer of river sand on the soil surface in the present study would have had little effect on the evaluations of the calibration equations. The reduced soil temperature fluctuations would have had no effect on the calibration because electrical resistance measurements were corrected for direct temperature effects with soil temperature data measured at the same time as each individual electrical resistance measurement. Effects of the mulch on soil evaporation are likely to have been small in the pepper treatment periods when the evaporative demand was moderate. In the melon treatment period, the reduced soil evaporation is likely to have reduced somewhat the overall rate of soil drying which may have ameliorated the effect of rapid soil drying observed in this treatment period.

The CV determined in the current study for SMP measured with the Watermark sensor were 12–24% compared to 14–41% for tensiometers. The lower CVs associated with the Watermark sensor are presumably due to its smaller responsiveness compared to tensiometers. The relatively small CV values suggest that with accurate positioning in relation to the dripper and plant, and sufficient replication, that variability between Watermark sensors is not a major problem when used with drip-irrigated vegetable crops.

Even with selection of the most accurate calibration equation, SMP measured with the Watermark sensor is best considered as providing an indication of SMP, rather than accurate measurement. Being an indirect measurement, SMP values derived from Watermark sensor electrical resistance readings are dependent upon the calibration equation used. The data from the current study suggest that even where calibrations equations are specifically developed or verified for a particular soil, different growing conditions can appreciably reduce the accuracy of those calibration equations. Additional factors may influence SMP data obtained with Watermark sensors. Small irrigations or rainfall events have been reported to cause inadequate responses (McCann et al. 1992). The effects of soil salinity on the calibration of the Watermark sensor have yet to be described.

In conclusion, the data from the current study suggest that the Watermark sensor can be used to provide a good indication of SMP in moderately textured soils receiving drip irrigation and subjected to moderate evaporative conditions. It appears that there is considerable uncertainty in SMP values measured with the Watermark sensor in rapidly drying soils, at least with the calibration equations considered in this study. To optimise the accuracy of Watermark SMP data, it is recommended that calibration equations be developed or verified, for each set of growing conditions. This will also serve to identify the effective SMP range for the selected calibration equation in the given growing conditions. The Watermark sensor is a potentially useful sensor for SMP measurement, in both commercial farming and research applications. However, selection of the most appropriate calibration equations and knowledge of performance characteristics are essential to the quality of the SMP data obtained.

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References

Allen R (2000) Calibration for the Watermark 200SS soil water potential sensor to fit the 7–19.96 "calibration #3" table from Irrometer. University of Idaho, Kimberley. http://www.kimberly.uidaho.edu/water/swm/calibration_Watermark2.htm Confirmed 4 August 2004

Allen RG, Pereira LS, Raes D, Smith M (1998) Crop evapotranspiration. Guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper. FAO, Rome, Italy

Bausch W, Bernard TM (1996) Validity of the watermark sensor as a soil moisture measuring device. In: Camp CR, Sadler EJ, Yoder ER (eds) Evapotranspiration and irrigation scheduling. Proceedings of the international Conference American Society of Agricultural Engineers pp 933–1108

Campbell GS, Campbell MD (1982) Irrigation scheduling using soil moisture measurements: theory and practice. Adv Irrig Sci 1: 25–42

Campbell GS, Mulla DJ (1990) Measurement of soil water content and potential. In: Stewart BA, Nielsen DR (eds) Irrigation of agricultural crops. American society of agronomy, Madison, USA, pp 127–142

Cassel DK, Klute A (1986) Water potential: tensiometry. In: Klute A (ed) Methods of soil analysis, part 1. Physical and mineralogical methods. American society of agronomy, Madison, USA, pp 563–596

Dasberg S, Or D (1999) Drip irrigation. Springer, Berlin Heidelberg New York

Eldredge EP, Shock CC, Stieber TD (1993) Calibration of granular matrix sensors for irrigation management. Agron J 85: 1228–1232

FAO (1991) Protected cultivation in the Mediterranean climate. Plant Protection Paper 90. FAO Rome, Italy

Fernández MD, Orgaz F, Fereres E, López JC, Céspedes A, Pérez J, Bonachela S, Gallardo M (2001) Programación del riego de cultivos hortícolas bajo invernadero en el sudeste español. Cajamar, Almería, Spain

Hanson B, Schwankl L, Fulton A (1999) Scheduling irrigations: when and how much water to apply. Division of agriculture and natural resources publication 3396. University of California Irrigation Program. University of California, Davis

Hanson BR, Orloff S Peters D (2000) Monitoring soil moisture helps refine irrigation management. Calif Agric 54: 38–42

Irmak S, Haman DZ (2001) Performance of the watermark granular matrix sensor in sandy soils. Appl Eng Agric 17:787–795

Leib BG, Jabro JD, Matthews GR (2003) Field evaluation and performance comparison of soil moisture sensors. Soil Sci 168:396–408

McCann IR, Kincaid DC, Wang D (1992) Operational characteristics of the watermark Model 200 soil water potential sensor for irrigation management. Appl Eng Agric 8: 603–09

Meron M, Hallel R, Shay G, Feuer R (1996) Soil-sensor actuated automatic drip irrigation of cotton. In: Camp CR, Sadler EJ, Yoder ER (eds) Evapotranspiration and irrigation scheduling. Proceedings of the international conference American society agricultural engineers, pp 886–891

Mitchell JP, Shennan C, Grattan SR, May DM (1991) Tomato fruit yields and quality under water deficit and salinity. J Am Soc Hortic Sci 116: 215–221

Sanders DC, Howell TA, Hile MMS, Hodges L, Meek D, Phene CJ (1989). Yield and quality of processing tomatoes in response to irrigation rte and schedule. J Am Soc Hortic Sci 114: 904–908

Scanlon BR, Andraski BJ, Bilskie J (2002) Miscellaneous methods for measuring matric or water potential. In: Dane JH, Topp GC (eds) Methods of soil analysis, part 4—Physical methods. Am. Agron. Soc., Madison, USA, pp 643–670

Shock CC, Barnum JM, Seddigh M (1998) Calibration of watermark soil moisture sensors for irrigation management. Proc. Int. Irrig. Show, San Diego California USA, pp 139–146

Shock CC (2004) Granular matrix sensors, http://www.crop-info.net/granular.htm confirmed 4 August 2004

Spaans EJA, Baker JM (1992) Calibration of Watermark soil moisture sensors for soil matrix potential and temperature. Plant Soil 143:213–217

Taber HG, Lawson V, Smith B, Shogren D (2002) Scheduling microirrigation with tensiometers or Watermarks. Int Water & Irrig 22:22–26

Thomson SJ, Armstrong CF (1987) Calibration of the Watermark model 200 soil moisture sensor. Appl Eng Agric 3:186–189

Thomson SJ, Younos T, Wood K (1996) Evaluation of calibration equations and application methods for the watermark granular matrix soil moisture sensor. Appl Eng Agric 12:99–103

Young MH, Sisson JB (2002) Tensiometry. In: Dane JH, Topp GC (eds). Methods of soil analysis, Part 4—Physical methods. Am. Agron. Soc., Madison, USA, pp 575–608

Wittwer SH, Castilla N (1995) Protected cultivation of horticultural crops worldwide. Hort Technol 3:6–19