EVALUATION OF THE PERFORMANCE OF SOIL MOISTURE SENSORS IN LABORATORY-SCALE LYSIMETERS

by

SOPHIE PROULX

A Thesis
Submitted to the Faculty of Graduate Studies
in Partial Fulfillment of the Requirements
for the Degree of

MASTER OF SCIENCE

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EVALUATION OF THE PERFORMANCE OF SOIL MOISTURE SENSORS IN LABORATORY-SCALE LYSIMETERS

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ABSTRACT

Soil moisture sensors were evaluated in laboratory-scale lysimeters. The performances of tensiometers, granular matrix sensors (GMS), capacitance sensors, phase transmission sensors, and of a portable capacitance probe and a frequency-domain reflectometry (FDR) sensor was observed in loam (31.5% sand, 45.2% silt, and 23.1% clay) and silt loam (20% sand, 54% silt, and 26% clay) of the Ramada Series. The experiment was conducted over two drying cycles in loam for moisture contents decreasing from 34.0 to 17.0% by volume for the 1999 trial and decreasing from 43.1 to 20.0% by volume for the 2000 trial and over a single drying cycle in silt loam for moisture decreasing from 45.8 to 19.5% by volume. The lysimeters were designed with hydraulic weighing systems to facilitate continuous monitoring of the soil moisture content. For the purpose of comparison, the readings obtained with the sensors were converted to volumetric water contents. Soil matric potentials obtained with the tensiometers and GMS were converted using soil-specific moisture characteristic curves. A conversion equation was developed, based on texture-specific calibration curves published by the manufacturer, to calibrate the readings of the Aqua-Tel sensors. The procedure followed for converting the readings of the Aquaterr probe was also partially developed by the experimenter to obtain more accuracy.

The FDR sensor was the most accurate instrument to measure soil moisture content in both soils over the entire drying cycle and thus, it is most suitable to monitor irrigation needs with accuracy, precision, and ease of use. Both capacitance sensors, the Aquaterr probe and the Aqua-Tel sensors, also performed well, measuring soil moisture content accurately although with less precision. Tensiometers and Watermark sensors although very precise were mainly inaccurate due to problems with data conversion. However, they could serve as triggering devices for initiating an automatic irrigation system for soils in the high moisture range. The evaluation of the VIRRIB sensors' performance remains inconclusive due to the malfunction of the sensors resulting from calibration.

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1 INTRODUCTION

1.1 Problem statement

Good irrigation water management requires soil moisture content data to ensure higher water use efficiencies and to achieve better yields. Properly scheduled irrigation can conserve water and energy for pumping and also minimize the potential for groundwater contamination due to deep percolation losses. Several sources of information are available to help growers make irrigation decisions. Both measured and forecasted meteorological data including precipitation, temperature, relative humidity, radiation, and wind velocity; soil water status in the form of soil moisture content or soil matric potential; and plant-based measurements provide producers with useful data. Combinations of these are often used, with soil moisture status being the most common, reliable, and direct indicator of irrigation needs. Various approaches such as remote sensing, hydrological models, and *in situ* sensing can be used to determine soil moisture conditions. Many *in situ* methods including lysimetry, tensiometry, nuclear techniques such as neutron scattering and gamma ray attenuation, heat dissipation approaches, and electromagnetic techniques have been used for soil moisture determination. Electromagnetic techniques, also called dielectric methods, include capacitive approaches such as time-domain and frequency-domain methods as well as resistive techniques.

Numerous sensing instruments based on those techniques have been commercialised and are available to producers. However, very little information concerning their performance is available. Thus, the most suitable methods to monitor the need for irrigation are yet to be determined. The best sensing instruments should measure soil water accurately, precisely, quickly, and should be easy to use. The use of a sensor implies installing and operating the instrument as well as interpreting the readings obtained, which can require calibration or conversion of the measured quantity to soil moisture units.

During the growing seasons of 1998 and 1999, we conducted a field study to evaluate the performance of tensiometers (Soilmoisture Equipment Corp., models 2710AR and 2725AR), Watermark granular matric sensors (Irrometer Co.), Aqua-Tel electrical capacitance sensors (Automata Inc., model Aqua-Tel94-29), the Aquaterr electrical capacitance probe (Aquaterr Instruments Inc., model 200), and VIRRIB phase transmission sensors (Environmental Sensors Inc.) (Fig. 1). Different installation patterns, i.e. orientation of the sensing probes, were also included as treatments. Soil moisture data obtained with the different instruments were compared to the gravimetric sampling method which was used as the standard for comparison. However, the high standard error of the volumetric water content of the samples collected from the field using the gravimetric method indicated a wide variability in water content of the soil under field conditions. Based on the results of the field experiments, further testing under controlled conditions was recommended (Proulx et al. 1998). Consequently, a laboratory study was carried out to test the sensors in more-homogeneous soil-water conditions.

1.2 Objectives

The objective of the laboratory study was to evaluate the performance of soil moisture sensors under controlled soil moisture conditions in laboratory-scale lysimeters. In addition to the five types of sensors previously tested in the field trials, and in the laboratory trial of 1999, another dielectric probe was included in the laboratory trial of

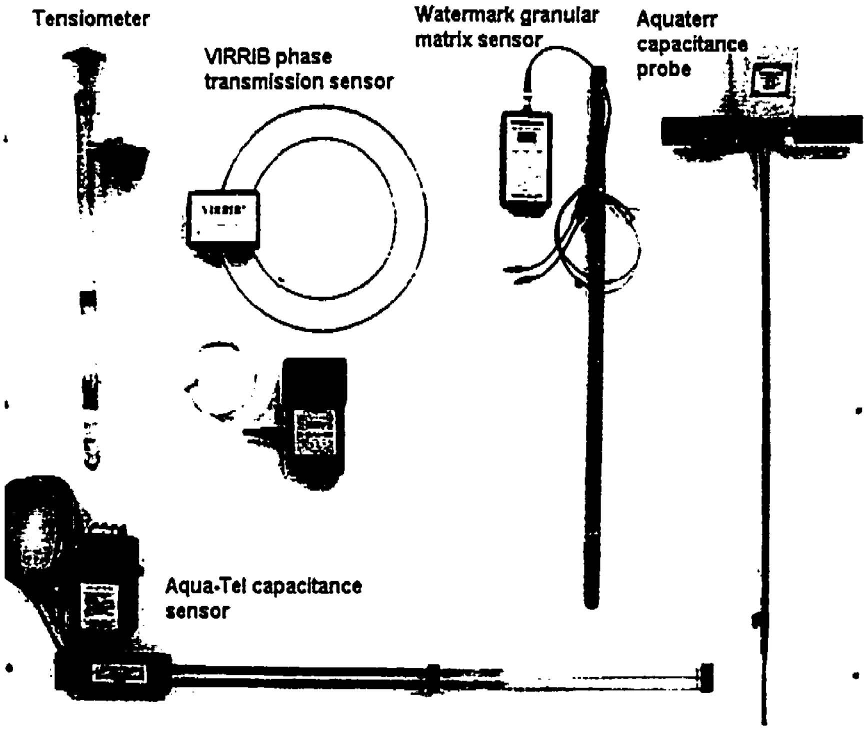

Fig. 1 Soil moisture sensors tested in the field and laboratory trials. Tensiometers, Watermark GMS, VIRRIB sensors, Aqua-Tel sensors, and the Aquaterr probe were tested.

Fig. 2 View of the ThetaProbe sensor tested the laboratory trial of 2000.

2000. The ThetaProbe (Delta-T Devices Ltd, type ML2), shown in Fig. 2, which can also be buried permanently in the soil, was used as a portable sensor. The performance of the sensors was evaluated in loam and silt loam soils of the Ramada Series taken from the experimental plots located at the Manitoba Crop Diversification Centre, Carberry, Manitoba.

1.3 Scope

This thesis presents only a brief overview of the field testing conducted in 1998 and 1999. Because the main focus of the research was the evaluation of soil moisture sensors under controlled moisture conditions, a detailed description of the lysimeter study is given. The literature review describes the basic theory behind various soil moisture measurement techniques, the principles of operation of the instruments tested, as well as the performance of similar soil-moisture-measurement equipment reported in the literature. The experimental methods of the field and laboratory study are presented, followed by results. The results from the lysimeter study are then discussed and conclusions are presented. Finally, recommendations addressed to both producers and researchers are stated.

2 LITERATURE REVIEW

2.1 Review of sensors' performance

Despite the wide array of soil moisture measuring devices available in the market, very few studies comparing the performance of the sensors investigated in the present study have been reported in the literature. Yoder et al. (1998) compared the performance of the Troxler neutron gage, Troxler Sentry 200-AP capacitance probe, Aqua-Tel capacitance sensors, time-domain reflectometry (TDR) probes, gypsum blocks, Watermark granular matrix sensors (GMS), and Agwatronics heat dissipation blocks under controlled soil moisture conditions. Their study was conducted in loam and sandy loam using 0.61-m deep soil columns equipped with a tension-controlled drainage system and weighed with load cells. Their results showed that, in order of decreasing performance, Aqua-Tel sensors, the Sentry probe, the Troxler neutron gauge, and Watermark sensors performed best when considering accuracy, reliability, durability, and ease of installation.

Ripley et al. (1998) evaluated the performance of various types of soil moisture sensors, including time-domain reflectometry probes, the ThetaProbe (Model ML-1), capacitance sensors, and neutron probes at three locations. They reported that the TDR probes and the ThetaProbe performed satisfactorily and were well suited for unattended operation as opposed to neutron probes that require constant assistance. They recommended the ThetaProbe over TDR probes because it was insensitive to temperature, bulk density, and soil texture.

Hanson (1999) evaluated the performance of tensiometers, Watermark GMS, gypsum blocks, and the dielectric instruments Sentry 200-AP, TRIME, TRACE, Enviroscan, Aquaterr, and ThetaProbe. The investigator reported that both tensiometers and GMS showed good response to changes in moisture content except in loamy sand where they failed to respond. The response of the GMS, however, tended to lag that of tensiometers. The ThetaProbe performed very accurately and consistently over a wide range of soil textures and was the only dielectric sensor to perform well.

Eldredge et al. (1993) compared GMS readings to soil water measurements obtained with tensiometers, a neutron probe, and gravimetric sampling. The experiment was conducted in a potato field in a silt loam soil. They reported that the Watermark GMS measurements were closely related to those obtained with the other techniques. They also established that, when calibrated against tensiometers, the Watermark meter model 30KTC had a linear response over the range from 0 to -80 kJ/kg represented by the following relationship with a significance of 89%: $\Psi=-6.44-0.738 \bullet R$, where Ψ is the soil matric potential in J/kg and R is the meter's readings in dimensionless units. However, because GMS measure soil matric potential rather than soil moisture content, they were found to be more suited for automatic irrigation triggering based on preset soil matric values.

Phene et al. (1989) reported the use of a soil matric potential sensor (SMPS) for automatically initiating irrigation when the soil matric potential has reached a preset level. They found a linear response between -10 ± 3.3 and -300 ± 5.5 J/kg (J/kg = kPa = cBars).

Research conducted by Stieber and Shock (1995) established that the performance of Watermark sensors in silt loam, in a potato field, was largely dependent on the depth of installation of the sensor. They found the ideal location of the sensors to be 0.15 m offset from the centre of the hill and buried at a depth of 0.1 to 0.2 m. The sensors responded within four hours of wetting and within 12 hours of drying. Sensors placed deeper than 0.3 m responded slowly and inconsistently.

McCann et al. (1992) evaluated the static and dynamic response characteristics of the Watermark model 200 using the pressure plate method and experiments conducted in greenhouses. They found the sensor's resistance to respond nearly linearly to water potential over the range from 0 to -200 kPa. They also concluded that the Watermark model 200 did not fully respond to rapid drying or partial re-wetting of the soil.

Lischmann (1991) evaluated the performance of the VIRRIB phase transmission sensor in the laboratory by installing the sensor and a gypsum resistance block in an isolated block of soil placed on a scale. The VIRRIB readings were monitored over several drying cycles and compared to the total mass on the scale and to the gypsum block measurements. Vinegar and sulfuric acid were added to the soil block to evaluate the effect of the soil solution's composition on the VIRRIB performance. A field study was also conducted to determine the performance of the sensor under field conditions. At completion of both studies, it was concluded that VIRRIB sensors can be used to monitor irrigation needs.

Tensiometers and granular matrix sensors have been widely used and several research projects evaluated their performance as a tool for triggering events (Phene et al. 1989; McCann et al. 1992; Shock and Barnum 1993; Stieber and Shock 1995). Information reporting the performance of the Aquaterr soil moisture meter, Aqua-Tel capacitance sensors, VIRRIB phase transmission sensors, and the ThetaProbe, however, remains scarce. The present study provides more information on these sensors.

2.2 Background theory

2.2.1 Gravimetric method The gravimetric method first requires sampling of the soil and immediate weighing of the moist sample. The sample is then dried at 105°C for 24 h in a convection oven and weighed again after cooling in a desiccator. The mass basis water content of the sample is calculated using:

$$\theta_m = \frac{m_w}{m_s} \tag{1}$$

where:

θ_m = gravimetric water content (mass fraction),

m_w = mass of water contained in the sample (kg),

m_s = mass of dry soil in the sample (kg).

To determine the volumetric water content of the soil, the gravimetric water content is multiplied by the apparent specific gravity (ASG) of the soil. The ASG is defined as the ratio of the soil bulk density to the density of water. The relationship is simplified as follows:

$$\theta_v = \theta_m \bullet \mathrm{ASG} \tag{2}$$

where:

θ_v = volumetric water content (volume fraction),

ASG = apparent specific gravity (decimal fraction).

2.2.2 Tensiometric method The tensiometric method relies on the relationship that exists between the soil matric potential and its moisture content. The soil matric potential, which can also be called matric suction or tension, is the resultant of the combination of capillary and adsorptive forces occurring in porous media. Capillary forces are mainly surface tension forces caused by the adhesion of water and the soil and by the narrowness of the pores (Smedema and Rycroft 1983). The capillary pressure is a function of the size of the pores and can be approximated using:

$$P_{cap} = \frac{-3000}{D} \tag{3}$$

where:

P_{cap} = capillary pressure (m),

D = diameter of the pore (µm).

Adsorption forces comprise van der Waals and electrostatic forces exerted on the water by the negatively charged colloidal surfaces of the soil particles. Tensiometers are used to measure the matric potential of soils.

2.2.3 Electromagnetic methods Techniques that rely on the propagation of electromagnetic waves through a medium to measure its electrical properties fall into the category of electromagnetic methods. Those methods, often referred to as dielectric techniques, comprise various type of instruments, probes, or sensors that differ from each other mainly by the characteristics of the signal sent and the measurement quantities. For example, voltage steps are commonly used to measure travel time in a medium whereas sine waves may be used to measure frequency shift or amplitude variation.

The principle behind the use of electromagnetic waves to measure the electrical characteristics of the medium through which they travel is based on the propagation of electromagnetic waves in transmission lines. The velocity of propagation is described by the following equation:

$$V = \frac{c}{\sqrt{\mu_r \bullet \varepsilon_r}} \tag{4}$$

for which

$$\mu_r = \frac{\mu}{\mu_o} \tag{5}$$

and

$$\varepsilon_r = \frac{\varepsilon}{\varepsilon_o} \tag{6}$$

where:

v = velocity of propagation (m/s),

μ_r = relative permeability constant (decimal fraction),

μ = absolute permeability of the medium (H/m),

μ_o = permeability of free space (= 1.257×10^{-7} H/m),

ε_r = relative permittivity or dielectric constant (decimal fraction),

ε = absolute permittivity of the medium (F/m),

ε_o = absolute permittivity of free space (= 8.854×10^{-12} F/m),

c = velocity of light in free space (= 3×10^{8} m/s).

The velocity of wave propagation in a transmission line can also be expressed by

$$v = \frac{d}{t} \tag{7}$$

where:

d = distance of travel (m),

t = propagation time to travel the distance, d, (s).

Although the physical configuration of sensing instruments can vary greatly, they all require that the medium be placed somewhere within the electric field produced either by simple electrodes or by a transmission line. In the most simple configuration, the porous medium is positioned between two electrodes which form the plates of a capacitor. In more complex systems, the medium forms either a portion or the whole dielectrics of a transmission line, which can itself vary in its configuration. The electrical properties of the surrounding medium therefore directly affect the propagation of the electromagnetic signal through the media.

In this case, the medium consists of moist soil. Electrical properties of moist soil can be described by the relative complex dielectric permittivity function:

$$\varepsilon(f) = \varepsilon'(f) - i\left[\varepsilon''(f) + \frac{\sigma}{2\pi f \varepsilon_0}\right] \tag{8}$$

where:

ε(f) = relative complex dielectric permittivity of the moist bulk soil (dimensionless),

ε'(f) = real part of ε(f) (dimensionless),

ε''(f) = relaxation losses (dimensionless),

f = measurement frequency (Hz),

i = square root of -1,

σ = conductivity of the moist bulk soil (S/m).

The real part of the relative complex permittivity function is a measure of the energy stored by the dipoles aligned in the applied electromagnetic field. In other words, $\varepsilon'(f)$ is a measure of the polarization and in turn a measure of the capacitance of the media. In soils, because most of the dipoles that are free to respond to polarization are water molecules, $\varepsilon'(f)$ is closely correlated to the water volume fraction. The imaginary part of $\varepsilon(f)$ is a measure of the energy losses caused by relaxation losses, $\varepsilon''(f)$, and conductivity losses, $\sigma/(2\pi f\varepsilon_o)$. The dependence of the relative complex dielectric permittivity of bulk soil on frequency is due to the frequency dependence of free water's dielectric properties. The Cole-Cole function describes the frequency dependent relative complex dielectric permittivity of free water, $\varepsilon_{wf}(f)$, as follows:

$$\varepsilon_{wf}(f) = \varepsilon_{\infty,w} + \left[\frac{\varepsilon_{s,w} - \varepsilon_{\infty,w}}{1 + \left(if/f_{rel,w}\right)^{1-\beta_w}}\right] - \frac{i\sigma_{fw}}{2\pi f\varepsilon_0} \qquad (9)$$

where:

$\varepsilon_{\infty,w}$ = high-frequency limit of the real dielectric permittivity (=4.22),

$\varepsilon_{s,w}$ = static value of the real dielectric permittivity (=80.10),

$f_{rel,w}$ = relaxation frequency of water (=17.113 GHz),

f = measurement frequency (Hz),

i = square root of -1,

β_w = parameter accounting for a spread in relaxation frequency (=0.013),

σ_{fw} = conductivity of free water (S/m).

Those values are given at 25°C (Heimovaara et al. 1994). Values of the relative complex dielectric permittivity of free water as a function of frequency are given by Thomas (1966). The real part of $\varepsilon(f)$ is nearly independent of the measurement frequency over the range from about 50 to 1000 MHz and it varies merely from 81 to 78 over the temperature range of 15 to 25°C. The imaginary part of $\varepsilon(f)$, for free water without dissolved impurities, has a value of about 20 at 10 MHz which decreases as frequency increases to reach 2 at 100 MHz. Energy losses in that frequency range are mostly due to conductivity losses. Conductivity losses can be substantial at measurement frequencies below 50 MHz in soils due to conductive solids and dissolved impurities such as soluble salts. The cut-off frequency value below which conductivity losses can be important is not well defined and values ranging from 20 to 50 MHz were reported in the literature reviewed (Thomas 1966; Heimovaara et al. 1994; Topp et al. 1980). As the frequency increases to the GHz range, relaxation losses become important reaching a value of about 30 at 10 GHz. Consequently, because both the real dielectric permittivity and the conductivity losses are functions of frequency and do not vary at the same rate nor reach the same maxima and minima, a measurement frequency can be chosen, depending on the application, to obtain significant measurement quantities. For example, to measure soil salinity which is determined by measuring the soil conductivity, a frequency of 10 MHz would be more appropriate than one of 100 MHz.

Moist bulk soil is a mixture of solids, air, and bound and free water. The relative complex permittivity of the bulk soil is therefore a function of $\varepsilon(f)$ of each constituent and their respective volume fraction. For non-conductive solids, low salts concentration, temperature ranging from 15 to 25°C, and at frequencies between 50 MHz and 1 GHz,

$\varepsilon(f)$ of solids is between 2 and 5, that of air is assumed to be equal to that of free space i.e.1, that of tightly bound water is close to that of ice i.e. approximately 3, whereas $\varepsilon(f)$ of free water ranges from 78 to 81. The free water volume fraction has, thus, a great effect on the bulk soil relative complex permittivity.

Besides the frequency effect, other parameters such as soil texture and range of moisture contents have an influence on the bulk soil's dielectric properties. As it was observed by Eller and Denoth (1996) and Thomas (1966), the real dielectric permittivity of moist soil as a function of soil moisture content cannot be expressed with a single relationship over the entire moisture range from 0% by volume to saturation. The $\varepsilon'(f)$ function increases slower at low moisture content, where a large portion of the water is tightly bound to the soil particles, than at higher moisture content. As the soil moisture content increases, the layer of bound water at the surface of soil particles becomes larger and the binding forces decrease. Thus, as the moisture content increases, the proportion of water molecules that are free to get polarized also increases thereby causing a rapid increase of $\varepsilon'(f)$. Since the adhesive force varies with soil texture, $\varepsilon'(f)$ of bulk soil is dependent on the particle size distribution, or soil texture, at low moisture contents.

Empirical relationships and mixing models are commonly used to determine soil moisture content from $\varepsilon(f)$ measurements. Thomas (1966) established two empirical relationships between soil moisture, θ, and the real relative dielectric permittivity of bulk soil, ε'. A linear equation described the $\varepsilon'(f)$-θ correlation for θ below 10.0% by volume whereas a semi-logarithmic relationship was selected for θ from 4.5 to 45.0% by volume. He concluded that soil texture did not have a significant effect on fringe capacitance measurements made with a dielectric sensor operating at a frequency of 30 MHz. In 1980, Topp et al. developed a nonlinear equation that has been widely accepted as reference for time-domain reflectometry (TDR) determination of soil moisture content as a function of the apparent dielectric permittivity. The apparent dielectric permittivity, referred to by Topp et al., is the measured dielectric permittivity which is in fact the relative complex dielectric permittivity of the medium. Because their measurements were made in low-loss, nearly homogenous material, the apparent dielectric conductivity was assumed equal to the real dielectric permittivity. Topp et al. (1980) compared their findings to several other studies, including Thomas' (1966) work, and concluded that bulk soil dielectric permittivity was only weakly dependent on soil texture, bulk density, temperature, and frequency, between 20 MHz and 1 GHz. Although they did not conclude on the effect of soluble salt content on the measurements, they noted that an increase in the conductivity of the medium also increased the attenuation of the transmitted signal while not affecting its propagation time. More recently, Eller and Denoth (1996) developed a nonlinear relationship between θ and ε' measurements, for four soils, taken with a capacitive probe operating at 35 MHz. Their second-degree polynomial equation, which held for θ greater or equal to 3% by volume, showed no influence of soil types on ε'. Perdok et al. (1996) used a frequency domain sensor operating at 20 MHz to correlate ε' to gravimetric water content and bulk density. Measurements of the complex dielectric permittivity, ε, were taken with an impedance analyser for laboratory use from which ε' and the electric conductivity were derived.

Dielectric mixing models range in complexity from Wagner's dielectric spheres model, which consists of only two phases, to the semidisperse model, which is a complex multi-phase system. Wobschall (1977) described the semidisperse model as well as the chronological development of the Hanai/Bruggelman/Wagner (HBW) theory. The semi-disperse model proposed that the water and particles are mutually interdispersed. It can be simplified to a moist particle phase consisting of a solid particle within which water-filled micropores are dispersed and around which is a water layer. In soils, the moist particles and air are dispersed in the remaining water. This multi-phase model used the two-phase HBW theory to partially solve each portion of the more complex model. Three-phase (solids, air, and water) and four-phase (solids, air, and bound and free water) models have been widely used to correlate bulk soil complex dielectric permittivity to the complex dielectric permittivity and the volume fraction of each of the soil's constituents (Heimovaara et al. 1994; Gardner et al. 1998).

Various characteristics of the electromagnetic signal sent through the soil can be observed to obtain dielectric permittivity measurements. The amplitude and phase of the reflected signal or the combination of the incident and reflected signals, the propagation time of a signal and of its reflection, and the frequency shift can be observed to measure dielectric properties of a medium. Soil moisture sensors are made of a wide range of electronic devices used with various configurations of sensing probes. At frequencies below 200 MHz, vector impedance meters and radio-frequency bridges can be used. Thomas (1966) used a Wayne-Kerr very high frequency (V.H.F.) admittance bridge which measured capacitance and conductance to determine soil moisture content by fringe capacitance at 30 MHz. Fringe capacitance can be defined as the capacitance measured by the fringing field generated by two electrodes. In the case of two flat electrodes facing each other, the fringing field is essentially the part of the field not included between the two plates. For coplanar electrodes, the fringing field is the entire field generated (Thomas 1966). Eller and Denoth (1996) determined soil moisture content by measuring the impedance at 32 MHz using a twin T-bridge which had been modified to cover a large range of permittivities. Wobschall (1978) described a frequency shift dielectric soil moisture sensor operating at 31 MHz that used a capacitor T network to connect the electrodes to the frequency determining resonance LC network (Fig. 3). The capacitor forms part of the feedback loop of the oscillator. The resonance frequency can be expressed as a function of the change in capacitance due to C_s and G_s (Eq. 10).

$$f \approx f_0\left[1-\frac{\Delta C_T}{2C_0}\right] \tag{10}$$

with:

$$f_0 = \frac{1}{2\pi\sqrt{C_0 L_r}} \tag{11}$$

and

$$C_0 = C_d + C_r \tag{12}$$

where:

f = resonance frequency (Hz),

f_0 = resonance frequency for C_s and G_s equal zero (Hz),

ΔC_T = change in capacitance due to C_s and G_s (F),

C_0 = total capacitance of the oscillator circuit (F),

C_d = capacitance in the oscillator circuit (F),

C_r = capacitance in the oscillator circuit due to L_r (F),

L_r = inductance in the oscillator circuit (H).

The frequency shift method was also used by Dean et al. (1987) and Gardner et al. (1998).

For greater frequencies, measurement techniques such as the slotted line, the

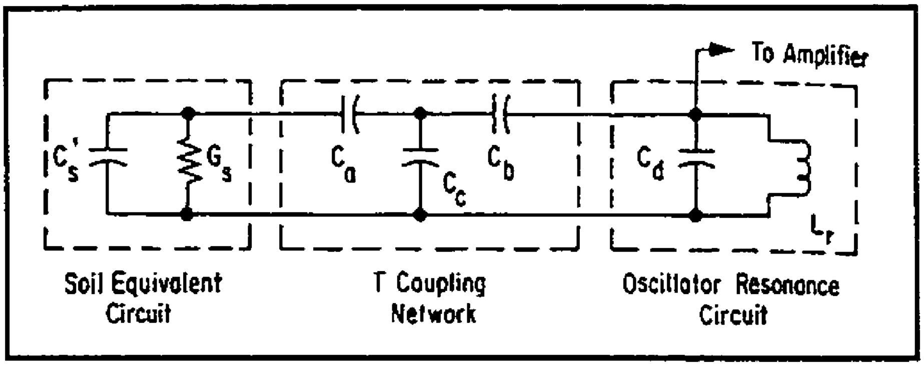

Fig. 3 Equivalent circuit of a capacitance sensor. The effect of the soil capacitance (C_s) and conductance (G_s) on the oscillator resonance frequency is shown. The connection is made via the T network (Wobschall 1978).

vector voltmeter, or the swept frequency method are required. The slotted line measures the ratio of the maximum voltage to the minimum voltage which is termed the voltage standing wave ratio (VSWR). The VSWR is in fact the ratio of the maximum amplitude to the minimum amplitude on the transmission line. The vector voltmeter used with a dual directional coupler measures the voltage amplitude and the phase difference between two points on the transmission line. The swept frequency method, developed by Hewlett-Packard and considered an improvement of the two techniques previously described, uses a network analyser to measure the load reflection coefficient, i.e. the ratio of the reflected voltage to the incident voltage, as a magnitude and a phase quantity as a function of frequency (Sinnema 1988). Morgan et al. (1993) used a reflectometer to measure the amplitude and phase differences at a frequency of 1.25 GHz. The values of complex permittivity thereby measured were processed to determine the real permittivity of soil.

2.3 Literature review of lysimetry

When studying parameters of the soil solution, a lysimeter can generally be defined as a large soil block with a bare or vegetated surface, in a container opened to the atmosphere, located in a natural environment. Lysimeters provide information related to the water balance of the system, e.g. precipitation, infiltration, water storage capacity, evapotranspiration, and percolation. Furthermore, the percolates can be collected and analyzed for chemical composition. Other devices, also called lysimeters, are used for sampling the soil solution by means of a vacuum applied to a porous cup introduced into the soil. This type of lysimeter will not be further discussed nor referred to in this paper.

Lysimeters can be divided into two major categories based on whether a weighing system is used to determine the water balance. Non-weighing lysimeters, which are also referred to as volumetric, drainage, or compensation lysimeters, rely on the collection of the percolate to establish the hydrological properties of the soil block. Thus, the water balance is indirectly determined by subtracting the drainage water collected from the total water input. The other type of lysimeter, called the weighing lysimeter, determines the water balance by measuring the change of mass of the soil block. Here, the drainage component and the soil water conditions can be measured independently and simultaneously (Hillel 1971). This means that small variations of moisture content can be measured even in dry soil when no percolation has occurred. This explains why most of the lysimeters used in evapotranspiration studies are of the weighing type (Howell et al. 1991; Grebet and Cuenca 1991).

Weighing lysimeters can be classified in four subcategories that group the lysimeters based on the weighing principles or devices utilized. Lysimeters equipped with mechanical scales are referred to as mechanical weighing lysimeters. The same way, electronic weighing lysimeters use strain-gauge load-cells that output electronic signals. Hydraulic weighing lysimeters are based on measurements of pressure changes in a hydraulic load cell. Finally, floating lysimeters are based on measurements of changes in buoyancy or flotation.

The soil block contained within the lysimeter boundaries can be reconstituted by two methods. The simplest one is called the filled-in method. As the term indicates, the method consists of filling the soil container with loose soil taken from the natural environment where the lysimeter will be placed. This technique disturbs the soil properties and gives, therefore, results that are not representative of the surrounding soil. The monolith method solves that problem by encasing an undisturbed block of soil into the container. This method is the most cumbersome of the reconstitution methods and can be very costly (Bhardwaj and Sastry 1979). A variant from the monolith method, called the Ebermeyer method, also uses an undisturbed soil block that is not isolated laterally by vertical walls of a container.

For all types of lysimeters, a system is required to allow the water to flow through the lysimeter. Two basic types of drainage systems were reported in the literature based on the driving force causing the flow of water (Aboukhaled et al. 1982). In a free-drainage system, the excess water is drained by gravity. Whereas, in a suction-controlled system, constant suction, also called tension, is artificially maintained to control drainage. Porous collectors, generally made of ceramic, are placed at the bottom of the soil block and connected to a vacuum system. Suction-controlled systems should be used for deep lysimeters to overcome variations of moisture content within the soil profile. Lysimeters equipped with tension systems are often used to simulate dry conditions or to maintain a high watertable in water stress studies. Yoder et al. (1998) utilized such a drainage system to control the soil moisture content in a lysimeter used to evaluate soil moisture sensors' performance.

Lysimeter history covers a period of about 300 yr and their application in various fields of research has been largely documented (Aboukhaled et al. 1982). Aboukhaled et al. (1982) presented the evolution of lysimetry techniques through a detailed review of literature. Whereas non-weighing lysimeters are mostly used for characterization of soil solution percolates, weighing lysimeters cover a wider field of utilizations ranging from evapotranspiration measurements of different canopies (Fritschen 1991; Klocke et al. 1985) to irrigation scheduling (Phene et al. 1991). Pruitt et al. (1991) and Kutilek and Nielsen (1994) reported the use of floating lysimeters to measure the shear stress on the crop canopy caused by wind. In addition to those agricultural applications, weighing lysimeters have been used in environmental impact assessment studies either to quantify the factors affecting migration of pollutants in soil (Phillip et al. 1991; Campbell et al. 1991) or to evaluate remediation technologies (http://www.pharm.arizona.edu/centers/tox_center/ superfund/projects/core_cl.html, February 1999).

3 PRINCIPLES OF SOIL WATER CONTENT MEASUREMENT

3.1 Commonly used techniques

3.1.1 Tensiometric method Tensiometers give direct measurements of the soil water potential which can also be called soil water tension or soil matric potential. The tensiometer consists of a ceramic cup connected to a vacuum gauge by a rigid tube. The tube can vary in length allowing for measurement at various depths in the soil.

Prior to installation, the tube is filled with de-aired water and the water is allowed to saturate the porous tip of the tensiometer. A suction pump is then attached to the tube to remove the dissolved air from the porous tip as well as the water column within the tensiometer to insure that most of the dissolved air is evacuated from the system. De-aired water is poured into the stem to fill it up to the O-ring seal. The cap is screwed into place carefully without trapping any air in the tensiometer. The tensiometer is then sealed and ready to be installed.

Once buried in the soil, the water contained in the porous cup reaches equilibrium with the soil water in the pore space. Thus, in a completely saturated soil, the gauge of the tensiometer would indicate zero since the free soil water would be in equilibrium with the water contained in the tip. Under unsaturated conditions, the soil contains less water and consequently has a higher capillary tension. This creates a tension on the water contained within the porous ceramic cup which releases water until the tension within the cup is equal to the tension existing in the surrounding soil. The reading on the gauge of the tensiometer thus indicates the soil water tension.

When the soil water potential exceeds the air entry pressure of the porous ceramic cup causing air to break through the largest pores in the cup, the tensiometer has reached its limit of operation. At this point, the gauge will indicate zero and the tensiometer reading is no longer useful. At this stage, the tensiometer has to be refilled and a vacuum re-established prior to further use in a wetter soil environment.

3.1.2 Electromagnetic methods

3.1.2.1 Resistance sensors: Electrical resistance can be used indirectly to determine the moisture content of a medium. The resistance measured between electrodes placed directly in the medium or in a material in hydraulic equilibrium with the medium is directly related to the medium's moisture content. Because moist soil resistivity is also a function of temperature, soil salinity, and solids' conductivity, a soil-specific calibration is required.

3.1.2.2 Time-domain sensors: The propagation time of a signal can be used to determine the dielectric properties of the medium. Systems operating on time measurements are referred to as time-domain sensors.

Time-domain reflectometry (TDR) is a well-known and widely used technique in which a signal travelling along a transmission line is reflected when meeting an impedance discontinuity and its reflection is then superimposed on the transmitted signal at the transmitter. The time measured is the time required for the signal to travel from the transmitter to the end of the transmission line and to come back to the transmitter as a reflection. In other words, the two-way propagation time is measured. When applied to soil moisture measurement devices, the TDR sensor consists of a discontinued transmission line extending into the soil for which the soil is part of the dielectric thereby creating the impedance discontinuity that causes the reflection of the signal. The signal sent is a pulse and the operating frequency is fixed and generally greater than 250 MHz in cable fault detection (Sinnema 1988).

Another time-domain technique, referred to as time-domain transmissometry

(TDT), can be used to measure soil moisture content. In the TDT technique, the signal is observed at the end of the transmission line. The time measured is thus the one-way propagation time and the reflection is not involved in the measurements (http://www.envsens.com, April 2000).

3.1.2.3 Frequency-domain sensors: The most elementary design of frequency-domain sensors is also referred to as a capacitance sensor. It consists essentially of a pair of electrodes which form a capacitor for which the soil acts as dielectric. A free running oscillator generates an alternative current (AC) field and adjusts to the capacitor to form a tuned circuit (Eqs. 9, 10, and 11). The resonance frequency is then related to the dielectric permittivity, and in turn to the soil moisture content, by calibration.

A more sophisticated type of frequency-domain sensor uses the reflectometry technique to measure dielectric properties of media. This frequency-domain reflectometry (FDR) sensor operates at a fixed frequency and the signal used is a sinusoidal wave. FDR sensors generally have the same extended transmission line configuration as TDR probes for which the bulk soil act as dielectric. The frequency of the transmitted signal is swept under control and the reflection caused by the impedance discontinuity is added to the transmitted signal. The voltage standing wave ratio (VSWR), which is the quantity of interest, is then obtained by plotting the reflection as a function of the swept frequency (http://www.sowacs.com/sensors/whatistdrfdt.html, Smit (1996), April 2000).

3.1.2.4 Phase-domain sensors: The phase shift of a sinusoidal wave, relative to its original phase, depends on the length of travel, the frequency, and the velocity. When operating at fixed frequency over a known distance, the phase shift depends only on the velocity, which is a function of the dielectric properties, and thus of the moisture content of the surrounding medium (http://www.sowacs.com/sensors/virrib.html Starr, April 2000). No information concerning techniques used to measure phase shift could be found in the literature.

3.2 Sensors tested in this research

3.2.1 Tensiometers Two models of tensiometers were included in the studies: the 2710AR and the 2725AR which are both manufactured by Soilmoisture Equipment Corp. (PO Box 30025, Santa Barbara, CA 93105, USA) and distributed in Canada by Hoskin Scientific (239 East 6th Ave., Vancouver, B.C.). The only difference between the two models is the reservoir. We used the 2710AR without a reservoir whereas the 2725AR was equipped with the Jet Fill reservoir cap. The Jet Fill reservoir features a mechanism that allows for the refill of the stem of the tensiometer and the removal of accumulated air. Without removing the cap, the water contained in the reservoir is injected in the stem by pushing the button of the Jet Fill. The flexible reservoir's cover fits tightly around the button to prevent air from entering the reservoir. Both models of tensiometers can measure soil matric potential from saturation to approximately $^-85$ kPa (Soilmoisture Equipment Corp., 1984).

3.2.2 Watermark granular matrix sensors Watermark granular matrix sensors give indirect readings of the soil water potential based on measurement of electrical resistance within a granular matrix in contact with the moist soil. The GMS sends an electrical resistance measurements ranging from 0.5 to 30.0 kΩ to the meter which then converts the value using a programmed calibration function that relates the signal output to soil matric potential. This moisture sensor consists of two concentric electrodes embedded in a porous matrix. The matrix is composed of loose granular material held in place with a permeable membrane covered by a perforated metal case. A solid gypsum wafer divides the granular material in two sections. In the lower section of the sensor, the soil solution is allowed to move freely in and out of the sensor. In the upper section, however, the granular material is isolated from the surrounding soil. This way, the soil solution has to travel through the lower section and the gypsum wafer, which will buffer the effect of salinity, before entering the section that contains the electrodes. The granular matrix sensor operates on the principles that the movement of water in a porous medium is a function of the pore sizes of the material and the electrical resistance of that medium is a function of its water content, which can also be expressed as water potential. Therefore, the movement of water in a granular matrix with pore sizes still remaining wet similar to that of the surrounding soil closely represents the soil water potential of the soil. The electrical resistance of the sensor is therefore an indirect measurement of the soil water potential. Watermark sensors cover a range of water potentials from 0 to 200 kPa (Irrometer Co., Box 2424, Riverside, CA 92516, USA).

3.2.3 Aquaterr The Aquaterr (Aquaterr Instruments Inc., 3459 Edison Way, Fremont, CA 94538, USA) is a portable electrical capacitance probe. The electrodes are encapsulated in the tip of a rigid metal stem attached to the meter. The electrical capacitance (C) measured at the tip of the instrument is converted in the meter to a value (R) ranging from 0 to 100 that is then displayed on the meter. No information concerning the principle of operation of the Aquaterr was found in the literature. An on-site calibration against moisture content requires that the reading be set to 100 while the sensing tip is submerged in water. It can therefore be assumed from the calibration procedure and the colour-coded legend shown on the meter that the C-to-R conversion is not based on a linear relationship. The conversion function seems to resembles the calibration curves illustrated in the Aqua-Tel user's manual. Those calibration curves show that the measured quantity does not vary a lot for moisture contents approaching or above soil saturation which is due to the high value of the dielectric constant of water compared to that of solids and air. Because the geometry of the electrodes is not revealed by the configuration of the probe, it can only be assumed that the dielectric properties of the medium are derived from fringe capacitance measurements. The flat-shaped sensing tip does not have any opening or gap that would allow for the medium to be positioned between the electrodes. Furthermore, the exposed portion of the sensing tip seems to be made of two coplanar plate-electrodes covered by a protective polymer which closely match the probe designed by Thomas (1966). The effective volume of the Aquaterr is not specified in the literature. The effective volume of the probe, also called the volume of influence, is the volume of the medium surrounding the sensing device that affects the measurements. The range of operating frequencies of the Aquaterr is also not specified. Thus, it can only be hypothesised, from the fact that the readings require calibration against soil texture, that the operating frequencies are in the range where conductivity losses are not negligible, i.e. below 50 MHz.

3.2.4 Aqua-Tel The Aqua-Tel (Automata Inc., 10551 E. Bennett Road, Grass Valley, CA 95945-7806, USA) is a capacitance sensor. The Aqua-Tel, model Aqua-Tel94-29, consists of two parallel electrodes attached to a small electronic module. The 0.83-m (29 in) long electrodes, made of stainless steel, are flat, which leads to the hypothesis that the dielectric properties are derived from measurements of fringe capacitance. The effective volume of the Aqua-Tel sensors is not specified in the literature. As for the Aquaterr, readings made with the Aqua-Tel require calibration against soil texture which can demonstrate the effect of conductivity losses and thus leads to the assumption that the operating frequencies are below 50 MHz.

3.2.5 VIRRIB The VIRRIB is a phase transmission sensor that was manufactured in the Czech Republic and distributed in North America by Environmental Sensors Inc. (PO Box 720698, San Diego, CA 92172-0698, USA), who seems to have bought the rights to the technology but are not distributing it anymore. Environmental Sensors Inc. (ESI) is now manufacturing a TDT sensor, called the GroPoint, that has the same transmission line configuration as the VIRRIB but is presented as a new product. For that reason, the principle of operation of the GroPoint given by ESI cannot, with certainty, be applied to the VIRRIB. Furthermore, descriptions of the operating principles of the VIRRIB found in the literature differ from the information concerning the GroPoint. The main disagreement between the TDT and phase-domain (PD) technique lies in the signal sent. The TDT method uses a pulse whereas the description of the PD methods implies that only a sinusoidal wave can be used. In addition, the description given by Litschmann (1991) does not provide technical information related to the electromagnetic technique employed. It states that the sensor uses DC current with a voltage of 12 to 20 Volts from an external source and that the output data is measured by means of a current loop, for which the intensity of the output is directly proportional to the moisture content of the surrounding medium.

It reads within a range of 0 to 55% of water by volume (Environmental Sensors Inc.). The sensor consists of two rod electrodes shaped as concentric circles with an outer ring of 0.28 m diameter and an inner ring of 0.20 m diameter. The volume of influence of the sensor extends to a distance of 0.06 m from the rings in all directions.

3.2.6 ThetaProbe The ThetaProbe is a frequency-domain reflectometry (FDR) sensor manufactured by Delta-T Devices Ltd. in the United Kingdom (128 Low Road, Burwell, Cambridge CB5 OEJ, England) and is distributed in Canada by Lakewood Systems Ltd. (8709, 50 Avenue, Edmonton, AB, T6E 5H4). It operates at a fixed frequency of 100 MHz. The sensor consists of a coaxial transmission line that extends into the soil via the sensing probes which is formed of four 0.050-m long stainless steel rods, three of which, positioned in the periphery of the rod transmitting the electromagnetic signal, are at ground potential. Even if the effective volume of the probe is relatively small (a cylinder of 0.025 m in diameter and 0.060 m in length accounts for 90% of the influence on the measurements), holding the probe while taking measurements may affect the results. Although the ThetaProbe operates at a frequency for which conductivity losses are minimal, soil-specific calibration is recommended by the manufacturer. In the user's manual, an accuracy of ±2% of θ_v is specified after soil-specific calibration whereas ±5% of θ_v is specified if the supplied calibration factors are used.

4 MATERIALS AND METHODS

4.1 Field study

During the growing season of 1998, we conducted a field experiment to determine the most suitable methods to measure soil moisture in potato fields under Manitoba conditions. Moreover, this first trial was intended to help develop a protocol for proper installation, calibration, and use of tensiometers, Watermark granular matrix sensors, the Aquaterr soil moisture meter, Aqua-Tel capacitance sensors, and VIRRIB phase transmission sensors. At the completion of the field trial of 1998, it was recommended that a laboratory study under controlled soil moisture conditions be conducted. A first laboratory trial was therefore carried out during the winter of 1999 following the protocol for installation, calibration, and use of the sensors established from the first field study. During the growing season of 1999, another field trial was conducted hoping to obtain more information concerning the performance of the soil moisture sensors previously tested. The results from the second field trial, as those from the 1998 trial, were not conclusive due to soil heterogeneity and high soil moisture variability within the experimental plot and thus, laboratory testing was resumed in the winter of 2000.

4.1.1 Experimental site description For both seasons, the experiment was carried out at the Manitoba Crop Diversification Centre in Carberry, Manitoba. The soil in that area is from the Ramada series. For the experimental plots of 1998, the first 0.4 m of the soil profile was composed of loam (31.5% sand, 45.2% silt, and 23.1% clay) whereas the underlying layer, from 0.4 to 0.6 m, consisted of silt loam (20% sand, 54% silt, and 26% clay). For the 1999 trial, the plot was located in an area where the loam layer was on average 0.50-m thick. Potatoes (*Solanum tuberosum* L. CV. Russet Burbank) were grown on hills.

For the first field trial, the sensors were installed on two plots exposed to different water treatments. Plot A was irrigated when the soil moisture content, monitored with neutron gauges, was less than 35% of the available water, which represented a volumetric water content of approximately 25% whereas plot B was rainfed. The available water content is the water that can be used by the plant and it is equal to the difference between the moisture content at field capacity (FC) and at the permanent wilting point (PWP). Field capacity is the water content that a given soil attains after it has been fully saturated and allowed to drain for 2 d. The permanent wilting point is the water content that a soil reaches at the time water extraction by plants has ceased (Hanks and Ashcroft 1980). For the second field trial, the sensors were installed on a single plot which was irrigated when needed and did not follow any pre-established conditions.

4.1.2 Sensors installation

4.1.2.1 Tensiometers: In 1998, a total of 17 tensiometers was used for the experiment: 9 on plot A and 8 on plot B. The tensiometers were grouped in sets of three sensors installed at three different depths, 0.20, 0.30, and 0.50 m below the soil surface. This way, each set covered the whole root zone. A middle-length tensiometer was broken during the installation. Thus, one set on plot B lacked a meter at the 0.3-m depth. In 1999, 12 tensiometers were used. They were grouped in pairs, installed at 0.25 and 0.45 m below the soil surface. Thus, in 1999, all sensors were tested in loam only.

To install tensiometers, an auger hole with a smaller diameter than the tensiometers was made to the required depth. The resulting hole was then partially filled with water and the tensiometer inserted into it. The soil surface was lightly packed around the tensiometer to prevent preferential flow along the stem.

4.1.2.2 Watermark GMS: In 1998, 18 Watermark sensors were tested whereas only 12 were used during the following season. Before installation, the sensors were soaked in water, then allowed to dry, and soaked again. The user's manual published by Irrometer Co. recommends that Watermark sensors be installed wet. The sensors were installed following the same procedure and pattern of sets as for the tensiometers.

4.1.2.3 Aquaterr: The Aquaterr is a portable probe therefore a single sensor was required. To take water content readings, the probe was pushed into the soil to the desired depth. A soil auger was used to drill an access hole for measurements at depths greater than 0.30 m. A measurement immediately followed the drilling of the required access hole to prevent soil moisture loss by evaporation Readings were taken on each plot following the pattern of sets described for the tensiometers.

4.1.2.4 Aqua-Tel: For the 1998 experiment, only three Aqua-Tel sensors were used. They were all installed at a depth of 0.20 m. In the irrigated plot, two probes were installed, one with the blades flat and the other with the blades on the edge or side position. The last sensor was installed in the side position in the rainfed plot. In 1999, four probes were used and they were all installed in the side position at a depth of 0.25 m.

To install the Aqua-Tel sensor, a trench was dug to the installation depth. The sensor was placed at the bottom of the trench in the desired position. Then, the opening was filled with soil and packed to ensure good contact between the blades and the soil.

4.1.2.5 VIRRIB: In 1998, four VIRRIB moisture sensors were used. The two VIRRIB sensors used on each plot were installed in different orientations, buried in the hill either across or along the rows. In 1999, six sensors were used, all installed along the rows.

To cover the whole sensor, a trench 0.30 m deep was dug, the sensor positioned, and the trench filled.

4.1.3 Data collection In 1998, data were collected over a period of 8 wk on five occasions for the irrigated plot and on four occasions for the rainfed plot. In 1999, data were collected on seven occasions over a period of 25 d. Soil samples for the gravimetric method were taken following the same pattern of sets described for the tensiometers, i.e. a total of 9 samples were taken, triplicates at each of the three depths. The location of each set was randomly determined and documented on each occasion to ensure the sampling of undisturbed soil. The Aquaterr required onsite calibration against moisture content. The probe was submerged into a bucket of water and the meter set to 100 between each set of readings. The Watermark sensors required that soil temperature be measured at the three depths at which the sensors are installed, which was done by inserting a stainless steel thermometer at proximity of the sensors. Then, the soil temperatures measured at each depth were entered in the meter accordingly, so that it automatically calibrated the sensor against temperature. The other moisture sensors did not require any on-site calibration as stated by their respective manufacturers.

4.2 Laboratory study

4.2.1 Lysimeters

4.2.1.1 Lysimeter design: The lysimeters were designed with hydraulic weighing systems to facilitate continuous monitoring of the soil moisture content. This design was preferred to the other weighing systems because of its simplicity and low cost.

The soil container was an open box, consisting of a 1.10 m long, 1.10 m wide, and 0.27 m deep wooden box with an open bottom. The required dimensions of the container were selected based on the effective volume of each soil moisture sensor, i.e. the soil region that affects the measurements. To maintain uniformity of moisture within the soil blocks, the maximum depth of soil in the lysimeters was limited to 0.20 m. This was well below the displacement pressure of the soils selected for testing and thus, suction-controlled drainage systems were not required. Each wall of the soil container was made of three pieces of wood (S-P-F No.2) 0.038-m thick and 0.089-m wide, fastened together by means of 0.050-m long screws. The interior of the wooden frame was lined with a polyethylene sheet to prevent the wood from absorbing the water from the soil. A steel grate, shown in Fig. 4, was attached to the bottom of the box to support the weight of the soil. A 0.013 m mesh acrylic grid, 0.013 m thick, was placed on the steel grate as a support for the permeable fibreglass mesh. The fibreglass mesh prevented the soil from passing through the acrylic grid while allowing for good drainage and air exchange through the bottom. The soil block could dry both from the top and bottom surfaces.

Another wood box, on which the soil container described above rests, constituted the drainage collector. One side of the box had an 0.14-m high opening along its entire length to provide an exit for the drained water as well as a channel for air to circulate through the soil. A polyethylene sheet collector stapled to the bottom of the soil bin, intercepted the water draining from the soil and led it outside the lysimeter. This was done to ensure that all water within the lysimeter remained within the soil. Figure 5 shows the lysimeter from the top looking through the empty soil container into the drainage collector. An elevation view showing the opening of the drainage collector is also shown in Fig. 6. The bottom wooden frame was fastened to a sheet of plywood which acted as a base. The base provided more stability to the structure and uniformly

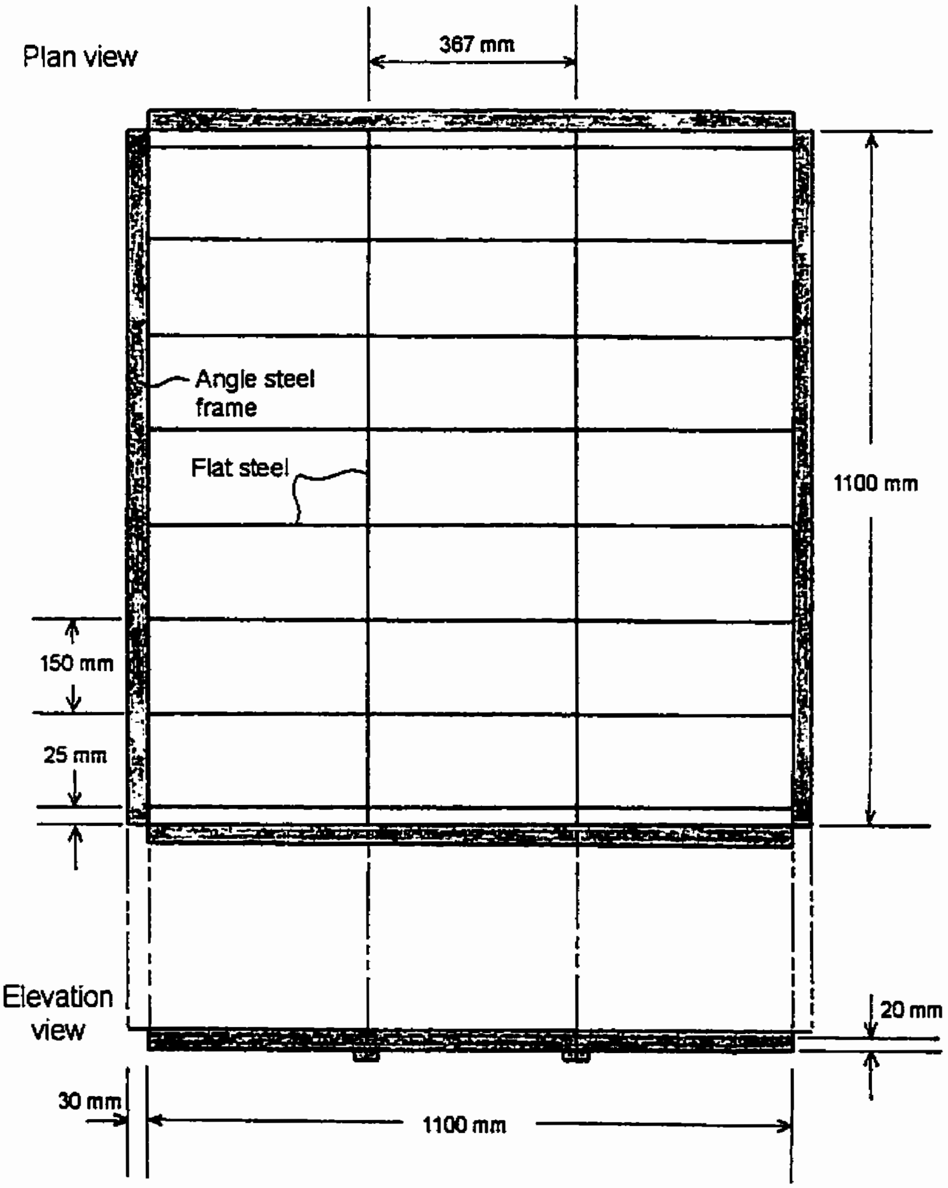

Fig. 4 Top view and elevation view of the steel grate. The top view also illustrates the dimensions of the soil block.

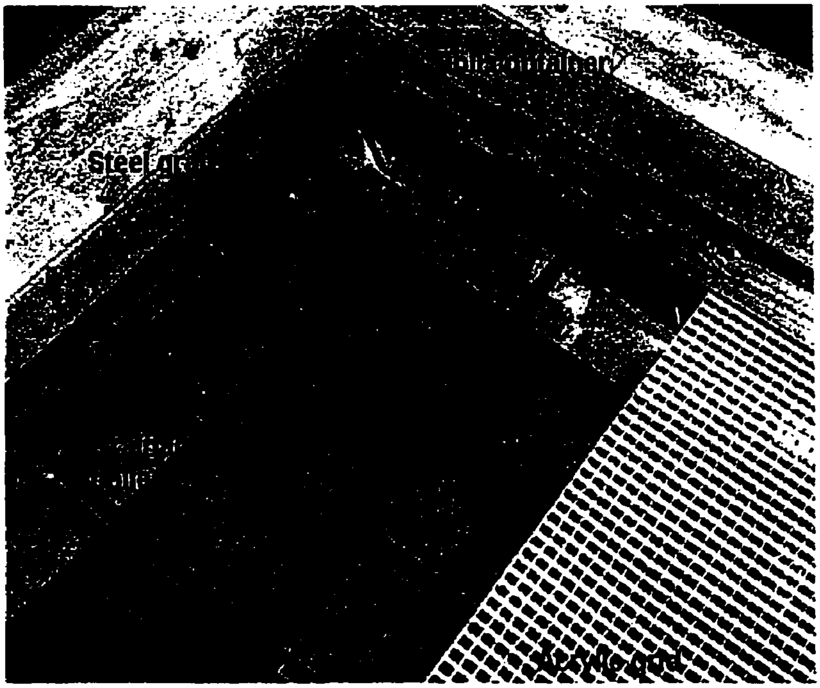

Fig. 5 Top view of the lysimeter. The empty soil container is shown with the steel grate and the acrylic grid. The drainage collector is seen through the open bottom of the soil container.

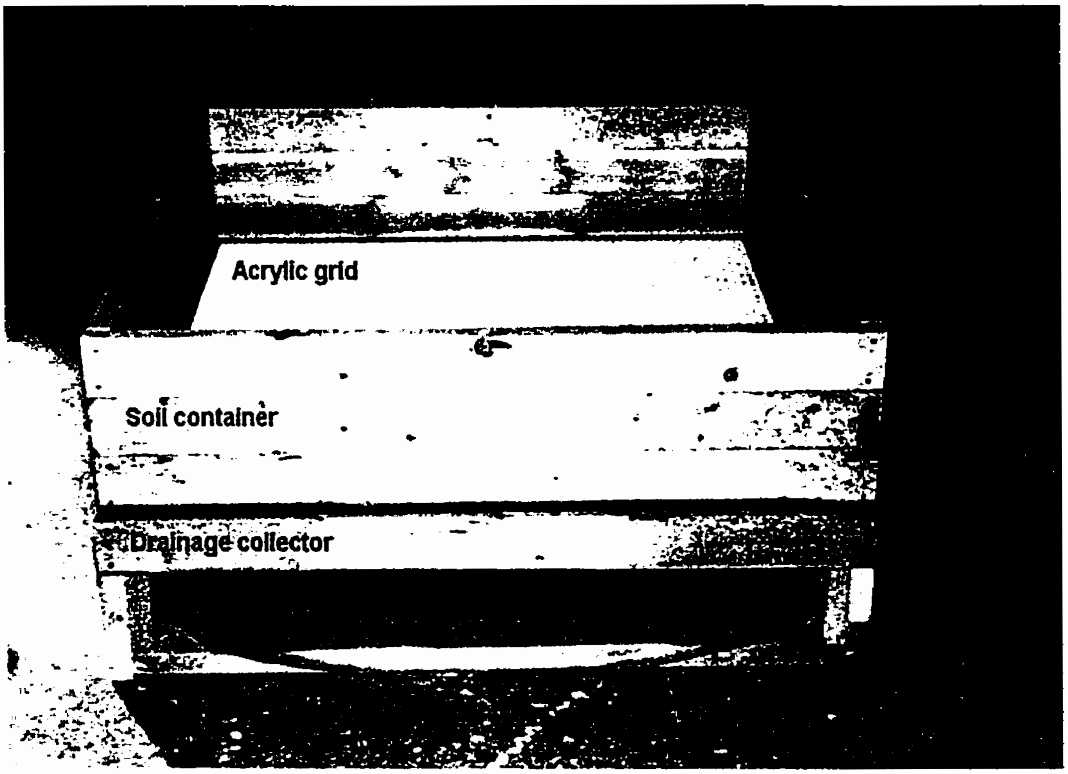

Fig. 6 Elevation view of the lysimeter. The empty soil container and the drainage collector with the opening are illustrated.

distributed the weight of the lysimeter on the hydraulic load cell.

The weighing system consisted of a hydraulic load cell connected to a manometer. The manometer was inclined to increase the precision of the weighing system. An angle of 15° from the horizontal was selected because it increased the precision of the lysimeter by a factor of four. An inner tube filled with water was used as the hydraulic load cell. The inner tube was made of butyl rubber and had an outside diameter of 0.915 m and an inside diameter of 0.485 m when totally deflated.

4.2.1.2 Lysimeter calibration: A calibration of the weighing system was required to establish a relationship between the mass of the lysimeter and the fluid pressure inside the hydraulic load cell. First of all, the weighing system was calibrated by placing weights of known mass incrementally on the lysimeter, up to the estimated soil mass at saturation, to verify the linearity of the relationship. We found that an increase in mass of the lysimeter of 5 kg caused an increase of pressure inside the load cell corresponding to 52 mm in height of water column on the manometer for both lysimeters. The precision of the weighing system was then determined in terms of variation of soil moisture content ($\Delta\theta_v$), in percentage, for a change of 1 mm in height of water column by first calculating the $\Delta\theta_v$ corresponding to adding 5 kg of water to the lysimeter and then, by dividing $\Delta\theta_v$ by the change in height of water column caused by such a variation in mass, i.e. 52 mm. The precision thereby calculated for both lysimeters was a $\Delta\theta_v$ of 0.4% per mm of water column height. To assess the long-term stability of the weighing system, maximum loading of the lysimeter was maintained over a period of 96 h followed by a 96-h period without any load. The stability test showed that the fluid pressure inside the hydraulic load cell tended to decrease over time under maximum loading whereas it tended to increase over time under no loading. This drifting effect was attributed to the stretching and shrinking of the load cell membrane. Variations of the ambient conditions, such as temperature and atmospheric pressure, also had an effect on the precision of the weighing system. Those factors, however, could not be controlled and thus were considered part of the experimental error. The calibration was also verified by measuring the actual soil water content by gravimetric sampling at three locations within the soil block on several occasions during the course of the study. Gravimetric sampling was done on five occasions during the lysimeter study of 1999 and on four occasions during the trial of 2000.

4.2.1.3 Soil blocks: The lysimeters were filled with soil brought from the field site, i.e. loam and silt loam from the Ramada series, that had been air dried and sieved through a 0.01-m mesh. The filled-in method was used for reconstituting the soil blocks. Uniform bulk density was achieved by packing the soil in the container in small equal sized lifts thereby providing homogenous hydrological conditions for testing of the soil moisture sensors. Layers of loose soil, approximately 0.05-m deep, were packed consecutively using a 0.75-m long piece of lumber, 0.038-m thick and 0.178-m wide, on which the experimenter applied pressure. Pressure was applied uniformly by systematically placing the lumber on an area of loose soil, by stepping on it 50 times, and by repeating this process until the soil of the entire surface area of the lysimeter was packed. For the first laboratory trial, conducted in 1999, only one lysimeter was used. The lysimeter was filled with loam packed to a dry bulk density of 1190 kg/m^3. Both lysimeters were used for the laboratory trial of 2000. Because the soil contained in the lysimeter used in the trial of 1999 had been disturbed by the removal of the sensors, the loam was packed once again. The dry bulk density reached was 1150 kg/m^3. The second lysimeter was filled with silt loam packed to a dry bulk density of 1250 kg/m^3.

The soil bulk density was determined by monitory the mass of soil used to fill the soil box and measuring the depth of soil in the box once it was filled. Then, knowing the surface area of the soil container, ρ_b was calculated using the following equation:

$$\rho_b = \frac{m_s}{A \bullet h} \tag{13}$$

where:

m_s = mass of dry soil in the soil container (kg),

A = surface area of the soil container (= 1.21 m^2),

h = depth of dry soil packed in the soil container (m).

Prior to each trial, the soil blocks were slowly saturated and allowed to equilibrate for 72 h. During the trials, between testing, air was blown through the bottom of the soil container to increase the drying rate. After each fan-drying period, which never exceeded 2 h in duration, the soil was left to dry at ambient conditions, i.e. without forced aeration. Each drying period was followed by an equilibration period of at least 12 h during which the lysimeter was covered with a polyethylene sheet to prevent evaporation.

4.2.2 Sensors installation and calibration Three sensors of the tensiometers, Watermark GMS, and VIRRIB probes were installed in each of the lysimeters used in all the trials. Three Aqua-Tel probes were installed in the loam lysimeter for both trials. The spatial arrangement of the sensors in the lysimeters is shown in Fig. 7. The Aquaterr, which is a portable probe, was used for all trials and the grey area shown in Fig. 7 was assigned for its testing. The ThetaProbe, which was also used as a portable probe, was introduced in the trial of 2000 and was tested in the same area assigned to the testing of the Aquaterr. The VIRRIB and the Aqua-Tel probes were installed at a

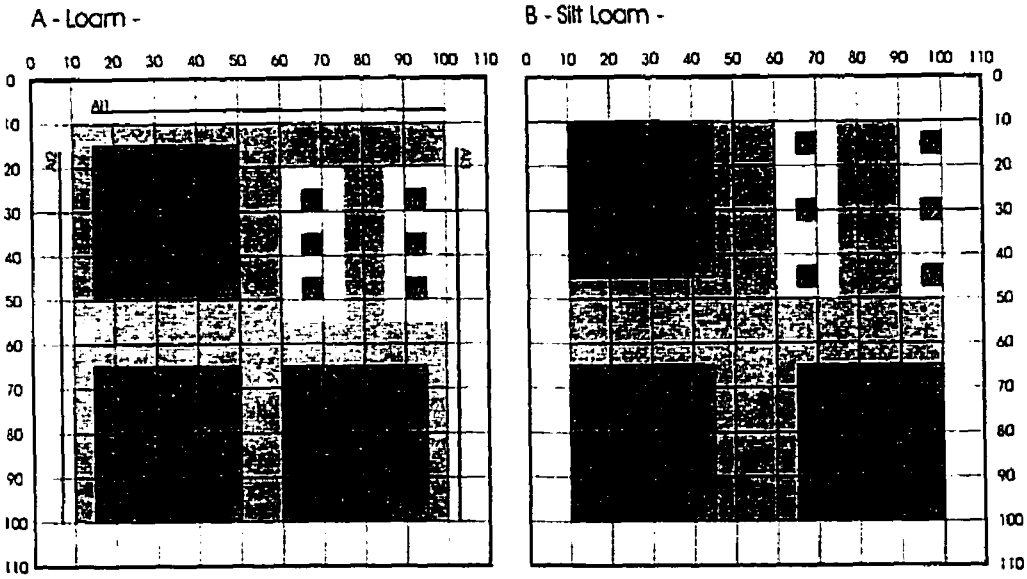

Fig. 7 Spatial arrangement of the soil moisture sensors inside the soil container of the lysimeter (top view). The area reserved to tensiometers (T), Watermark GMS (W), and VIRRIB sensors (V) is identified with the darker grey whereas the area allocated for testing the portable probes (Aquaterr and ThetaProbe) is in lighter grey. The Aqua-Tel sensors (Al) were installed only in loam.

depth of 0.10 m while filling the soil container as presented in Fig. 8. The VIRRIB sensors were installed horizontally and the Aqua-Tel sensors were installed on the side. The tensiometers and GMS were installed at a depth of 0.13 m in saturated soil, following the procedure described in section 4.1.2.1.

Prior to the lysimeter study of 2000, the VIRRIB probes were calibrated in each soil. Although the VIRRIB probes had been calibrated during the manufacturing process, a soil-specific calibration would likely improve their performance. After the sensors had been installed in dry soil, a first reading was taken with each probe and the actual volumetric water content of the soil was determined by gravimetric sampling and converted using Eq. 1. Then, the soil was saturated and a second reading was taken as well as the actual volumetric water content. The setting value, SV, was then calculated as follows:

$$SV = (F_2 - F_1) \bullet K \tag{14}$$

with:

$$K = \frac{W_2}{(W_2 - W_1)} \tag{15}$$

where:

F_1 = sensor's reading in dry soil (m^3/m^3),

F_2 = sensor's reading in wet soil (m^3/m^3),

W_1 = volumetric water content of the dry soil (m^3/m^3),

W_2 = volumetric water content of the wet soil (m^3/m^3),

K = constant (dimensionless).

The output signal of each sensor is then adjusted to its respective setting value by

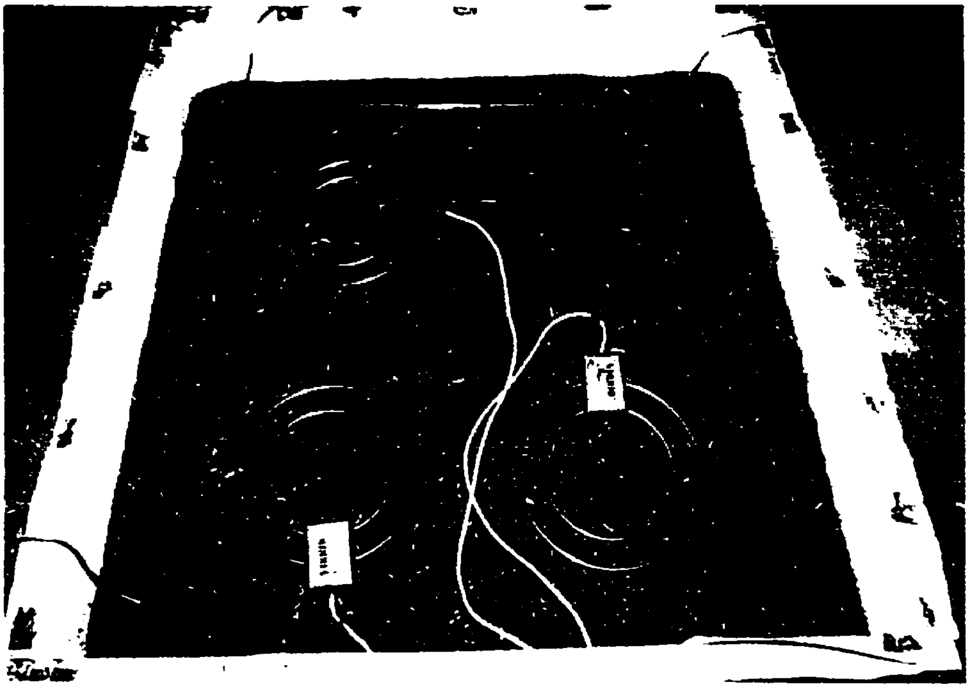

Fig. 8 Top view of the half-filled lysimeter. The installation position of the VIRRIB and Aqua-Tel sensors are shown.

turning the resistive trimmer capacitor labelled "OFFSET", located on the back of the sensing probe. To access the "OFFSET" button, a trench was dug to uncover the electronic module without uncovering the rods of the probe. The protective seal was open and the setting value was set by turning the button using a screw driver. The second resistive trimmer capacitor, labelled "AMPLIFICATION", which is also located at the back of the sensing probe on the electronic module, was used to adjust the signal gain by setting the probe's reading to the actual volumetric water content, W_2. Finally, the "OFFSET" and "AMPLIFICATION" buttons were filled with caulking paste and covered with electrical tape to prevent moisture from entering the electronic module.

4.2.3 Data collection Data were collected 24 times over a period of 34 d, in 1999, and 17 times over a period of 51 d, in 2000. The location where each reading was taken with the portable probes, i.e. Aquaterr and ThetaProbe, as well as each sampling location was randomly chosen and documented to ensure that measurements and samples be taken in undisturbed soil. Watermark GMS and the Aquaterr were calibrated as described in section 4.1.3. To follow the recommendations made in conclusion of the field study, a period of 90 s was allowed for temperature equilibration before each Aquaterr reading. Furthermore, the temperature of the water used for calibration was monitored and kept within 3 °C of the soil temperature. A voltmeter and a power supply were used with the ThetaProbe instead of a data logger. Once the probe had been inserted into the soil, an input voltage of 10 V DC at about 19 mA was provided to the probe and the VSWR read by the probe was displayed on the voltmeter and manually recorded. Although Delta-T Devices Ltd stated that for complete stability a warm-up time of 5 s is sufficient, a period of 90 s was allowed for stabilization for each measurement.

4.3 Data conversion

The readings obtained with the sensors required conversion to a unit of reference, which in this case was volumetric water content.

4.3.1 Tensiometers and Watermark granular matrix sensors Tensiometers and Watermark GMS gave soil matric potential readings, in cBar and kPa, respectively. Those soil moisture tension measurements were converted to volumetric water contents using the soil moisture characteristic curve for the particular soil at a given soil bulk density (Figs. 9, 10, and 11).

4.3.2 Aquaterr The Aquaterr's readings also had to be converted to volumetric water content, θ_v. The relationship between the meter's readings, R, and θ_v was established for each soil at different bulk densities based on the soil-specific moisture characteristic curves previously determined and the data provided by Aquaterr Instruments Inc. The R-values at different moisture conditions estimated from the information provided in the user's manual are presented in Table I.

Table I. R-values for the Aquaterr at different moisture conditions.

	Loam	Silt Loam
R(saturation)	100	100
R(field capacity	93	95
R(permanent wilting point)	25	30

The R-values were then correlated to the corresponding volumetric water contents using the soil moisture characteristic curves of each soil at each soil bulk density. Assuming a linear relationship, readings obtained with the Aquaterr were converted to volumetric water content by interpolation as follows:

for $R \geq R(FC)$,

$$\theta_v = \theta_v(FC) + \left(R - R(FC)\right) \bullet \frac{\theta_v(\phi) - \theta_v(FC)}{R(\phi) - R(FC)} \tag{16}$$

for $R(PWP) \leq R < R(FC)$,

$$\theta_v = \theta_v(PWP) + \left(R - R(PWP)\right) \bullet \frac{\theta_v(FC) - \theta_v(PWP)}{R(FC) - R(PWP)} \tag{17}$$

and for $R < R(PWP)$,

$$\theta_v = R \bullet \frac{\theta_v(PWP)}{R(PWP)} \tag{18}$$

where:

$R(\phi)$ = R(saturation) referred to in Table I,

= meter's reading at saturation (dimensionless),

$R(FC)$ = R(field capacity) referred to in Table I,

= meter's reading at field capacity (dimensionless),

$R(PWP)$ = R(permanent wilting point) referred to in Table I,

= meter's reading at permanent wilting point (dimensionless),

$\theta_v(\phi)$ = volumetric water content of the soil at saturation (m^3/m^3),

$\theta_v(FC)$ = volumetric water content of the soil at field capacity (m^3/m^3),

$\theta_v(PWP)$ = volumetric water content of the soil at permanent wilting point (m^3/m^3).

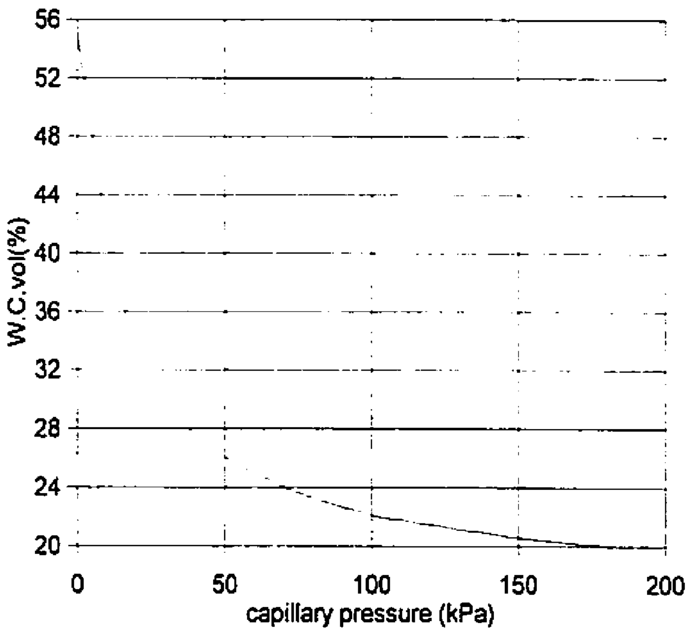

Fig. 9 Soil moisture characteristic curve for Loam with ρ_b=1190 kg/m^3.

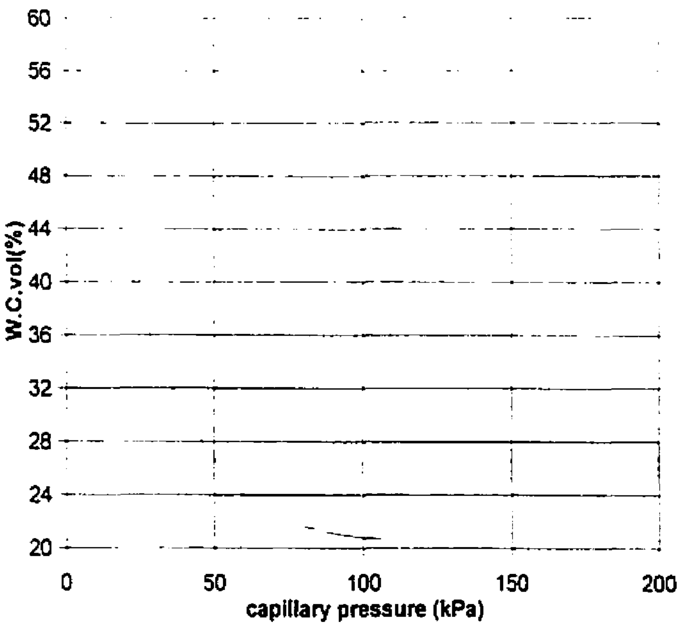

Fig. 10 Soil moisture characteristic curve for Loam with ρ_b=1150 kg/m^3.

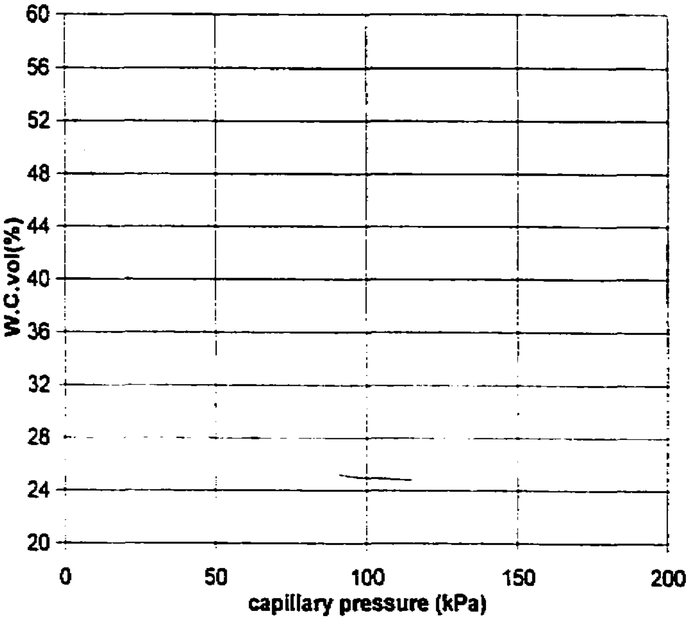

Fig. 11 Soil moisture characteristic curve for Silt Loam with ρ_b=1250 kg/m^3.

4.3.3. Aqua-Tel A calibration equation was developed to convert data collected with the Aqua-Tel capacitance sensors to volumetric water content. The equation was established from a statistical analysis of the numerical values derived from soil-specific curves published by Automata Inc. We found, from the statistical analysis of the calibration curves presented in the user's manual, that the volumetric water content value, θ_v, was dependent only on the meter readings, R, and the proportion of sand (%), S, with a significance of 97% (R=0.976). This relationship is expressed by the following equation:

$$\theta_v = -2.698 + 66.237R - 170.003R^3 + 154.197R^4 + 4.257\times10^{-8}S^4 \qquad (19)$$

4.3.4 VIRRIB Data obtained with the VIRRIB phase transmission sensors did not require conversion; readings were directly displayed in volume fraction units.

4.3.5 ThetaProbe The voltage standing wave ratio (VSWR) measurements obtained with the ThetaProbe were converted to volumetric water contents by first correlating the voltage output read on the voltmeter, V, to the apparent dielectric permittivity of the bulk soil, ε, which was then correlated to θ_v. The square root of the apparent dielectric permittivity, $\sqrt{\varepsilon}$, was correlated to V using the following third degree polynomial equation provided by Delta-T Devices Ltd:

$$\sqrt{\varepsilon} = 1.07 + 6.4V - 6.4V^2 + 4.7V^3 \qquad (20)$$

where:

V = VSWR (mV).

The volumetric water content, θ_v, was correlated to $\sqrt{\varepsilon}$ as follows:

$$\theta_v = \frac{\sqrt{\varepsilon} - a_0}{a_1} \qquad (21)$$

where:

a_0, a_1 = soil-specific constants (dimensionless).

To determine a_0 and a_1, the probe was inserted into dry soil, a VSWR measurement was taken, V_0, and the volumetric water content of the dry soil, θ_0, was determined by gravimetric sampling followed by conversion using Eq. 1. A first $\sqrt{\varepsilon}$-value was obtained from Eq. 20, which was then substituted in Eq. 21, for which θ_v was equal to θ_0. The probe was then inserted in wet soil, a second VSWR measurement, V_w, was taken, and the volumetric water content of the wet soil, θ_w, was determined. A new $\sqrt{\varepsilon}$-value was calculated with Eq. 20 and substituted in Eq. 21, for which θ_v was replaced by θ_w. The values used to calculate the constants a_0 and a_1 are shown in Table II. Finally, the two equations were solved to obtain values of a_0 and a_1 for each soil (Table III).

Table II. Measured values used to calculate a_0 and a_1 for loam and silt loam.

	V_0 (V)	θ_0 (%)	V_w(V)	θ_w (%)
Loam	0.1277	4.372	0.8747	39.304
Silt Loam	0.1373	4.031	0.8820	41.506

Table III. Calculated constants, a_0, and a_1 of Eq. 21, for loam and silt loam.

	Loam	Silt Loam
a_0	1.4016	1.5047
a_1	0.0894	0.0833

5 RESULTS and DISCUSSION

5.1 Field study

For both field trials, the standard error of the volumetric water content measurements obtained by gravimetric sampling exceeded 8%, which was attributed to the heterogeneity of the soil properties, such as bulk density (ρ_b), soil structure, and moisture conditions, within each experimental plot. We observed that soil moisture contents also varied within small sampling areas due to variation in soil moisture intake by plants and variations in evaporation from the soil surface due to the irregular coverage by potato plant canopy. Since the gravimetric method was used as a reference to evaluate the performance of the sensors, this wide variability in soil moisture contents led us to question the validity of the field study results.

Furthermore, we questioned the validity of the field study with regards to the testing conditions required for the Aquaterr probe, Aqua-Tel sensors, and VIRRIB sensors. These sensors required uniform soil conditions within their effective volume in order to give measurements representative of the surrounding soil. Consequently, the presence of roots, potato tubers, and air pockets in the proximity of these probes caused erroneous measurements. The erosion resulting from an intense rain or water application also contributed to the disturbance of the soil along the slopes of the growing hills, creating air gaps and sometimes exposing the soil moisture probes.

Finally, due to the high amount of precipitation received during the growing seasons of 1998 and 1999, the performance of the sensors could not be evaluated over a wide range of soil moisture contents in the field study. Consequently, we decided that the field study was inconclusive and that further testing, under controlled soil and water conditions, was required. An example of the field results is shown in Fig. 12.

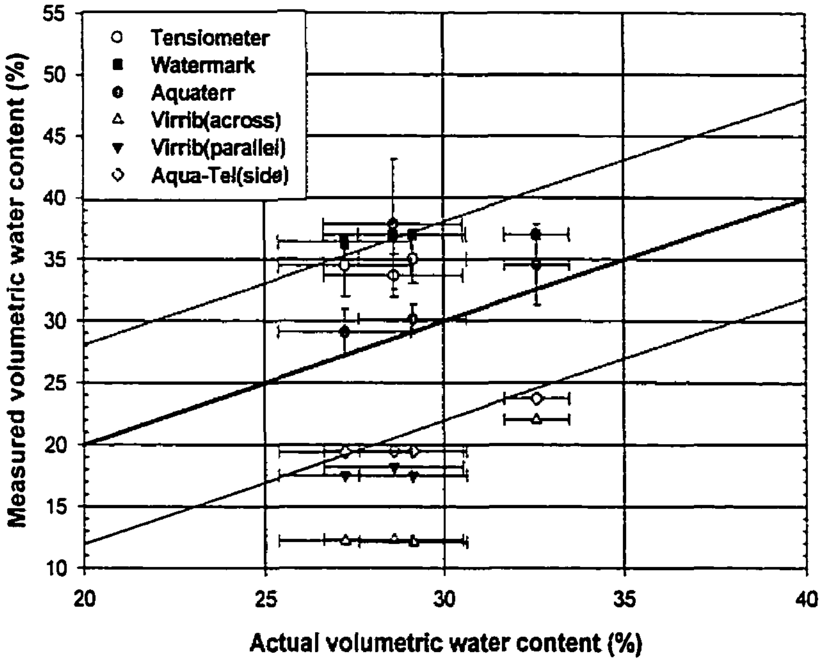

Fig. 12 **Results from the field study of 1998 in Loam, in the rain fed experimental plot.** Horizontal error bars illustrate the 95% confidence interval calculated on the average of three θ_v measurements obtained with gravimetric sampling. Vertical error bars show the 95% confidence interval calculated on the average of three θ_v measurements obtained with the sensors (when no error bar, only one θ_v is represented). The thin lines offset from the 1:1 line shows the maximum standard error calculated for the gravimetric method.

5.2 Lysimeter study

5.2.1 Experimental design In the 2000 test, all sensors responded to variations in soil moisture content within their specified operational limits except for the VIRRIB sensors . If the method or, in other words, the principle of operation alone had been the focus of the experiment, we could have concluded that all those sensing methods were adequate to measure soil moisture variations. However, the objective of this experiment was to evaluate the performance of various soil moisture sensors with regard to accuracy; precision; quickness of the response to moisture variation; and ease of use, which encompasses installing and operating the instrument as well as interpreting the readings. The main difficulty of evaluating the performance of the sensors was in understanding the readings obtained with the instruments. In most cases, the readings had to be converted to a meaningful soil-water value that can be used for calculating the irrigation water requirements. Furthermore, the assessments of an instrument's accuracy and precision were based on the converted quantities, i.e., soil moisture data. In some instances, the conversion required other soil properties that were difficult to measure reliably, thereby, adding the error caused by the conversion process to the errors attributed to the sensor.

Over the entire course of the experiment, tensiometers, Watermark GMS, VIRRIB sensors, and the Aquaterr were tested over two drying cycles in loam (in 1999, volumetric water contents (θ_v) ranging from 34.0 to 17.0%;in 2000, θ_v ranging from 43.1 to 20.0%) and over one drying cycle in silt loam (in 2000, θ_v from 45.8 to 19.5%). The Aqua-Tel probes were installed in loam only for both years whereas the ThetaProbe was tested in both lysimeters but only in the trial of 2000. Because the response time, i.e., the time required by an instrument to respond to a moisture variation, is essential in field applications such as irrigation scheduling, an experiment designed over short hydrologic cycles would be required to assess the adequacy of the sensors for real-time field applications. As stated in the literature for the Watermark sensors, some instruments might not respond to partial rewetting (McCann et al. 1992). Because this experiment was designed to test the sensors under uniform soil moisture conditions, it was assumed that a 12-h period between drying periods was sufficient for the system to reach equilibrium; thereby, assuming that all instruments had sufficient time to respond to the moisture depletion.

5.2.2 Calibration of the weighing system Because the calibration relationship is a direct conversion of the height of the water column on the manometer to the volumetric water content, its accuracy is affected by variations of the ambient conditions, i.e., temperature and atmospheric pressure; fluctuation of the load cell volume; and soil moisture variation within the lysimeter.

To lessen the effect of the fluctuation of ambient temperature, the readings were taken around the same time of day on each occasion at the proximity of the lysimeters, using a mercury thermometer. The ambient temperature varied from 18 to 25 °C for the trial of 1999 and from 19 to 25 °C for the trial of 2000. Fluctuations of atmospheric pressure have a direct effect on the height of the water column due to the surface area of the lysimeter compared to the surface area of the water column. Stretching and shrinking of the load cell membrane, as it was observed during the calibration of the lysimeter, also affected the pressure read on the manometer. Prior to the trial, a 72-h period was allowed for equilibration of the soil moisture conditions and thus, this time period was assumed sufficient for the membrane to stabilize. Furthermore, the calibration relationship was compared periodically with gravimetric sampling of the soil from the lysimeter.

5.2.3 Accuracy and precision of the sensors The term accuracy means the conformity of an indicated value to an accepted standard or true value (CSA 1979). The term precision means the quality of being sharply defined or stated (CSA 1979), it can also be defined as the repeatability of the measurement. Sensors' readings were compared with soil moisture contents determined with the lysimeters. The volumetric water content measurements obtained with the various sensors, expressed as a percentage and labelled sensors θ_v, were plotted against the volumetric water contents derived from the hydraulic weighing system of the lysimeters, also expressed as a percentage and labelled lysimeter θ_v (Figs. 13a to 28).

In the present study, the accuracy of an instrument is an evaluation of the conformity of the θ_v obtained with the sensor, sensors θ_v, to the soil moisture content measured with the lysimeter, lysimeter θ_v. The assessment of accuracy was based on the 95% confidence interval of the linear regression performed on the θ_v measured with the sensors (Figs. 13a to 24b, 27, and 28). Measurements were qualified as *very accurate* in a given θ_v range when the 1:1 line was contained within the dashed lines delimiting the 95% confidence interval of the linear regression. For cases where the 1:1 line did not fall within the 95% confidence interval of the linear regression but the data points or the error bars were touching the 1:1 line, the measurements were qualified as *accurate*. Finally, the measurements were qualified as inaccurate in a given θ_v range when these conditions were not met.

The precision of a sensor was assessed based on the 95% confidence interval calculated for each data point illustrated by the error bars in s. 13a to 24b, 27, and 28. The precision was qualified as *excellent* when the error bars corresponded to a range of θ_v of less that 2% for most data points over the entire drying cycle; as *very good* when the error bars covered a range of θ_v of less that 4%; as *good* when they represented a

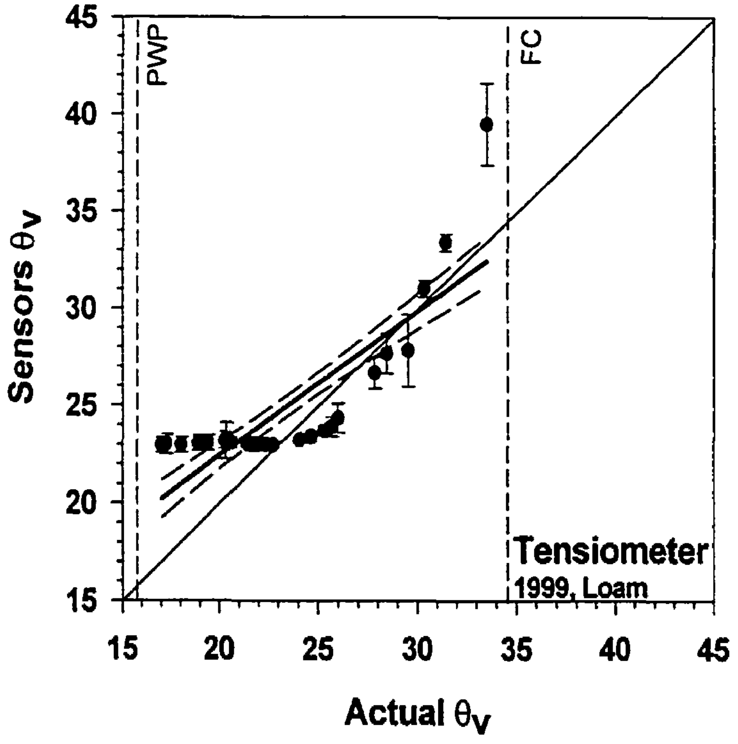

Fig. 13a **Tensiometers results in loam of ρ_b= 1190 kg/m^3.** Volumetric water content, in percentage, measured with tensiometers as a function of θ_v, in percentage, obtained with the lysimeter. Each data point represents the mean of the θ_v-measurements from three different sensors. The error bars represent the 95% confidence interval based on the three measurements. The thick line illustrates the linear regression and the dashed line represents the 95% confidence interval for the linear regression.

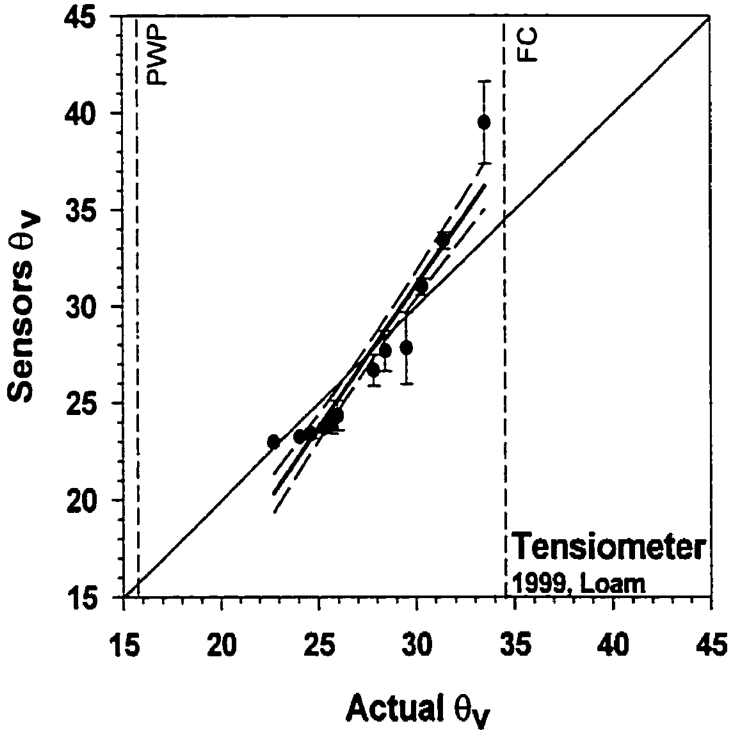

Fig. 13b **Tensiometers results in loam of ρ_b= 1190 kg/m^3 (modified).** Modified version of Fig. 13a for which data points were excluded when at least one of the three tensiometers had reached its operational limit or had failed.

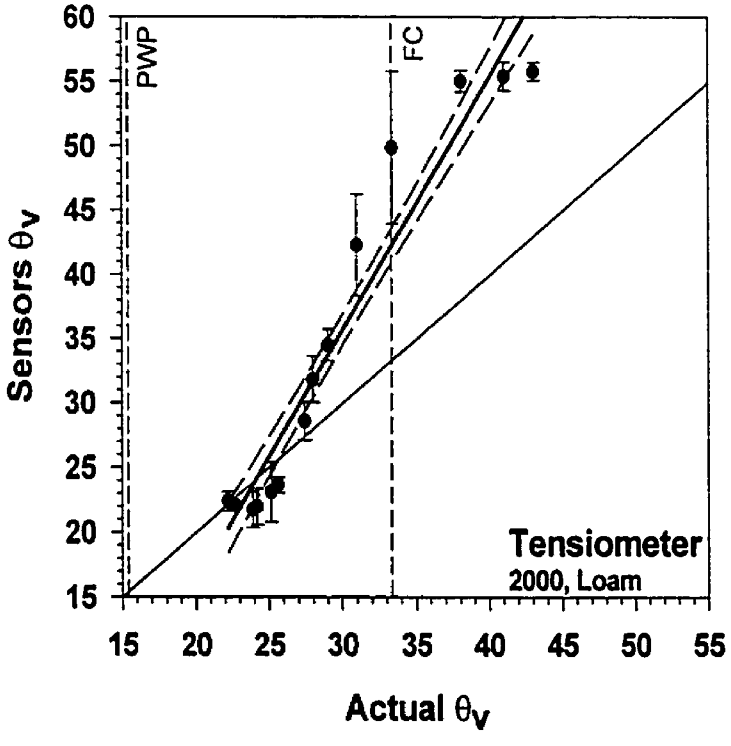

Fig. 14a **Tensiometers results in loam of ρ_b= 1150 kg/m^3.** Volumetric water content, in percentage, measured with tensiometers as a function of θ_v obtained, in percentage, with the lysimeter. Each data point represents the mean of the θ_v-measurements from three different sensors. The error bars represent the 95% confidence interval based on the three measurements. The thick line illustrates the linear regression and the dashed line represents the 95% confidence interval for the linear regression.

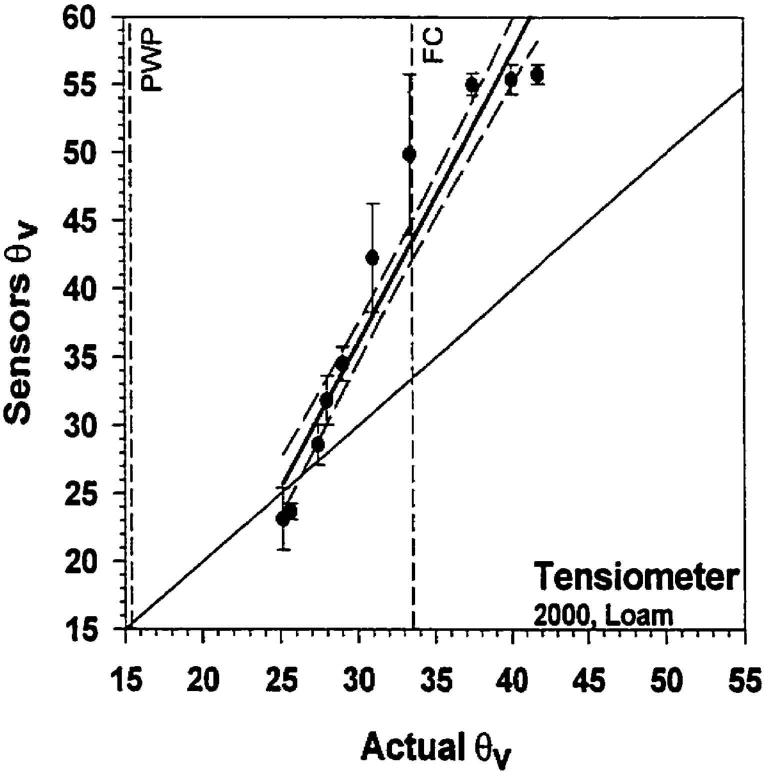

Fig. 14b **Tensiometers results in loam of ρ_b= 1150 kg/m^3 (modified).** Modified version of Fig. 14a for which data points were excluded when at least one of the three tensiometers had reached its operational limit or had failed.

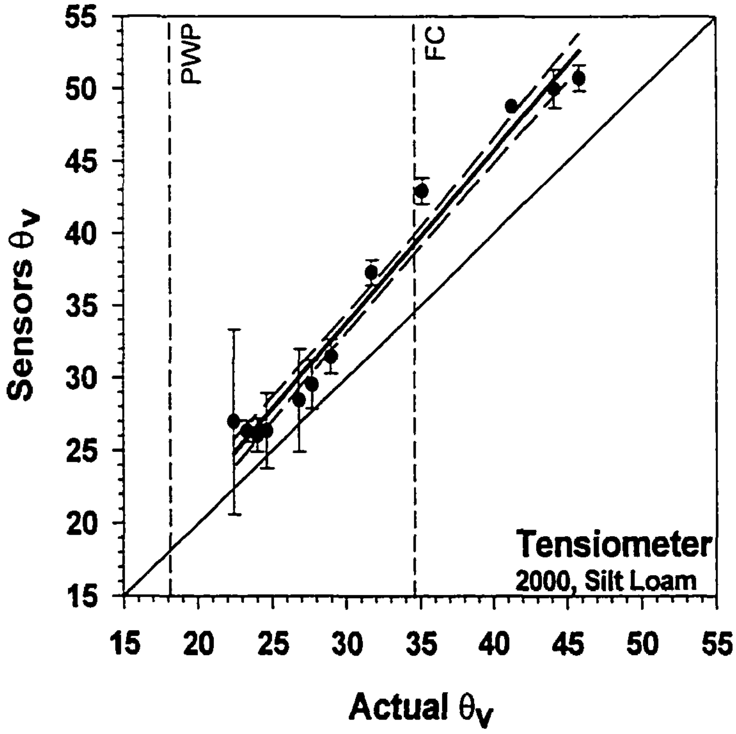

Fig. 15a **Tensiometers results in silt loam of ρ_b= 1250 kg/m^3.** Volumetric water content measured with tensiometers, in percentage, as a function of θ_v obtained with the lysimeter, in percentage. Each data point represents the mean of the θ_v-measurements from three different sensors. The error bars represent the 95% confidence interval based on the three measurements. The thick line illustrates the linear regression and the dashed line represents the 95% confidence interval for the linear regression.

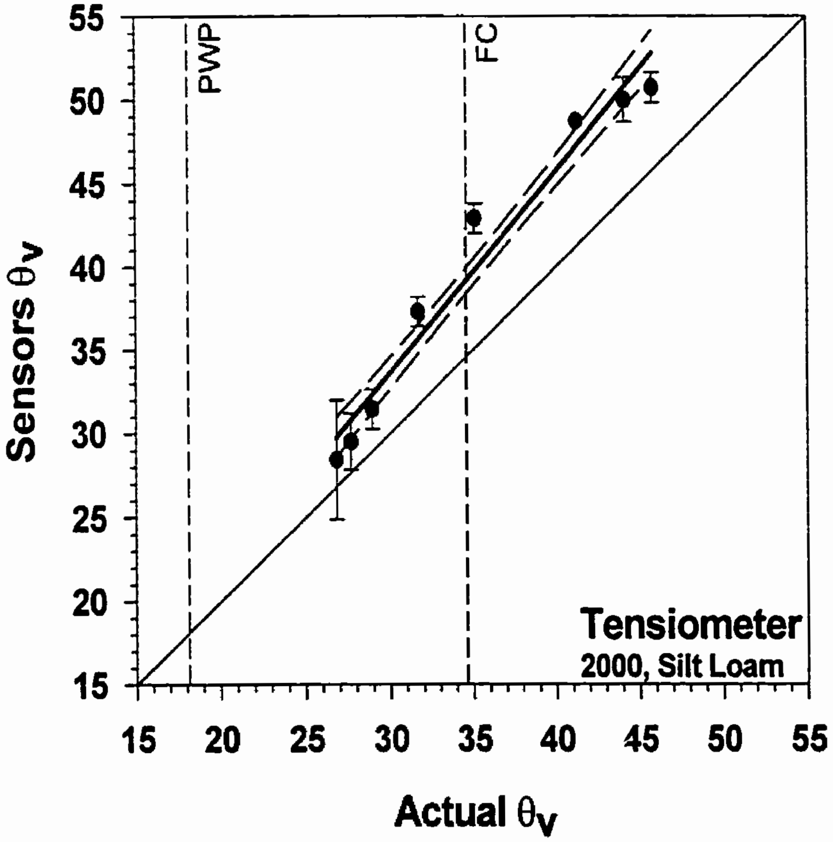

Fig. 15b **Tensiometers results in silt loam of ρ_b= 1250 kg/m^3 (modified).** Modified version of Fig. 15a for which data points were excluded when at least one of the three tensiometers had reached its operational limit or had failed.

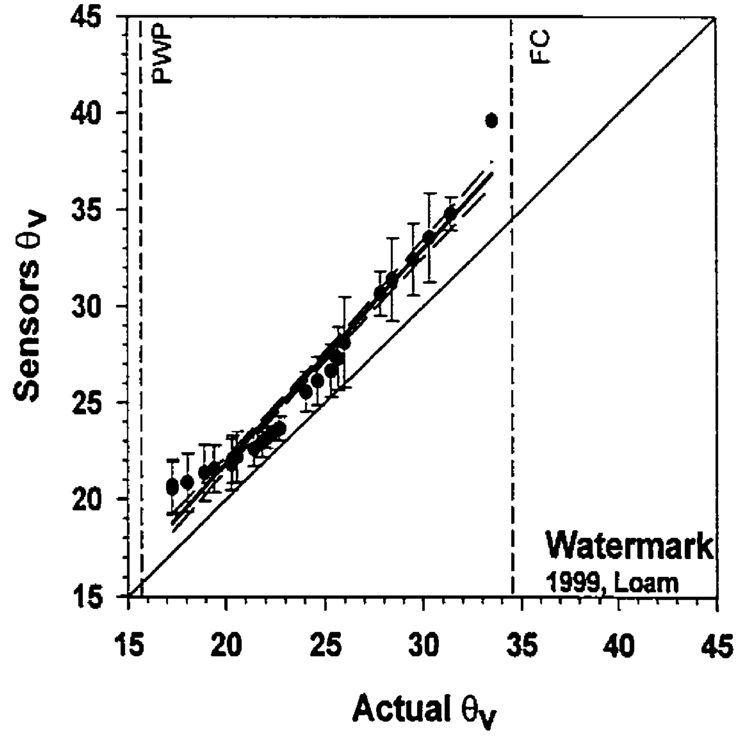

Fig. 16 **Watermark results in loam of ρ_b= 1190 kg/m^3.** Volumetric water content measured with Watermark GMS, in percentage, as a function of θ_v obtained with the lysimeter, in percentage. Each data point represents the mean of the θ_v-measurements from three different sensors. The error bars represent the 95% confidence interval based on the three measurements. The thick line illustrates the linear regression and the dashed line represents the 95% confidence interval for the linear regression.

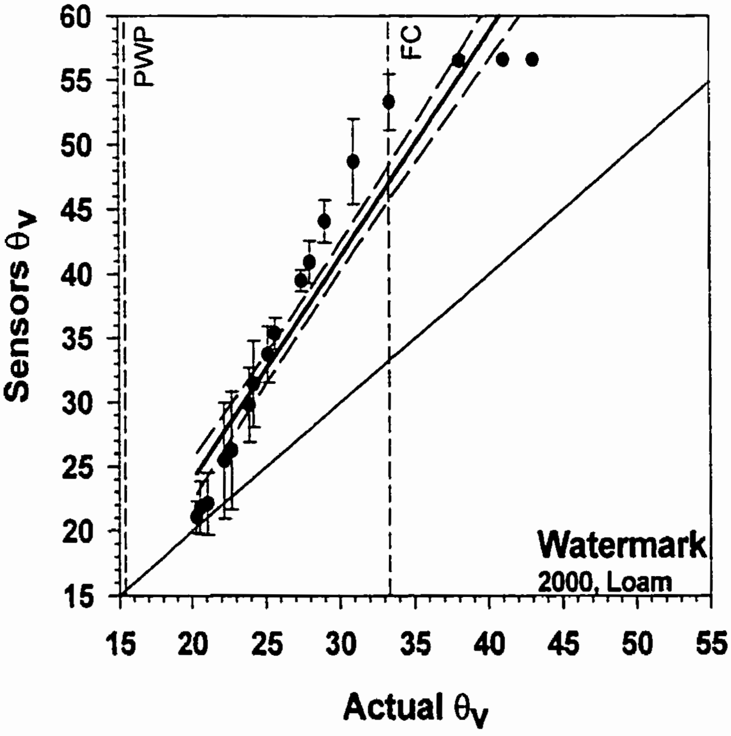

Fig. 17a **Watermark GMS results in loam of ρ_b= 1150 kg/m^3.** Volumetric water content measured with the sensors, in percentage, as a function of θ_v obtained with the lysimeter, in percentage. Each data point represents the mean of the θ_v-measurements from three different sensors. The error bars represent the 95% confidence interval based on the three measurements. The thick line illustrates the linear regression and the dashed line represents the 95% confidence interval for the linear regression.

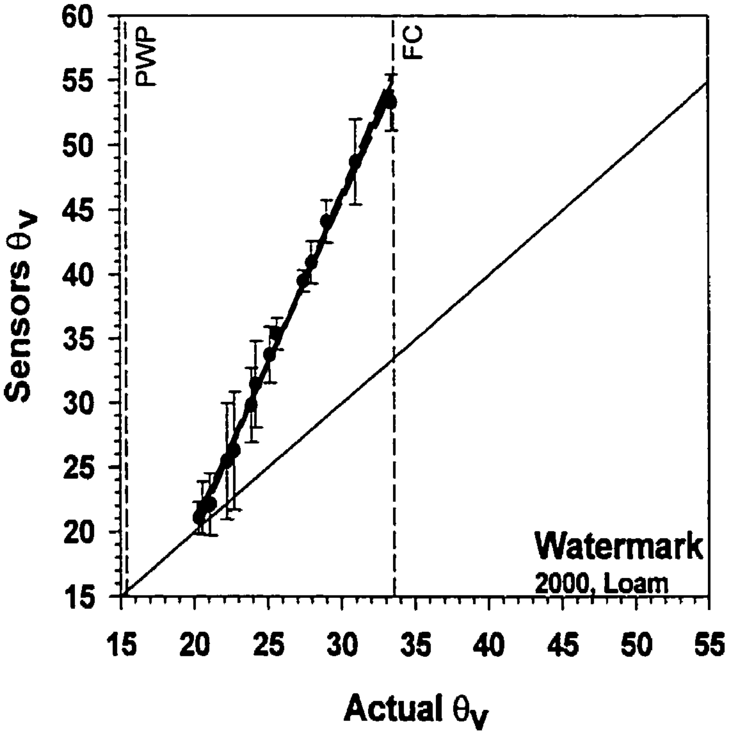

Fig. 17b **Watermark GMS results in loam of ρ_b= 1150 kg/m^3 (modified).** Modified version of Fig. 17a for which Ψ-measurements below 10 kPa were rejected.

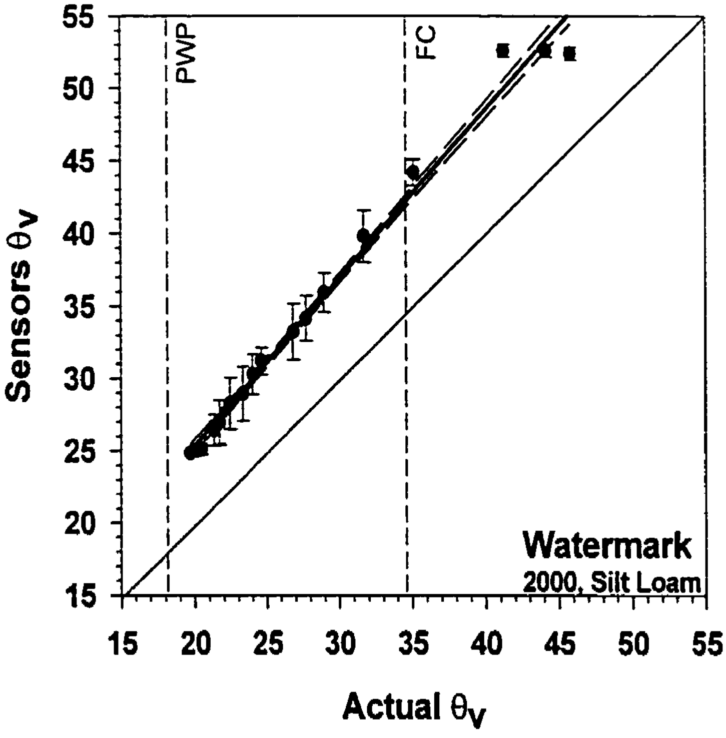

Fig. 18a **Watermark GMS results in silt loam of ρ_b= 1250 kg/m^3.** Volumetric water content measured with the sensors, in percentage, as a function of θ_v obtained with the lysimeter, in percentage. Each data point represents the mean of the θ_v-measurements from three different sensors. The error bars represent the 95% confidence interval based on the three measurements. The thick line illustrates the linear regression and the dashed line represents the 95% confidence interval for the linear regression.

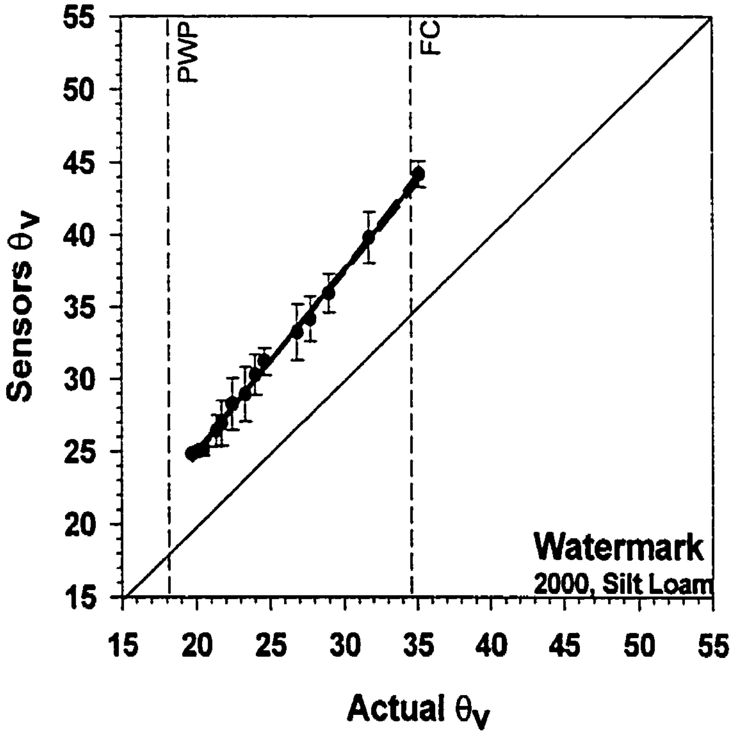

Fig. 18b **Watermark GMS results in silt loam of ρ_b= 1250 kg/m^3 (modified).** Modified version of Fig. 18a for which Ψ-measurements below 10 kPa were rejected.

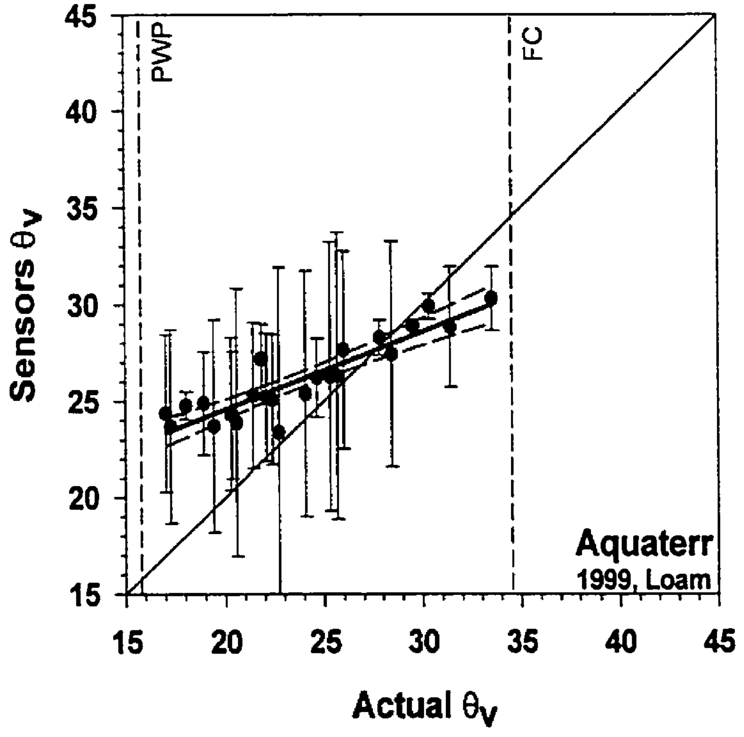

Fig. 19 **Aquaterr results in loam of ρ_b= 1190 kg/m^3.** Volumetric water content measured with the probe, in percentage, as a function of θ_v obtained with the lysimeter, in percentage. Each data point represents the mean of the θ_v-measurements taken at three different locations with the portable device. The error bars represent the 95% confidence interval based on the three measurements. The thick line illustrates the linear regression and the dashed line represents the 95% confidence interval for the linear regression.

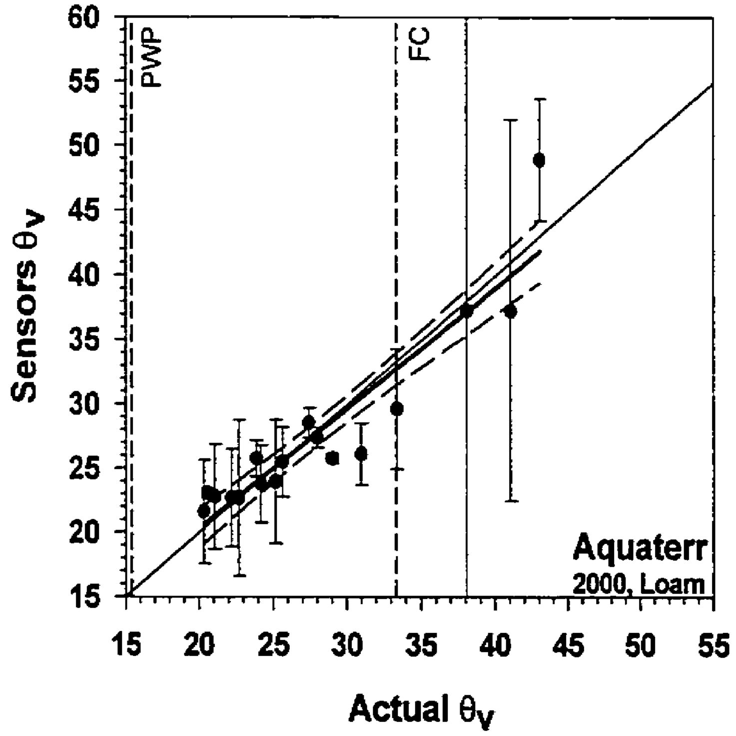

Fig. 20 **Aquaterr results in loam of ρ_b= 1150 kg/m^3.** Volumetric water content measured with the probe, in percentage, as a function of θ_v obtained with the lysimeter, in percentage. Each data point represents the mean of the θ_v-measurements taken at three different locations with the portable device. The error bars represent the 95% confidence interval based on the three measurements. The thick line illustrates the linear regression and the dashed line represents the 95% confidence interval for the linear regression.

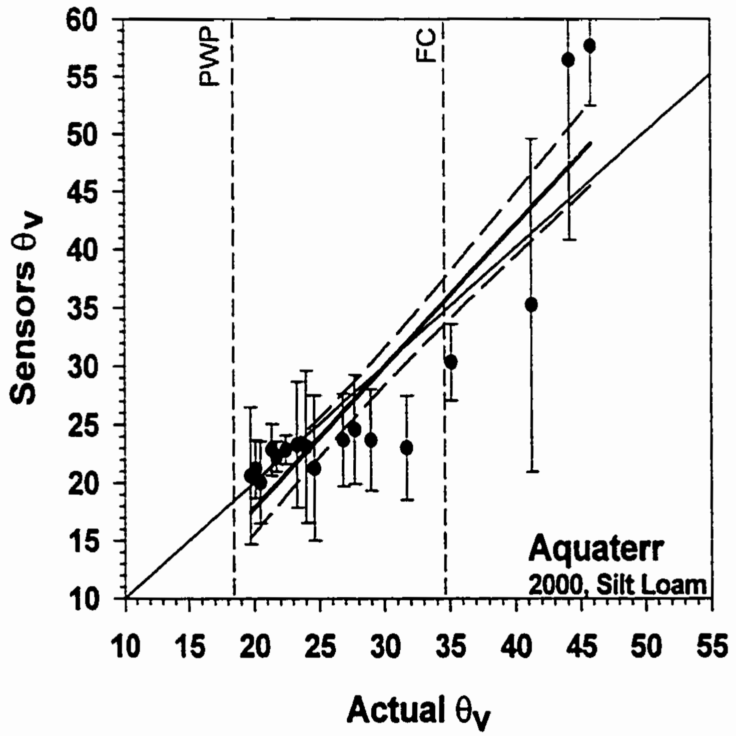

Fig. 21a **Aquaterr results in silt loam of ρ_b= 1250 kg/m^3.** Volumetric water content measured with the probe, in percentage, as a function of θ_v obtained with the lysimeter, in percentage. Each data point represents the mean of the θ_v-measurements taken at three different locations with the portable device. The error bars represent the 95% confidence interval based on the three measurements. The thick line illustrates the linear regression and the dashed line represents the 95% confidence interval for the linear regression.

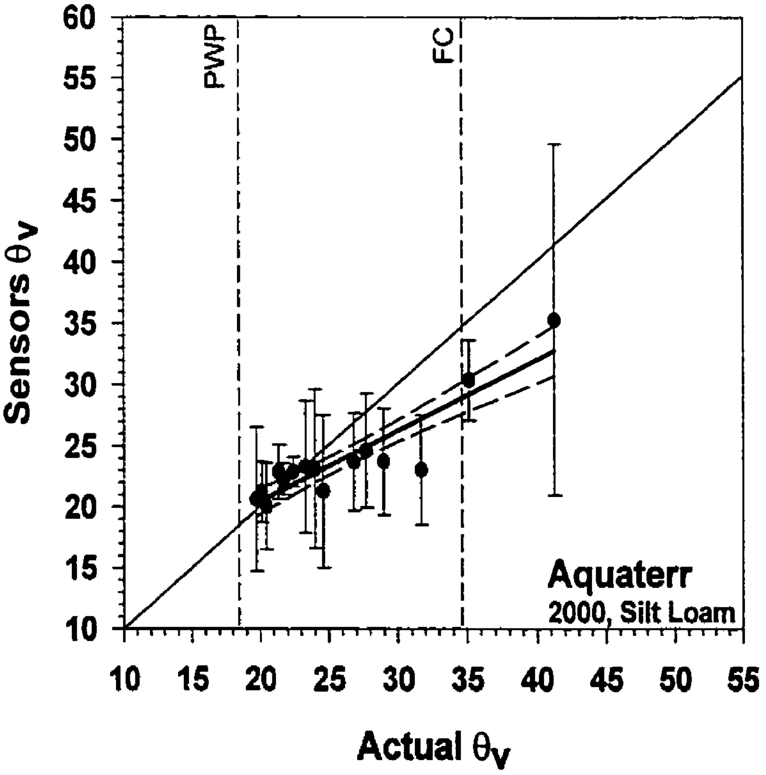

Fig. 21b **Aquaterr results in silt loam of ρ_b= 1250 kg/m^3 (modified).** Revised version of Fig. 21a for which readings exceeding 100 were rejected.

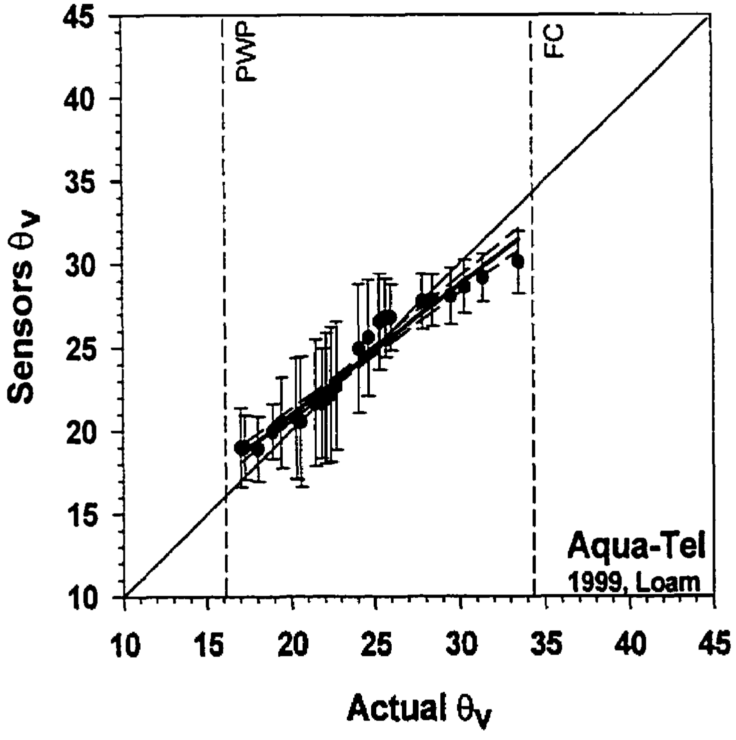

Fig. 22 **Aqua-Tel sensors results in loam of ρ_b= 1190 kg/m^3.** Volumetric water content measured with the sensors, in percentage, as a function of θ_v obtained with the lysimeter, in percentage. Each data point represents the mean of the θ_v-measurements from three different sensors. The error bars represent the 95% confidence interval based on the three measurements. The thick line illustrates the linear regression and the dashed line represents the 95% confidence interval for the linear regression.

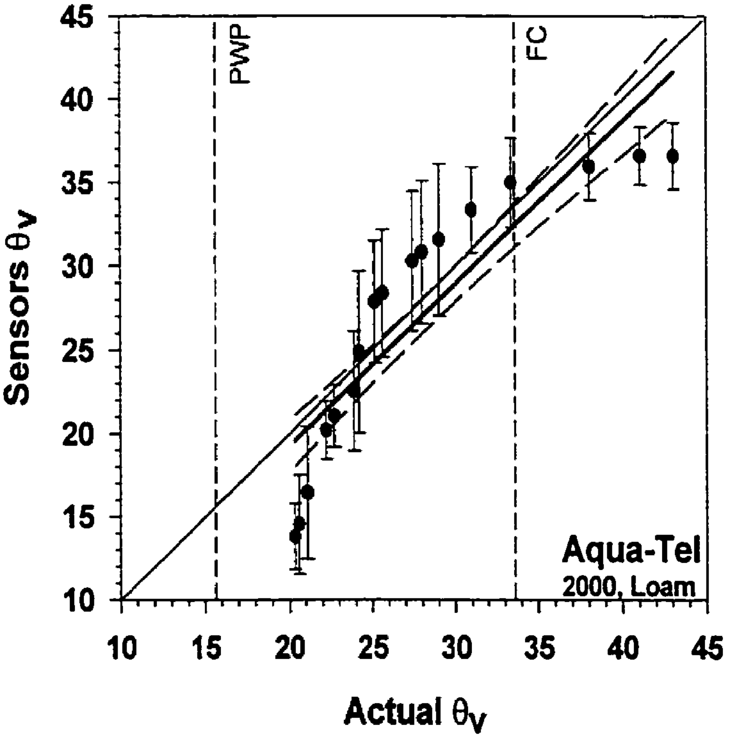

Fig. 23 Aqua-Tel sensors results in loam of ρ_b= 1150 kg/m^3. Volumetric water content measured with the sensors, in percentage, as a function of θ_v obtained with the lysimeter, in percentage. Each data point represents the mean of the θ_v-measurements from three different sensors. The error bars represent the 95% confidence interval based on the three measurements. The thick line illustrates the linear regression and the dashed line represents the 95% confidence interval for the linear regression.

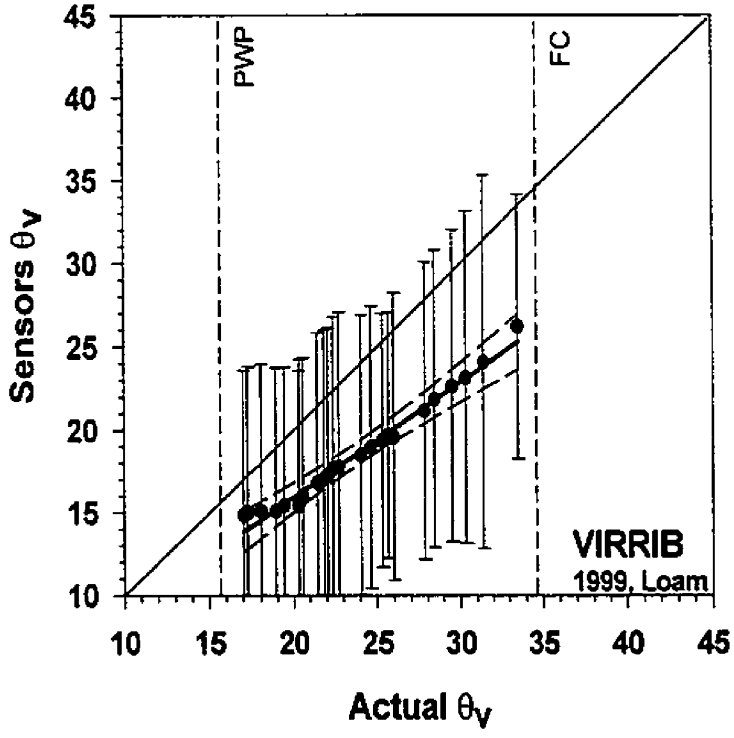

Fig. 24a VIRRIB sensors results in loam of ρ_b= 1190 kg/m^3. Volumetric water content measured with the sensors, in percentage, as a function of θ_v obtained with the lysimeter, in percentage. Each data point represents the mean of the θ_v-measurements from three different sensors. The error bars represent the 95% confidence interval based on the three measurements. The thick line illustrates the linear regression and the dashed line represents the 95% confidence interval for the linear regression.

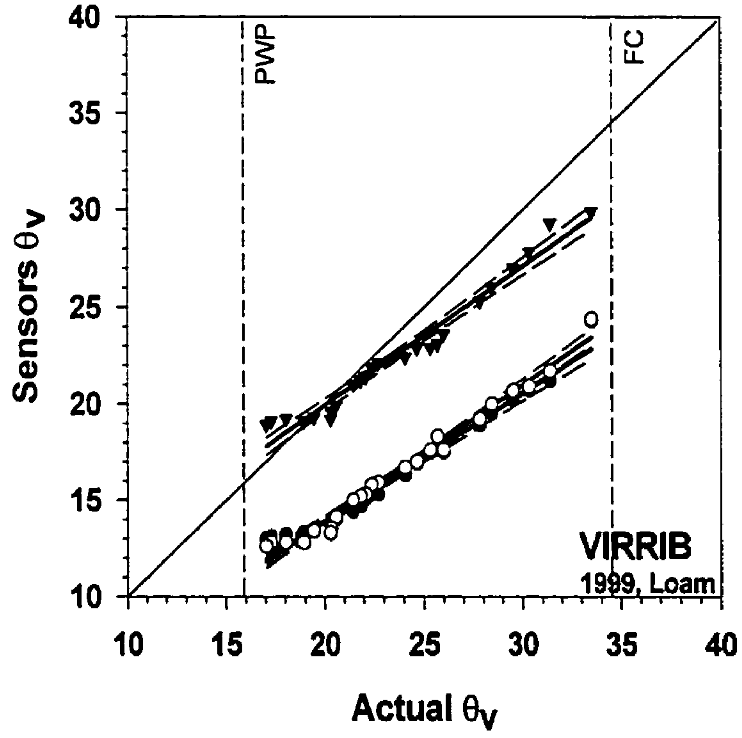

Fig. 24b **VIRRIB sensors results in loam of ρ_b= 1190 kg/m^3(modified).** Modified version of Fig. 24a: each data point represents a single θ_v-measurement taken with a sensor.

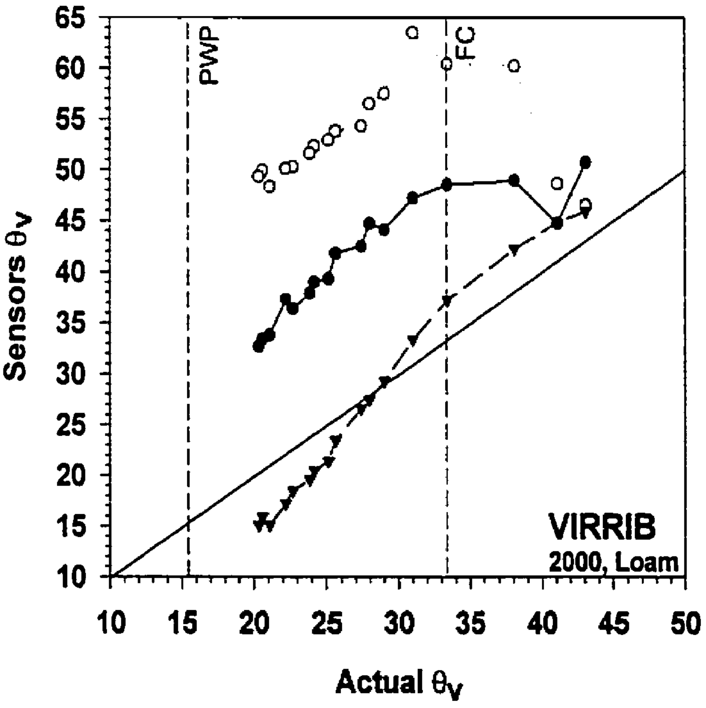

Fig. 25 **VIRRIB sensors results in loam of ρ_b= 1150 kg/m^3.** Volumetric water content measured with a sensor, in percentage, as a function of θ_v obtained with the lysimeter, in percentage. Each data point represents a single θ_v-measurement taken with a sensor.

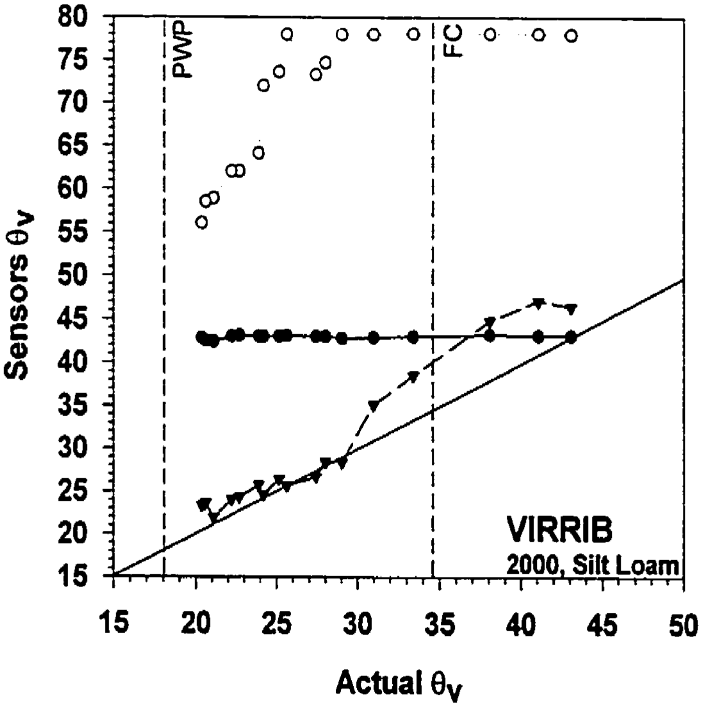

Fig. 26 **VIRRIB sensors results in silt loam of ρ_b = 1250 kg/m^3.** Volumetric water content measured with a sensor, in percentage, as a function of θ_v obtained with the lysimeter, in percentage. Each data point represents a single θ_v-measurement taken with a sensor.

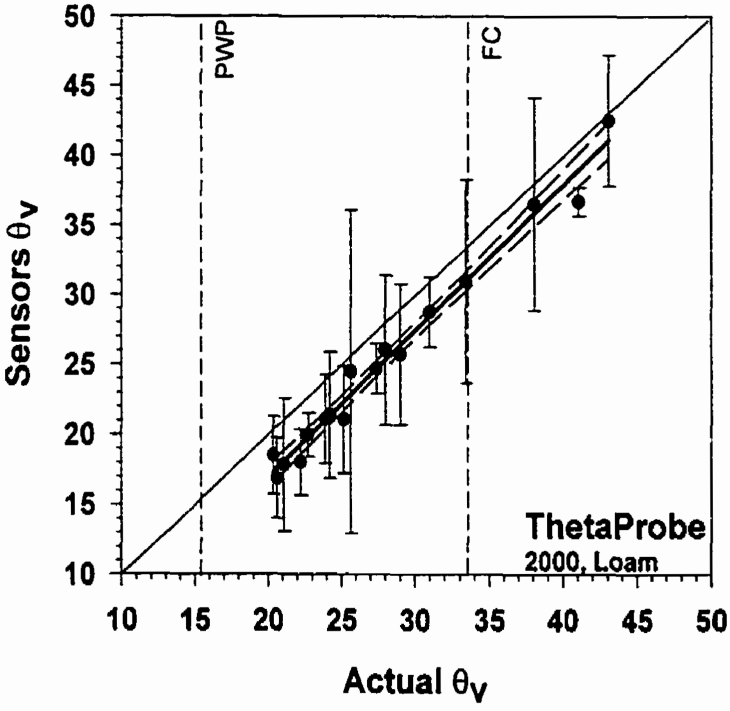

Fig. 27 **ThetaProbe sensor results in loam of ρ_b= 1150 kg/m^3.** Volumetric water content measured with the probe, in percentage, as a function of θ_v obtained with the lysimeter, as percentage. Each data point represents the mean of the θ_v-measurements taken at three different locations with the portable device. The error bars represent the 95% confidence interval based on the three measurements. The thick line illustrates the linear regression and the dashed line represents the 95% confidence interval for the linear regression.

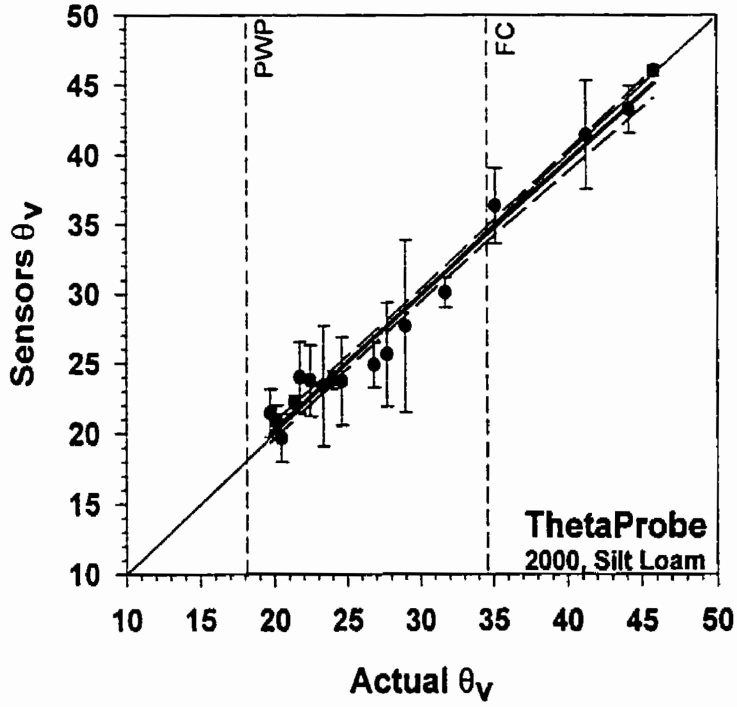

Fig. 28 **ThetaProbe sensor results in silt loam of ρ_b= 1250 kg/m^3.** Volumetric water content measured with the probe, in percentage, as a function of θ_v obtained with the lysimeter, as percentage. Each data point represents the mean of the θ_v-measurements taken at three different locations with the portable device. The error bars represent the 95% confidence interval based on the three measurements. The thick line illustrates the linear regression and the dashed line represents the 95% confidence interval for the linear regression.

range of θ_v of 6% or less; and as *poor* when they corresponded to a range of θ_v greater than 6%.

During the first lysimeter trial, tensiometers, Watermark sensors, the Aquaterr soil moisture meter, Aqua-Tel sensors, and VIRRIB sensors were tested in loam with a ρ_b of 1190 kg/m^3 over one drying cycle for moisture contents ranging from 34.0 to 17.0% (Figs. 13a, 13b, 16, 19, 22, 24a, and 24b). The standard errors calculated on the lysimeter θ_v, i.e. the volumetric water content obtained by gravimetric sampling used to calibrate the lysimeter readings, did not exceed 0.6%.

During the lysimeter trial of 2000, the performance of tensiometers, Watermark sensors, the Aquaterr soil moisture meter, Aqua-Tel sensors, VIRRIB sensors, and the ThetaProbe FDR sensor was evaluated in loam with a ρ_b of 1150 kg/m^3 over a range of moisture contents from 43.1 to 20.0% (Figs. 14a, 14b, 17a, 17b, 18, 23, 25, and 28). The standard errors calculated on the lysimeter θ_v did not exceed 1.2% except for the first sampling event where it was 5.5%. The performance of tensiometers, Watermark sensors, the Aquaterr soil moisture meter, VIRRIB sensors, and the ThetaProbe FDR sensor was also assessed in silt loam with a ρ_b of 1250 kg/m^3 for moisture contents ranging from 45.8 to 19.5% (Figs. 15a, 15b, 18a, 18b, 21a, 21b, 26, and 28). The standard errors calculated for the lysimeter θ_v did not exceed 0.3%.

Each of the data point shown in Figs. 13a, 13b, 14a, 14b, 15a, 15b, 16, 17a, 17b, 18a, 18b, 22, 23, and 24a represents the average of the θ_v-measurements from three different sensors. In Figs. 19, 20, 21a, 21b, 27, and 28, each data point represents the mean of θ_v-measurements taken with one of the portable probes, i.e. Aquaterr or ThetaProbe, at three different locations within a lysimeter on a given occasion. The error bars represent the 95% confidence interval based on the three measurements for each type of sensor. Whenever the error bar is not visible in Figs.

13a, 13b, 15a, 15b, 16, 17a, 18a, 18b, 19, 20, and 28, the symbol is larger than the error bar itself. The linear regression, represented by the thick line, was done on the average of the three θ_v-

measurements taken on each occasion for each type of sensor. The dashed line represents the 95% confidence interval for the linear regression.

In Figs. 24b, 25, and 26, each data point represents a single θ_v-measurement taken with a sensor on a given occasion, which explains why there is no error bar. Moreover, in Fig. 24b, the linear regression was done for the θ_v-measurements taken with each sensor, giving three linear regression lines. No linear regression was performed in Figs. 25 and 26 since the sensors response was not linear over the entire range of soil moisture contents.

As mentioned earlier, the challenge of evaluating the performance of soil moisture sensors lied mostly in the task of understanding the readings obtained from the various instruments, which in many cases required conversion to more meaningful soil-water information. The conversion can require several steps that are for some instruments performed in part by the device but mostly requires that the user be familiar with the quantity displayed by the meter, which in itself might require conversion. All these conversions may induce error that has to be considered when evaluating the performance of the various soil moisture sensors.

5.2.3.1 Tensiometers and Watermark GMS: The θ_v-measurements obtained with the tensiometers are compared with the lysimeter θ_v-measurements in Figs. 13a to 15b. Figures 13a, 14a, and 15a present the complete data collected during the lysimeter studies whereas Figs. 13b, 14b, and 15b are the respective modified versions for which some data points were excluded. A data point was rejected when at least one of the three water tension readings did not show a decrease of soil moisture content because it meant that at least one of the tensiometers had reached its limit of operation and had released water from the ceramic cup thereby increasing the moisture content of the soil in the vicinity.

For the 1999 trial, tensiometers measured θ_v accurately over the 23 to 30% range, for which the measurements were qualified of very accurate in the 26 to 30% range based on the 95% confidence interval of the linear regression (Fig. 13b). The tensiometers tended to overestimate θ_v above 30% and they did not respond to moisture change below 23%, which corresponded to their operational limit of -85 kPa. In the 2000 trial, tensiometers mainly overestimated θ_v in both lysimeters, i.e. in both soils. In Fig. 14b, the regression line shows that the difference between the tensiometers θ_v-measurements and the lysimeter θ_v increased with soil moisture. Accurate measurements were obtained in the narrow 25-28% range whereas a divergence of as much as 18% was observed for lysimeter θ_v of 38%. In silt loam, the regression line is offset from the 1:1 line by less than 3% at lysimeter θ_v of 27% and by 7% at 45%.

The variability of the tensiometers θ_v-measurements was generally small for all trials, illustrated by error bars covering on average a θ_v range of less 4%, and thus, we found the tensiometers to have very good precision. A few data points, however, show large error bars in the 2000 trial: two data points for loam (Fig. 14b) and one for silt loam (Fig. 15b).

The θ_v-measurements obtained with the Watermark GMS are compared with the lysimeters θ_v-measurements in Figs. 16 to 18b. Figures 17b and 18b are modified versions of Figs. 17a and 18a, for which measurements of soil matric potential (Ψ) below 10 kPa were rejected. The first three data points were discarded for both trials in 2000, i.e. in loam and silt loam, because it had been observed that Watermark sensors do not respond linearly to changes in soil moisture in the 0-10 kPa range (Phene et al. 1989), which correspond to θ_v-values above 55% in loam and above 50% in silt loam.

Granular matrix sensors gave accurate readings in loam for the 1999 trial in the 20-26% range and slightly overestimated θ_v below and above that range. The regression line is offset from the 1:1 line by less that 3% (Fig. 16). In 2000, the θ_v-measurements obtained with the GMS in both soils followed the same trend as observed for tensiometers, mainly overestimating θ_v. In Fig. 17b, the regression line shows that the difference between the sensors θ_v-measurements and the lysimeter θ_v increased with soil moisture. Accurate measurements were obtained in the narrow 20-23% range whereas a divergence of as much as 20% was observed at lysimeter θ_v of 34%. In silt loam, the difference between the sensors θ_v-measurements and the lysimeter θ_v also increased with soil moisture; the regression line is offset from the 1:1 line by 5% at θ_v of 20% and by 9% at 45%.

The precision of the Watermark sensors was very good for all trials. A few data points, however, show error bars of about 5% in magnitude in loam: three data points in the 1999 trial (Fig. 16) and four in the 2000 trial (Fig. 17b).

Soil matric potential is a quantity of significance in agriculture and thus measurements obtained with tensiometers and Watermark GMS would not require conversion for an experienced user. For the purpose of comparison however, the Ψ-values were converted to θ_v using the soil moisture characteristic curve respective to each soil (Figs. 9, 10, and 11). The soil moisture characteristic curves specific to loam and silt loam of the Ramada series were not available, thus they were determined in the laboratory with the pressure plate method.

Moreover, the deviation of the converted θ_v-values from the lysimeter θ_v obtained with the lysimeter followed the same trend for both tensiometers and GMS, greatly overestimating θ_v in both soils for the trial of 2000. This can indicate that the Ψ-to-θ_v conversion or more specifically the soil moisture characteristic curves estimated for the soil conditions of 2000 may have been prone to error.

5.2.3.2 Aquaterr soil moisture meter: The θ_v-measurements obtained with the Aquaterr soil moisture meter are compared with the lysimeters θ_v-measurements in Figs. 19 to 21b. Figure 21b is a revised version of 21a for which Aquaterr readings exceeding 100 were rejected. Because a reading of 100 is set by immersing the probe in water, values exceeding that were therefore assumed erroneous. The first two data points were discarded because all three readings in the first test and two of the three readings in the second test were higher than 100.

In the 1999 trial, the θ_v-measurements obtained with the Aquaterr in loam matched the lysimeter θ_v accurately over the 23-31% range, for which the measurements were qualified of very accurate in the narrow 27 to 30% range based on the statistical evaluation of accuracy described in section 5.2.3 (Fig. 19). Although the error bar of the data points in the θ_v range of 19 to 31% touch the 1:1 line, the regression line shows that the Aquaterr probe overestimated θ_v below 24% whereas it tended to underestimate it above 31%. In 2000, the Aquaterr gave very accurate measurements of θ_v in loam over the entire drying cycle (Fig. 20). In silt loam, accurate θ_v-measurements were obtained for θ_v below 28% from which measurements in the 20 to 24% range were very accurate (Fig. 21b). However, the Aquaterr showed poor precision, illustrated by the large error bars, for all trials, especially in the 1999 trial.

As for the Watermark GMS, the data conversion for the Aquaterr probe was performed in two stages. Firstly, the electrical quantity measured with the capacitance sensor was converted to a scale of 0 to 100 that was displayed on the meter. Then, the displayed value (R) was compared with a colour-coded legend that interpreted the readings in terms of soil moisture conditions (saturation, field capacity, and permanent wilting point) for three general soil textures. The correlation between R and the moisture conditions specific to the soils used in the experiment was estimated by interpolation (Table I). Finally the readings were converted to θ_v using the linear relationships developed from both the correlation between R and the moisture conditions and the θ_v and the moisture conditions. Once again, the soil moisture characteristic curves were used in the conversion. As it was discussed for the tensiometers and the Watermark GMS, the final conversion was performed for the purpose of comparing the Aquaterr's readings to the θ_v obtained with the lysimeter.

5.2.3.3 Aqua-Tel capacitance probes: The θ_v-measurements obtained with the Aqua-Tel capacitance sensors are compared with the lysimeters θ_v-measurements in Figs. 22 and 23. In the 1999 trial, the Aqua-Tel sensors measured θ_v accurately below 31% from which measurements in the 20 to 27% range were very accurate (Fig. 22). The regression line shows that the capacitance probes underestimated θ_v above 30%. In the 2000 trial, although the regression line follows closely the 1:1 line, the θ_v-measurements obtained with these capacitance sensors were accurate for θ_v ranging from 22 to 38% and θ_v was underestimated below and above that range (Fig. 23). For both trials, the precision of the Aqua-Tel sensors was qualified as good which is illustrated by error bars covering on average a range of θ_v before 4 to 6% (Figs. 22 and 23). However, poor precision was observed for a few readings in the 2000 trial, illustrated by large error bars covering, in some cases, a range of θ_v of about 9% (Fig. 23).

The data conversion for the Aqua-Tel was performed in a single step. The electrical quantity sent to the meter from the electronic module connected to the electrodes, ranging from 0 to 1 mA, was amplified to be displayed on a scale of 0 to 100 on the meter. The calibration equation (Eq. 19) used to convert the reading displayed was developed with a statistical analysis of texture-specific calibration curves published by Automata Inc. Equation 19 represents the data points of all the curves with a R-squared value of 97.6%. When plotted against readings from 0.0 to 100.0 however, the maximum volumetric water content returned was 47.8% which does not match θ_v at saturation of the soil tested (for loam: in 1999, 55.1% and in 2000, 56.6%). This was due to the fact that only 9% of the data points from the manufacturer's calibration curves represented moisture contents above 35%.

5.2.3.4 VIRRIB phase transmission sensors: The VIRRIB readings are compared with the lysimeters' θ_v-measurements in Figs. 24a to 26. In 1999, the VIRRIB sensors gave average readings that were about 3 to 7% less than the lysimeter θ_v (Fig. 24a). Figure 24b shows the readings of each of the three probes as a function of the lysimeter θ_v. One VIRRIB sensor gave very accurate measurements of θ_v in the 18 to 23% range. In 2000, only one of the six probes tested gave accurate measurements of θ_v over the 20 to 30% range. In loam, all three VIRRIB sensors gave measurements following the same trend at volumetric water content below 30%. Two of the three sensors, however, greatly overestimated θ_v; one by about 15% and the other by close to 30%. In silt loam, one sensor did not respond to changes in soil moisture content giving θ_v-readings of about 43% over the entire trial. Another sensor did not respond to soil moisture variations above 29% and overestimated θ_v by as much as 50% in that range. The third sensor tested in silt loam gave accurate measurements of θ_v in the 20-30% range and overestimated θ_v by about 5% above that range.

As for the Aqua-Tel sensors, the data conversion for the VIRRIB sensors was performed in a single step. In the case of the VIRRIB sensors the electronic module receives an electromagnetic quantity then converts it to a value on a scale from 0 to 55 which is then sent to the meter to be displayed as volumetric water content. The conversion equation that is used can be calibrated by first calculating the amplification and offset required and then adjusting the sensor by turning the specific resistive trimmer capacitor located on the electronic module for each sensing device. In 1999, the manufacturer's setting was used and it was concluded from the results obtained that a calibration specific to each soil was required. The calibration was done prior to the trial of 2000. Although the electronic module was resealed after the adjustment of the resistive trimmer capacitors, water entered all sensors despite the caulking and electrical tape used. The water intrusion caused the malfunction of the sensors for the first part of the drying cycle down to θ_v of 30%. Five of the sensors responded to variations of soil moisture below 30% whereas one sensor did not respond over the entire test. A single sensor however, gave accurate measurements in the 20 to 30% range which led to conclude that the calibration performed was inadequate for five sensors out of six.

5.2.3.5 ThetaProbe FDR sensor: The θ_v-measurements obtained with the ThetaProbe FDR sensor are compared to the lysimeters' θ_v-measurements in Figs. 27 and 28. In loam, the ThetaProbe measured accurately θ_v over the entire soil moisture range (Fig. 27). The regression line shows that the probe responded linearly to moisture changes with an offset from the 1:1 line of less than 3%. In silt loam, the probe gave very accurate measurements. The linear regression follows the 1:1 line perfectly (Fig. 28).

Greater variability was observed for measurements made in loam than for those made in silt loam. Based on the 95% confidence interval of the mean of the three measurements taken on each occasion, the ThetaProbe had good precision in loam and very good precision in silt loam. However, a few measurements showed very high variability; in loam, three data points have an error bar covering a range of θ_v larger than 14% whereas only one data points has an error bar larger than 8% in silt loam.

The data conversion for the ThetaProbe frequency-domain reflectometry sensor was performed in a single step. Because a voltmeter and a power supply were used instead of the programmable data logger manufactured by Delta Devices Ltd., the texture-specific calibration equation was used by the experimenter to convert the value displayed on the voltmeter to volumetric water content. The calibration equation was developed by first correlating the voltage output read to the apparent permittivity of the soil which was then correlated to the soil moisture content.

Two distinct sources of error are associated with developing the calibration equation. One is related to gravimetric sampling and the other, to the electronic circuitry made of the power supply, the voltmeter, the probe, the soil, and all the cables and wires. The maximum standard error calculated for gravimetric sampling performed to determine the calibration equation was 0.44% in loam and 0.65% in silt loam. Because the output voltage kept oscillating even after a period of 120 s was allowed for stabilization, we assumed that the signal would not stabilize thus, the readings were taken precisely 90 s after the transmission of the signal had begun for all tests. By doing so, the experimenter tried to counter the error associated with the electronic circuitry by measuring the output voltage at the same location on the output signal with regard to the phase of the electromagnetic signal.

5.3 Functional considerations

Several functional aspects of the various instruments tested should be considered when evaluating their suitability for field applications. The following considerations are based on observations made in both the field and the laboratory trials of the present study.

5.3.1 Tensiometers Tensiometers require continuous monitoring to ensure that they are adequately filled with water and air entry has not taken place. They also need to be handled with care since the porous cup made of ceramic can be easily damaged and any material coming in contact with the cup could block its pores. Furthermore, the operational limit of the tensiometers (-85 cBar) is not sufficient for certain crops or applications.

5.3.2 Watermark GMS Granular matrix sensors are not as brittle as tensiometers but they can wear out. The membrane covering the granular matrix may become clogged and impede water flow through the sensing device. The gypsum wafer used to buffer the effect of soil solution's salinity will dissolve over time. These factors contribute to the loss of sensitivity to moisture changes. Watermark sensors are affected by temperature and thus, soil temperature must be independently monitored and entered onto the meter for calibration purposes. When soil moisture is measured deep below the soil surface, soil temperature measurements can be difficult. Watermark GMS do not fully respond to rapid drying or partial rewetting of the soil (McCann et al. 1992). This can result in underestimating the actual soil moisture content and thus to increasing the cost of irrigation due to over application.

5.3.3 Aquaterr portable capacitance probe The Aquaterr capacitance probe was found to be affected by temperature variations between the water used for the calibration and the soil. To lessen this effect, the temperature of the calibration water should be kept within 3°C of that of the soil, which can become a difficult task in the field on a warm summer day.

Measurements at shallow depths in loose-structured soil are difficult due to the configuration of the instrument. The electrodes are at the tip of the long stem attached to a meter and two handles. The mass of the meter coupled with the length of the stem makes it difficult to maintain a good contact between the electrodes and the soil. However, for deeper measurements, the probe is more stable and a firm soil-sensor contact is easy to establish and sustain. Although the Aquaterr is built to be pushed into the soil to the desired depth, it was found that for most soils an access hole was required to insert the probe to depths greater than 0.30 m.

5.3.4 Aqua-Tel capacitance sensors The Aqua-Tel sensors consist of electrodes of 0.83-m in length and therefore can sample a large area. Although this can be an advantage for certain applications, large sensing devices can also be a disadvantage when used for crops which have tubers such as potatoes. Disturbances and air pockets in the effective volume of the sensor will greatly affect the measurements.

5.3.5 VIRRIB phase transmission sensors As for the Aqua-Tel sensors, the dimensions of the VIRRIB sensors can be too large for crops like potatoes. In addition, the configuration of the probe with regard to the calibration procedure is awkward. The calibration requires the adjustment of the resistive trimmer capacitors located on the electronic module which has to be buried in the soil while the adjustment is carried out.

The VIRRIB sensor is affected by interferences from transmission lines. The body of the operator can also interfere with the measurements. It was observed that the distance from the body of the operator to which the meter was held influenced the readings. Furthermore, the distance between the operator and the sensor's electrodes also affected the readings. For this reason, the operator should always hold the meter in the same manner to sustain the same distance between his body and the meter each time measurements are taken. The operator should also position himself at the same distance from the sensor's electrodes.

5.3.6 ThetaProbe FDR sensor As for the VIRRIB sensors, the ThetaProbe measurements were affected by interferences caused by the experimenter's body.

Although the ThetaProbe was used as a portable sensor, it can also be installed permanently. In both cases, care should be taken to avoid disturbances and air pockets in the effective volume of the instrument which can greatly affect the measurements.

6 CONCLUSIONS

6.1 Experimental considerations

As discussed in the previous section, the use of volumetric water content as a unit of reference for the purpose of comparing sensors was unfavourable to the tensiometers, Watermark GMS, and Aquaterr probe since an additional conversion had to be performed. The conversion from soil matric potentials to volumetric water contents required soil-specific information that introduced a new source of error.

Furthermore, in order to evaluate the performance of the various sensors tested with regard to the principle of operation used, the experiment would have required several distinctive stages. First, to observe the unprocessed output signal sent from the sensing device to the meter. Then, to assess the conversion or processing of the data integrated in the electronic module if applicable. And finally, to interpret the displayed value for the purpose of comparison.

6.2 Performance of the sensors

6.2.1 Accuracy and precision Tensiometers, granular matrix sensors, capacitance probes, phase transmission sensors, and the frequency-domain reflectometry tested however, did not measure soil moisture with the same accuracy and precision in the entire range. The assessment of accuracy was based on 1:1 line falling within the 95% confidence interval of the linear regression performed on the θ_v measured with the sensors. The precision of a sensor was assessed based on the length of the error bars. The detailed criteria for the assessment of both accuracy and precision are presented in section 5.2.3.

The ThetaProbe frequency-domain reflectometry sensor was the most accurate instrument to measure soil moisture content in both soils over the entire drying cycle. That is, in loam for θ_v ranging from 20.0 to 43.1% and in silt loam, from 19.5 to 45.8%. The precision of the measurements was very good in silt loam and good in loam.

The Aqua-Tel capacitance sensors gave accurate measurements of θ_v in loam over the 17 to 30% range from which measurements in the 20 to 27% range were very accurate in the trial of 1999 and from 22 to 38% in the trial of 2000. The sensors showed good precision in both trials.

The Aquaterr portable capacitance probe was accurate in loam in 1999 over the 23-31% range, for which the measurements were qualified of very accurate in the narrow 27 to 30% range based on the statistical evaluation of accuracy. In 2000, the Aquaterr gave very accurate measurements of θ_v in loam over the entire drying cycle. In silt loam, accurate θ_v-measurements were obtained for θ_v below 28% from which measurements in the 20 to 24% range were very accurate. The precision of the Aquaterr was poor for all trials.

Tensiometers and Watermark granular matrix sensors measured soil moisture accurately only in narrow ranges in the trial of 1999 whereas they greatly overestimated θ_v in both soils in 2000. Nevertheless, tensiometers and Watermark GMS were the most precise instruments for all the tests. The repeatability of the measurements indicated that the data conversion might be the source of inaccuracy.

Only one of the VIRRIB phase transmission sensors used to measure θ_v in loam in 1999 was accurate. Furthermore, those accurate measurements were obtained only over a narrow range of θ_v from 18 to 23%. The other two sensors responded to variations of soil moisture content in the same manner with an offset of about 5% of θ_v. For the trial of 2000, the VIRRIB sensors did not respond to changes in θ_v due to water leaking into the electronics resulting from the calibration process. Nonetheless, one sensor gave accurate measurements of θ_v in loam in the 20 to 30% range after the moisture inside the module had dried out.

6.2.2 Ease of use In addition to their accuracy and precision, the sensors were evaluated with regard to their ease of use. That is, the various soil moisture sensors were assessed in relation to the tasks to accomplish the installation, calibration, and operation of the sensing device as well as for the interpretation of the readings obtained. The assessment was mostly qualitative and was based on time consumption, labour intensiveness, and knowledge required to perform the tasks.

Tensiometers are easy to install, do not require calibration, and the measurements are continuously displayed. The measured quantity however is the soil matric potential. Furthermore, tensiometers need to be refilled periodically and because of the fragility of the sensing tip, they must be handled with care.

Watermark GMS are also simple to install and the measurements are instantaneously displayed at the press of a button. Nevertheless, because they require a calibration against temperature, the operator must measure soil temperature independently and enter it onto the meter. Watermark sensors display values of Ψ that need to be converted to volumetric water content.

The Aquaterr capacitance probe is a portable device and thus can easily measure soil moisture in several locations. It is labourious however, to insert the probe at depths greater than 0.30 m without previously digging an access hole. On the other hand, it is difficult to establish a good soil-electrodes contact when inserting the sensing tip shallowly in soils with low bulk density. The Aquaterr also needs onsite calibrations against moisture content which requires submerging the sensing tip in water. The temperature of the calibration water should be within 3°C of that of the soil as temperature was found to have an effect on the measurements. The readings are interpreted based on a colour code specific to three general soil textures, i.e., sand, loam, and clay, provided on the meter. To achieve a certain level of accuracy though, the operator needs to correlate the displayed value to soil moisture content which requires soil-specific information such as texture and moisture characteristics.

The Aqua-Tel capacitance sensors do not need onsite calibrations and the measurements are obtained instantaneously by pressing a button. The installation of the 0.83-m long electrodes requires that a trench be dug. The readings must be converted using texture-specific calibration curves published by the manufacturer or with the equation developed by the experimenters for which texture only has minimal influence on the conversion.

The VIRRIB phase transmission sensors display a reading of θ_v directly at the trigger of a button. Due to the size and configuration of the sensing device, the installation requires digging trenches as for the Aqua-Tel sensors. The VIRRIB sensors also need a calibration which is time consuming and labour intensive due to the location of the adjustment knobs.

The ThetaProbe FDR sensor was used as a portable probe in this experiment but can also be permanently installed. An access hole is required to insert the sensing device in the soil without compacting it excessively. The user's manual specifies an accuracy of ±5% of θ_v when calibration constants provided by the manufacturer are used. However, a specified accuracy of ±2% of θ_v can be achieved when a soil-specific calibration is performed. The ThetaProbe can be used with a hand-held meter or a data logger both manufactured specially for the use with the sensor. In this experiment, measurements were made using a power supply and a voltmeter. The data logger is programmable so that the readings can be converted to θ_v automatically. However, when the meter is used, the output voltage must be converted by the user with the aid of a calibration equation.

6.2.3 Overall performance A summary of the quantitative evaluation of the performance with regards to the accuracy and the precision of the sensors, based on the criteria described in section 5.2.3, is presented in Table IV.

Table IV. Summary of accuracy and precision of the soil moisture sensors.

Sensors	Accuracy	Precision
Tensiometers	inaccurate	very good
Watermark	inaccurate	very good
Aquaterr	accurate	poor
Aqua-Tel	accurate	good
VIRRIB	inaccurate	poor
ThetaProbe	very accurate	good (loam); very good (silt loam)

A summary of the qualitative evaluation of the performance with regards to the ease of use of the sensors, based on the criteria described in section 6.2.2, is presented in Table V. From both aspects of performance evaluation, i.e. quantitative and qualitative, we conclude that the ThetaProbe FDR sensor is most suitable to monitor irrigation needs with accuracy, precision, and ease of use. Both capacitance sensors, the Aquaterr probe and the Aqua-Tel sensors, also performed well, measuring soil moisture content accurately although with less precision. Tensiometers and Watermark sensors although very precise were mainly inaccurate due to problems with data conversion. The evaluation of the VIRRIB sensors' performance remains inconclusive due to the malfunction of the sensors resulting from calibration.

Table V. Summary of the evaluation of the sensors' ease of use.

Sensors	Installation	Onsite calibration	Operation
Tensiometers	easy, quick	no	easy, quick
Watermark	easy, quick	yes (temperature)	easy, quick
Aquaterr	easy	yes (moisture)	easy
Aqua-Tel	labour intensive	no	easy, quick
VIRRIB	labour intensive	no	easy, quick
ThetaProbe	easy	no	easy

Finally, all the sensors tested in the present study responded to soil moisture variations and thus, they could be used as good triggering devices for turning on irrigation systems. However, a clear understanding of the calibration and data conversion associated with the various instruments coupled with a soil-specific calibration are required to establish a fully automated irrigation system.

7 RECOMMENDATIONS

7.1 Recommended future research

The following are recommendations addressed to researchers who are interested in evaluating the performance of soil moisture sensors more effectively:

1) To evaluate the performance of the soil moisture sensors over subsequent drying cycles to observe their sensitivity to partial rewetting and their response time;

2) To determine systematically the effective volume measured by each sensor and to adjust the dimensions of the lysimeter accordingly.

7.2 Application of research results

The following recommendations are based on the evaluation of the performance of tensiometers (Soilmoisture Equipment Corp., model 2725AR), Watermark granular matrix sensors (Irrometer Co.), the Aquaterr electrical capacitance probe (Aquaterr Instruments Inc., model 200), Aqua-Tel electrical capacitance sensors (Automata Inc., model Aqua-Tel94-29), VIRRIB phase transmission sensors (Environmental Sensors Inc.), and the ThetaProbe FDR sensor (Delta-T Devices Ltd, type ML2). These recommendations are addressed to both producers and researchers for the selection of a sensing device assuming that there are no cost limitations.

First, I recommend the ThetaProbe be used as a portable device for application requiring very accurate measurements of soil moisture content and several sampling locations.

Assuming the soil moisture characteristics specific to the field are known, I also recommend the use of tensiometers and Watermark granular matrix sensors, because they are easy to install and operate and they are very precise. Moreover, I recommend the use of the Watermark sensors assuming that soil temperature can be monitored as required for the calibration. As for the tensiometers, their use is recommended with the assumption that measurements will be performed for moisture contents within their operational limits of 0 to -85 kPa.

Finally, I recommend the Aquaterr for applications that do not need high accuracy and precision and that require numerous sampling locations (e.g. to determine the uniformity of soil moisture within a garden or the infiltration depth after applying water) because it is relatively easy to use and portable.

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