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Design of an automated tension infiltrometer for unsaturated hydraulic conductivity
measurement

Cranfield University at Silsoe
M.Sc. by Research

Cranfield University

Cranfield University at Silsoe
NSRI

M.Sc. by Research
2006

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Word length: 17,973

Date of submission: 27 September 2006

This thesis is submitted in full fulfilment of the requirements for the Degree of Master of Science by Research.

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Acknowledgement

A lot of thanks to my supervisor Cédric Kéchavarzi for all the help, support and guidance during each part of the project.

Many thanks to Marc Dresser who has been of great support in practical issues with data-logging and Mariotte bottle design.

Many thanks to my mentor Richard J. Godwin for his support and constructive comments.

Many thanks to Kim Blackburne, and Peter Leeds-Harrisson for their invaluable advice.

Many thanks to Roger Swatland for help with the electronic aspect of the project. A lot of thanks to Roy Newland and Simon Stranks for preparing the soil profile in the soil bin for laboratory experiments, and also to the personnel of the Soil and water lab for material support.

Many thanks to Radka Kodešová for the help and advice with HYDRUS program.

Many thanks to Patricia Bellamy for the help in statistical data processing and interpretation.

A special thanks to Svatopluk Matula, Josef Kozák and to the Pedology and Geology department of the Czech University of Agriculture in Prague who enabled me to study at Silsoe and also for their financial support.

Abstract

A tension infiltrometer for field use, where both water level changes measurement and tension settings could be automated, was built in-house. Differential pressure transducers were used to automate the water level measurement in the reservoir. The Mariotte bottle was automated by a set of solenoid valves which were connected via tubing to pre-defined depths in the Mariotte bottle. Based on design parameters tested in the laboratory (sensor sensitivity, water reservoir diameter, and bubbling rate) three identical tension infiltrometers connected to a single Mariotte bottle were built. A new reservoir system made of two plexiglass tubes of different diameter slotted in each other was found to reduce the measurement fluctuations caused by the disturbance created to rising bubbles in the reservoir.

The new system was tested on a uniform sandy loam profile prepared in the soil bin laboratory and different analytical and numerical data analysis methods were compared. The measured steady state data were used to determine $K(h)$ at different suctions using the analytical method proposed by Reynolds and Elrick (1991). The $K(h)$ points obtained were fitted with the van Genuchten's equation (van Genuchten, 1980) using the RETC program to calculate the best fit parameters K_s , α and n . These parameters were used as initial estimates of the soil hydraulic parameters in the numerical models HYDRUS 1D and 2D, in which transient cumulative flow data was used to determine the soil hydraulic functions via inverse modelling. The analysis of variance determined significantly higher $K(h)$ values calculated by HYDRUS 1D while the other methods did not differ from each other.

Finally, the tension infiltrometer was used in the field on a sandy loam soil to characterise five different tillage treatments (conventional plough, shallow plough, minimum tillage, direct drill, and no-tillage). The effect of wheel traffic was also evaluated by measuring the infiltration rates in the wheel-marks. The fully automated system allowed the measurement of infiltration rates for 8 tensions in triplicate per day with hardly any human intervention apart for refilling the reservoir. The results show that the tillage practices and wheel-traffic have a significant influence on the soil hydraulic function $K(h)$.

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Nomenclature

Roman alphabet

Symbol	Description	Dimension	Applied unit
a	Dimensionless length (Wooding's eq.)	-	-
b	Constant relating shape factor for the soil water diffusivity function	-	-
$C(h)$	Soil water capillary function	L^{-1}	cm^{-1}
C_1, C_2	Substitution coefficients (Haverkamp's eq.)	-	-
D	Soil water diffusivity	$L^2 T^{-1}$	$cm^2 min^{-1}$
h	Soil water potential, water pressure head, water tension	L	cm
$\bar{h}$	Arithmetic mean of h_1 and h_2	L	cm
h_b	Bubbling pressure in Brooks and Corey eq.	L	cm
h_0	Applied tension, applied pressure head	L	cm
h_1, h_2	Two different applied pressure heads	L	cm
$h_{i+1/2}$	Midpoint pressure head between two consequently set pressure heads h_i and h_{i+1}	L	cm
h_n	Initial soil pressure head	L	cm
h_p	Soil water potential at distance z underneath the disc	L	cm
I	Cumulative infiltration	L	cm
I_{cum}	Cumulative infiltration	L^3	cm^3
I_{1D}	Cumulative infiltration during one-dimensional process	L	cm
I_{3D}	Cumulative infiltration during axisymmetric three-dimensional process	L	cm
K	Hydraulic conductivity	$L T^{-1}$	$cm min^{-1}$
K_r	Relative hydraulic conductivity $K_r = K(h) K_s$	-	-
$K(h)$	Hydraulic conductivity function	$L T^{-1}$	$cm min^{-1}$
K_0	Hydraulic conductivity at supply pressure h_0	$L T^{-1}$	$cm min^{-1}$
K_s	Saturated hydraulic conductivity	$L T^{-1}$	$cm min^{-1}$
l	Pore connectivity parameter	-	-
ln	Natural logarithm	-	-
log	Common logarithm	-	-
m	Represents different sets of measurements (cumulative infiltration I , or final water content θ_f) in inverse solution	-	-
m	Exponent parameter in van Genuchten's eq., $m = 1-1/n$ or $m = 1-2/n$	-	-
n	Curve shape parameter in van Genuchten's eq.	-	-
n_j	Number of measurements in a particular set	-	-
q	Bubble rate (in section Test measurements)	$L T^{-1}$	$ml min^{-1}$
q_∞	Steady-state infiltration rate	$L T^{-1}$	$cm min^{-1}$
Q	Infiltration flux	$L T^{-1}$	$cm min^{-1}$
$Q_{cum(1D)}$	Cumulative infiltration flow	$L^3 L^{-2}$	$cm^{-3} cm^{-2}$
$Q_{cum(2D)}$	Cumulative axisymmetric infiltration flow	$L^3 L^{-2} L$	$cm^{-3} cm^{-2} cm$
Q_∞	Steady-state cumulative water outflow	$L^3 T^{-1}$	$cm^3 min^{-1}$
Q^*	Dimensionless flux (Wooding's eq.)	-	-
q_1, q_2	Steady-state infiltration rates at disc 1 and 2	$L^3 T^{-1}$	$cm^3 min^{-1}$
q_1, q_2	Steady-state infiltration rates at pressure heads h_1 and h_2	$L^3 T^{-1}$	$cm^3 min^{-1}$
q_i	Steady-state infiltration rate at applied pressure head h ($i=1, ..., n-1$)	$L^3 T^{-1}$	$cm^3 min^{-1}$

$q_{i+1/2}$	Steady-state infiltration rate at the midpoint between two consequently set pressure heads h_i and h_{i+1}	$L^3 T^{-1}$	$cm^3 min^{-1}$
$q_j(t_i, \beta)$	Corresponding model predictions for the parameter β	$L^3 T^{-1}$	$cm^3 min^{-1}$
$q_j^*(t_i)$	Specific measurements at time t_i for j th measurement set	$L^3 T^{-1}$	$cm^3 min^{-1}$
q_{rd}	Steady-state infiltration rate at disc with a certain radius r_d	$L^3 T^{-1}$	$cm^3 min^{-1}$
r	Radial coordinate	L	cm
R	Radius of the disc	L	cm
r_1, r_2	Radius of disc 1, radius of disc 2	L	cm
r_d	Radius of the disc	L	cm
S_0	Sorptivity	$L T^{-1/2}$	$cm min^{-1/2}$
S_1, S_2	Sorptivity at potentials h_1 and h_2	$L T^{-1/2}$	$cm min^{-1/2}$
t	Time	T	min
v_j, w_j	Weighting coefficients	-	-
z	Vertical coordinate	L	cm
z_1	Distance underneath the disc	L	cm

Greek symbols

Symbol	Description	Dimension	Applied unit
α	Scaling parameter of van Genuchten's eq.	L^{-1}	cm^{-1}
α_g	Sorptive number, Gardner's scaling parameter	L^{-1}	cm^{-1}
$\alpha_{g+1/2}$	Sorptive number, Gardner's scaling parameter at the midpoint between two consequently set pressure heads h_i and h_{i+1}	L^{-1}	cm^{-1}
β	Constant $0 < \beta < 1$ (Haverkamp's eq.)		
β	Vector of optimised parameter ($\theta_r, \theta_s, \alpha, n, K_s$)		
γ	Radial coordinate	L	cm
γ	Proportionality constant (Haverkamp's eq.)	-	-
Δ	Difference		
ϕ_0	Matrix flux potential	$L^2 T^{-1}$	$cm^2 min^{-1}$
ψ	Soil water potential, water pressure head, water tension	L	cm
λ	Soil characteristic parameter in Brooks and Corey eq.	-	-
λ_c	Macroscopic capillary length	L	mm
θ	Volumetric water content	$L^3 L^{-3}$	$cm^3 cm^{-3}$
θ_0	Volumetric water content at applied pressure head h_0	$L^3 L^{-3}$	$cm^3 cm^{-3}$
θ_1, θ_2	Volumetric water contents at pressure heads h_1 and h_2	$L^3 L^{-3}$	$cm^3 cm^{-3}$
θ_E	Effective water content, $\theta_E = (\theta - \theta_r) / (\theta_s - \theta_r)$	-	-
θ_f	Final volumetric water content	$L^3 L^{-3}$	$cm^3 cm^{-3}$
θ_n	Initial volumetric water content	$L^3 L^{-3}$	$cm^3 cm^{-3}$
θ_r	Residual volumetric water content	$L^3 L^{-3}$	$cm^3 cm^{-3}$
θ_s	Saturated volumetric water content	$L^3 L^{-3}$	$cm^3 cm^{-3}$
σ_i	Standard deviation for specific measurement	variable	

Abbreviations

Ap	Cultivated horizon
i.d.	Inner diameter
MS	Mean of squares
o.d.	Outer diameter
OF	Objective function
SD	Standard deviation
SS	Sum of squares
TDR	Time domain reflectometry

Notes

psi	Non SI unit for pressure, for simplicity used in the text. Conversion to SI units: 1psi = 6894.75729 Pa.
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1 Introduction

In situ techniques for hydraulic conductivity measurements are essential to assess the effect of soil and water management practices on water infiltration, temporal changes and spatial variability of surface hydraulic properties. The tension infiltrometer method is a unique in situ technique, which enables to characterise the infiltration capacity of different pore classes by measuring infiltration rates at different water tensions. The unsaturated hydraulic conductivity of the soil matrix can be obtained without the influence of preferential flow usually affecting saturated hydraulic conductivity measurements. In addition to the unsaturated hydraulic conductivity, the soil diffusivity, macroscopic capillary length, and representative pore size can be determined by using the tension infiltrometer.

There are many applications employing the tension infiltrometer. Watson and Luxmore (1986), and Wilson and Luxmore (1988) reported a study about macroporosity and mesoporosity characterisation. Lin and Mc. Innes (1995) investigated a contribution of the macropore flow to infiltration of water and dye transport. Tillage effect, and wheel-traffic effect on infiltration was studied by Ankeny et al.(1991), temporal tillage effects on hydraulic properties by Messing and Jarvis (1993) and Logsdon (1993). Murphy et al. (1993) studied changes in soil hydraulic properties during the growing season, and compared two different tillage treatments. Spatial variability of surface hydraulic properties associated with traffic and cropping systems was researched by Mohanty et al. (1994), spatial variability of unsaturated hydraulic parameters within a tilled field at different times by Logsdon and Jaynes (1996), scaling of unsaturated hydraulic conductivity and spatial variability of different soil types and field positions by Shouse and Mohanty (1998). Soil structure and texture effects on infiltration were studied by Jarvis and Messing (1995), and Courtadeur (2002). However, one of the main disadvantage of using the tension infiltrometer, which is usually manually operated, is that it is time consuming and thus costly.

Hence some effort has been invested in the automation of tension infiltrometer measurements. Constantz and Murphy (1987) employed a single transducer at the top of the water reservoir to measure the water level changes and infer infiltration rates, whereas Ankeny et al. (1988) used two transducers, one at the top and one at the bottom of the water reservoir, to improve the accuracy of the measurement. Casey and Derby (2002) based on the work of Ankeny et al. (1988) improved the accuracy of the measurement by employing one differential pressure transducer. Castiglione et al. (2005) developed a fully automated tension infiltrometer for laboratory measurement of very small flow rates in rocks (10 mm year^{-1}). However a fully automated system for the field use has not yet been developed, and any detailed study of design parameter effects on accuracy of the measurement has not been presented.

In addition, the analysis of the infiltration rates data obtained with tension infiltrometer rely on commonly used analytical models, such as the model proposed by Reynolds and Elrick (1991), in order to calculate the unsaturated hydraulic conductivity of the soil. However these analytical methods are based on the assumptions that steady-state infiltration rates are measured at each tension. This can pose a series of practical problems where achieving steady-state can be very time consuming and require the infiltration of large volumes of water increasing the risk of unwanted subsurface boundary effects. Recently it has been shown (Šimůnek and van Genuchten, 1996, 1997, Šimůnek et al. 1998) that inverse modelling methods provide information on the hydraulic conductivity function and also on the soil water retention curve by using transient data from tension infiltrometer measurements.

The aim of this study was to develop a fully automated tension infiltrometer with automated recording of water level changes in the reservoir and automated tension setting that could provide steady-state or transient data that could be analysed with analytical or numerical methods.

The first objective of this study was to build the tension infiltrometer device, to automate the water level changes recording and tension settings, and to test the effect of design factors on the accuracy of the measurements.

The second objective was to test the newly developed device in controlled conditions in the soil bin laboratory in order to compare different data analysis methods using both steady-state and transient data but also to determine and compare the $K(h)$ function in the field on plots with different tillage treatment.

PART I

Tension infiltrometer design

2 Review of tension infiltrometer development and design

2.1 Tension infiltrometers operating manually

There were many techniques for hydraulic conductivity measurements, which preceded to the tension infiltrometer method. According to White et al. (1992), Wiliard Gardner and Walter Gardner developed a negative head permeameter as early as 1939. Nothing appears to have been published on the device or about the results obtained with it (W.H. Gardner, 1990, personal communication; cited in White et al., 1992). As reported in Perroux and White (1988), the first tension infiltrometer was built in 1982 by K.M. Perroux by modification of the sorptivity tube design reported by Clothier and White (1981).

Perroux and White (1988) presented a summary of techniques leading to the tension infiltrometer method. White et al. (1992) described the development of in situ techniques to measure the hydraulic properties of the soil surface and to assess quantitatively the contributions of preferential flow paths, and the impact of soil management practices on water entry into field soils. Angulo-Jaramillo et al. (2000) presented a review and recent developments on the application of tension infiltrometer in field measurement of surface hydraulic properties and solute transport parameters.

The tension infiltrometer method can be divided into three groups: single disk with single tension; single tension with discs having different radii; and single disk with multiple tensions. The methods used for data analysing are described later in Section 3.

Single disk, single tension

Dixon (1975) designed a closed-top single-ring infiltrometer, to characterise the flow in macropores. Water is applied to a closed-top system, which applies the negative pressure on the ponded water surface. A simplification was made by Topp and Zebchuk (1985) (Figure 1). The limitation of this device is that the infiltration has to

be started by ponding the infiltrometer, so the positive pressure is applied at the start, and then is adjusted to the negative pressure.

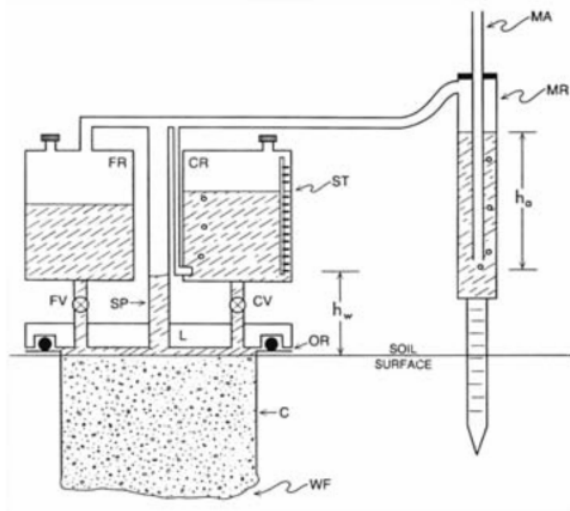


Figure 1. Closed-top infiltrometer of Topp and Zebchuk (1985).

Dirksen (1975), following the work of Smiles and Harvey (1973), designed a sorptivity apparatus, in which a ceramic plate was used as a base (Figure 2). On the basis of Dirksen's (1975) design, Clothier and White (1981) developed a sorptivity tube, which was able to provide a constant negative pressure on the soil surface (Figure 3). The sorptivity tube was then modified by K.M. Perroux, into the first tension infiltrometer in 1982 (unpublished work, reported by Perroux and White, 1988).

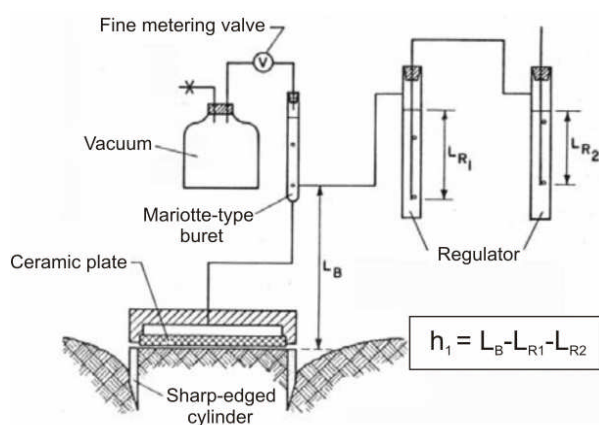


Figure 2. Sorptivity apparatus of Dirksen (1975).

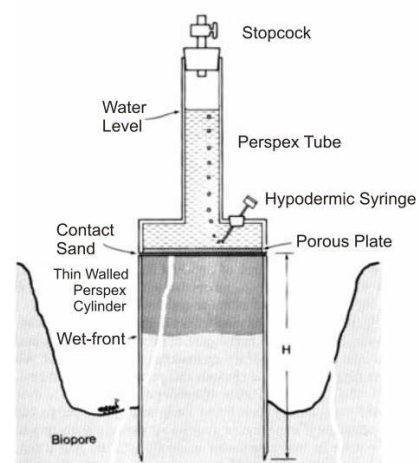


Figure 3. Sorptivity tube of Clothier and White (1981).

Single tension with discs having different radii

The hydraulic conductivity is calculated from the infiltration rates of two, or three experiments employing discs of different radii only for one tension. Smettem and Clothier (1989) modified the twin ring method of Scotter et al. (1982) by extending the ponded method to unsaturated discs of two contrasting radii. Thony et al. (1991) developed an alternative approach which is based on using three discs of different radii.

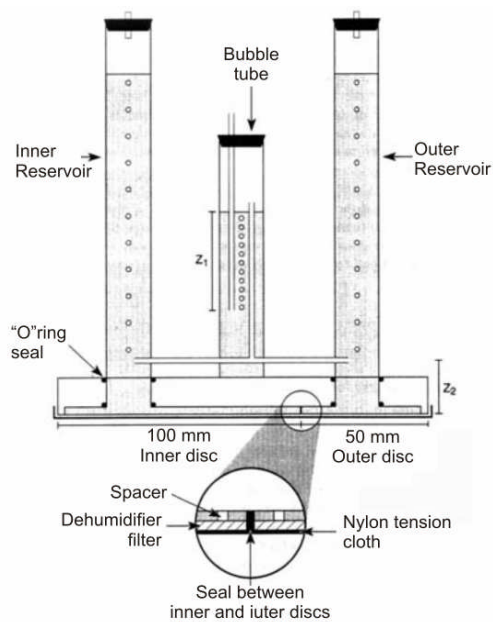


Figure 4. Double-disc tension infiltrometer of Smettem et al. (1995).

Single disk, multiple tensions

This method is more advantageous, because only one infiltrometer (disc) is needed to determine the unsaturated hydraulic conductivity. Perroux and White (1988) presented designs for tension infiltrometers, where water could be supplied at both positive and negative tensions (Figure 5). Angulo-Jaramillo (2000) following the design of Perroux and White (1988) developed a system of three tension infiltrometers TRIMS - triple ring infiltrometers at multiple suction (Figure 6) to evaluate and compare multiple disc approach with a single disc at multiple tensions approach.

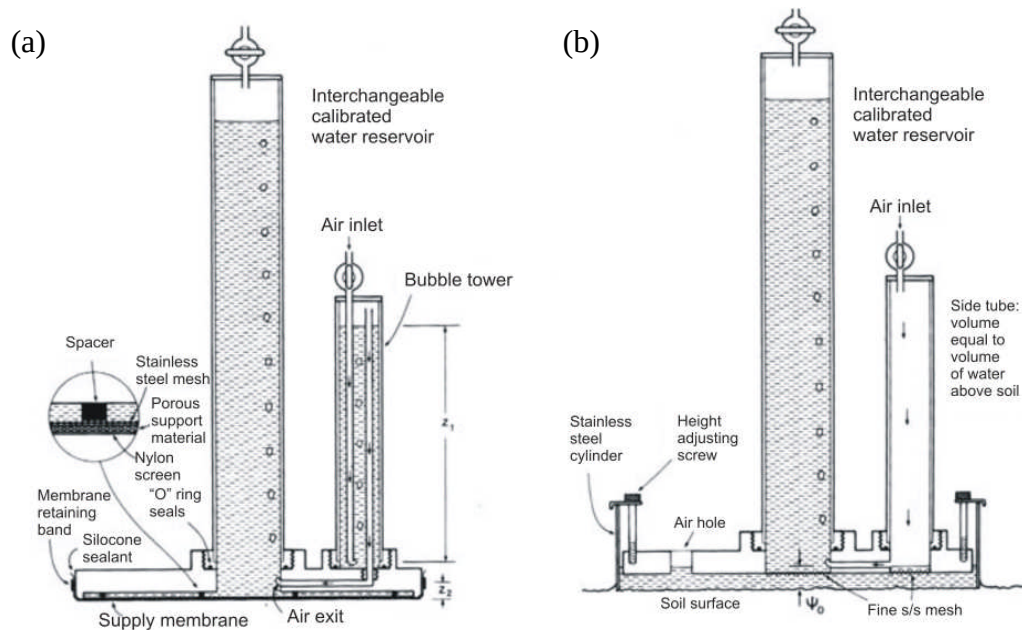


Figure 5. Schematic diagram of tension infiltrometer for supplying water at pressures less or equal to zero (a) and at positive pressures (b) of Perroux and White (1988).

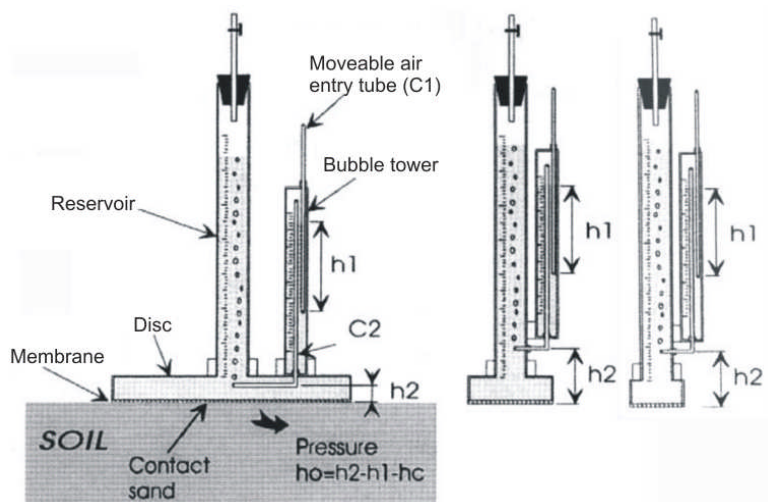


Figure 6. Triple ring infiltrometer at multiple suction of Angulo –Jaramillo et al. (2000).

2.2 Automated tension infiltrometer designs

Constantz and Murphy (1987) published an automated technique for flow measurements from water reservoirs. The flow measurement was observed by using a single pressure transducer on the top of a water reservoir and the gas pressure changes during outflow were monitored with a programmable datalogger. The reservoir gas pressure was linearly related to the water level changes with time, so the datalogger could convert the transducer signal into outflow/flux values. It was pointed out that measurement precision was dependent upon the diameter of the water reservoir. The use of reservoir with a smaller diameter at low flow rates gave a bigger change of the height than with a bigger diameter, so better accuracy of the measurement could be achieved.

Ankeny et al. (1988) presented a design for an automated tension infiltrometer. A schematic diagram of the Ankeny's (1988) device is shown in Figure 7. The main components were: bubble tower, water reservoir, base for soil contact, pressure transducer, and datalogger for data collection and storage. There were four air-entry ports in the bubble tower, which control the tension. Water reservoirs of different diameters are used to optimise the accuracy of the measurement according to the infiltration rate. For a contact between the tension infiltrometer and the soil surface, a 400-mesh nylon membrane with air entry value of about 250 mm of water was used.

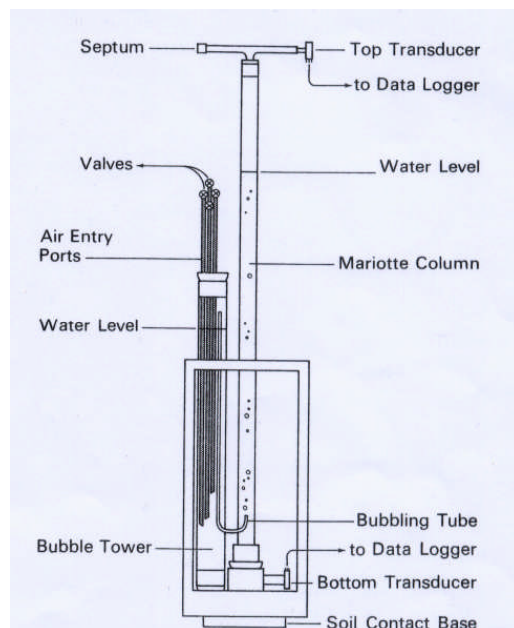


Figure 7. Tension infiltrometer of Ankeny et al. (1988).

The membrane was fitted to a circular acrylic faceplate, which was glued to an acrylic ring in the base of the instrument. The infiltration surface was 53.5 cm². The modified technique of Constantz and Murphy (1987) was used to automate the water level changes in the reservoir. Two pressure transducers (Omega Engineering) with range of 0-5 psi and the Campbell 21X datalogger (Campbell Scientific, Inc.) were used. One pressure transducer was mounted at the top of the water reservoir and the second at the bottom, near the base of the infiltrometer; paired readings of top and bottom transducers were recorded, which improved the accuracy of the water level measurement compared to the measurement only at the top. The tension fluctuations caused by bubbling in the Mariotte bottle were reduced by employing two transducers.

As suggested by Ankeny et al. (1988), Casey and Derby (2002) developed a tension infiltrometer that uses one differential pressure transducer (Omega Engineering) for water level changes measurements. Schematic of the set up is shown in Figure 8.

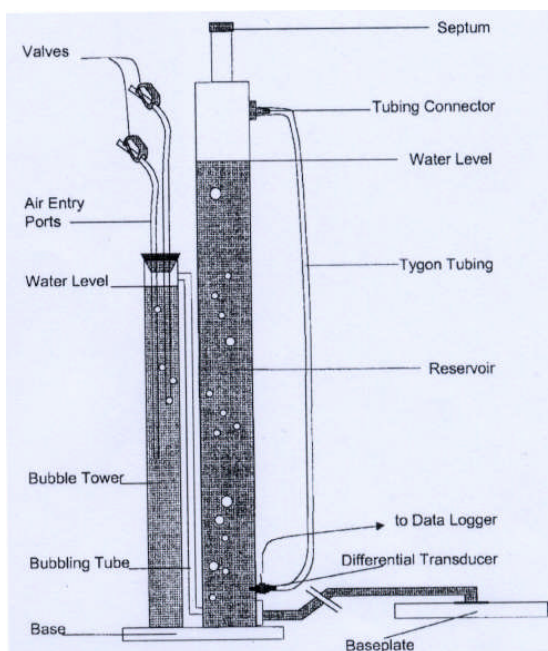


Figure 8. Schematic of the tension infiltrometer configured with a single differential transducer of Casey and Derby (2002).

The precision of the measurement was reported as a very precise, with low variability (SD = 0.5 mm), which was a significant improvement compared to the

precision reported by Ankeny et al. (1988) ($SD = 2.2$ mm for two gage transducers, and $SD = 6.2$ mm for a single gage transducer). The bigger fluctuations for two transducers system were caused by the error in precision of two calibration curves and synchronisation of the two transducer measurements (Casey and Derby, 2002).

Moret et al. (2004) developed an automated method to measure the water level changes in the reservoir by the use of time domain reflectometry (TDR) (Figure 9). This method is based on the different pulse travel times in the air and in the water. A TDR cable tester generates an electromagnetic pulse which is distributed along the three rods placed in the centre of the water reservoir from top to bottom. The reflection of the pulse is automatically transferred to a computer, where the waves are analysed. The time for the electromagnetic wave to travel is determined by the dielectric constants of the medium (specific for air, water, soil, and other porous media). This method was reported as a simple and accurate method, which provides comparable results with those obtained by pressure transducer methods. The volumetric water content below the infiltrometer disc can be measured at the same time as the water flow measurements.

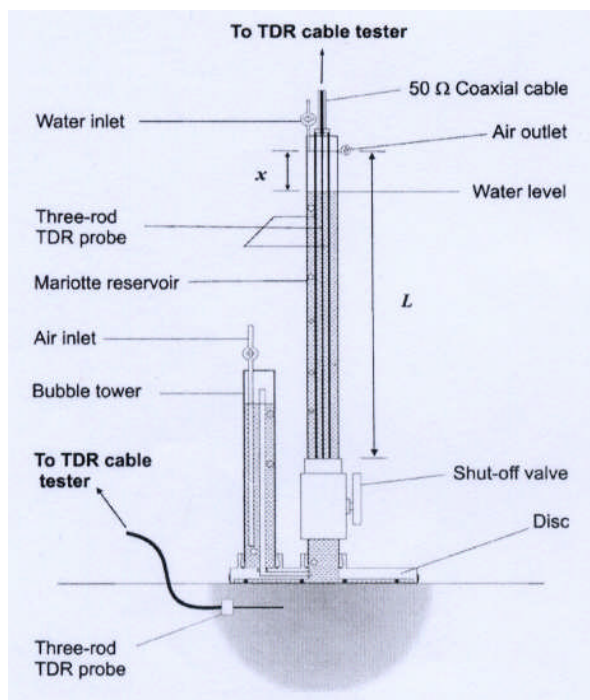


Figure 9. Tension infiltrometer configured with a TDR probe inside the water-supply reservoir of Moret et al. (2004).

Castiglione et al. (2005) developed a tension infiltrometer suited for accurate measurements of infiltration into fractured rock at very low flow rates and for long equilibration times (Figure 10). The prototype instrument consisted of porous stainless-steel membrane, stainless-steel casing, acrylic tubing, temperature compensating pressure transducers, solenoid valves used to set the required tension, and a datalogger for automated control and data storage. An automated refill system was also developed to facilitate long unattended equilibration periods. The device is able to make measurements of the fluid flux as low as 10 mm year^{-1} at a pressure head of about -110 cm.

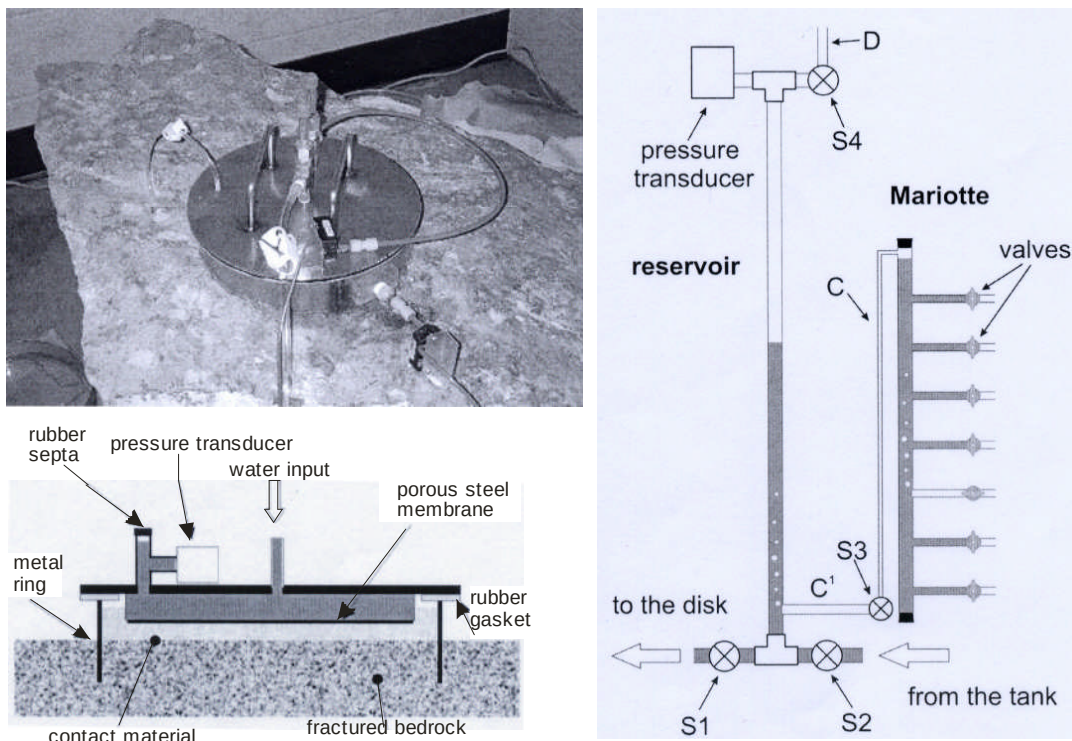


Figure 10. Schematic of the tension infiltrometer designed for measuring very low flow rates of Castiglione et al. (2005).

2.3 Current commercial tension infiltrometers

Commercial tension infiltrometers based on the designs described above are available. Soil Measurement System (SMS) infiltrometer is based on Ankeny's (1998) design with an optional selection of an automated water level changes measurement by using a pressure transducer (Figure 11a, 11b). Two different disc

sizes, diameters of 20 cm or 8 cm, are available. The water tension can be set up to -30 cm (www.soilmeasurement.com, accessed in 05/2006).

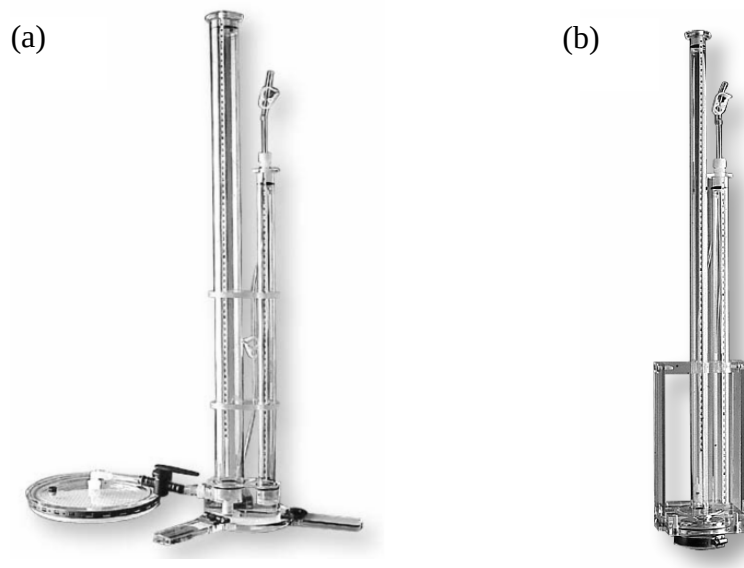


Figure 11. SMS detachable base tension infiltrometer with a 20 cm diameter (a) and 8 cm diameter (b) (www.soilmeasurement.com, accessed in 05/2006).

Decagon Devices, Inc. distributes mini-disc infiltrometers, which comprises of a polycarbonate tube, semi-permeable stainless steel sintered disc, and adjustable steel tube to set the tension (Figure 12). The tube is 32.7 cm high with a diameter of 3.1 cm; the water reservoir is 21.2 cm high, and the disc with 4.5 cm diameter is 0.3 cm thick. The tension can be set between -6 cm and -0.5 cm (www.decagon.com, accessed in 05/2006).

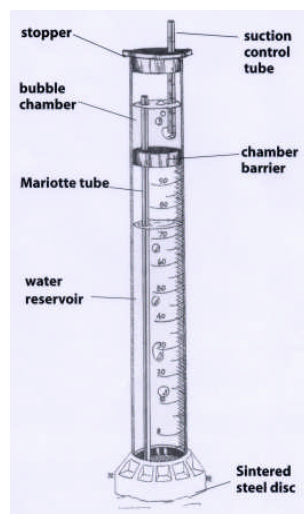


Figure 12. Decagon devices - mini disc infiltrometer (www.decagon.com, accessed in 05/2006).

Umwelt Geräte Technik (UGT) distributes a hood infiltrometer, which consists of an infiltration vessel, U-tube-manometer, and two hoods with a ratio 2:1 in terms of the infiltration area (Figure 13). A Mariotte bottle system is used to apply tension, and the circular shaped hoods can be placed directly on the soil surface, while no contact material is used (www.ugt-online.de, accessed in 05/2006).



Figure 13. Umwelt Geräte Technik - Hood infiltrometer (www.ugt-online.de, accessed in 05/2006).

3 Review of data analysis methods

3.1 Description of water flow from tension disc infiltrometers

While water infiltrates from a disc infiltrometer into the soil, the flow underneath the disc is axisymmetric and three-dimensional. There are two groups of methods characterising the flow: methods using the steady-state infiltration rates, and methods using transient data from early time observations. Richard's equation quantitatively describes the water movement. There are two processes characterising the water content at a particular point in the soil profile; different pressure gradients in the soil water, and gravity force. Three dimensional wetting under a disc from tension infiltrometer is schematically described in Figure 14 (Clothier and Scotter, 2002).

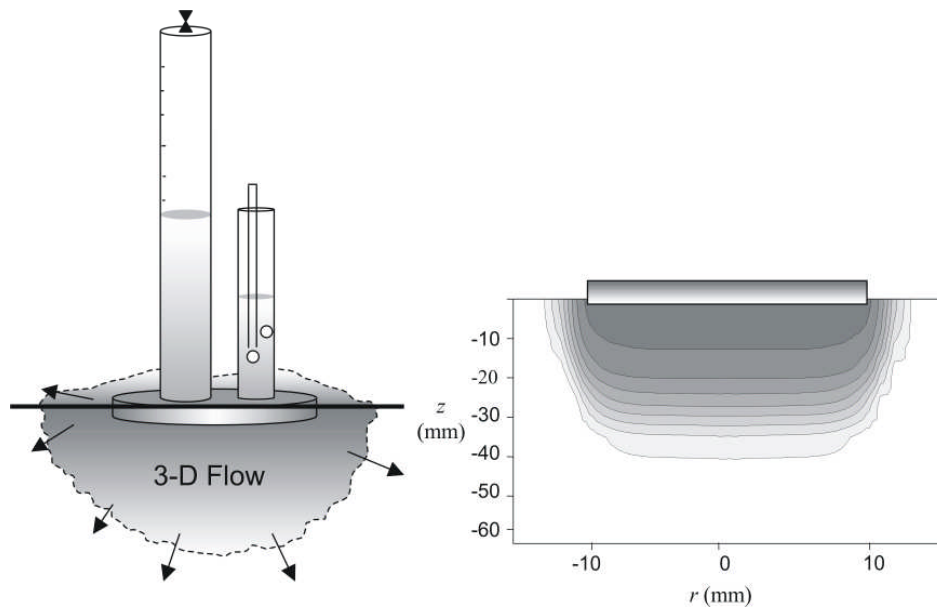


Figure 14. Three-dimensional wetting under a tension disc infiltrometer (Clothier and Scotter, 2002).

As presented by Angulo-Jaramillo (2000), the following axisymmetric form of Richard's equation can be used to describe the flow of water from a disc. In Eq. 1 it is assumed that the soil is isotropic, but not necessarily homogeneous.

$$C(h) \frac{\partial h}{\partial t} = \frac{\partial}{\partial z} \left[K(h) \left(\frac{\partial h}{\partial z} - 1 \right) \right] + \frac{\partial}{\partial r} \left[K(h) \frac{\partial h}{\partial r} \right] + \frac{K(h)}{r} \frac{\partial h}{\partial r} \quad (1)$$

where $C(h)$ is the soil water capillary capacity function which is equal to $d\theta/dh$ (L^{-1}), θ is the volumetric water content ($L^3 L^{-3}$), h is the water pressure head (L), $K(h)$ is the hydraulic conductivity function ($L T^{-1}$), r is radial coordinate (L), and z is vertical coordinate (L).

The uniform initial conditions for water infiltration into the soil underneath the disc in terms of θ and h is given by Warrick (1992):

$$h(r, z, t) = h_n, \quad z \geq 0, \quad r \geq 0, \quad t = 0 \quad (2)$$

$$\theta(r, z, t) = \theta_n, \quad z \geq 0, \quad r \geq 0, \quad t = 0 \quad (3)$$

where h_n is initial soil pressure head, and θ_n is initial soil moisture content.

Boundary condition for the disc at a given pressure h_0 is given by Warick (1992):

$$h(r, z, t) = h_0(t), \quad 0 < r < r_d, \quad z \geq 0, \quad t > 0 \quad (4)$$

where r_d is the radius of the disc (L).

It is assumed that no vertical flow beyond the rim of the disc is present.

$$\frac{\partial h}{\partial r} = 0, \quad z = 0, \quad r > r_d, \quad t > 0 \quad (5)$$

It is also assumed that the subsurface boundary conditions do not affect the infiltration, because they are positioned far enough from the disc

3.2 Steady-state method

The steady-state theory has been presented and discussed by many authors. The most significant are the following: Perroux and White (1988), Smettem and Clothier (1989), White and Perroux (1989), Thony et al. (1991), and Warrick (1992).

To describe the three-dimensional flow underneath the disc, a special formulation taking into account the lateral water absorption must be employed. The analyses are based on the Wooding's steady-state analysis (Wooding, 1968). For steady infiltration from a circular source, Wooding (1968) found that this curve never departs far from the straight line:

$$Q^* = 2\pi a + 4 \quad (6)$$

where Q^* is the dimensionless flux, a is a dimensionless length equal to $(\alpha_g r_d/2)$, where r_d is the radius of the disc (L), and α_g (L^{-1}) is the sorptive number (White and Sully, 1987) or the parameter of the following Gardner's (1958) hydraulic conductivity function (Eq. 7)

$$K(h) = K_s \exp(\alpha_g h) \quad (7)$$

where K is the unsaturated hydraulic conductivity ($L T^{-1}$), K_s is the saturated hydraulic conductivity ($L T^{-1}$), and h is soil water potential (L).

The actual steady-state infiltration rate q_∞ is defined as follows:

$$q_\infty = \frac{Q_\infty}{\pi r_d^2} = \phi_0 \left(\alpha_g + \frac{4}{\pi r_d} \right) \quad (8)$$

where Q_∞ is the cumulative steady-state water outflow ($L^3 T^{-1}$), and ϕ_0 is the matrix flux potential ($L^2 T^{-1}$), which is defined as follows:

$$\phi_0 = \int_{h_n}^{h_0} K(h) dh \quad (9)$$

where h_0 is the applied potential (L), and h_n is the initial potential of the soil (L).

From Gardner's hydraulic conductivity relationship (Eq. 7), the matric flux potential can be written as:

$$\phi_0 = \alpha_g^{-1} [K(h_0) - K(h_n)] \quad (10)$$

The subscript $_0$ refers to the condition imposed at the disc, and the subscript $_n$ denotes the initial condition of the soil before the infiltration started.

Substituting this relationship into Eq. 8, a more general equation is obtained:

$$q_{\infty} = [K(h_0) - K(h_n)] \left(1 + \frac{4}{\alpha_g \pi r_d} \right) \quad (11)$$

The first term of the equation takes into account the flow due to the gravitational forces, and the second term the flow due to the capillary absorption. If $K(h_n)$ is neglected because of the assumption of an initially dry soil then the Wooding's equation which approximates the steady-state infiltration rate, q_{∞} , from a disc becomes:

$$q_{\infty} = K(h_0) \left(1 + \frac{4}{\alpha_g \pi r_d} \right) \quad (12)$$

Various analyses derived from Wooding's solution for estimating hydraulic conductivity from disc permeameter measurements have been proposed.

Analysis for a single tension and single disc method

White and Sully (1987) suggested an analytical method based on Wooding's (Wooding, 1968) solution for a single tension applied on a single disc:

$$q_{\infty} = K(h_0) + \frac{4bS_0^2}{\pi r_d \Delta\theta} \quad (13)$$

where S_0 is sorptivity, b is a shape factor between $1/2$ and $\pi/4$, $\Delta\theta$ is the change in water content during infiltration.

Analysis for a single tension with different discs radii method

Scotter et al. (1982) suggested to use two discs of different radii, r_1 and r_2 , and solved simultaneously two equations of the form suggested by White and Sully (1987) (Eq. 13) and obtained:

$$K(h_0) = \frac{q_1 r_1 - q_2 r_2}{r_1 - r_2} \quad (14)$$

$$\phi_0 = \frac{\pi}{4} \frac{q_1 - q_2}{\frac{1}{r_1} - \frac{1}{r_2}} \quad (15)$$

$$S_0 = \left(\frac{4\phi_0 \Delta\theta}{\pi} \right)^{1/2} \quad (16)$$

where, r_1 , and r_2 are radii of discs 1, and 2, $q_1 = Q_\infty / \pi r_1^2$ and $q_2 = Q_\infty / \pi r_2^2$ are the flow rates for disc 1 and 2, respectively.

The method of Smettem and Clothier (1989) is a modification of the twin-ring method of Scotter et al. (1982) for more disc radii. The method used a linear regression of $Q_\infty / \pi r_d^2$ against $1/r$ to determine parameters S_0 and K from Eq. 13.

$$q(r_d) = K_0 + \frac{4bS_0^2}{\pi\Delta\theta} \frac{1}{r_d} \quad (17)$$

where r_d is the particular radius of the disc, and $q(r_d) = Q_\infty / \pi r_d^2$ is the flow rate for the disc.

Analysis for multiple tension measurement from a single disc method

White and Perroux (1989) used the earlier work of Smiles and Harvey (1973) and derived an equation to calculate the hydraulic conductivity from measurements of sorptivity S_1 and S_2 , at two different potentials h_1 and h_2 :

$$K(\bar{h}) = \frac{\bar{S}\Delta S}{\Delta\bar{\theta}\Delta h} - \left(\frac{\bar{S}}{2\Delta\bar{\theta}} \right)^2 \frac{(\theta_1 - \theta_2)}{\Delta h} \quad (18)$$

where $\bar{S}$ is the arithmetic mean of S_1 and S_2 , $\Delta S = S_1 - S_2$, θ_1 , and θ_2 are the volumetric water contents at pressure head h_1 and h_2 , respectively, $\bar{\theta}$ is

the arithmetic mean of θ_1 and θ_2 , $\Delta\bar{\theta} = \bar{\theta} - \theta_n$, θ_n is the initial volumetric water content, $\bar{h}$ is the arithmetic mean of h_1 and h_2 , and $\Delta h = h_1 - h_2$.

Ankeny et al. (1991) solved two forms of Wooding's equation simultaneously for two measured infiltration rates at two different potentials h_1 and h_2 . It is assumed that the macroscopic capillary length λ_c is constant in the potential range $\Delta h = h_1 - h_2$. This method is presented in the work of Cook and Broeren (1994) as follows:

$$K(h_1) = \frac{q_1}{\pi r^2 + 2\Delta h r \frac{(1 + q_2/q_1)}{(1 - q_2/q_1)}} \quad (19)$$

$$K(h_2) = \frac{q_2 K(h_1)}{q_1} \quad (20)$$

$$\lambda_c = \frac{\Delta h [K(h_1) + K(h_2)]}{2[K(h_1) - K(h_2)]} \quad (21)$$

where: $q_1 = q_\infty$ at h_1 [$L^3 T^{-1}$], and $q_2 = q_\infty$ at h_2 [$L^3 T^{-1}$].

Reynolds and Elrick (1991) presented a data analysis procedure to determine the saturated and near saturated hydraulic conductivities. The method is using the steady-state infiltration data measured by one disc applying several tensions. A piecewise exponential function is applied between two consecutive tensions. Interpolation between two points (applied tensions) is used to estimate K at a mid-point between the two points. The analysis is a modification of Wooding's solution, which is combined with numerically determined shape factors describing interaction effects between flow geometry and soil properties. The procedure for estimating $K(h)$ for a series of tension infiltrometer measurements is described as follows. Firstly, a sequence of q_i values ($i = 1, 2, \dots, n-1$) is measured by setting a sequence of h_i values ($i = 1, 2, \dots, n-1$ applied tensions) on a tension infiltrometer (Figure 15). Then the value of α is calculated by using Eq. 22 as the piecewise linear slope between adjacent (h_n, q_n) data pairs:

$$\alpha_{g(i+1/2)} = \frac{\ln[q_i/q_{i+1}]}{(h_i - h_{i+1})} \quad (22)$$

After that, the value of $q_{i+1/2}$ is then calculated via Eq. 23, where $h_{i+1/2} = (h_i + h_{i+1})/2$:

$$q_{i+1/2} = \exp\left[\frac{\ln(q_i) - \ln(q_{i+1})}{2}\right] \quad (23)$$

And finally, the value of $K_{i+1/2}$ is calculated by using Eq. 24:

$$K_{i+1/2} = \frac{q_{i+1/2}}{1 + \frac{4}{\pi r_0 \alpha_{g(i+1/2)}}} \quad (24)$$

Reynolds and Elrick (1991) reported an overall accuracy of this method as about $\pm 7\%$ compared to the method of White and Peroux (1989), and accuracy about $\pm 5\%$ while comparing to the approximate analytical models of Green and Ampt (1911), Knight (1983), and Broadbridge and White (1988). The effect of local soil heterogeneity is reduced, because only one infiltration surface is needed for the measurement. These characteristics make it an attractive method that is now commonly used. This piecewise exponential solution was tested further in works of Messing and Jarvis (1993), and Jarvis and Messing (1995), and is widely used for tension infiltrometer data analyses (Lin et al. (1999), Joel and Messing (2000), Holden et al. (2001), Coutadeur et al. (2002)).

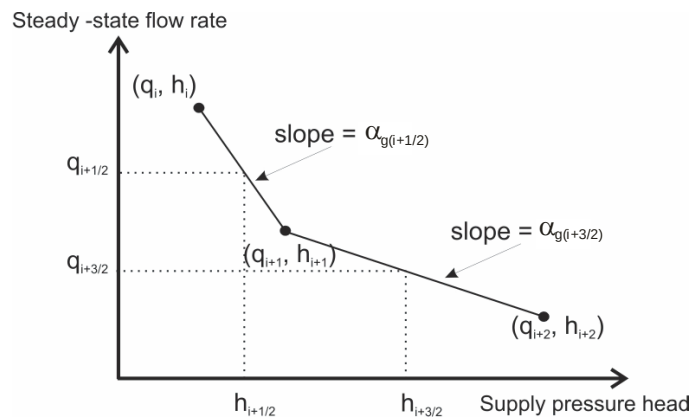


Figure 15. Steady –state infiltration rate versus the soil water pressure head using a piecewise exponential relationship.

Logsdon and Jaynes (1993) assumed Gardner's $K(h)$ relationship (Gardner, 1958) (Eq. 7) and estimated the K_s and α_g parameters from all different h_0 and q data simultaneously by using nonlinear regression. For a correct regression procedure more than two measurements (h_0, q) are needed.

$$q(h_0) = \left(1 + \frac{4}{\pi r_d \alpha_g}\right) K_s \exp(\alpha_g h_0) \quad (25)$$

Wang et al. (1998) tested a method based on a Darcy-Buckingham law, and obtained results comparable with those, obtained by Wooding's solution.

$$q(h_0) = K_s \left\{ \frac{\exp[\alpha_g (h_p - h_0 + z_1)] - 1}{\exp(\alpha_g z_1) - 1} \right\} \exp(-\alpha_g h_p) \quad (26)$$

where h_p is known water tension at given depth z_1 .

3.3 Transient flow

Methods using transient data have some advantages, compared to the steady-state methods, as shorter measurement times, and therefore smaller soil volumes are used, which comply better with the assumptions of homogeneous soil, and uniform initial water content.

Transient axisymmetric infiltration from a circular source at the soil surface has been described by several researchers. Turner and Parlange (1974) calculated an approximate analytical expression for the lateral flux at the periphery of the one-dimensional infiltration process. Smettem et al. (1994) based on the work of Turner and Parlange (1974) showed that the additional term accounting for the side effects due the axisymmetric flow geometry is linear in time:

$$I_{3D} - I_{1D} = \frac{\gamma S_0^2}{R(\theta_0 - \theta_n)} t \quad (27)$$

where the subscripts $_{3D}$ and $_{1D}$ refer to axisymmetric three-dimensional and one-dimensional process, R is the disc radius, γ is a constant theoretically equal to $\sqrt{0.3}$

when gravity effects are neglected at the periphery of the disc; experimental results showed that an appropriate value for γ is 0.75.

Haverkamp et al. (1994) established a physically based infiltration equation for tension disc infiltrometers valid for short to medium time on a basis of Eq. 27:

$$I_{3D} = S_0 \sqrt{t} + \left[\frac{2 - \beta}{3} K + \frac{\gamma S_0^2}{R(\theta_0 - \theta_n)} \right] t \quad (28)$$

where β is a constant ranging between $0 < \beta < 1$.

Eq. 28 can be also written in the following form:

$$I = C_1 \sqrt{t} + C_2 t \quad (29)$$

Two-term forms of equation similar to Eq. 29 were found by Warrick (1992) and by Zhang (1997), but expressions for the coefficients C_1 and C_2 were obtained empirically and are different from those in Eq. 28 and 29. Zhang (1997) related C_1 to capillary forces, and C_2 to gravity forces.

Inverse methods

Inverse methods are especially appropriate when in situ conditions do not comply with the assumptions of homogeneous soil, and uniform initial water content.

Šimůnek and van Genuchten (1996), and Šimůnek et al., (1998) suggested a numerical method to estimate hydraulic properties from cumulative infiltration data from a disc infiltrometer at several consecutive pressure heads. This method using numerical simulations is able to provide information on the hydraulic conductivity function, and on the soil water retention curve. The flow for radially symmetric flow, in an isotropic porous medium is described by the Richards (1931) equation:

$$\frac{1}{r} \frac{\partial}{\partial r} \left(r K \frac{\partial h}{\partial r} \right) + \frac{\partial}{\partial z} \left[K \left(\frac{\partial h}{\partial z} + 1 \right) \right] = \frac{\partial \theta}{\partial t} \quad (30)$$

where r is the radial coordinate (L), z is the vertical coordinate positive upward (L), t is time (T), h is the pressure head (L), K is the hydraulic conductivity ($L\ T^{-1}$), and θ is the volumetric water content ($L^3\ L^{-3}$). Eq. 30 is then solved for given boundary and initial conditions using hydraulic functions relating, θ , K and h . More detailed description can be find in work of Šimůnek et al. (1999). Different expressions of these hydraulic functions can be used.

Brooks and Corey (1964) compared a large number of experimental data and determined a general equation describing the soil water retention curve:

$$\theta_E = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \left(\frac{h}{h_b} \right)^{-\lambda} \quad (31)$$

where θ_E is dimensionless effective soil water content, θ_s is the saturated volumetric water content, θ_r is the residual volumetric water content, h_b is the bubbling pressure, h is the positive value of the applied pressure, and λ is a soil characteristic parameter. For large values of the pressure head it is possible to write Eq. 31 in the following form:

$$\theta_E = (\alpha h)^{-mn} \quad (32)$$

where α is a parameter inversely related to the bubbling pressure, $m = 1-1/n$ and hence $\lambda = n-1$ for the Mualem (1976) theory, and $m = 1-2/n$ and hence $\lambda = n-2$ for the Burdine (1953) theory. Based on the Burdine (1953) theory the relative hydraulic conductivity K_r can be predicted by:

$$K_r(\theta_E) = \theta_E^{3+2/\lambda} \quad (33)$$

$$K_r(h) = (\alpha h)^{-2-3\lambda} \quad (34)$$

where K_r is the relative hydraulic conductivity, $K_r = K/K_s$.

Similar expressions were derived based on the Mualem (1976) theory:

$$K_r(\theta_E) = \theta_E^{5/2+2/\lambda} \quad (35)$$

$$K_r(h) = (\alpha h)^{-2-5\lambda/2} \quad (36)$$

Another expression for the soil water retention curve widely used was derived by van Genuchten (1980).

$$\theta_E = \left[\frac{1}{1 + (\alpha h)^n} \right]^m \quad (37)$$

Based on the Mualem (1976) theory the following expressions for the $K(\theta_E)$ and $K(h)$ functions were derived:

$$K_r(\theta_E) = \theta_E^{1/2} \left[1 - (1 - \theta_E^{1/m})^m \right]^2, \quad 0 < m < 1 \quad (38)$$

$$K_r(h) = \frac{\left\{ 1 - (\alpha h)^{n-1} \left[1 + (\alpha h)^n \right]^{-m} \right\}^2}{\left[1 + (\alpha h)^n \right]^{m/2}} \quad (39)$$

For the Burdine (1953) theory the following equations were derived:

$$K_r(\theta_E) = \theta_E^2 \left[1 - (\theta_E^{1/m})^m \right], \quad 0 < m < 1, \quad n > 2 \quad (40)$$

$$K_r(h) = \frac{1 - (\alpha h)^{n-2} \left[1 + (\alpha h)^n \right]^{-m}}{\left[1 + (\alpha h)^n \right]^{2m}} \quad (41)$$

To estimate the parameters of the above equations, an objective function has to be minimised. The objective function expresses the differences between the infiltration flow rates and those predicted by the numerical model. The objective function for multiple measurement sets is defined as (Šimůnek and van Genuchten, 1996):

$$OF(\beta, q_1, \dots, q_m) = \sum_{j=1}^m \left(v_j \sum_{i=1}^{n_j} w_{ij} \left[q_j^*(t_i) - q_j(t_i, \beta) \right]^2 \right) \quad (42)$$

where m represents the different sets of measurements (such as the cumulative infiltration data, or additional information), n_j is the number of measurements in a particular set, $q_j^*(t_i)$ are the specific measurements at time t_i for the j th measurement

set, β is the vector of optimised parameters, $q_i(t_i, \beta)$ are the corresponding model predictions for the parameter vector β , v_j and w_{ij} are weights associated with a particular measurement set or point, respectively. The weighting coefficients v_j , are given by Clausnitzer and Hopmans (1995); Clausnitzer et al. (1998), and Šimůnek et al. (1998):

$$v_j = \frac{1}{n_j \sigma_j^2} \quad (43)$$

This defines the objective function as an average weighted squared deviation normalised by measurement variances σ_j^2 .

The inverse modelling is performed by a numerical code HYDRUS. 1D, 2D, and 3D. HYDRUS is a finite element numerical model, which has been developed to simulate water, heat, and solute transport in variably saturated porous media. The water flow simulation is carried out by solving the Richard's equation (Eq. 30) by using either Brooks and Corey (1964) or van Genuchten (1980) models described above, or other models, which were not described as they are not commonly used. It includes a graphic editor with a finite element mesh to define the experiment (Šimůnek et al., 1999).

3.4 Limitations of the tension infiltrometer for $K(h)$ determination

The limitations are mainly given by the assumptions that the soil is uniform, homogeneous, and non-swelling. In practice, the water content, bulk density, and texture can differ in the profile.

Ankeny et al. (1991) reported four design criteria for the field method to measure hydraulic conductivity in-situ: 1) only steady-state infiltration data should be used, and information about the initial soil water potential or content should not be required; 2) soil pore structure should not be disturbed by driving a ring into soil;

3) measurements should be taken on the same soil surface; 4) calculation of hydraulic conductivities should be straightforward.

White et al. (1992) pointed out some limitations of the tension disc infiltrometer: 1) uniform, homogeneous and non-swelling soil is assumed; 2) Wooding's solution is based on a simplified model of the $K(h)$ relationship; 3) the time to reach steady-state can be very long; 4) close contact between the base plate and the soil is needed; 5) the infiltrometer must be levelled and the soil has to be able to support the weight of the device (unstable soil and the collapse of the soil structure can reduce the infiltration rate).

Some advantages and disadvantages of the various methods were summarised by Minasny (2000). The single disc and single tension method has the advantage that it provides estimates of K at specified potential from single measurement. However the disadvantages are that: θ beneath the disc (at supply potential) needs to be measured, negative K can be obtained due to the overestimation of sorptivity S_0 from early-time infiltration or underestimation of $\Delta\theta$; the determination of S_0 requires relatively dry soil before infiltration, and requires accurate infiltration rate measurements during early times. The method using different radii, and a single tension has the following advantage: error in estimates of S_0 from early-time measurements can be avoided because only steady-state rate is measured; and disadvantage: measurements at different locations are required to give one estimate of K , and are very sensitive to spatial variations. The method using a single disc and multiple tensions has the following advantages: error in estimates of S_0 from early-time measurements can be avoided because only steady-state rate is measured; K values at different potentials at one location can be determined, small scale variability can be avoided due to only one infiltration surface.

As presented in Hussen and Warrick (1993) the method using a single disc and multiple tensions gives fast and stable results compared to the other methods. However it has the disadvantages that two measurements are required to give one

estimate of K , and identifying the change in q for a small change in potential is difficult.

Bagarello et al. (2000) summarised factors, like the sequence of applied tensions and contact layer, which affect measurement of the near-saturated hydraulic conductivity. Applying tension in a decreasing manner will give higher values of K compared with the increasing ones due to the hysteretic effect and simultaneous wetting and draining (Logsdon, 1993).

An intimate hydraulic contact between the soil surface and the water supplying membrane is essential for the measurement; therefore several investigations have been carried out. Perroux and White (1988) recommended the use of porous material (to 5 mm thick) with both high sorptivity and conductivity. Fine sand with $S_0 \approx 2 \text{ mm s}^{-1/2}$ and saturated hydraulic conductivity $K_s \approx 3.10^{-2} \text{ mm s}^{-1}$ was suggested as a suitable material. The influence of the layer of contact sand can usually be neglected in determining the steady-state flux as at large times the sand has small influence on the flux. But at early times, especially when the sand is dry, the high sorptivity of the sand may mask the true sorptivity of the soil.

Reynolds and Zebchuk (1996) investigated the effect of contact material on the pressure head and hydraulic head gradient under tension infiltrometer. They found a discrepancy between the pressure head of the soil surface and the pressure head on the tension infiltrometer membrane. They reported that the hydraulic gradient between the contact sand and soil surface could be greater than one, which creates a difference in potential head between the supply membrane and soil surface. The discrepancy depends on the thickness and hydraulic properties of the sand. The authors recommended the use of highly uniform glass sphere medium with $K_s = 1.1 \times 10^{-1} \text{ mm s}^{-1}$ and presented a calculation procedure for correcting the supply potential on top of the soil surface.

Close et al. (1998) found a non-uniform wetting pattern of the sand at the membrane interface. This resulted in differences in infiltration rate and variations in infiltrating

area and depth of infiltration. This paper stressed the need for good contact between the sand and soil. This study resulted in standard guidelines to improve the contact between silica sand and membrane of the tension infiltrometer. Bagarello et al. (2001) investigated the change in hydraulic properties of two types of contact materials after repeated use of the materials and evaluated the effect of contact material on steady-state infiltration rates. Re-using a natural sand contact material resulted in increasing values of saturated hydraulic conductivity, due to a progressive loss of fine-textured particles, which probably originated from aggregate breakdown. Similarly to Reynolds and Zebchuk (1996) it was concluded that glass spheres (Spherglass No. 2227) are adequate for both use and reuse as tension infiltrometer contact material, and that contact material is required to maintain good hydraulic connection with the soil surface even when the surface has been smoothed and levelled.

4 Design of a fully automated tension infiltrometer

4.1 Design requirements

Tension infiltrometers need to be portable and easy to set up in the field. They need to be stable to withstand wind. Refilling needs to be done with minimum disturbance to the infiltration surface. In addition, tension infiltrometers need to give accurate results. There are compromises between these requirements and other factors such as cost and intended use (fast approximate estimates of the hydraulic conductivity at few tensions, determination of the $K(h)$ function at more tensions and characterisation of the pore classes) as shown by the many different designs presented in Section 2.

4.2 Design, materials, and dimensions

The tension infiltrometer developed in this study (Figure 16, and Appendix 3) consists of an aluminium base, valve, connector, and Plexiglas tubes. The bottom of the base and the top of the water reservoir are connected to a differential pressure transducer through push fit fittings and tubing. The total height is 1200 mm and the total weight with full water reservoir is 4015 g. Three such tension infiltrometers were built. They are all connected to a single automated Mariotte bottle, which is described in more details later in this section. The differential pressure sensors are connected to a Campbell 21X datalogger (Campbell Scientific Inc.) which is connected to a data acquisition card on a laptop computer. The data logging software Dasy Lab[®] is used to record the data. The Mariotte bottle is controlled with the Dasy Lab[®] program using an USB-based analog and digital input/output module USB-1208LS (Measurement Computing[™]).

The overview of the materials and dimension used for the tension infiltrometer is presented in Table 1.

Table 1. Tension infiltrometer materials and dimensions – overview

Part	Material	Dimension - diameter, height (i.d.=inner diameter, o.d.=outer diameter)	Weight
Base (including fittings)	Aluminium	155 mm o.d.	1856.0 g
Perforated plate	PVC	140 mm o.d. density of 2 mm diameter hole is 240 per 10 cm ²	30.8 g
Membrane	Nylon	5 micron pore size	4.9 g
O-ring	Rubber	125 mm i.d.	20.7 g
Valve + fitting	Metal	19.05 mm diam.	589.9 g
Total weight without water and without the Mariotte bottle:			2502.3 g
Mariotte bottle	Perspex	22 mm i.d.	499.4 g
Water reservoir	Perspex	Inner diameter - outer tube: 44 mm Inner diameter - inner tube: 21 mm Wall thickness - outer and inner tubes: 6 mm Height of the tubes: 120 cm	
Total weight - full water reservoir without Mariotte bottle:			4015.9 g
Total pressure of the device full of water, and ready for the measurement:			0.2 N cm⁻²

Base

The base of the tension infiltrometer needs to be relatively heavy to ensure both good stability of the device in windy conditions and good contact between the base and the soil surface. An aluminium cylinder was used for the base. Aluminium was chosen because it is a non-corrosive material. The height of the base is 50 mm; the diameter is 147 mm and its weight is 1856 g (Figure 16, no. 1). The inside of the base was machined into a conical shape to facilitate the upward movement of bubbles. A groove on the outside of the base was machined to enable to fit the membrane by a rubber o-ring. A thread was placed at the top of the base to connect the water reservoir. Two push-fit fitting were installed on the top of the base to enable the connection of the Mariotte bottle and the differential pressure transducer.

A 5 micron mesh nylon membrane (Bio Design Inc.) with high entry pressure (approximately 4 m) was used to avoid leakage. The membrane is backed by a circular 147 mm diameter plastic plate, which is fitted in the aluminium base. The plastic plate is perforated with holes with a 2 mm diameter (hole density is approximately 240 holes per 10 cm²), which allows unimpeded flow. The perforated

plate is supported by the base, so no deformation of the contact surface occurs during the infiltration measurement even at higher tensions.

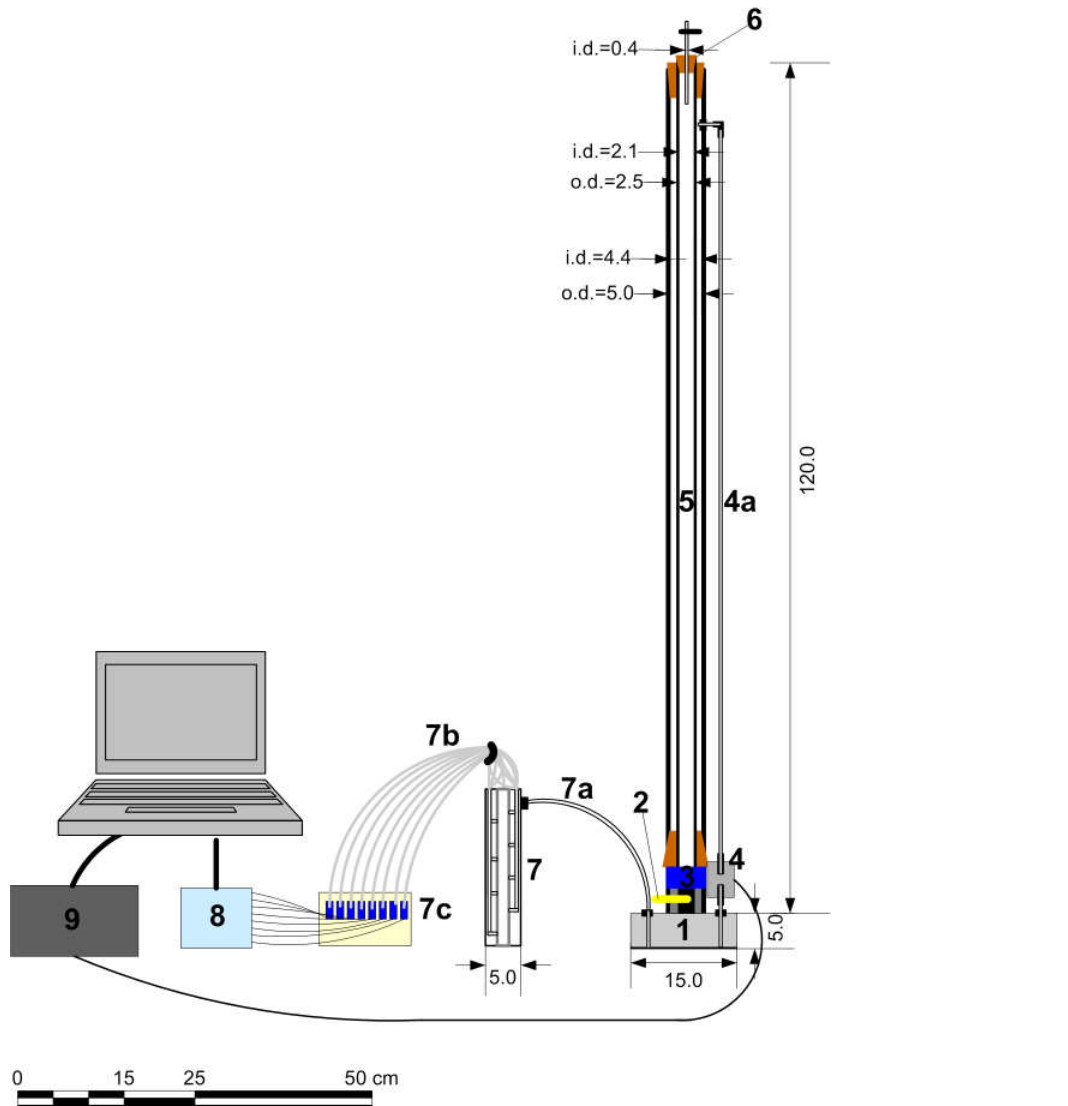
Water reservoir

To enable the refilling of the reservoir with minimum disturbance to the infiltration surface a valve between the base and water reservoir was fitted (Figure 16, no.2). The valve can be closed during the test measurements, typically between two tensions, to refill the tension infiltrometer without having to remove it from the soil surface.

Everything else being equal, the accuracy of the water level changes measurements in the reservoir is dependant on the reservoir diameter. For a given flow rate, the measurement resolution will increase with a decrease in diameter. However the disturbance due to rising air bubbles and the resulting water level fluctuations will increase. In practise there is also a compromise between accurate measurements of water level in the reservoir and the number of interventions needed to refill the reservoir. Too many interventions defeat the purpose of having an automated system. The present system uses a relatively large reservoir diameter; however the reservoir consists of two transparent tubes (Perspex) 1200 mm high of different diameters embodied in each other. The outer tube has an inner diameter of 44 mm, and the inner tube an inner diameter of 21 mm (Figure 16, no.5). As shown in Section 5.3 this system reduces the disturbance of the noise caused by bubbling, because the bubbles are travelling in the smaller inner tube, while the water level measurement is taken in the outer tube. This allows large volumes of water to be used before having to refill with an increase in accuracy compared to a single tube reservoir of the same diameter. Nevertheless, for small flow rates a single smaller diameter (i.d. = 21 mm) can be used without any specific modification.

Water level changes measurement

Differential pressure transducers (Honeywell) of the same type as used by Casey and Derby (2002) were employed. The differential pressure transducer has two ports, one is connected via tubing (4 mm o.d., and 2.4 mm i.d. transparent Tygon tube) to the head space of the water reservoir, and the other port is connected via tubing through the aluminium base to top of the plastic plate holding the membrane (Figure 16, no.4, no.4a). The four pins of the transducer are connected to a Campbell 21X datalogger (Campbell Scientific Inc.) (Figure 16, no.9). Sensors with two pressure ranges, 0-5 psi and 0-1 psi, were tested. Based on the design testing results presented in Section 5.1, the more sensitive sensor with pressure range of 0-1 psi was used for the three tension infiltrometers. For each sensor, two tests (one from each side of the sensor) were carried out to determine the linear relationships between the heights of water in the reservoir and the pressure sensor readings. The calibration was performed by emptying a burette step by step using a 3-way valve and recording the datalogger output in mV. All the calibration measurements had similar relationships. The calibration equation for the 0-5 psi sensor was $y = 77x$ ($R^2 = 0.999$), and for all three 0-1 psi sensors $y = 47x$ ($R^2 = 0.999$), where y is the height of the water column in mm and x is the datalogger output in mV.



- 1 - Base with a semi-permeable membrane
- 2 - Valve for refilling
- 3 - Connector (connecting the water reservoir tubes with the valve)
- 4 - Differential pressure transducer
- 4a – Tubes connecting the transducer with the base at the bottom and the top of the water reservoir
- 5 - Water reservoir (double tube system)
- 6 - Stopper enabling refilling
- 7 - Body of the automated Mariotte bottle
- 7a - Tube connecting body of the Mariotte bottle with the membrane on the base
- 7b – Tubes reaching different depths in the Mariotte bottle and connecting it to the solenoid valves
- 7c – Solenoid valves enabling the tension changes
- 8 - USB-based analog and digital input/output module for tension control
- 9 -Campbell 21X datalogger recording the pressure transducer measurements

Figure 16. Schematic of the automated tension infiltrometer developed in this study.

Mariotte bottle

The prismatic body of the Mariotte bottle has dimensions of 20 cm x 5 cm x 5 cm (Figure 17). There are eight air entry points connected via Tygon tubing to eight solenoid valves (Figure 16, no.7b, no.7c). The air entry points are at pre-defined depths, corresponding to the tensions -13 cm, -11 cm, -9 cm -7 cm, -5 cm, -3 cm, -2 cm, and -1 cm (Figure 17). The system of solenoid valves is controlled by a USB based analog and digital input/output module (USB-1208 LS; Measurement Computing™) via a set of relays. All the valves are closed, except the one at which the infiltrometer is operating. The head space of the Mariotte bottle is connected via Tygon tubing through the top of the aluminium base to the top of the plastic plate to which the membrane is attached (Figure 16, 7a). The time period for a selected tension can be easily set in the Dasy Lab® program.

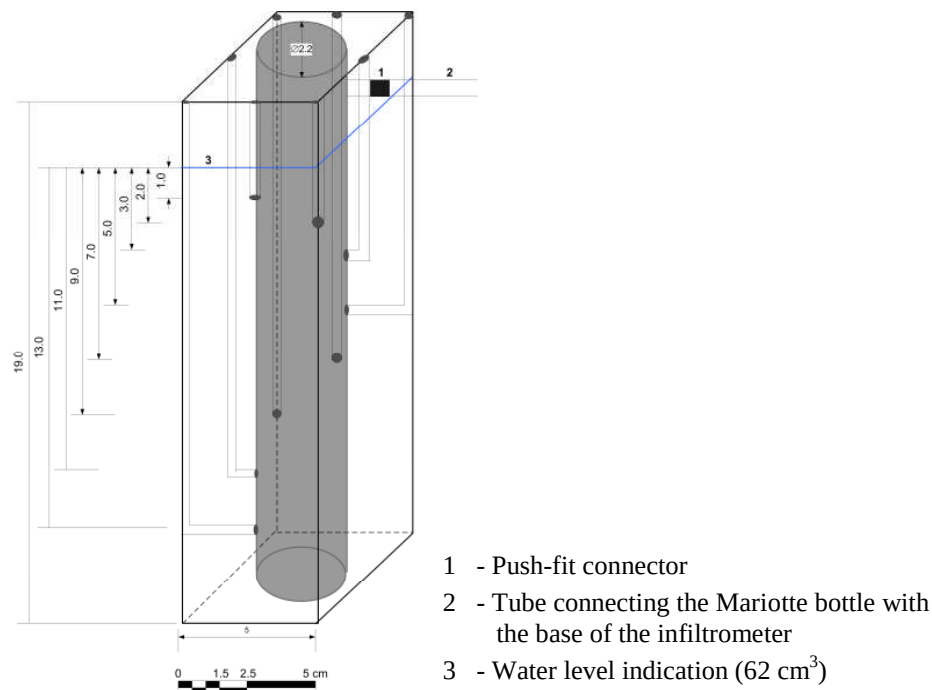


Figure 17. Schematic of the body of an automated Mariotte bottle

Costs

The costs of this device (excluding laptop, acquisition cards, Campbell scientific datalogger, and software licences) are estimated at just over a thousand pounds for the whole system consisting of three tension infiltrometers and a single automated Mariotte bottle (details in Table 2).

Table 2. Costs estimates for the automated tension infiltrometer system, which includes three replicates and a single automated Mariotte bottle.

Component	Price*
Akuminium base (3*£25)	£75
Semi-permeable membrane (3*£1)	£3
PVC for perforated plate (3*£1)	£3
Water reservoir (3*£10)	£30
Pressure transducer (3*£18 + 3*£5 for the box)	£69
External fitting (3*£10)	£30
Wiring and tubing (3*£10)	£30
Machining (3*£100)	£300
Datalogger	£100
Solenoid valves (8 x £25)	£200
Relay (incl. socket and wiring) (8 x £6)	£48
Box for valves and relays	£10
Mariotte bottle material	£18
Machining	£120
Total price	£1 036

* prices for years 2005/2006

5 Laboratory testing of design factors affecting the measurement

The use of two single pressure transducers (top and bottom) was discussed by Ankeny et al. (1988) who concluded that differential pressure transducers were preferable. In the work of Casey and Derby (2002) the use of a differential pressure transducer is tested. However a more detailed study on the effects influencing the differential pressure transducer measurements has not yet been carried out. The noise in the measurement created by bubble disturbances is influenced by sensor sensitivity, water reservoir diameter, and bubbling rate. These factors were tested in the laboratory and the data was statistically processed (F test, $\alpha = 0.05$).

The laboratory tests were carried out by using an automatic syringe pump to create bubbles through a Mariotte bottle. The syringe was connected to the top of the infiltrometer. The bottom of the infiltrometer was open to the atmosphere. The piston of the syringe was withdrawn at a constant rate q creating suction in the upper part of the water reservoir and provoking the release of bubbles from the Mariotte bottle in which the tension was kept constant at -0.5 cm. The bubbling rate q was changed by changing the pumping rate. Water could not leave the reservoir as it could not flow through the membrane. Therefore there were no water level changes in the reservoir due to water flow during the experiments. Only bubbles caused the reading fluctuations. A schematic of the experimental setup is shown in Figure 18. The bubbling pattern in the reservoir for all bubbling flow rates tested is schematised in Figure 19 based on visual observations. All statistical results are presented in Appendix 1.

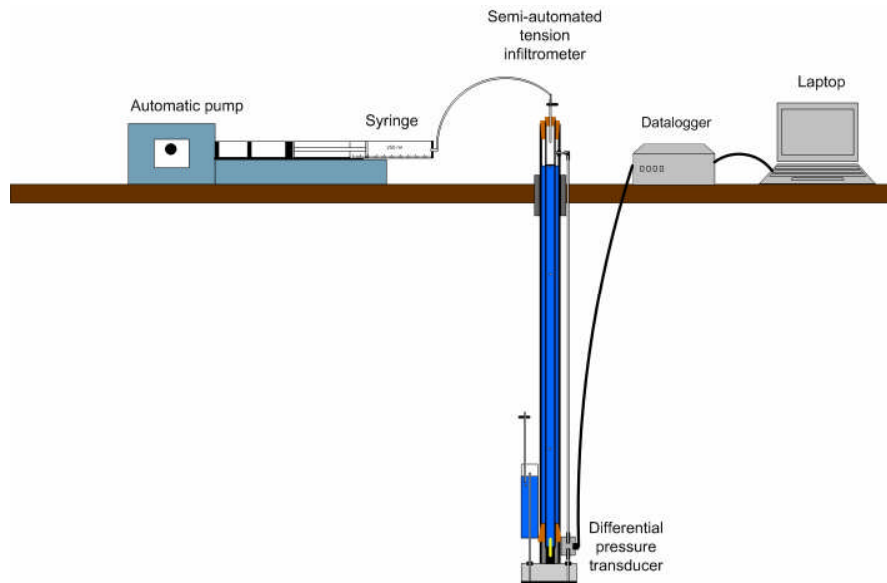


Figure 18. Experimental set up to determine significant factors influencing the pressure transducer output fluctuations.

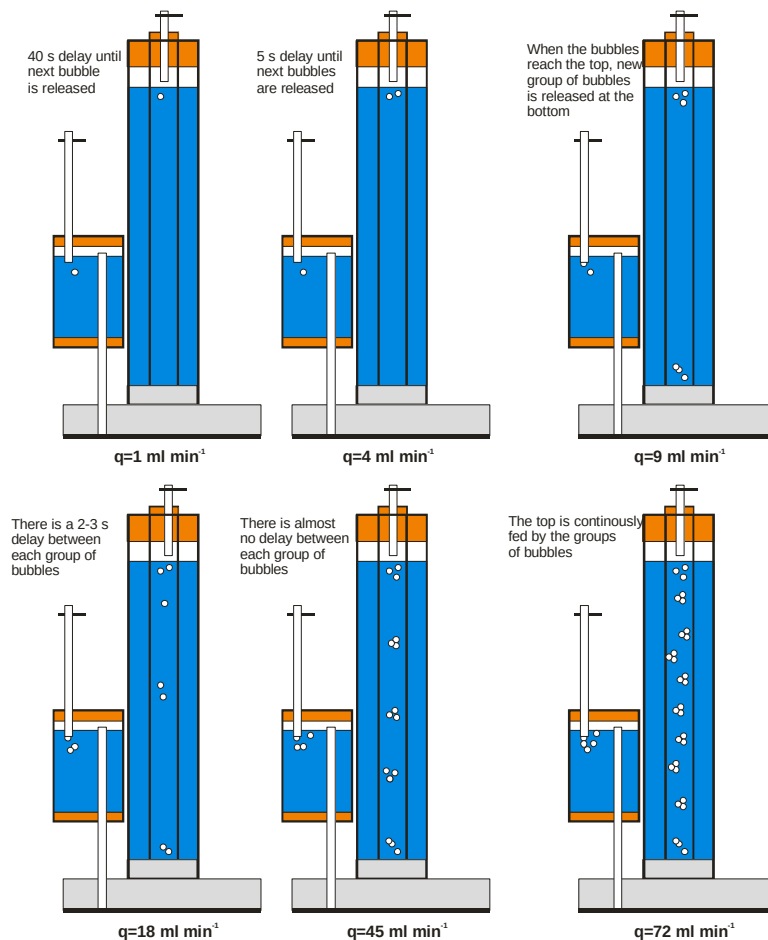


Figure 19. Schematic of the bubbling pattern for different bubbling rates (the schematic is not to scale).

5.1 Effect of sensor sensitivity

Two differential pressure sensors with pressure ranges of 0-1 psi, and 0-5 psi were tested at the following bubbling rates q : 0 ml min⁻¹, 9 ml min⁻¹, 18 ml min⁻¹, 45 ml min⁻¹, and 72 ml min⁻¹. As expected the more sensitive 0-1 psi sensor performed better than the 0-5 psi sensor (significantly for four bubble rates from five) even for $q = 0$ ml min⁻¹. However the difference in standard deviations is relatively small and there is no reason why not to use the 0-5 psi sensor. The standard deviations (SD) for the 0-1 psi sensor ranged from 0.08 mm to 1.69 mm and from 0.25 mm to 2.64 mm for the 0-5 psi sensor. Subsequent experiments were carried out with the 0-1 psi sensor only.

5.2 Effect of differential vs. single transducer measurement

Two types of experiments, each for two bubbling rates (18 ml min⁻¹ and 45 ml min⁻¹) on the double tube system infiltrometer (see Section 5.3 describing the effect of reservoir type) were carried out. In the first experiment the bottom part of the differential transducer was disconnected, so only the pressure changes at the top of the reservoir were measured as in the work of Constantz and Murphy (1987), and Ankeny et al. (1988). These were compared to the results obtained with the differential measurements for the same bubbling rates. The measurement records are presented in Figure 20. As expected, the noise measured with the single transducer was significantly higher than that measured with the differential transducer for both selected bubbling rates. At $q = 18$ ml min⁻¹ the standard deviation was $SD = 3.75$ mm for the single measurement, whereas it was $SD = 1.69$ mm for the differential measurement. At $q = 45$ ml min⁻¹ it was $SD = 3.3$ mm for the single measurement, and $SD = 2.15$ mm for the differential measurement. This experiment confirms the results obtained by Casey and Derby (2002) for a single bubbling rate.

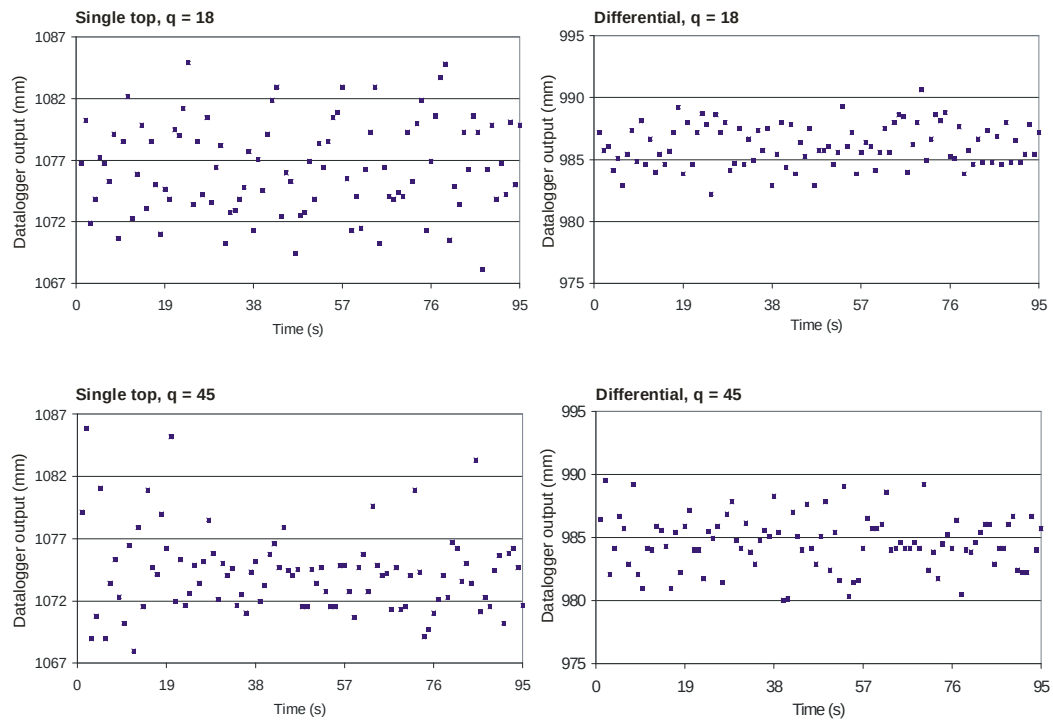


Figure 20. Single top(left) vs. differential (right) measurements for two bubbling rates.

5.3 Effect of water reservoir

The noise due to bubbling obtained for the newly developed double tube reservoir was compared to that obtained for two single tube reservoirs with different diameter. The diameters of the tested systems were as follows: double tube reservoir – i.d. of the outer tube = 44 mm, i.d. of the inner tube = 21 mm; small single tube reservoir – i.d. = 21 mm; large single tube reservoir – i.d. = 44 mm. The systems were tested for five bubbling rates; 0 ml min⁻¹ as a control, then 9 ml min⁻¹, 18 ml min⁻¹, 45 ml min⁻¹, and 72 ml min⁻¹. The record of all the measurements is presented in Figure 21.

The comparison between the double tube system and the single tube with large diameter resulted in the following: there was no significant difference between the measurements at the control rate $q = 0$ ml min⁻¹; at the four remaining rates the double tube system was better than the single large tube, but resulting in significantly less noise only for two bubbling rates. Standard deviations ranged from 0.08 mm

to 1.69 mm for the double tube system, and from 0.1 mm to 2.64 mm for the single large tube.

Comparison with the single tube with a small diameter confirmed the previous results. There was no significant difference between the control measurements at $q = 0 \text{ ml min}^{-1}$. However the double tube system was significantly better than the single small tube for all other bubbling rates. Standard deviation ranged between 0.09 mm and 3.5 mm for the single small tube.

When comparing the single large tube with the single small tube, there was no significant difference between the control measurements at $q = 0 \text{ ml min}^{-1}$ but the single large tube resulted in significantly less noise than the single small tube for three bubble rates out of four.

As expected the measurement noise due to bubbling is significantly smaller when using a single tube with a large diameter compared to that obtained for a single tube with a diameter approximately twice as small. This is because, for a given flow rate (bubble volume), the height of the displaced water by rising bubbles in a larger diameter tube is smaller. More interestingly, the measurement noise due to bubble disturbance is significantly reduced by using the double tube system. This is because the disturbances due to rising bubbles is mainly confined to the smaller inner tube while the pressure measurements at the top of the infiltrometer are made in the outer tube.

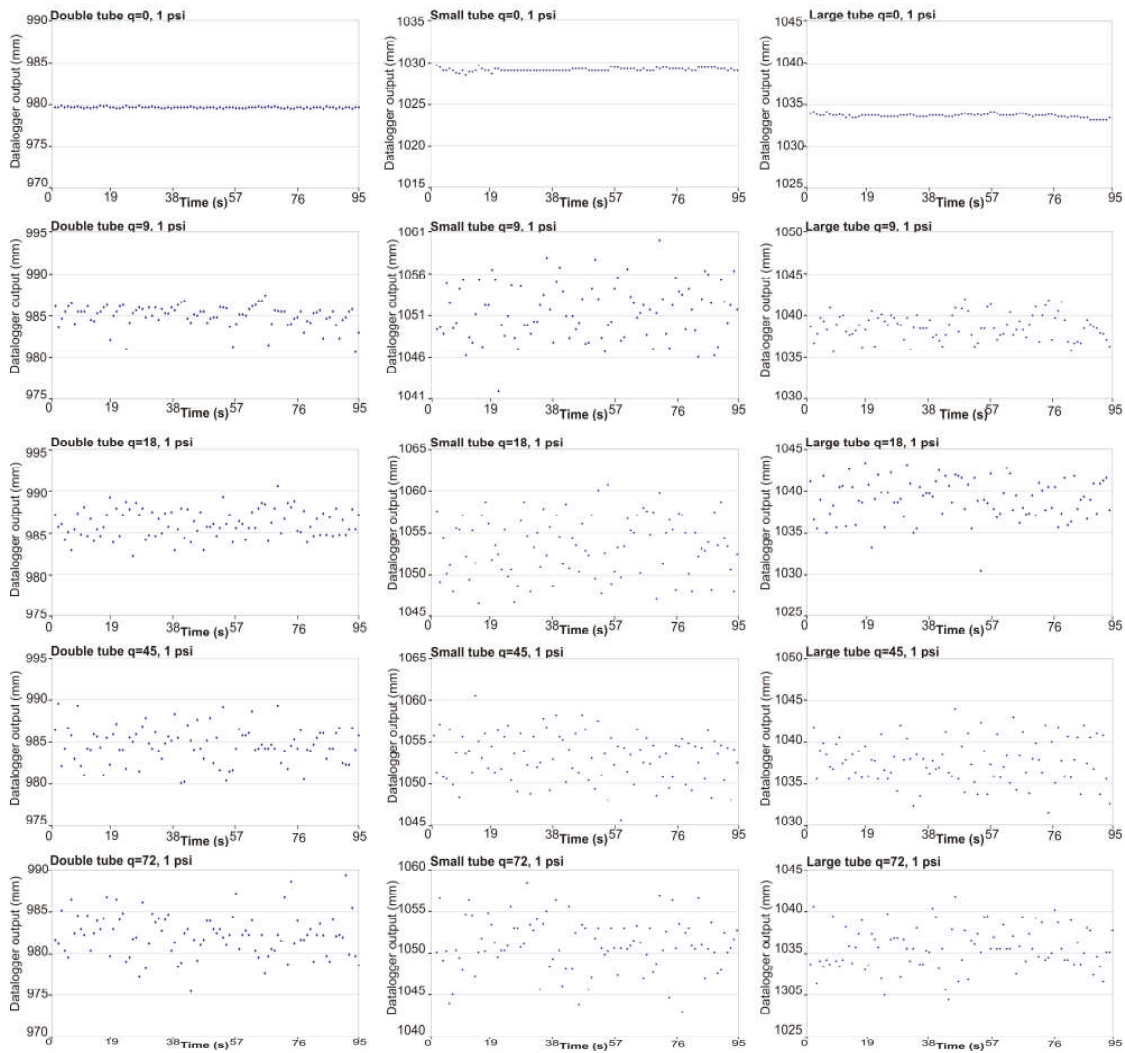


Figure 21. Effect of the water reservoir; from left: double tube system, single small tube, single large tube; increasing bubbling rate from the top to the bottom.

5.4 Effect of bubbling flow rate on noise

The influence of increasing bubbling rate on noise for the three tube systems is presented in Figure 22, which is a plot of the SD against flow rate. There is a large increase in noise with increasing flow rate at low flow rates. However the difference in noise between flow rates is small at large flow rates. This is because there is a point at larger flow rate when the water reservoir is constantly fed by bubbles, and as a consequence the variation in water level height due to the bubbles becomes almost constant.

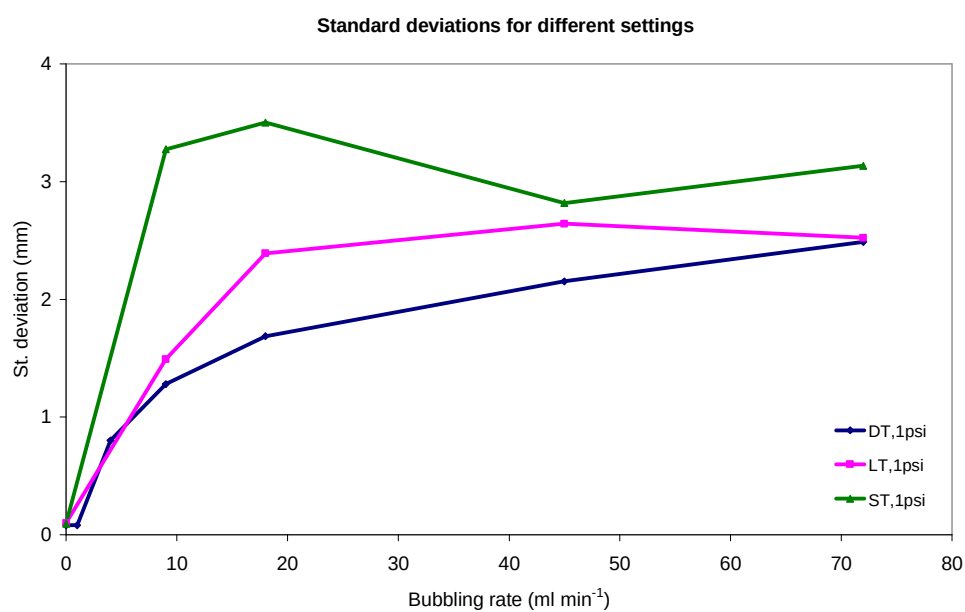


Figure 22. Standard deviations of data measured by different water reservoirs at different flow rates.

PART II

Determination of $K(h)$ with the fully-automated device

6 Soil bin laboratory experiments

6.1 Materials and methods

Soil bin laboratory

The hydraulic conductivity measurements were carried out under controlled conditions in the Soil dynamics laboratory at Cranfield University at Silsoe, which is a tank of soil, 20 m long, 1.7 m wide, and 1 m deep. The controlled conditions enabled to compare different data analysis methods without the influence of spatial variations between replicates.

The tests were carried out on an artificially prepared sandy loam soil profile (depth 80 cm) at bulk density 1.72 g cm^{-3} . The soil was placed into the soil tank in four layers; each layer was compacted by a heavy roller. Photographs of the experimental setup are shown in Figure 23.

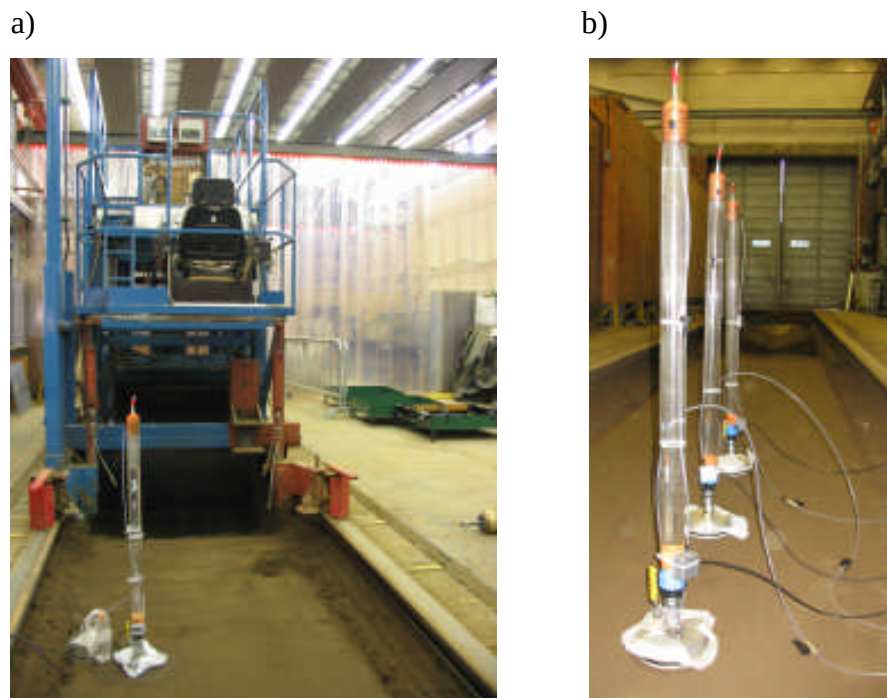


Figure 23. Soil bin laboratory: soil tank, roller, and one tension infiltrometer connected to an automated Mariotte bottle (a), test with three replicates in the soil bin laboratory (b).

Unsaturated hydraulic conductivity measurement

Three tension infiltrometers connected to a single Mariotte bottle were used to determine the unsaturated hydraulic conductivity. The infiltrometers could be placed on the surface straight away, because the surface was perfectly smoothed and levelled and ensured good contact between the infiltration surface and the semi-permeable membrane. The replicates were placed approximately 1 m apart.

Infiltration measurements were performed for 8 tensions in the following order: -13 cm, -11 cm, -9 cm, -7 cm, -5 cm, -3 cm, -2 cm, and -1 cm. The time allowed for infiltration at each tension was set to 60 minutes. It was assumed that this time was long enough to reach the steady-state infiltration rate in a sandy loam soil. Sampling interval of the water level measurements with the pressure transducers was set to 5 s.

Three disturbed soil samples from areas surrounding each infiltrometer site were taken to determine the initial soil moisture content. When the measurement was finished, three undisturbed soil samples were taken from below the infiltration surface. Final soil moisture content, saturated soil moisture content and dry bulk density were determined by oven-drying the undisturbed soil samples at 105°C for 48 hours.

Data analysis

Three data analysis methods were used to calculate the unsaturated hydraulic conductivity from the infiltration data: an analytical method using steady-state data (Reynolds and Elrick, 1991), and two numerical methods using transient data (HYDRUS 1D, and HYDRUS 2D). All three methods are described in detail in Sections 3.2, and 3.3.

- For the Reynolds and Elrick (1991) model, steady-state infiltration rates $q(h_0)$ ($\text{cm}^3 \text{min}^{-1}$) were used. They were determined from the last 15 min of water level records for each tension as follows:

$$q_{(h_0)} = \frac{\Delta H * 1.376}{\Delta t} \quad (43)$$

where ΔH (mm) is the water level decrease during the time period $\Delta t = 15$ min, and where 1 mm drop of water in the double tube water reservoir corresponds to 1.376 cm^3 .

Then the piecewise slope $\alpha_{g(i+1/2)}$ and the volume $q_{i+1/2}$ were calculated with Eq. 22 and Eq. 23, respectively, in order to obtain the value of $K_{i+1/2}$ using Eq. 24.

The program RETC was used to fit the van Genuchten's equation (Eq. 39) to the unsaturated hydraulic conductivity data points $K_{i+1/2}$ and K_s calculated with the Reynolds and Elrick (1991) method. RETC is a computer code which describes the hydraulic properties of unsaturated soils. It can be used to fit several analytical models (Brooks and Corey, (1964), van Genuchten, (1980) to observed water retention and unsaturated hydraulic conductivity data. It uses a non-linear least squares optimisation approach to estimate the unknown model parameters from observed data.

- The second approach uses transient data in an inverse modelling solution in the programs HYDRUS 1D and 2D. Water flow was simulated by an inverse solution to determine the soil hydraulic parameters. The number of iteration was selected as 50, and the number of data points in objective function (number of data records used) was selected as 160, which corresponds to the number of water level measurements obtained with a 3-minute time interval over the hour measuring period.

For both models the 160 data used to minimise the objective function consisted of the cumulative infiltration volumes calculated from the water level change data obtained during 3 minutes over the entire length of the experiment (8 hours). For HYDRUS 1D the unit of the cumulative volumes

were converted into $\text{cm}^3 \text{ cm}^{-2}$ by dividing by the area of the base of the tension infiltrometer. For the HYDRUS 2D they were converted into $\text{cm}^3 \text{ cm}^{-1}$ by multiplying by the diameter of the base. The upper boundary conditions for HYDRUS 1D were time variable pressure conditions defined by the imposed tensions at the base of the tension infiltrometer. For HYDRUS 2D these time variable pressure conditions at the upper boundary were imposed over a length corresponding to the diameter of the tension infiltrometer base but set equal to atmospheric pressure elsewhere on the upper boundary. For both models the lower boundary conditions consisted of free drainage conditions. Initial condition was defined by initial soil moisture content, which was determined from three disturbed soil samples taken at the beginning of the experiment from areas surrounding each infiltrometer.

The hydraulic model, which parameters were varied to fit the simulated infiltration rates to the measured ones, was the van Genuchten model. No hysteresis effects were included. The van Genuchten model requires that six hydraulic parameters (θ_r , θ_s , α , n , l , and K_s) are defined. The values of θ_s were determined in the laboratory by saturation and oven-drying of three undisturbed soil samples taken from beneath each infiltrometer after the measurements. The l parameter was set at the value 0.5, which was suggested by Mualem (1976) as an approximate value for most of soils. The K_s , α , and n were used as fitting parameters in the inverse modelling procedure.

Statistical analysis

An analysis of variance ($\alpha = 0.05$) was done to determine whether there were significant differences in resulting unsaturated hydraulic conductivities $K(h)$ calculated by applying the different data analysis methods. The analysis considered the fact that the potential at which the water infiltrates into the soil, the data analysis method, and possible interaction between the tension and data analysis are factors affecting the value of unsaturated hydraulic conductivity.

6.2 Results and discussion

Table 3 summarises the mean values of soil conditions for each replicate (initial, final, and saturated water contents and dry bulk densities). Figure 24, Figure 25, and Figure 26 show the calculated $K(h)$ and $\log K(h)$ points obtained with Reynolds and Elrick model fitted with the van Genuchten equation (Eq.39) as well as the $K(h)$ and $\log K(h)$ functions obtained with HYDRUS 1D and HYDRUS 2D programs. The van Genuchten's model parameter values as well as the R^2 values characterising the quality of the fit are presented in Table 4. R^2 value calculated by RETC program determines how well the Mualem-van Genuchten model fits the points calculated by method of Reynolds and Elrick (1991). R^2 value calculated by HYDRUS determines the correlation between the infiltration rates obtained by inverse modelling with HYDRUS 1D and HYDRUS 2D and those measured during the experiment.

Table 3. Summary of initial and final conditions for the soil bin laboratory test.

Date	Tillage treatment	Replicate no.	θ initial mean	θ initial - limit value for Hydrus	θ final mean	θ saturated mean	Bulk density mean (g cm ⁻³)
20.07.2006	Soil bin	1	0.128	0.12	0.378	0.400	1.72
20.07.2006	Soil bin	2	0.123	0.12	0.363	0.374	1.72
20.07.2006	Soil bin	3	0.078	0.07	0.373	0.385	1.72

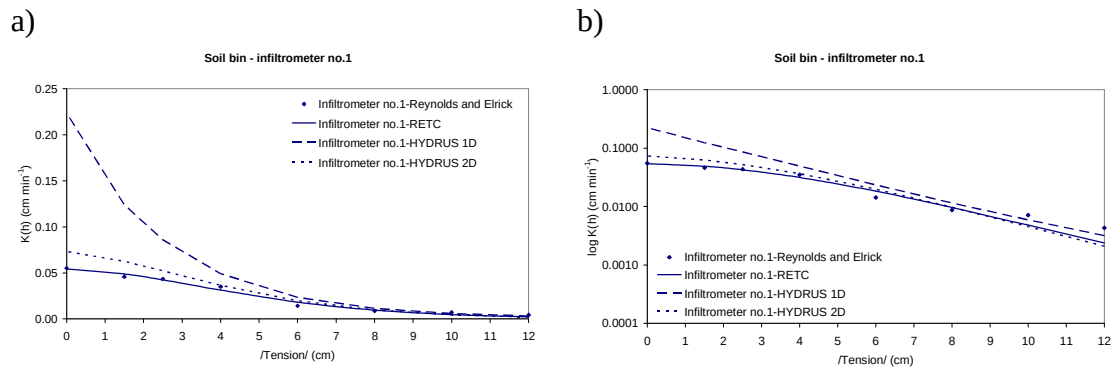


Figure 24. $K(h)$ (a) and $\log K(h)$ (b) functions for the soil bin laboratory experiment measured with infiltrometer no.1.

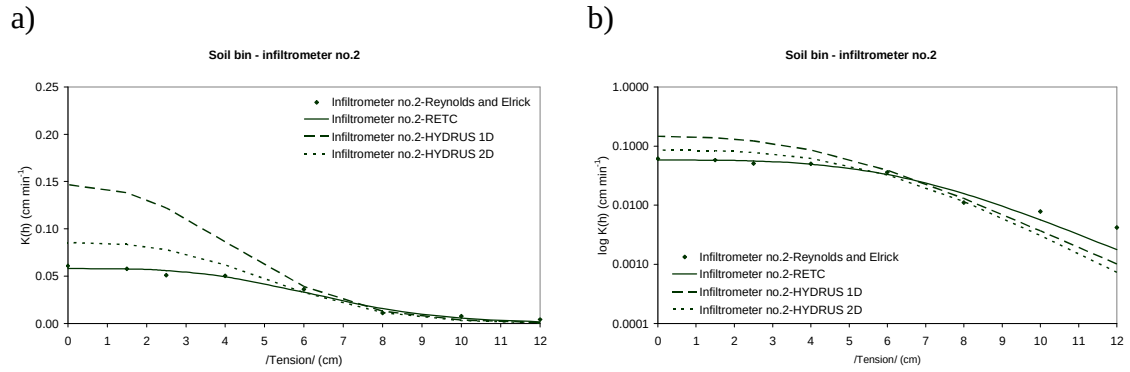


Figure 25. $K(h)$ (a) and $\log K(h)$ (b) functions for the soil bin laboratory experiment measured with infiltrometer no.2.

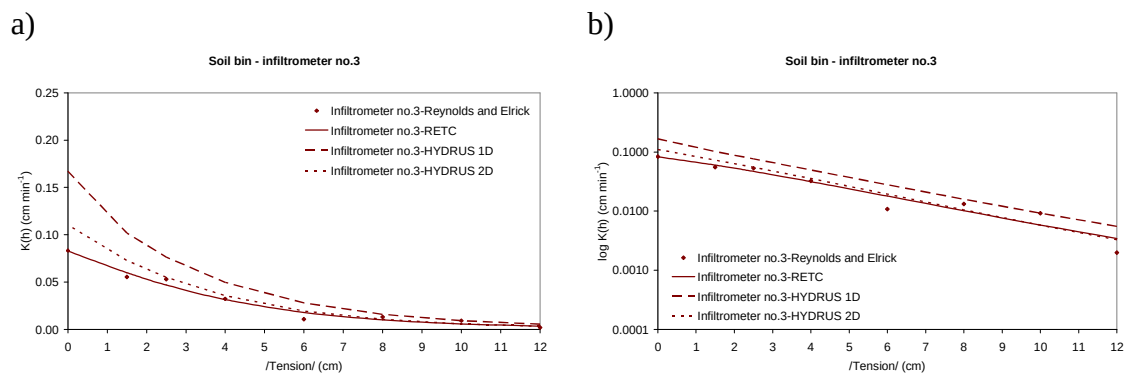


Figure 26. $K(h)$ (a) and $\log K(h)$ (b) functions for the soil bin laboratory experiment measured with infiltrometer no.3.

Table 4. Model parameter values for different data analysis applied on the soil bin data.

Replicate	Parameter	RETC	HYDRUS 1D	HYDRUS 2D
1	α (cm ⁻¹)	0.103	0.112	0.094
	n (-)	2.599	1.785	2.348
	K_s (cm min ⁻¹)	0.054	0.224	0.073
	R^2	0.983	0.999	0.998
2	α (cm ⁻¹)	0.105	0.114	0.107
	n (-)	3.993	3.056	3.476
	K_s (cm min ⁻¹)	0.058	0.147	0.086
	R^2	0.981	0.999	0.999
3	α (cm ⁻¹)	0.101	0.086	0.091
	n (-)	2.013	1.758	1.859
	K_s (cm min ⁻¹)	0.083	0.167	0.111
	R^2	0.977	1.000	1.000

Quite small values of hydraulic conductivities were recorded for a sandy loam. That was caused by the soil compaction (dry bulk density 1.72 g cm⁻³).

The variation of $\log_{10}$ -transformed $K(h)$ values at each of the tension is presented in Table 5. The biggest variations of $\log_{10}$ -transformed $K(h)$ values were observed at the highest tensions (-12 cm) for all data analysis.

The analysis of variance identified a statistically significant effect of data analysis method and applied tension on resulted $\log_{10}$ -transformed $K(h)$ values (Table 6). No interaction between applied tensions and data analysis was determined (Table 6), which means that the calculated $K(h)$ values did not statistically differ across the different tensions.

The effect of data analysis method is presented in Figure 27, and based on Fisher's LSD test (Table 7) it can be concluded, that the data analysis employing HYDRUS 1D provides significantly higher $K(h)$ values than all other methods, which are not significantly different from each other. This is because the HYDRUS 1D considers one dimensional vertical flow only. The contribution of horizontal flow to the overall flow process is not included, which leads to an overestimation of $K(h)$.

Table 5. $\log_{10}$ -transformed values of the hydraulic conductivity $K(h)$ in cm min^{-1} calculated by applying different data analysis methods.

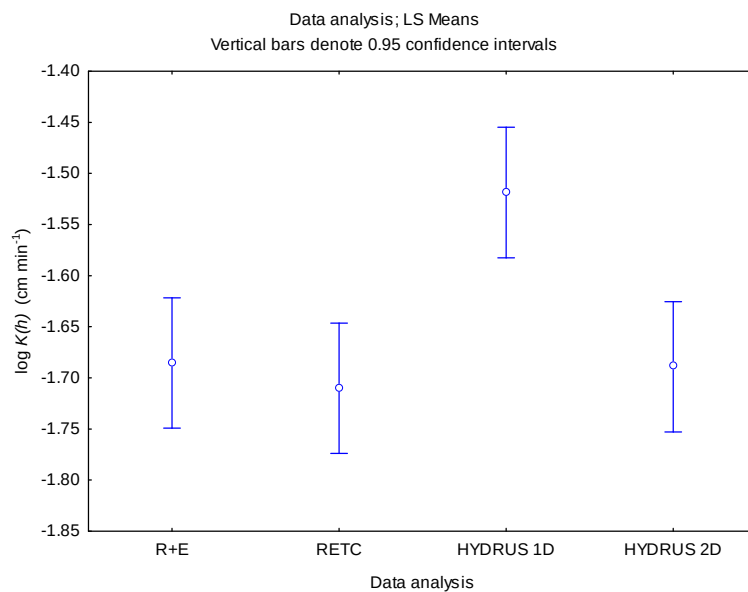
Tension (cm)	Effect	Reynolds and Elrick	RETC	HYDRUS 1D	HYDRUS 2D
-12	Mean	-2.482	-2.612	-2.582	-2.766
	Variance	0.037	0.021	0.140	0.111
-10	Mean	-2.097	-2.268	-2.232	-2.364
	Variance	0.003	0.002	0.040	0.019
-8	Mean	-1.965	-1.939	-1.875	-1.976
	Variance	0.008	0.014	0.005	0.001
-6	Mean	-1.752	-1.655	-1.531	-1.633
	Variance	0.075	0.023	0.013	0.016
-4	Mean	-1.415	-1.437	-1.225	-1.364
	Variance	0.010	0.013	0.019	0.018
-2.5	Mean	-1.310	-1.318	-1.032	-1.216
	Variance	0.002	0.004	0.011	0.009
-1.5	Mean	-1.277	-1.258	-0.919	-1.140
	Variance	0.003	0.002	0.004	0.004
0	Mean	-1.184	-1.195	-0.754	-1.053
	Variance	0.009	0.010	0.009	0.008

Table 6. Analysis of variance for $\log_{10}$ -transformed $K(h)$ values for different data analysis

Effect	SS	Degr. of freedom	MS	F	p
Intercept	261.6	1	261.6	14266.3	0.000
Data analysis	0.6	3	0.2	10.3	0.004
Error	0.1	8	0.0		
TENSION	26.9	7	3.8	181.9	0.000
TENSION*Data analysis	0.6	21	0.0	1.4	0.154
Error	1.2	56	0.0		

Table 7. Identification of homogeneous groups ($\alpha=0.05$) based on Fisher's test for $\log_{10}$ -transformed $K(h)$ values.

Data analysis	$\log K(h)$ mean (cm min^{-1})	Group 1	Group 2
RETC	-1.710	****	
HYDRUS 2D	-1.689	****	
R+E	-1.685	****	
HYDRUS 1D	-1.519		****

**Figure 27. Data analysis comparison of $\log_{10}$ -transformed $K(h)$ values.**

The $K(h)$ value obtained with the Reynolds and Elrick (1991) method and $K(h)$ function obtained with HYDRUS 2D compared relatively well (Table 7, Figure 27) suggesting that when steady-state data are available the Reynolds and Elrick model provides reliable $K(h)$ estimates. The two methods, however, depart slightly closer to saturation. The K_s calculated with the Reynolds and Elrick method is always lower

than that obtained with inverse modelling. It can be argued that the Reynolds and Elrick method underestimates K_s because it is calculated by extrapolating the closest piece-wise relation obtained from unsaturated data points.

The results are in agreement with those obtained by Šimůnek et al. (1998), who employed a tension infiltrometer to measure the infiltration rates on a sandy subsoil in the Sahel region of Africa. An inverse model HYDRUS 2D and analytical method based on Wooding's solution (Wooding, 1968) described by Reynolds and Elrick (1991) were used in order to determine the $K(h)$ function. It was reported that there was no significant difference in results obtained by the analytical method and inverse modelling. A very good agreement in $K(h)$ values at pressure heads between -10.25 cm and -2.00 cm was observed. The biggest differences of $K(h)$ values determined by different data analysis methods were observed at the tensions close to saturation.

The measurement of water below the tension infiltrometer is three-dimensional but axisymmetric and therefore can be fully described with a 2D model. It is therefore likely that HYDRUS 2D which models the entire flow process provides more accurate results. The other main advantage of the HYDRUS 2D is that transient data can be used therefore alleviating the need for steady-state data and reducing the experimental time completely. In addition if shorter infiltration times are used experimentally this reduces the size of the flow domain needed and the risk of subsurface boundaries influencing the flow process. Nevertheless, numerical models such as HYDRUS 2D, are quite expensive to purchase. In addition their use can be time-consuming when compared to simple analytical models.

7 Field experiments

7.1 Materials and methods

Site description

The infiltration tests were carried out between 27th July and 12th August 2006 on a sandy loam soil (Cottenham series according to the Soil survey of England and Wales) in the field on Cranfield University at Silsoe farm. According to existing data from years 2000/2001 the particle size distribution of the Ap horizon is as follows: 72% of sand (30% of fine sand, 36% of medium sand, and 6% of coarse sand), 16% of silt, and 12% of clay.

Five different tillage treatments: conventional plough, shallow plough, non inversion tillage, direct drill and untreated soil were tested. In three of the treatments (conventional plough, minimum tillage, and untreated soil) infiltration tests were also carried out in the wheel-marks created by wheel-traffic. The tillage operations were carried out one month before the experiments started. The soil was bare at the ploughed plots. On the direct drilled plot, the site for the infiltrometer was chosen on a place with minimum plants, which were cut at the soil surface. On the untreated plot the weeds were cut at the soil surface.

Unsaturated hydraulic conductivity measurement

Three tension infiltrometers connected to a single Mariotte bottle were used to determine the unsaturated hydraulic conductivity for each treatment. The soil surface was smoothed and levelled before the infiltrometers were placed on the plots but no contact material was used. The replicates were placed approximately 1 m apart. An example of the experimental setup is in Figure 28.



Figure 28. Experimental set up of the automated tension infiltrometer on a sandy loam soil.

Infiltration measurements were performed for 8 tensions in the following order: -13 cm, -11 cm, -9 cm, -7 cm, 5 cm, -3 cm, -2 cm, and -1 cm. The tensions were set to change automatically every 60 minutes. It was assumed that this time was long enough to reach the steady-state infiltration rate in a sandy loam soil. Sampling interval of the water level measurements was set to 180 s.

Three disturbed soil samples from areas surrounding each infiltrometer site were taken to determine the initial soil moisture content. When the measurement was finished, three undisturbed soil samples were taken from below the infiltration surface. Final soil moisture content, saturated soil moisture content and dry bulk density were determined by oven-drying the undisturbed soil samples at 105°C for 48 hours.

Data analysis

The steady-state data analysis method of Reynolds and Elrick (1991) was used to determine the unsaturated hydraulic conductivity $K(h)$. These $K(h)$ values were then

fitted with the Mualem-van Genuchten model by using RETC program. The fitted parameters K_s , α , and n were used as initial parameter estimates in HYDRUS 2D. HYDRUS 1D was not used because as shown in the previous section it did not compare well to the other two data analysis methods. The applied data analysis methods are described into more details in Section 6.1.

Statistical analysis

An analysis of variance ($\alpha = 0.05$) for the data calculated by the model HYDRUS 2D was done to determine whether there were significant differences in unsaturated hydraulic conductivities measured for different tillage treatments. The analysis considered the applied tension, the tillage treatment, and the presence of wheel-mark as factors influencing the value of $K(h)$. Also an interaction between the applied tension and tillage treatment was considered.

7.2 Results and discussion of the field experiments

The initial, final and saturated soil moisture contents together with dry bulk densities information for each of the field experiment are summarised in Table 8. Fitting parameters α , n , and K_s together with the R^2 , determined by the RETC and HYDRUS 2D programs are presented in Table 9. Means and variances of $\log_{10}$ -transformed $K(h)$ data calculated by HYDRUS 2D program are presented in Table 10.

The values of $K(h)$ for conventional tillage ranged between $0.0010 \text{ cm min}^{-1}$ at tension -12 cm and $0.5125 \text{ cm min}^{-1}$ as calculated saturated hydraulic conductivity value. The ranges of $K(h)$ for other tillage treatments were as follows: $0.0010 \text{ cm min}^{-1}$ to $0.6473 \text{ cm min}^{-1}$ for shallow plough, $0.0025 \text{ cm min}^{-1}$ to $0.5345 \text{ cm min}^{-1}$ for minimum tillage, $0.0011 \text{ cm min}^{-1}$ to $0.5162 \text{ cm min}^{-1}$ for direct drill, and $0.0012 \text{ cm min}^{-1}$ to $0.5404 \text{ cm min}^{-1}$ for no-tillage. The following ranges of $K(h)$ were measured on wheel-marks: $0.0004 \text{ cm min}^{-1}$ to $0.2651 \text{ cm min}^{-1}$ for conventional tillage,

0.0019 cm min⁻¹ to 0.3692 cm min⁻¹ for minimum tillage, and 0.0004 cm min⁻¹ to 0.2636 cm min⁻¹ for no-tillage.

Table 8. Summary of initial and final conditions for the field experiments.

Date	Tillage treatment	Replicate no.	θ initial mean	θ initial limit value for Hydrus	θ final mean	θ saturated average	Bulk density mean (g cm ⁻³)
27.07.2006	CP	1	0.090		0.287	0.335	1.39
27.07.2006	CP	2	0.106		0.289	0.362	1.38
27.07.2006	CP	3	0.103	0.10	0.303	0.348	1.40
31.07.2006	SP	1	0.074		0.263	0.315	1.38
31.07.2006	SP	2	0.081		0.307	0.326	1.38
31.07.2006	SP	3	0.089	0.08	0.279	0.327	1.40
02.08.2006	MT	1	0.088		0.261	0.329	1.43
02.08.2006	MT	2	0.096		0.243	0.343	1.38
02.08.2006	MT	3	0.109	0.10	0.276	0.325	1.42
05.08.2006	US	1	0.098		0.272	0.349	1.41
05.08.2006	US	2	0.088		0.276	0.352	1.45
05.08.2006	US	3	0.081	0.9	0.295	0.35	1.42
08.08.2006	DD	1	0.095		0.349	0.379	1.46
08.08.2006	DD	2	0.107		0.330	0.385	1.45
08.08.2006	DD	3	0.096	0.1	0.314	0.377	1.43
09.08.2006	MT+wheel	1	0.123		0.273	0.366	1.47
09.08.2006	MT+wheel	2	0.124		0.291	0.374	1.46
09.08.2006	MT+wheel	3	0.131	0.13	0.263	0.350	1.51
11.08.2006	CP+wheel	1	0.105		0.315	0.356	1.49
11.08.2006	CP+wheel	2	0.118		0.291	0.343	1.48
11.08.2006	CP+wheel	3	0.106	0.11	0.304	0.368	1.52
12.08.2006	US+wheel	1	0.098		0.272	0.349	1.51
12.08.2006	US+wheel	2	0.088		0.276	0.352	1.47
12.08.2006	US+wheel	3	0.081	0.90	0.295	0.350	1.52

Table 9. Model parameter values resulting from RETC, and HYDRUS 2D programs for different tillage treatments.

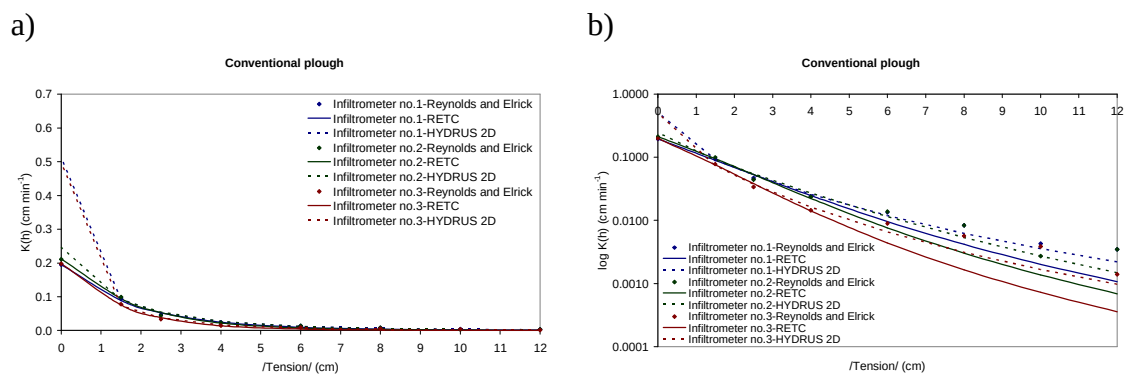
Tillage treatment + applied program	Replicate	Parameters			R ²
		α (cm ⁻¹)	n (-)	K _s (cm min ⁻¹)	
CP	1	0.185	1.864	0.195	0.997
RETC	2	0.210	1.934	0.212	0.995
	3	0.245	1.922	0.198	0.998
CP	1	0.156	1.374	0.513	1.000
HYDRUS 2D	2	0.144	1.618	0.246	0.995
	3	0.206	1.399	0.499	0.998
SP	1	0.236	1.781	0.276	0.966
RETC	2	0.202	1.843	0.221	0.994
	3	0.123	1.750	0.193	0.996
SP	1	0.202	1.474	0.499	0.995
HYDRUS 2D	2	0.193	1.386	0.647	0.999
	3	0.129	1.788	0.233	1.000
MT	1	0.171	1.755	0.228	0.994
RETC	2	0.157	1.727	0.202	0.993
	3	0.210	1.924	0.201	0.999
MT	1	0.125	1.323	0.535	0.998
HYDRUS 2D	2	0.107	1.396	0.333	0.998
	3	0.208	1.457	0.533	1.000
No-till	1	0.248	1.729	0.337	0.999
RETC	2	0.194	1.652	0.383	0.998
	3	0.194	1.652	0.319	0.998
No-till	1	0.198	1.435	0.540	0.998
HYDRUS 2D	2	0.184	1.550	0.532	0.998
	3	0.185	1.573	0.425	0.998
DD	1	0.248	1.729	0.362	0.999
RETC	2	0.248	1.729	0.346	0.999
	3	0.211	1.667	0.320	0.999
DD	1	0.197	1.476	0.500	0.998
HYDRUS 2D	2	0.199	1.474	0.488	0.998
	3	0.181	1.437	0.516	0.999
MT+wheel	1	0.168	1.648	0.181	0.998
RETC	2	0.124	1.814	0.113	0.997
	3	0.125	1.815	0.130	0.997
MT+wheel	1	0.144	1.354	0.369	0.998
HYDRUS 2D	2	0.113	1.535	0.199	1.000
	3	0.107	1.531	0.209	1.000
CP+wheel	1	0.106	1.674	0.129	1.000
RETC	2	0.194	1.683	0.114	0.998
	3	0.125	1.818	0.141	0.997
CP+wheel	1	0.020	1.715	0.224	1.000
HYDRUS 2D	2	0.199	1.734	0.265	0.998
	3	0.110	1.595	0.213	1.000
No-till+wheel	1	0.230	1.816	0.116	0.999
RETC	2	0.242	1.857	0.141	0.997
	3	0.206	1.769	0.145	0.997
No-till+wheel	1	0.227	1.437	0.264	0.999
HYDRUS 2D	2	0.177	1.393	0.259	0.998
	3	0.155	1.491	0.197	0.998

Table 10. Means and variances of $\log_{10}$ -transformed $K(h)$ data at each tension.

Tension (cm)	Effect	CP	SP	MT	No-till	DD	MT +wheel	CP +wheel	No-till +wheel
-12	Mean	-2.832	-2.839	-2.286	-2.943	-2.771	-2.615	-3.113	-3.183
	Variance	0.031	0.021	0.078	0.002	0.040	0.010	0.268	0.045
-10	Mean	-2.596	-2.582	-2.032	-2.695	-2.489	-2.404	-2.822	-2.946
	Variance	0.028	0.026	0.052	0.001	0.063	0.011	0.215	0.041
-8	Mean	-2.328	-2.292	-1.733	-2.409	-2.164	-2.168	-2.492	-2.673
	Variance	0.025	0.031	0.026	0.001	0.097	0.012	0.156	0.036
-6	Mean	-2.016	-1.958	-1.470	-2.073	-1.821	-1.902	-2.115	-2.353
	Variance	0.021	0.033	0.009	0.000	0.098	0.012	0.094	0.029
-4	Mean	-1.649	-1.571	-1.268	-1.668	-1.465	-1.599	-1.684	-1.969
	Variance	0.015	0.026	0.002	0.000	0.053	0.009	0.038	0.018
-2.5	Mean	-1.324	-1.237	-1.034	-1.303	-1.132	-1.338	-1.327	-1.622
	Variance	0.008	0.013	0.000	0.000	0.033	0.005	0.011	0.009
-1.5	Mean	-1.071	-0.984	-0.819	-1.018	-0.870	-1.139	-1.077	-1.349
	Variance	0.003	0.003	0.004	0.000	0.023	0.002	0.003	0.003
0	Mean	-0.401	-0.375	-0.341	-0.300	-0.304	-0.605	-0.632	-0.624
	Variance	0.032	0.053	0.014	0.000	0.003	0.022	0.002	0.005

Effect of tillage treatment on $K(h)$

Differences in $K(h)$ functions for five different tillage treatments were evaluated. The following figures (Figure 29, Figure 30, Figure 31, Figure 32, and Figure 33) show the replicated $K(h)$ function for all tillage treatments determined by two data analysis methods: Reynolds and Elrick (1991) fitted with the van Genuchten equation using RETC, and HYDRUS 2D.

**Figure 29. $K(h)$ (a) and $\log K(h)$ (b) functions for the field experiment; conventional plough.**

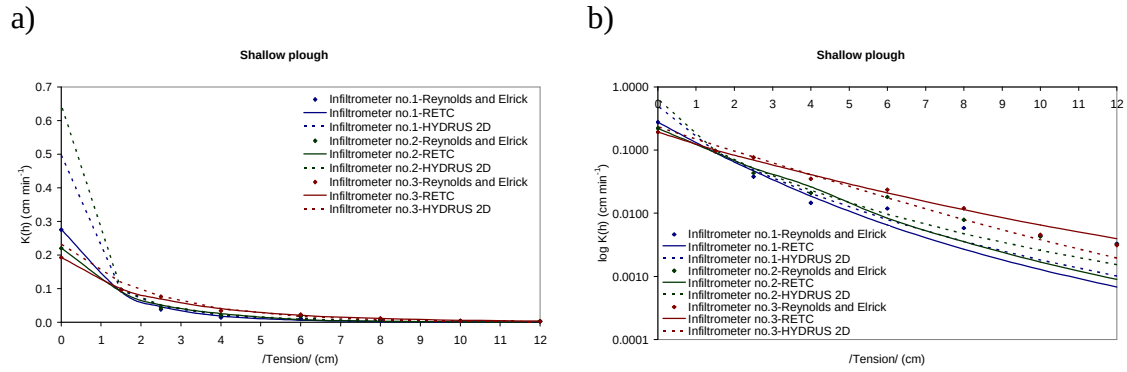


Figure 30. $K(h)$ (a) and $\log K(h)$ (b) functions for the field experiment; shallow plough.

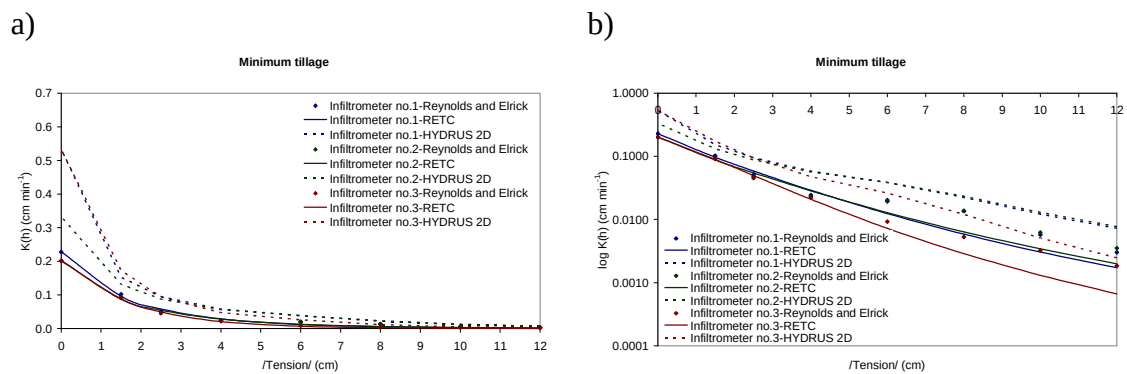


Figure 31. $K(h)$ (a) and $\log K(h)$ (b) functions for the field experiment; minimum tillage.

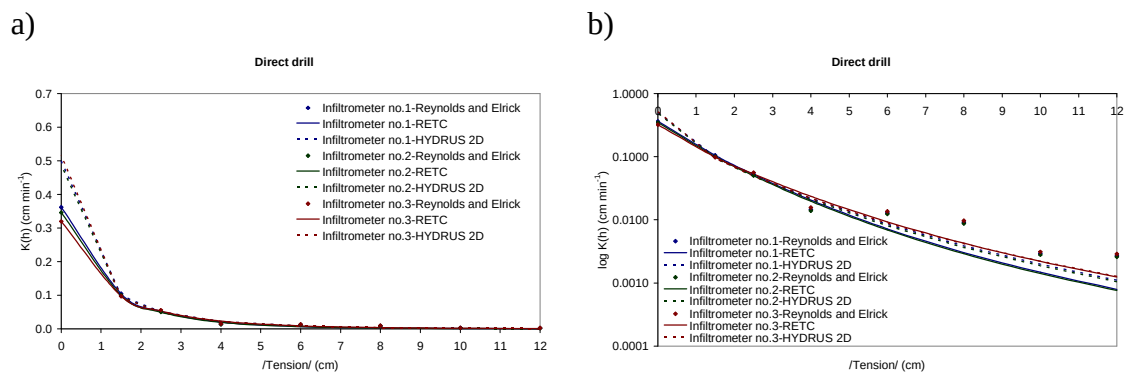


Figure 32. $K(h)$ (a) and $\log K(h)$ (b) functions for the field experiment; direct drill.

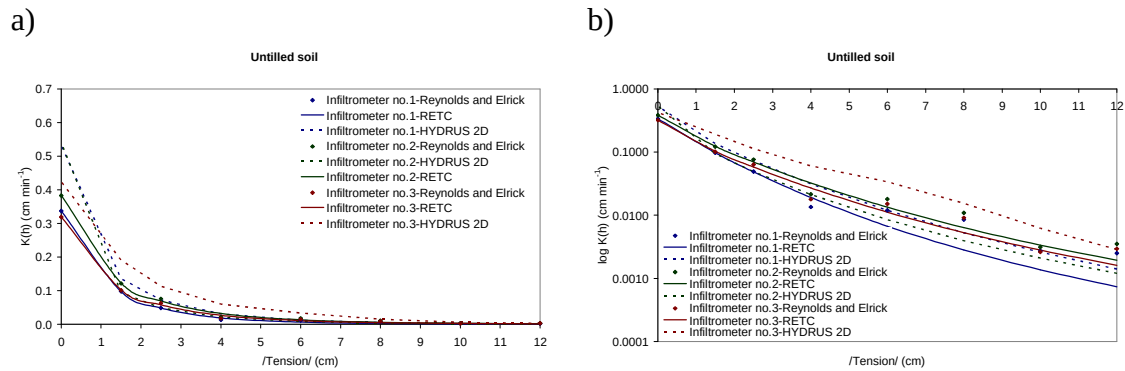


Figure 33. $K(h)$ (a) and $\log K(h)$ (b) functions for the field experiment; untilled soil.

The analysis of variance (Table 11) shows, that there are significant effects of tillage treatment and applied tension on the unsaturated hydraulic conductivity. Also an interaction between the tillage treatment and applied tension was significant, which means that the effect of tillage treatment on $K(h)$ is significant for certain tension. The analysis of variance did not identify homogeneous group for each of the treatment (Table 12, Figure 34) for the whole range of $K(h)$ values for each treatment.

Table 11. Analysis of variance for $\log_{10}$ -transformed $K(h)$ values for different tillage treatments calculated by HYDRUS 2D.

Effect	SS	Degr. of freedom	MS	F	p
Intercept	590.3	1	590.3	3978.0	0.000
Data analysis	7.3	3	1.0	7.0	0.001
Error	2.4	16	0.1		
TENSION	110.0	7	15.7	1051.0	0.000
TENSION*Data analysis	1.6	49	0.0	2.1	0.001
Error	1.7	112	0.0		

Table 12. Identification of homogeneous groups for tillage treatments ($\alpha=0.05$) based on Fisher's test for $\log_{10}$ -transformed $K(h)$ values calculated by HYDRUS 2D.

Tillage treatment	$\log K(h)$ mean (cm min^{-1})	Group 1	Group 2
DD	-1.801	****	
CP	-1.777	****	
SP	-1.730	****	
US-no-till	-1.627	****	
MT	-1.373		****

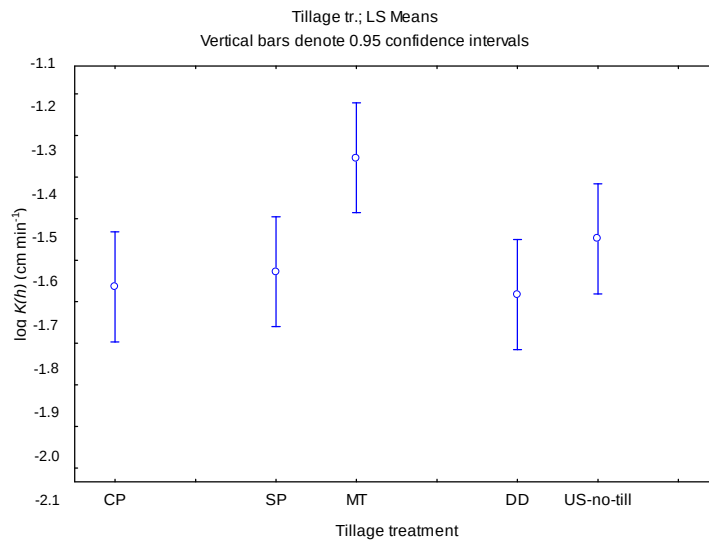


Figure 34. Comparison of $\log_{10}$ -transformed $K(h)$ values for different tillage treatments.

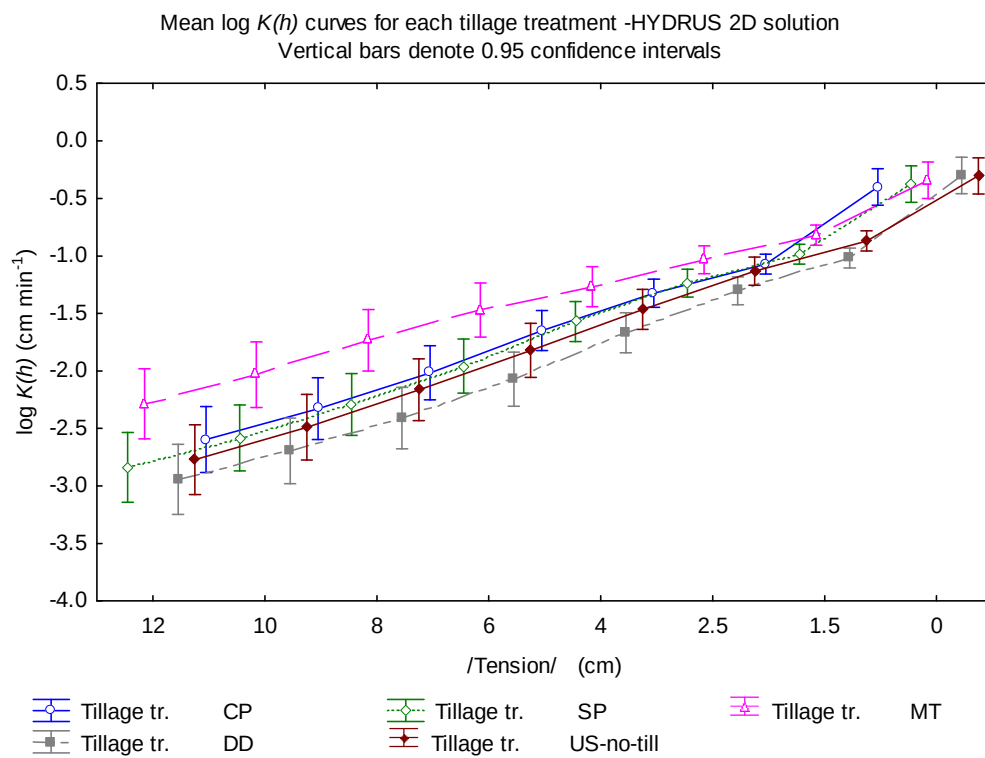


Figure 35. Results of analysis of variance determining significant differences between the $\log_{10}$ -transformed data for different tillage treatment at different tensions.

It was expected that $K(h)$ values measured on tilled soil would be considerably different than those measured on the untilled soil. The analysis of variance determined a statistically significant effect of tillage treatment; however the more detailed analysis (Table 12, Figure 34) did not always confirm this assumption. The highest $K(h)$ function was measured on plot with minimum tillage, and was significantly different from other treatments. $K(h)$ functions for all other tillage treatments did not significantly differ. The reason for that can be the big variation between the replicates resulting from the heterogeneity of the soil, or the occurrence of stones or clods in the soil profile. Another reason could be due to the fact that the tension infiltrometer method does not include the flow in preferential paths, which can be created by tillage.

The results were in agreement with those reported by Cortadeur et al. (2002), who studied variation of unsaturated hydraulic conductivity in a tilled soil, and compared the $K(h)$ functions of tilled and untilled soils. The reducing effect of ploughing on the $K(h)$ values was reported. The disruption of macropores due to the tillage was indicated as a main reason. The $K(h)$ in the ploughed soil was reported as one third of that measured on untilled soil.

In addition similar results were observed by Lampurlanés (2006), who compared the near-saturated hydraulic conductivities for different tillage treatments in semiarid area in Spain. No significant difference between the no-tillage and minimum tillage and subsoil tillage was reported. It was summarised that infiltration rates measured on soils with no-tillage are greater than measured on tilled soils. According to the author, these higher $K(h)$ values for the no-tilled soils were the consequence of a larger number of macropores in the soils enhanced by fauna activity and accumulated organic matter forming a litter of residues. The lower $K(h)$ values for tilled soils were due to the disruption of macropore continuity due to tillage operations.

However, as reported by Pelegrin (1990) and Ferreras et al. (2000), when the K_s was measured in situ, the values for tilled soils were significantly higher than those measured on untilled soils. This fact suggests that calculated or extrapolated K_s

values from tension infiltrometer data are underestimating the real saturated hydraulic conductivity.

Effect of wheel-traffic on $K(h)$

Effects of wheel-marks on $K(h)$ values for three different tillage treatments were assessed. The analysis of variance identified significant reductions for the whole $\log_{10}$ -transformed hydraulic conductivity function for wheel-marks on plots with minimum tillage and untilled soil. However, the reduction in $K(h)$ on conventionally ploughed soil was not statistically significant (Table 13, and Figure 36, Figure 37, Figure 38).

Table 13. Identification of homogeneous groups for wheel-marks ($\alpha=0.05$) based on Fisher's test for $\log_{10}$ -transformed $K(h)$ values calculated by HYDRUS 2D.

Tillage treatment	$\log K(h)$ mean (cm min^{-1})	Group 1	Group 2	Group 3	Group 4
US-no-till+wheel	-2.090			****	
CP+wheel	-1.908	****		****	
CP	-1.777	****	****		
MT+wheel	-1.721	****	****		
US-no-till	-1.627		****		
MT	-1.373				****

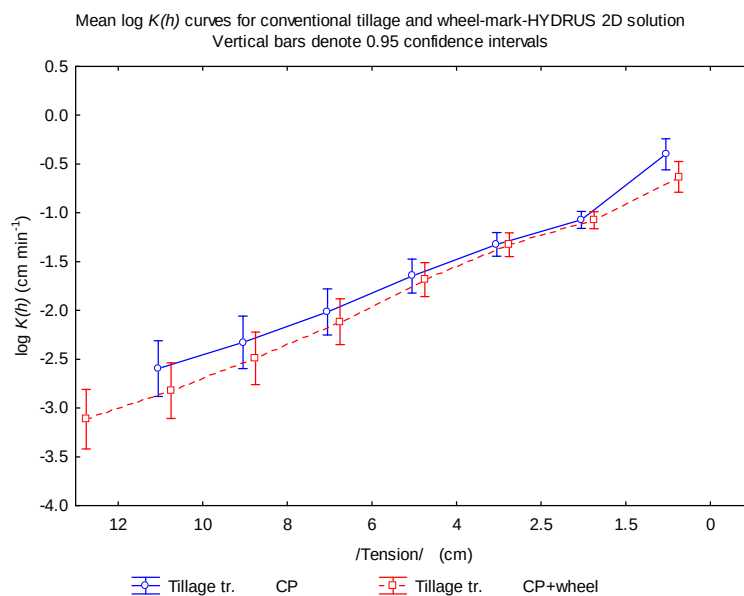


Figure 36. Results of analysis of variance determining significant differences between the $\log_{10}$ -transformed data for wheel-mark on conventionally ploughed soil at different tensions.

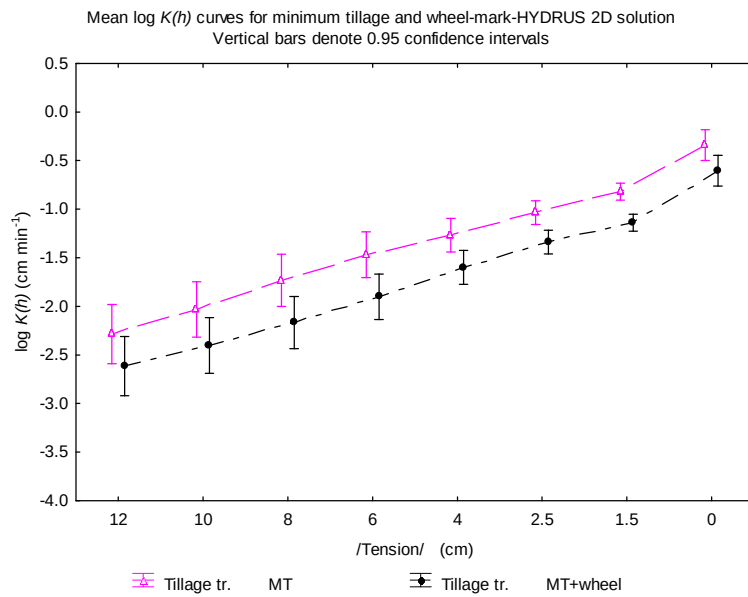


Figure 37. Results of analysis of variance determining significant differences between the $\log_{10}$ -transformed data for wheel-mark on soil with minimum tillage at different tensions.

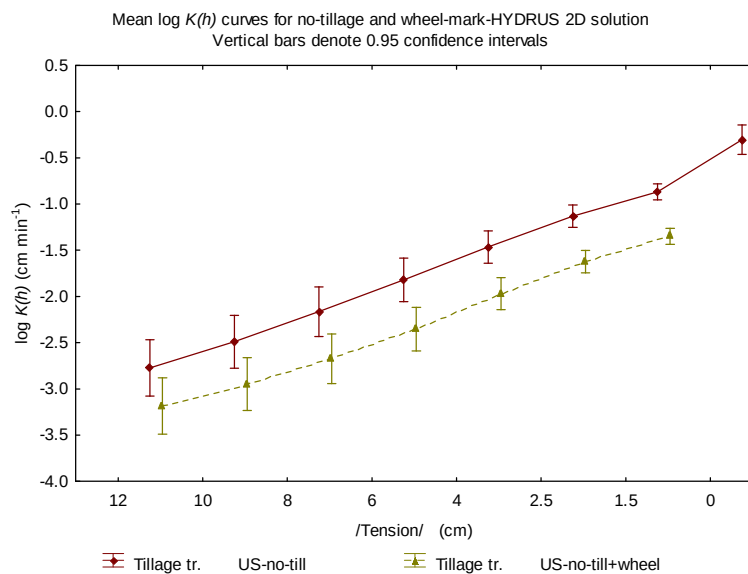
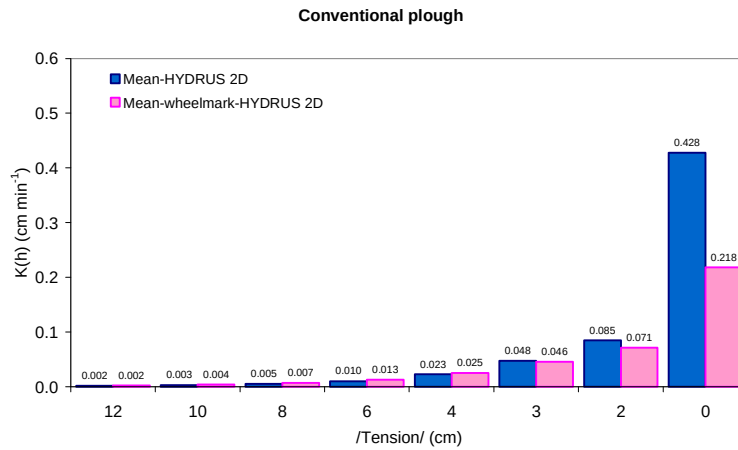


Figure 38. Results of analysis of variance determining significant differences between the $\log_{10}$ -transformed data for wheel-mark on untilled soil at different tensions.

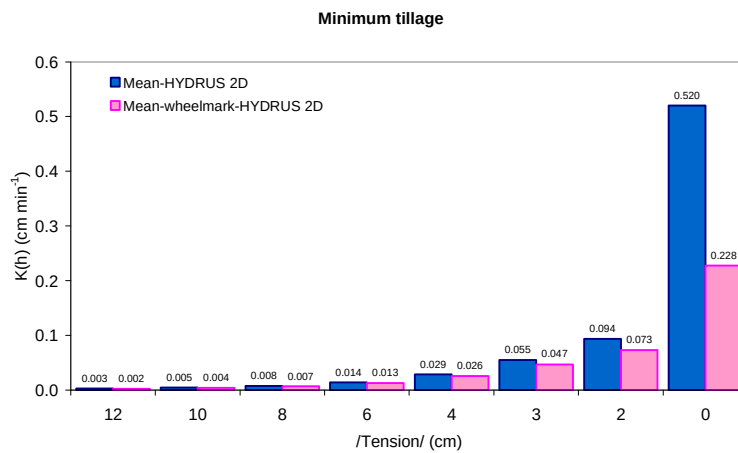
The $K(h)$ values obtained were plotted in the column graphs in Figure 39, where each column represents the $K(h)$ value measured at a certain tension for both the treatment under consideration and the associated wheel-mark. The biggest reduction was

observed at lower tensions (-2.5 cm, -1.5 cm, and estimated 0 cm) and was most significant for K_s with a reduction varying between 50% and 60%.

a)



b)



c)

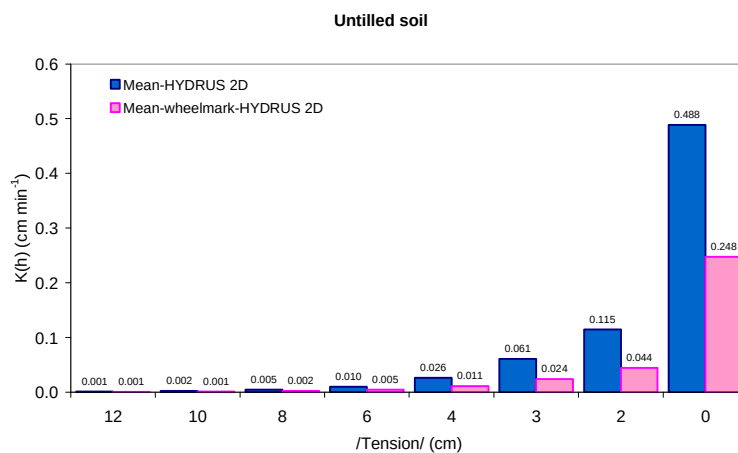


Figure 39. Comparison of $K(h)$ values at each tension for plots and wheel-marks on plots calculated by HYDRUS 2D; conventional plough (a), minimum tillage (b), untilled soil (c).

Based on the results it can be concluded, that the wheel-traffic has a significant reducing effect on the hydraulic conductivity function $K(h)$. Except for the conventionally tilled soil, the reduction of $K(h)$ values was significant for $K(h)$ values at almost all tensions. The soil compaction created by the wheels was confirmed by the values of dry bulk densities (Table 8), which were, for all three tillage treatments, significantly higher in the wheel-marks (t-test, $\alpha = 0.05$).

Other published works, as for example works by Ankeny (1990) and Mohanty (1994), presented wheel-traffic as the main source of soil compaction in agricultural fields. Soil compaction was reported as a cause of large pores destruction, which reduces saturated and near-saturated hydraulic conductivities. The effect of wheel-traffic on $K(h)$ was also reported by Courtadeur (2002) who measured a 60% reduction of saturated hydraulic conductivity in the wheel-mark of a tilled soil.

8 Conclusions

8.1 Automated tension infiltrometer design and development

An automated tension infiltrometer for the field use was developed. The system consists of three automated tension infiltrometer replicates all connected to a single automated Mariotte bottle. Design factors such as sensor sensitivity, water reservoir diameter and bubbling rate were tested, and results have been taken into consideration during the development process of the device.

The base of the infiltrometer was made of an aluminium cylindrical block with a diameter of 15 cm, which was quite heavy and thus ensures good stability of the device, and good contact with the infiltration surface. A 5 micron nylon mesh was attached to the base with a rubber o-ring, which was fitted into a groove machined on the side of the base. Between the base and the water reservoir, a valve enabled refilling without having to remove the infiltrometer from the surface. The water reservoir was relatively high (120 cm) and its diameter was relatively large (4.4 cm i.d. of the outer tube, and 2.1 cm i.d. of the inner tube), which reduced the need for refilling. A double tube system for the water reservoir was developed and it was shown that the fluctuations in water level measurements caused by bubbling were significantly reduced. However for very small flow rates, a single tube reservoir of the diameter of about half of the double tube system could still be used without any substantial modification.

The water level changes measurement was automated similarly to Casey and Derby (2002) by using a differential pressure transducer connected to a Campbell 21X (Campbell Scientific Inc.). One end of the transducer was connected via tubing to the head space of the outer tube of the water reservoir, and the other end was connected through the base to the membrane. The Mariotte bottle was automated similarly to Castiglione et al. (2005) by employing a set of solenoid valves connected via tubing to the pre-defined depths in the body of the Mariotte bottle. The solenoid valves were controlled with the Dasy Lab[®] program via digital input/output module (Measurement Computing[™]). Eight tensions could be set: -13 cm, -11 cm, -9 cm,

-7 cm, -5 cm, -3 cm, -2 cm, and -1 cm. Time period for each tension can be easily set and changed for each experiment. A longer time period can be chosen for higher tensions, to fulfil the assumption of a steady-state infiltration rate. The commonly used data analysis method of Reynolds and Elrick (1991) is based on the steady-state data; however the steady-state data are not required in the inverse modelling method.

Some parameters factors were tested in the laboratory using an automatic syringe pump to simulate the flow of bubbles in the tension infiltrometer reservoir. Water could not leave the infiltrometer, because it could not flow through the membrane. Only bubbles caused the reading fluctuations. Firstly, the effect of sensor sensitivity was tested. Sensors with ranges of 0-1 psi and 0-5 psi were compared. The more sensitive 0-1 psi sensor performed always better. Secondly, the effect of differential versus single transducer measurement was tested. The reading fluctuations were significantly higher for measurement with a single transducer connected to the top of the infiltrometer than with a differential transducer. Thirdly, the water reservoir diameter was tested. Single tube of large diameter, single tube of small diameter and a double tube system were compared. The measurement noise due to bubbling was significantly smaller when a single tube with large diameter was used, compared to that measured for a single tube of a diameter approximately twice as small. The measurement noise was significantly reduced by using the double tube system, because the disturbances due to rising bubbles was mainly confined to the smaller inner tube, while the water level measurement was taken in the outer tube. Fourthly, the effect of bubbling rate was tested. A large increase in noise with increasing flow rate at low flow rates was observed for all water reservoirs tested. However, the difference in noise between flow rates was small at large flow rates, as the water reservoir was constantly fed by bubbles.

8.2 Determination of $K(h)$ with the fully automated device

A preliminary test in the soil bin laboratory under controlled conditions was carried out to determine the possible effect of data analysis method on the resulting unsaturated hydraulic conductivity function $K(h)$. Three data analysis methods were

compared: Reynolds and Elrick (1991) in which steady-state data is used; and two methods using transient data HYDRUS 1D and HYDRUS 2D. The analysis of variance ($\alpha = 0.05$) identified a statistically significant difference between the results obtaining by HYDRUS 1D and other methods. The reason for that is, that in HYDRUS 1D it is assumed, that all the infiltrating water is moving downwards only, and thus the $K(h)$ values are always higher than for the other methods, where axisymmetric flow is assumed. The $K(h)$ values obtained with the Reynolds and Elrick (1991) method and the $K(h)$ function obtained with HYDRUS 2D did not statistically differ, suggesting that when steady-state infiltration rates are measured, the Reynolds and Elrick model provides reliable $K(h)$ estimates. Time needed for the experiment can be reduced by using transient data to determine the $K(h)$ function. Shorting the time of the experiment also means the reduction of need to refill the infiltrometer, which minimises the unwanted changes of the infiltration surface. However, the numerical models such as HYDRUS 2D are relatively costly, and their use can require more time than simple analytical models.

The developed automated tension infiltrometer was used in the field to determine the unsaturated hydraulic conductivity $K(h)$ of a sandy loam soil. Both data analysis methods, using the steady-state and transient infiltration data were employed to determine whether there was a significant difference between plots, where different tillage treatments were applied. The following tillage treatments were compared: conventional plough, shallow plough, minimum tillage, direct drill, and no-tillage. In three of the treatments (conventional plough, minimum tillage and no-tillage) infiltration tests were also carried out in the wheel-marks created by a vehicle to determine the influence of surface compaction on the $K(h)$ function. The soil in the field was naturally heterogeneous, and the heterogeneity was more pronounced after the tillage operations. The analysis of variance ($\alpha = 0.05$) was done for the inverse solution data obtained by HYDRUS 2D. Significant influence of applied tension, tillage treatment, and wheel-traffic was identified. The biggest reduction due to the wheel-traffic was measured for the low tensions (-2.5 cm, -1.5 cm). For the estimated value of K_s the reduction due to the wheel-marks was between 40% and 60%. The analysis of variance did not identify homogeneous group for each tillage

treatment. This could be influenced by the fact that the variances between replicates for each tillage treatment were quite large. However the tillage operations lead to damage of the soil structure and created preferential paths. The tension infiltrometer is a device, which characterise the infiltration characteristic of the soil matrix and the preferential flow is excluded. Water is infiltrating under a tension, which corresponds to pores with a certain diameter. It can be assumed that this is the reason, why the measured $K(h)$ values for the tilled soils were not significantly higher than for the plot where no tillage operation was applied.

9 Bibliography

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10 Appendices

- Appendix 1. Statistical analysis of test measurements of the design factors
- Appendix 2. Normality histograms and histograms of residues for $\log_{10}$ -transformed hydraulic conductivity data measured in the soil bin laboratory, and in the field
- Appendix 3. Photo –gallery

Appendix 1. Statistical analysis of test measurements of the design factors

	Mean Group 1	Mean Group 2	t-value	df	p	Valid N	Valid N	Std.Dev. Group 1	Std.Dev. Group 2	F-ratio Variances	p Variances	p Variances
TESTING OF TUBING SYSTEM EFFECT												
DT,1psi,q=0 vs. LT,1psi,q=0	979.6680	1033.650	-4.067.52	188	0.00	95	95	0.081580	0.099567	1.489584	0.054813	>0.05
DT,1psi,q=9 vs. LT,1psi,q=9	984.9363	1038.610	-2.66.312	188	0.00	95	95	1.278748	1.491208	1.359899	0.137978	>0.05
DT,1psi,q=18 vs. LT,1psi,q=18	986.1196	1038.985	-1.76.074	188	0.00	95	95	1.685918	2.391976	2.012987	0.000811	<0.001
DT,1psi,q=45 vs. LT,1psi,q=45	984.5952	1037.565	-1.51.453	188	0.00	95	95	2.152958	2.642931	1.506957	0.048172	<0.05
DT,1psi,q=72 vs. LT,1psi,q=72	982.1517	1035.640	-1.47.174	188	0.00	95	95	2.487125	2.522370	1.028543	0.891772	>0.05
DT,1psi,q=0 vs. ST,1psi,q=0	979.6680	1029.177	-3.873.15	188	0.00	95	95	0.081580	0.094167	1.332369	0.166045	>0.05
DT,1psi,q=9 vs. ST,1psi,q=9	984.9363	1051.381	-1.84.206	188	0.00	95	95	1.278748	3.274982	6.559154	0.000000	<0.001
DT,1psi,q=18 vs. ST,1psi,q=18	986.1196	1053.424	-1.68.776	188	0.00	95	95	1.685918	3.502172	4.315214	0.000000	<0.001
DT,1psi,q=45 vs. ST,1psi,q=45	984.5952	1053.092	-1.88.340	188	0.00	95	95	2.152958	2.816067	1.710862	0.009852	<0.05
DT,1psi,q=72 vs. ST,1psi,q=72	982.1517	1050.963	-1.67.609	188	0.00	95	95	2.487125	3.134667	1.588501	0.025903	<0.05
LT,1psi,q=0 vs. ST,1psi,q=0	1033.650	1029.177	3.18.0912	188	0.00	95	95	0.099567	0.094167	1.117997	0.589798	>0.05
LT,1psi,q=9 vs. ST,1psi,q=9	1038.610	1051.381	-3.4.5924	188	0.00	95	95	1.491208	3.274982	4.823267	0.000000	<0.001
LT,1psi,q=18 vs. ST,1psi,q=18	1038.985	1053.424	-3.3.1855	188	0.00	95	95	2.391976	3.502172	2.143686	0.000269	<0.001
LT,1psi,q=45 vs. ST,1psi,q=45	1037.565	1053.092	-3.9.1870	188	0.00	95	95	2.642931	2.816067	1.135309	0.539641	>0.05
LT,1psi,q=72 vs. ST,1psi,q=72	1035.640	1050.963	-3.7.1183	188	0.00	95	95	2.522370	3.134667	1.544419	0.036325	<0.05
DT,1psi,q=0 vs. DT,1psi,q=0a	979.6680	1018.338	-3.057.77	188	0.00	95	95	0.081580	0.092404	1.282955	0.228930	>0.05
DT,1psi,q=9 vs. DT,1psi,q=9a	984.9363	1036.012	-2.82.311	188	0.00	95	95	1.278748	1.214214	1.109123	0.616634	>0.05
DT,1psi,q=18 vs. DT,1psi,q=18a	986.1196	1029.776	-1.91.560	188	0.00	95	95	1.685918	1.446325	1.358754	0.139055	>0.05
DT,1psi,q=45 vs. DT,1psi,q=45a	984.5952	1032.983	-1.94.583	188	0.00	95	95	2.152958	1.113296	3.739812	0.000000	<0.001
DT,1psi,q=72 vs. DT,1psi,q=72a	982.1517	1023.917	-1.41.333	188	0.00	95	95	2.487125	1.452583	2.931659	0.000000	<0.001
TESTING OF SENSOR SENSITIVITY EFFECT FOR DT SYSTEM												
DT,1psi,q=0 vs. DT,5psi,q=0	979.6680	1228.887	-9.315.03	188	0.00	95	95	0.081580	0.247681	9.217587	0.000000	<0.001
DT,1psi,q=9 vs. DT,5psi,q=9	984.9363	1235.310	-1.185.12	188	0.00	95	95	1.278748	1.613965	1.593010	0.025014	<0.05
DT,1psi,q=18 vs. DT,5psi,q=18	986.1196	1235.407	-8.97.294	188	0.00	95	95	1.685918	2.119018	1.579780	0.027708	<0.05
DT,1psi,q=45 vs. DT,5psi,q=45	984.5952	1233.810	-7.12.140	188	0.00	95	95	2.152958	2.645572	1.509970	0.047099	<0.05
DT,1psi,q=72 vs. DT,5psi,q=72	982.1517	1232.784	-6.83.357	188	0.00	95	95	2.487125	2.567749	1.065884	0.757736	>0.05
TESTING OF DIFFERENTIAL MEASUREMENT EFFECT FOR DT SYSTEM												
DT,1psi,q=18 vs. DT,1psi,q=18,only top	986.1196	1076.400	-2.14.046	188	0.00	95	95	1.685918	3.749417	4.946007	0.000000	<0.001
DT,1psi,q=45 vs. DT,1psi,q=45,only top	984.5952	1074.227	-2.22.950	188	0.00	95	95	2.152958	3.274034	2.312572	0.000064	<0.001

	Mean Group 1	Mean Group 2	t-value	df	p	Valid N	Valid N	Std.Dev. Group 1	Std.Dev. Group 2	F-ratio Variances	p Variances	p Variances
TESTING OF BUBBLE RATE EFFECT FOR DT SYSTEM												
DT,1psi,q=0 vs. DT,1psi,q=1	979.6680	985.3284	-68.4402	253	0.00	95	160	0.081580	0.803023	96.89184	0.000000	<0.001
DT,1psi,q=0 vs. DT,1psi,q=4	979.6680	985.6749	-44.5120	188	0.00	95	95	0.081580	1.312808	258.9604	0.000000	<0.001
DT,1psi,q=0 vs. DT,1psi,q=9	979.6680	984.9363	-40.0739	188	0.00	95	95	0.081580	1.278748	245.6977	0.000000	<0.001
DT,1psi,q=0 vs. DT,1psi,q=18	979.6680	986.1196	-37.2549	188	0.00	95	95	0.081580	1.685918	427.0747	0.000000	<0.001
DT,1psi,q=0 vs. DT,1psi,q=45	979.6680	984.5952	-22.2903	188	0.00	95	95	0.081580	2.152958	696.4694	0.000000	<0.001
DT,1psi,q=0 vs. DT,1psi,q=72	979.6680	982.1517	-9.72832	188	0.00	95	95	0.081580	2.487125	929.4509	0.000000	<0.001
DT,1psi,q=1 vs. DT,1psi,q=4	985.3284	985.6749	-2.61657	253	0.01	160	95	0.803023	1.312808	2.672675	0.000000	<0.001
DT,1psi,q=1 vs. DT,1psi,q=9	985.3284	984.9363	3.008421	253	0.00	160	95	0.803023	1.278748	2.535793	0.000000	<0.001
DT,1psi,q=1 vs. DT,1psi,q=9	985.3284	984.9363	3.008421	253	0.00	160	95	0.803023	1.278748	2.535793	0.000000	<0.001
DT,1psi,q=1 vs. DT,1psi,q=45	985.3284	984.5952	3.881018	253	0.00	160	95	0.803023	2.152958	7.188112	0.000000	<0.001
DT,1psi,q=1 vs. DT,1psi,q=72	985.3284	982.1517	14.91610	253	0.00	160	95	0.803023	2.487125	9.592665	0.000000	<0.001
DT,1psi,q=4 vs. DT,1psi,q=9	985.6749	984.9363	3.928654	188	0.00	95	95	1.312808	1.278748	1.053980	0.799366	>0.05
DT,1psi,q=4 vs. DT,1psi,q=18	985.6749	986.1196	-2.02817	188	0.04	95	95	1.312808	1.685918	1.649189	0.016112	<0.05
DT,1psi,q=4 vs. DT,1psi,q=45	985.6749	984.5952	4.173497	188	0.00	95	95	1.312808	2.152958	2.689482	0.000003	<0.001
DT,1psi,q=4 vs. DT,1psi,q=72	985.6749	982.1517	12.21044	188	0.00	95	95	1.312808	2.487125	3.589162	0.000000	<0.001
DT,1psi,q=9 vs. DT,1psi,q=18	984.9363	986.1196	-5.45064	188	0.00	95	95	1.278748	1.685918	1.738212	0.007901	<0.05
DT,1psi,q=9 vs. DT,1psi,q=45	984.9363	984.5952	1.327501	188	0.19	95	95	1.278748	2.152958	2.834660	0.000001	<0.001
DT,1psi,q=9 vs. DT,1psi,q=72	984.9363	982.1517	9.704630	188	0.00	95	95	1.278748	2.487125	3.782905	0.000000	<0.001
DT,1psi,q=18 vs. DT,1psi,q=45	986.1196	984.5952	5.433445	188	0.00	95	95	1.685918	2.152958	1.630791	0.018626	<0.05
DT,1psi,q=18 vs. DT,1psi,q=72	986.1196	982.1517	12.87113	188	0.00	95	95	1.685918	2.487125	2.176320	0.000204	<0.001
DT,1psi,q=45 vs. DT,1psi,q=72	984.5952	982.1517	7.239885	188	0.00	95	95	2.152958	2.487125	1.334518	0.163687	>0.05

Appendix 2. Normality histograms and histograms of residues for $\log_{10}$ -transformed hydraulic conductivity data measured in the soil bin laboratory, and in the field

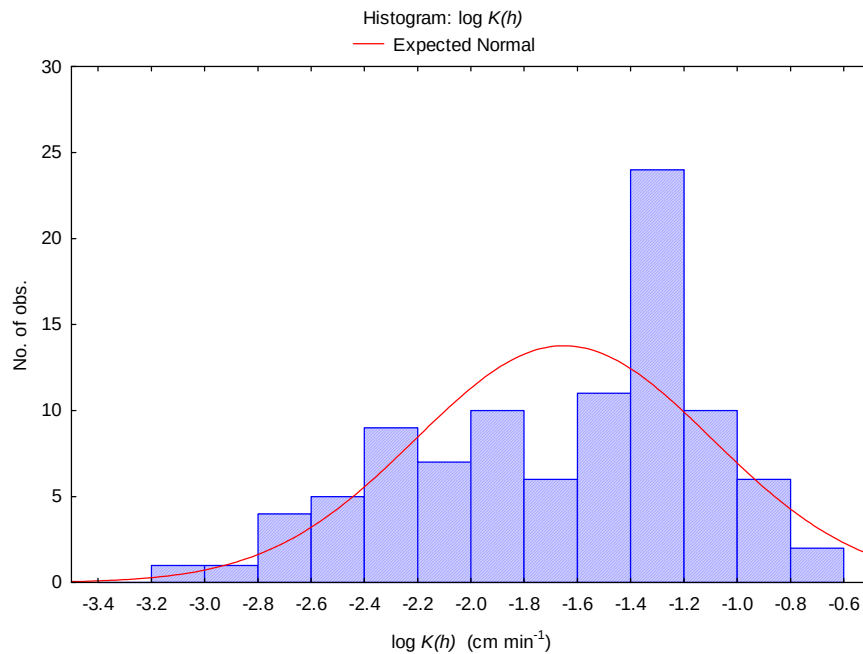


Figure 40. Histogram of the $\log_{10}$ -transformed $K(h)$ values determined from the soil bin laboratory measurements.

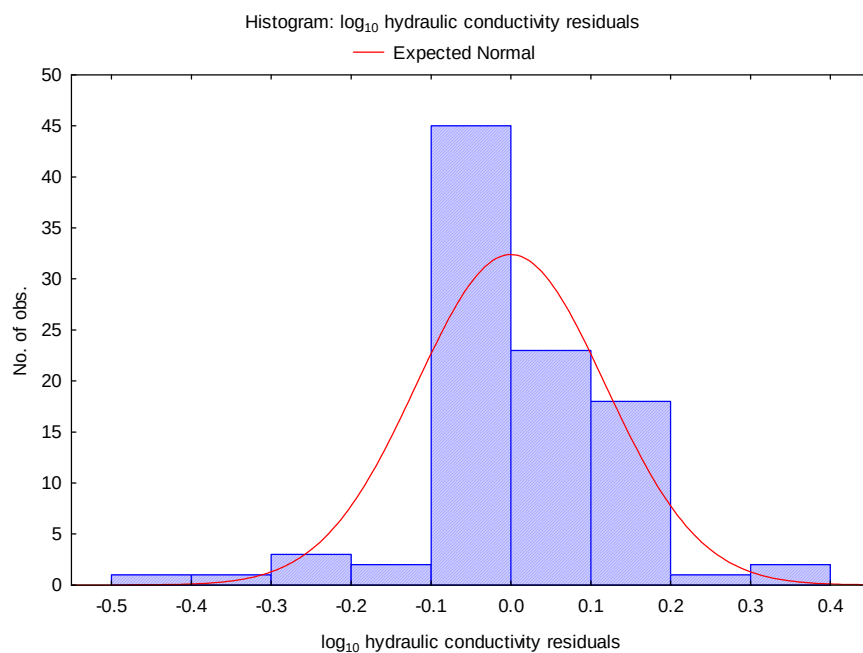


Figure 41. Histogram of the residues of the $\log_{10}$ -transformed hydraulic conductivity data measured in cm min^{-1} in the soil bin laboratory.

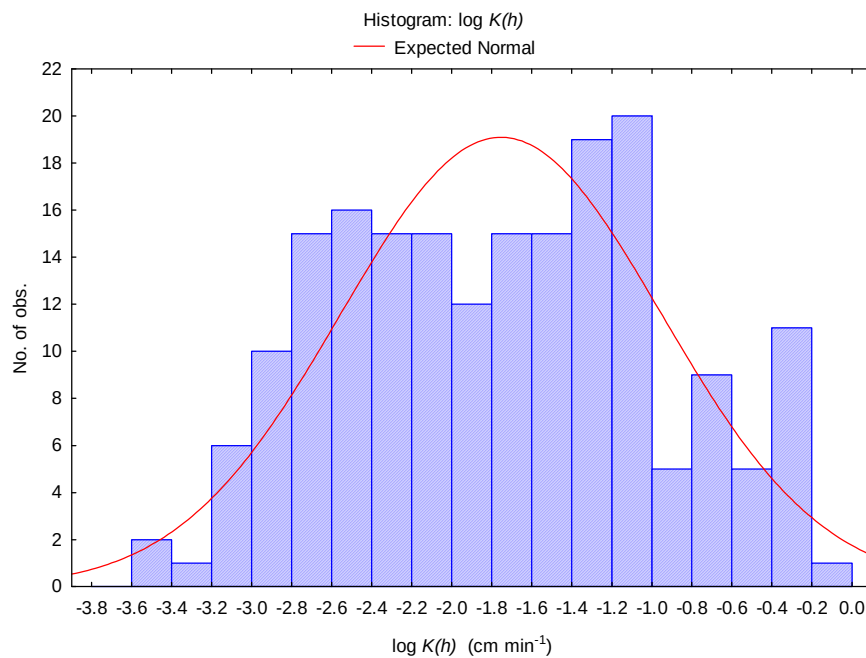


Figure 42. Histogram of the $\log_{10}$ -transformed $K(h)$ values determined from the field measurements.

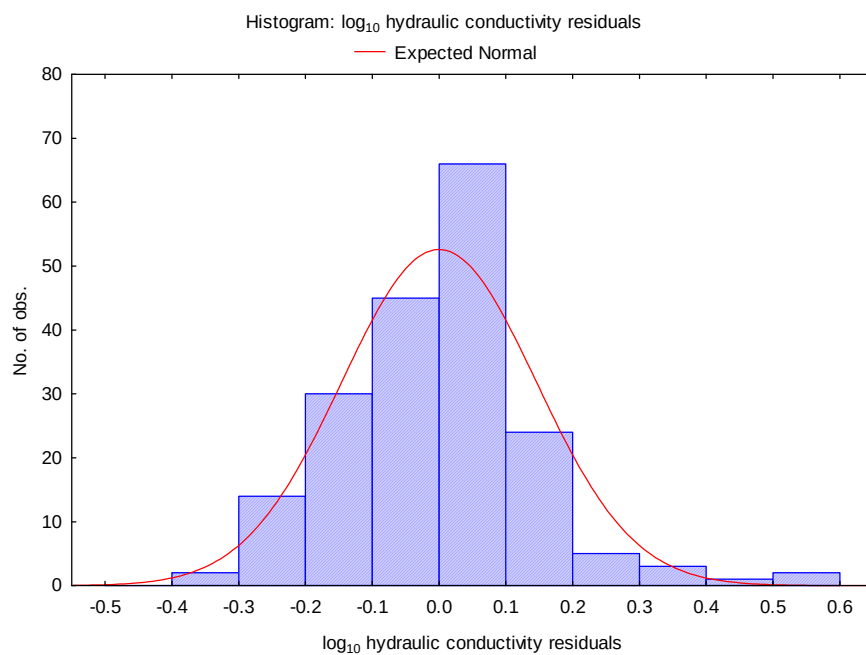
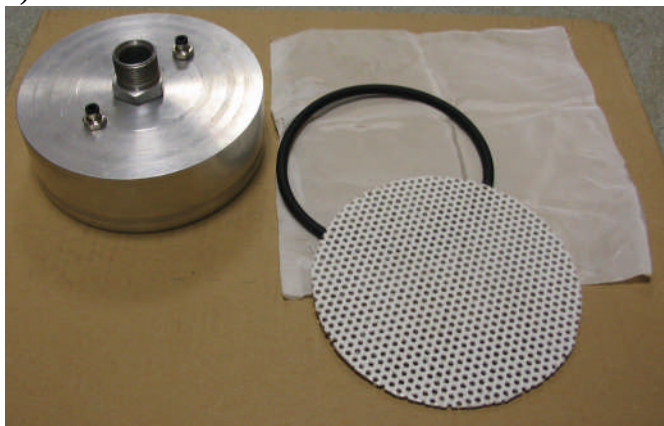


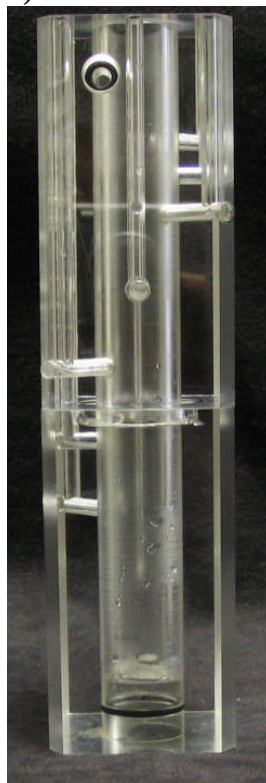
Figure 43. Histogram of the residues of the $\log_{10}$ -transformed hydraulic conductivity data measured in cm min^{-1} in the field.

Appendix 3. Photo –gallery

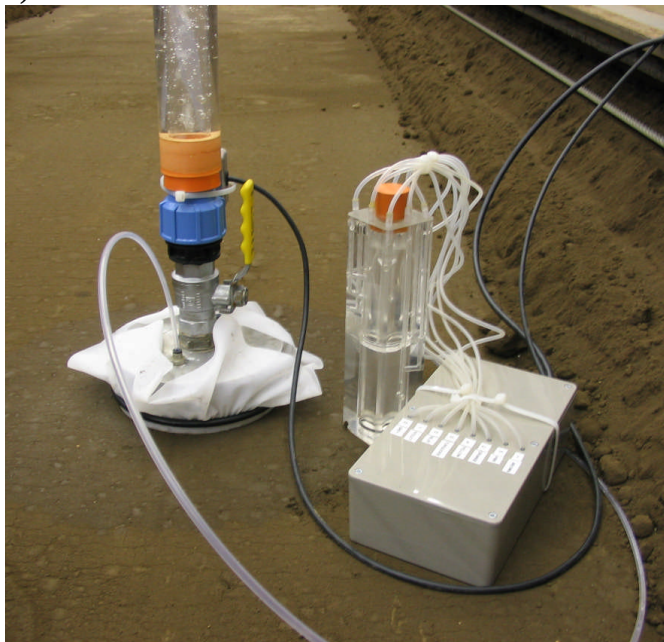
a)



b)



c)



d)

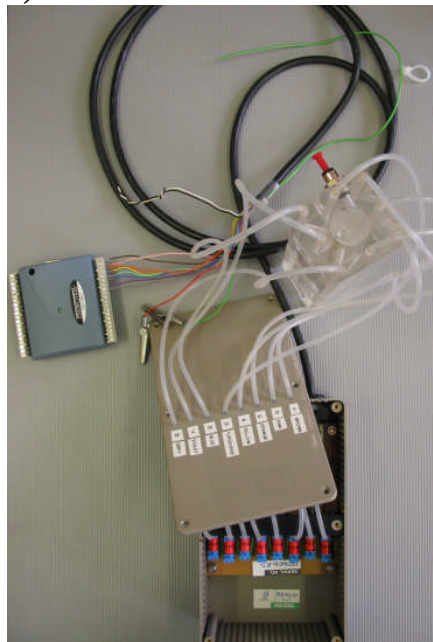


Plate 1. Main parts of the automated tension infiltrometer: aluminium base, plastic plate, rubber o-ring, nylon membrane (a), body of the Mariotte bottle (b), connection between the base and water reservoir, automated Mariotte bottle in operation (c), automation of the Mariotte bottle, solenoid valves (d).

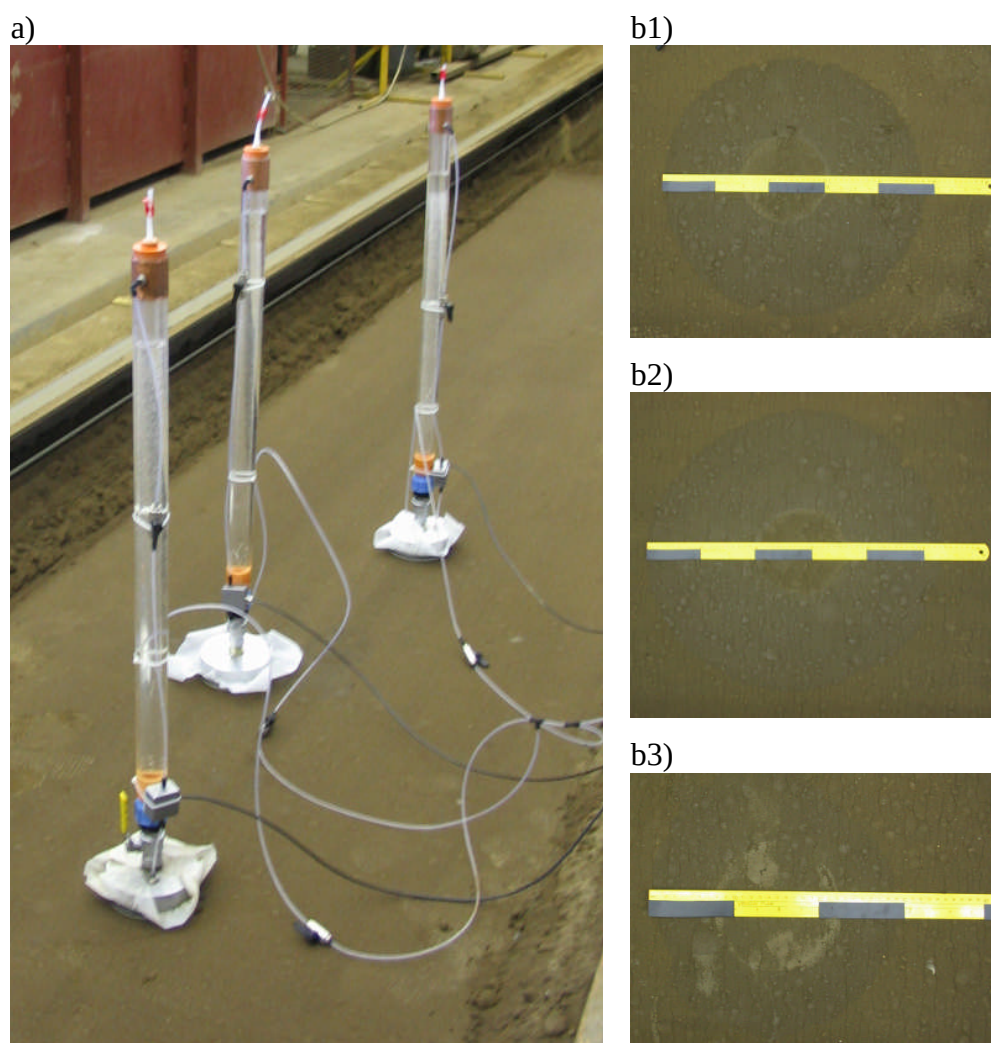


Plate 2. Automated tension infiltrometer experiment in the soil bin (a), wetted area after infiltration experiment for infiltrometers 1, 2, and 3 (b1, b2, b3).

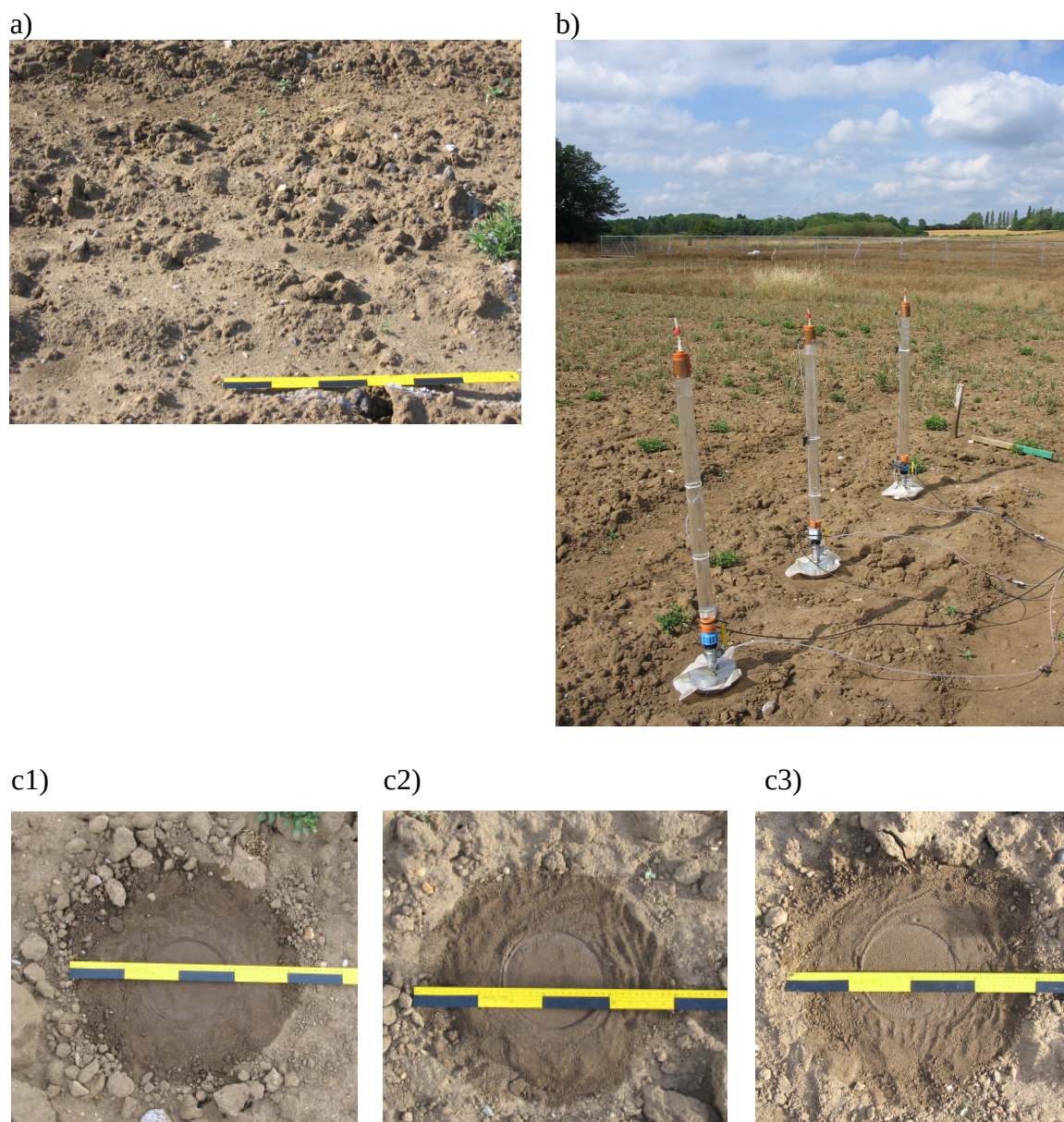


Plate 3. Field experiments – conventional plough; soil surface (a), experimental settings (b), wetted area after infiltration (c1, c2, c3).

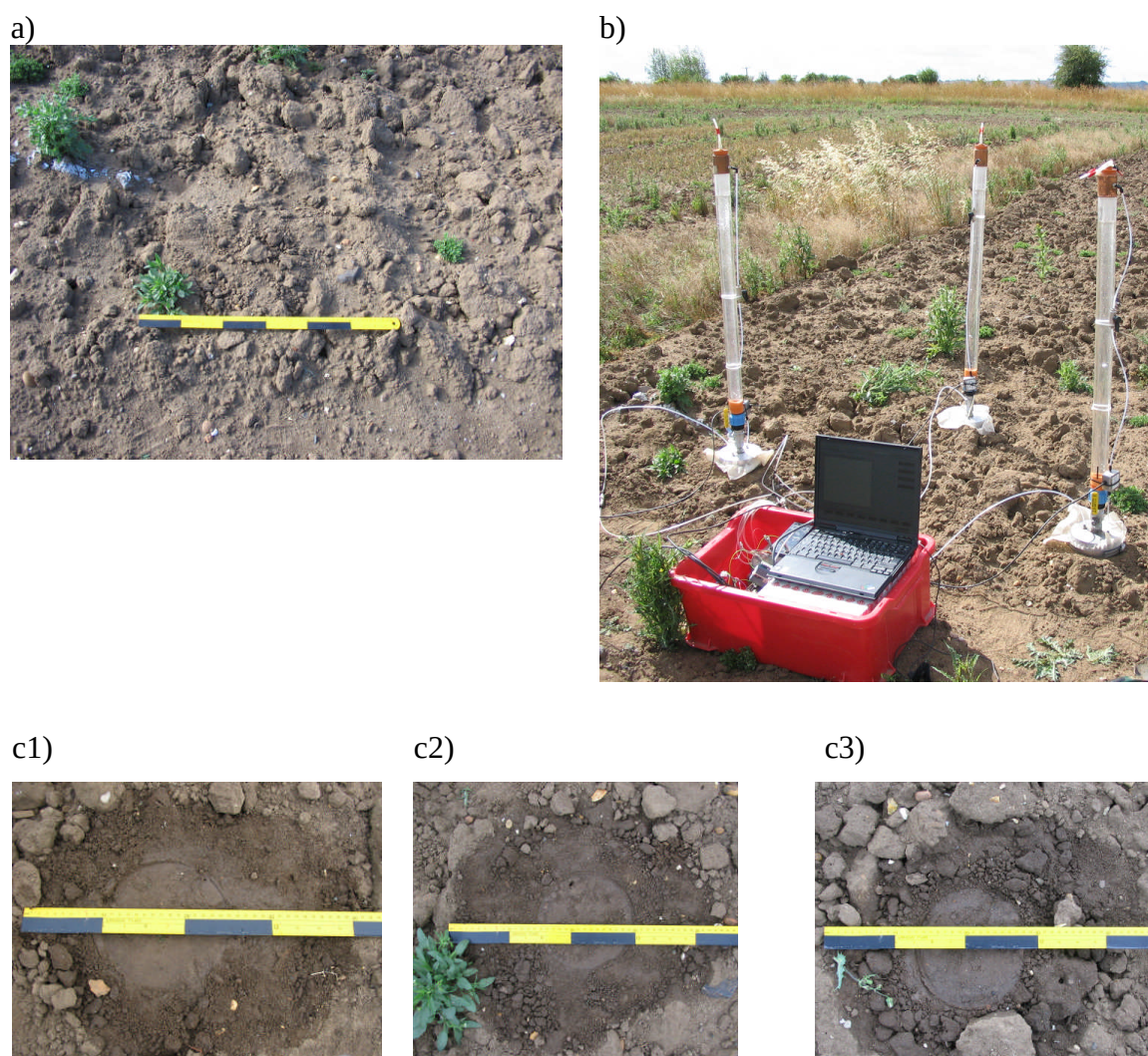


Plate 4. Field experiments – shallow plough; soil surface (a), experimental settings (b), wetted area after infiltration (c1, c2, c3).

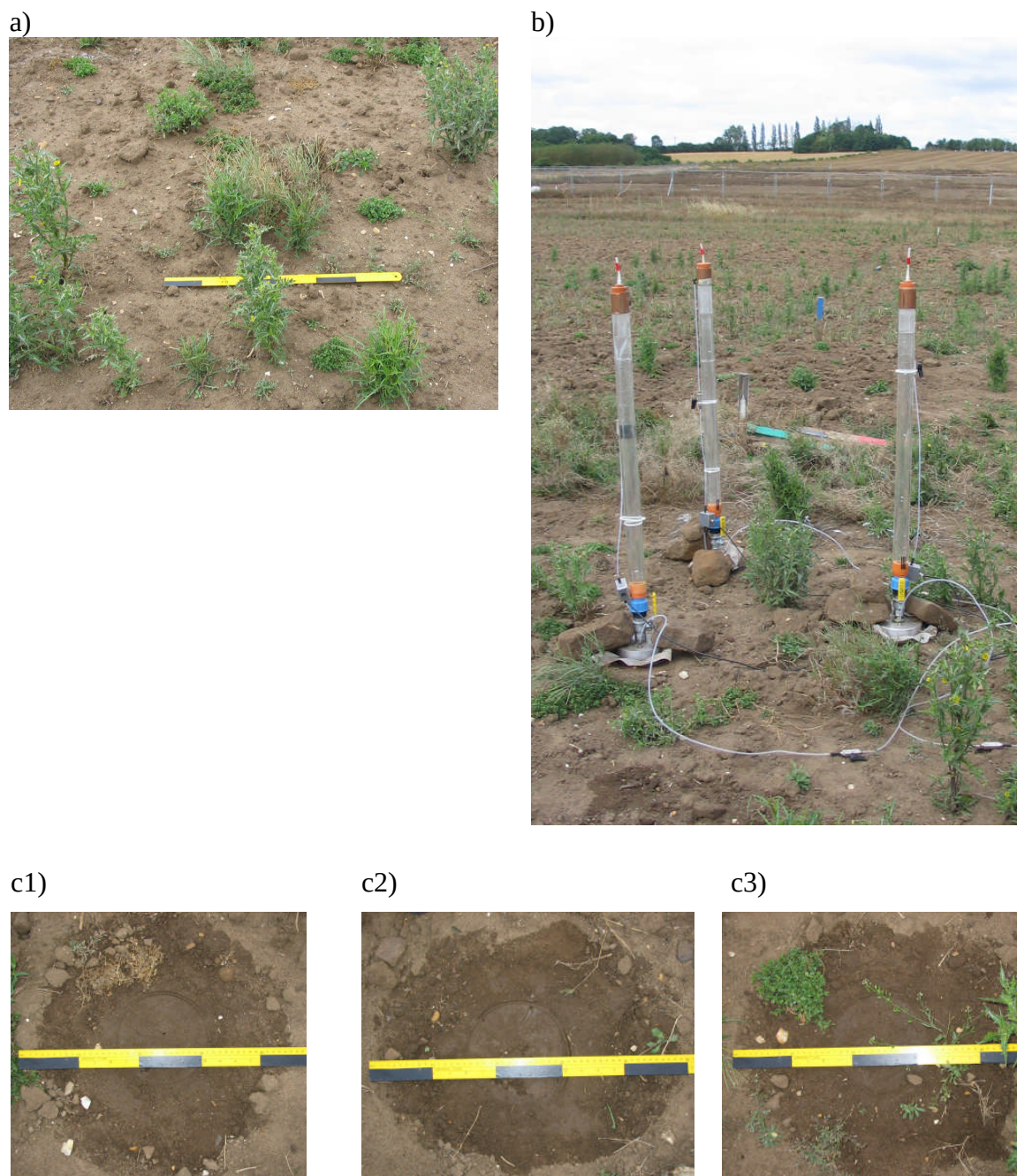


Plate 5. Field experiments – minimum tillage; soil surface (a), experimental settings (b), wetted area after infiltration (c1, c2, c3).

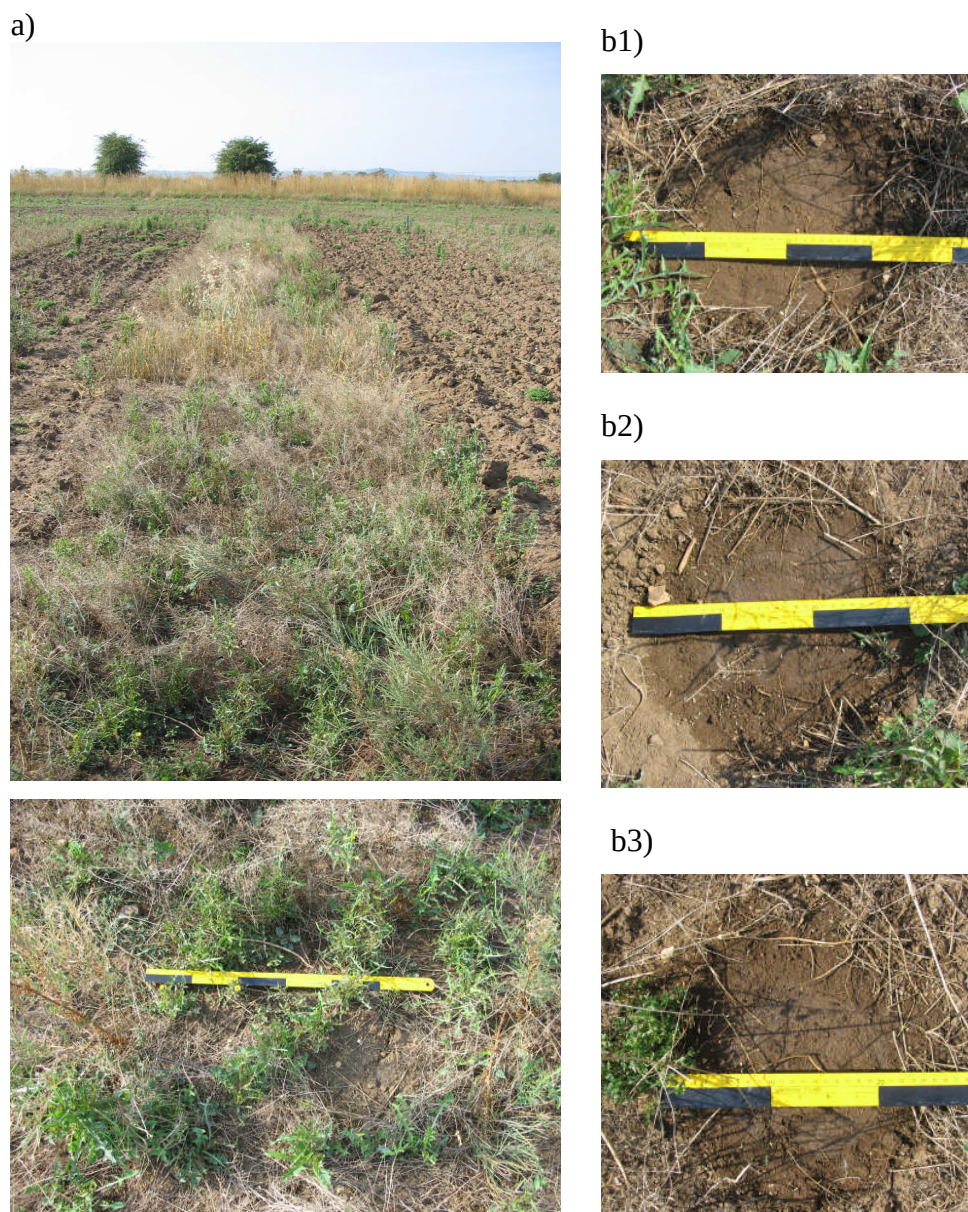


Plate 6. Field experiments – untreated and untilled soil (control); soil surface (a), wetted area after infiltration (b1, b2, b3).

a)



b1)



b2)



b3)



Plate 7. Field experiments – direct drill; soil surface (a), wetted area after infiltration (b1, b2, b3).

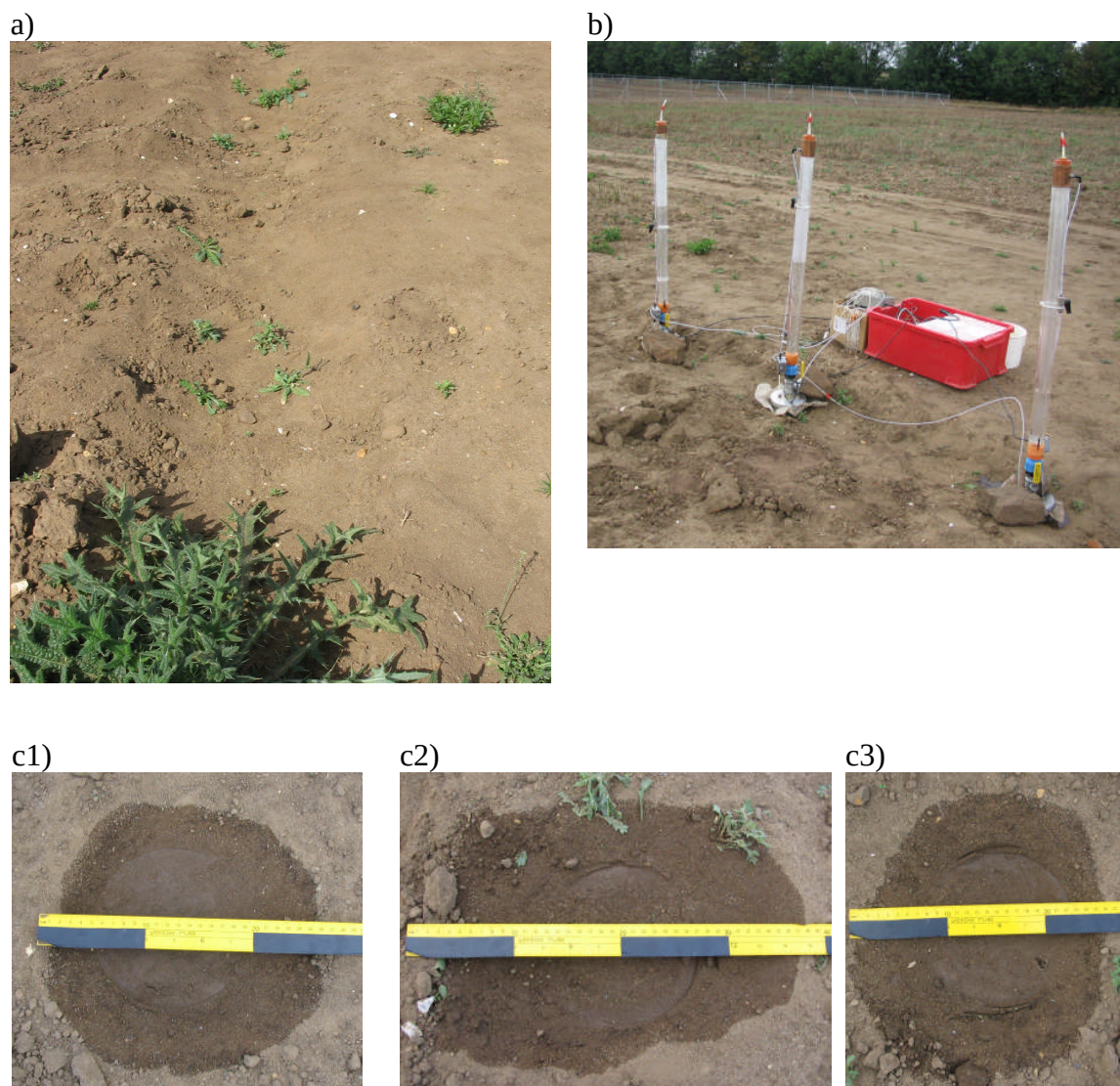


Plate 8. Field experiments – wheel-mark in conventionally tilled soil; soil surface (a), experimental settings (b), wetted area after infiltration (c1, c2, c3).

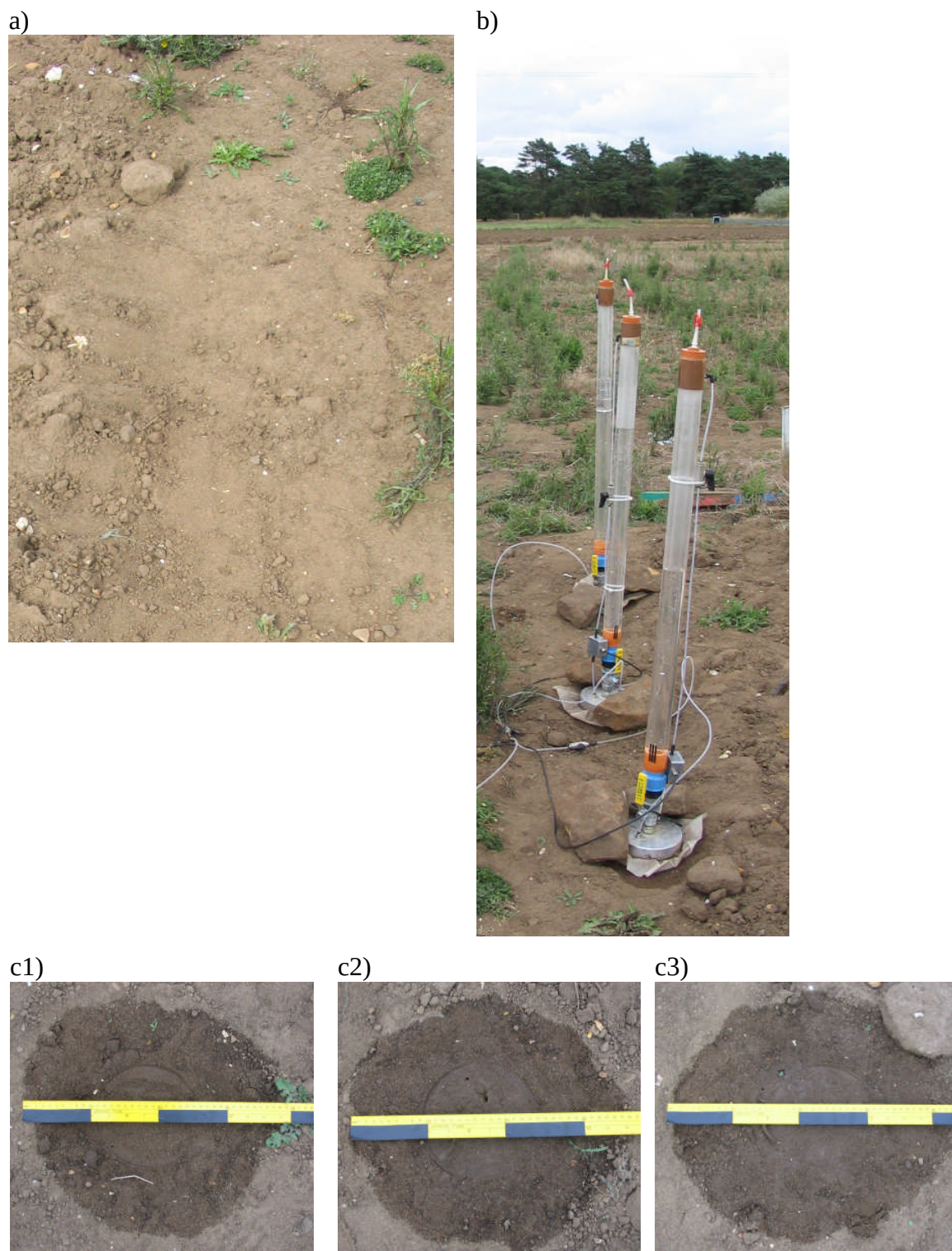


Plate 9. Field experiments – wheel-mark in soil where applied minimum tillage; soil surface (a), experimental settings (b), wetted area after infiltration (c1, c2, c3).

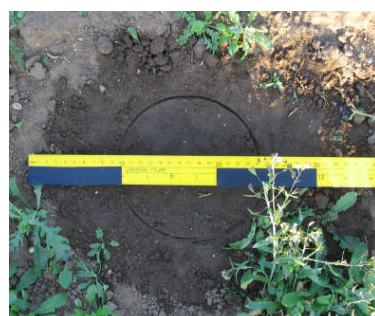
a)



b1)



b2)



b3)



Plate 10. Field experiments – wheel-mark in untilled soil; soil surface (a), wetted area after infiltration (b1, b2, b3).