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Master Thesis

Correlation Between Volumetric Water Content and Water Movement in a Soil Column Experiment

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Preface

This thesis was compiled at the Department of Water, Atmosphere and Environment, Institute of Hydraulics and Rural Water-Management at the University of University of Natural Resources and Applied Life Sciences, Vienna.

I would like to thank Univ.-Prof. Dipl.-Ing. Dr. Willibald Loiskandl and Ass.-Prof. Dipl.-Ing. Dr. Peter Cepuder for enabling the thesis and for their support. For hints and assistance at interpretation of the data and at laboratory work I thank Ass.-Prof. Dipl.-Ing. Dr. Gerhard Kammerer and Dipl.-Ing. Reinhard Nolz.

Special thanks go to my wife Birgit, who supported me strongly during my studies and to my sister-in-law Silvia, who always offered accommodation during my stays in Vienna.

Kurzfassung

Hauptziel dieses Laborexperiments war es zu klären, ob vollautomatische profilierende FDR-Systeme zur Messung des Bodenwasseranteils die Bestimmung von Sickerwasserraten erlauben. Ein lufttrockener toniger Lehm wurde 50 cm hoch in eine Bodensäule mit 38 cm Durchmesser eingebaut und mit Tensiometern und Wasseranteilssensoren in fünf verschiedenen Tiefen ausgestattet. Über einen Zeitraum von 68 Tagen wurde in wechselnden Zugaberaten eine Bewässerungshöhe von 1600 mm aufgebracht. Das Modell zur Abschätzung der Sickerwasserrate wurde auf Basis des Gesetzes von Buckingham und des Modells von Mualem entwickelt. Der beobachtete kumulierte Sickerwasserfluss diente zur Kalibrierung des Modells. Im Prinzip war es möglich von der Wasseranteilsmessung auf den Bodenwasserfluss zu schließen. Während des Experiments verhinderten ein langsam ansteigender Wassergehalt und ein teilweise eingeschränkter Abfluss aus der Bodensäule eine völlige Übereinstimmung zwischen modellierten und beobachteten Sickerwasserflüssen.

Schlüsselwörter: Bodenwasserbewegung, Laborexperiment, Wasseranteilsmessung, FDR-EnviroScan-Sensoren

Abstract

Main task of this laboratory experiment was to investigate whether automatic FDR-Systems measuring volumetric soil water content in access tubes are suitable for estimation of seepage water rate. An air-dry sandy loam soil was filled 50 cm high into a column with 38 cm diameter and equipped with tensiometers and water content sensors in 5 depths. An irrigation water depth of 1600 mm was applied on the surface in varying rates for 68 days from April to June 2008. The model for estimating seepage rate from water content measurement was developed based on the law of Buckingham and the model of Mualem. The observed cumulative water flow was used for calibration. Basically it was possible to conclude from soil water content to soil water flow. During the experiment rising water content and a partly blocked water flow prevented a total match between modelled and observed seepage.

Key words: soil water movement, laboratory experiment, water content measurement, FDR EnviroScan-sensors

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1 Introduction

Water content, water tension (or matric potential) and hydraulic conductivity in soils are interdependent. Unsaturated hydraulic conductivity function is derived from the relation between water content and water tension. Unsaturated hydraulic conductivity of a soil is the most important hydraulic property for calculations concerning the water movement and further water balance components. Since the measurement of water content is less elaborate than the measurement of water tension, it would be advantageous to predict soil water movement, with desired accuracy only from water content, not needing data of water tension. Further easy operating water content sensors are available for the whole soil water content range. Automatic FDR-Systems measuring volumetric soil water content in access tubes are used for irrigation control or for monitoring the profile water content of landfill covers. To test the functionality of the field set up a laboratory experiment was performed to ensure controlled condition and omit negative field effects. Main objective of this laboratory experiment was to investigate whether these profiling systems are suitable for estimation of seepage water rate and what other parameters are needed.

2 Problem and Hypothesis

2.1 Problem

A soil column was irrigated for 68 days. A total irrigation depth of 1600 mm was applied on the surface in varying rates. Water content and water tension were measured in 5 depths. Objective of the work is to find a method to calculate the soil water movement only based on water content measurements. The method is tested with 5 Sensors in different depths of a laboratory-scale soil column. Each sensor is evaluated separately.

2.2 Hypothesis

Soil water movement can be predicted reliably from time series of measured values of a FDR-Sensor and additional soil parameters.

3 State of knowledge

3.1 Mathematical description of flow processes in the vadose zone

3.1.1 Potential theory

The potential theory is used to describe the energetic state of soil water.

Total potential ψ_t

The International Society of Soil Science, 1962 defines the total potential of soil water as "the amount of work that must be done per unit mass of water in order to transport reversibly and isothermally an infinitesimal quantity of water from a pool of pure water at a specified elevation at atmospheric pressure, to the soil water (at the point under consideration)". The total potential is made up of different partial potentials. If the gas pressure on soil water is equal to atmospheric pressure and if the osmotic potential is negligible, it is sufficient to look at the matric potential and the gravitational potential for considerations of water movement (Equation 1).

Equation 1

$$\psi_t = \psi_m + \psi_g$$

ψ_t: total potential of soil water

ψ_m: matric potential

ψ_g: gravitational potential

Matric potential ψ_m

Matric potential (ψ_m) is defined as the amount of work that must be done per unit quantity of pure water in order to transport reversibly and isothermally an infinitesimal quantity of water, identical in composition with the soil water, from a pool at the elevation and the external gas pressure of the point under consideration, to the soil water (International Society of Soil Science, 1962). Matric potential describes the influence of the soil matrix on the movement of water in the soil. The forces caused by matrix effects are the stronger the smaller the volumetric water content is. In order to prevent confusion due to the negative sign of the matric potential, some authors prefer to replace matric potential by water tension *h*. Water tension is identical to the matric potential, but has a positive value in an unsaturated soil (Kammerer and Loiskandl, 2008).

Gravitational potential ψ_g

Gravitational potential is "the amount of work that must be done per unit mass of water in order to transport reversibly and isothermally an infinitesimal quantity of water from a pool containing a solution identical in composition to the soil solution at a specified elevation at atmospheric pressure, to a similar pool at the elevation (International Society of Soil Science, 1962). If the specific weight of water is used as reference unit, the gravitational potential corresponds to the vertical distance z to the reference level.

3.1.2 Gradient of total potential in soil columns

Soil water is moving if there are spatial differences in total potential. Soil water movement is directed from positions with a high potential towards positions with a lower potential. Different potentials in a soil cause a water flow, that seeks to compensate the difference in potential. Water flow ends when the total potential is equal at all points. It is assumed that during the experiment the gas pressure on soil water in the soil column is equal to atmospheric pressure and the osmotic potential is negligible.

Gradient of total potential in soil columns with unsaturated flow

The object of experimentation was a soil column with unsaturated flow. The typical distribution of total potential, matric potential and gravitational potential in soil column with unsaturated steady state flow is described in Kammerer and Loiskandl, 2008 (Figure 1). The soil column of the experiment is equipped with suction cups at the bottom. For this reason there is very likely no capillary fringe.

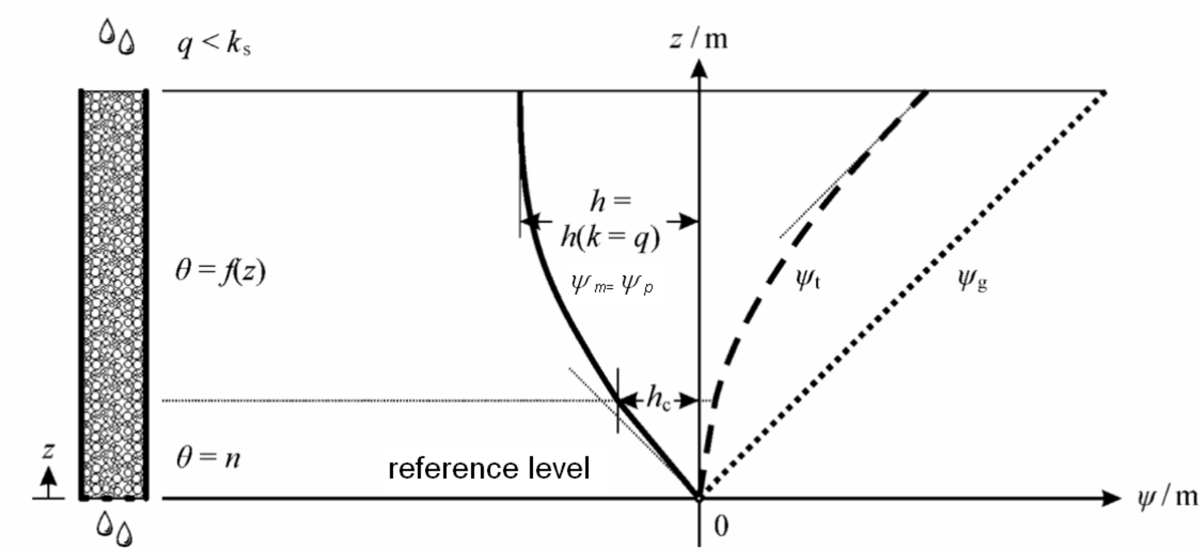

Figure 1: Total potential (ψ_t), matric potential (ψ_m) and gravitational potential (ψ_g) in a soil column with unsaturated flow and capillary fringe (Kammerer and Loiskandl, 2008)

3.1.3 Hydraulic conductivity in a saturated soil – Darcy's law

Water movement in a soil is caused by differences in the hydraulic potential and is affected by the conductivity of the soil. In accordance with Darcy's law (Equation 2) water flow is directly proportional to the gradient of potential. The proportionality factor is the saturated hydraulic conductivity k_s.

Equation 2

$$q = k_s * \text{grad}\,(\psi_h)$$

q: specific flow

k_s: saturated hydraulic conductivity

grad (ψ_h): total potential gradient

3.1.4 Hydraulic conductivity in an unsaturated soil – Buckingham's law

Buckingham's law (Equation 3) applies for unsaturated soils. Here the total potential gradient is the driving force for water movement. The hydraulic conductivity of unsaturated soils may be either related to the water content $k = f(\theta)$ or water tension $k = f(h)$.

Equation 3

$$q = k(\theta) * grad\ (\psi_t)$$

q	specific flow
$k(\theta)$	unsaturated hydraulic conductivity
$grad\ (\psi_t)$	total potential gradient

The flow section reduces with decreasing water content. Larger pores desaturate and do not contribute to the flow any more, additionally the water moves in smaller capillaries with higher friction and a longer flow path due to greater tortuosity. Both factors result in reduced hydraulic conductivity. With increasing water content the hydraulic conductivity increases. At saturation hydraulic conductivity reaches the maximal and constant hydraulic conductivity k_s.

3.1.5 Changing permeability of a soil

For various reasons the permeability of a soil may change in the course of an infiltration experiment. Baumgartner, Liebscher and Benecke, 1996 distinguish event-driven and non-event-driven factors (Table 1). The change of infiltration rate over time is exemplary shown in Figure 2.

Table 1: Factors that can influence the infiltration rate of a soil (Baumgartner, Liebscher and Benecke, 1996 cited in Schack-Kirchner, 2006)

Event-driven factors	Non-event-driven factors
water content and water tension at the beginning	stratification of a soil
precipitation intensity	soil structure
progress of precipitation	distribution of pore size
energy of raindrops (splash)	total pore volume
incrustation and siltation	thickness of humus layer
swelling and shrinking	inclined ground
inclusion and flow of soil air	intensity of soil compaction
hysteresis of soil characteristics	water retention curve
land use	unsaturated hydraulic conductivity
vegetation and growth-stage	
saturated hydraulic conductivity	

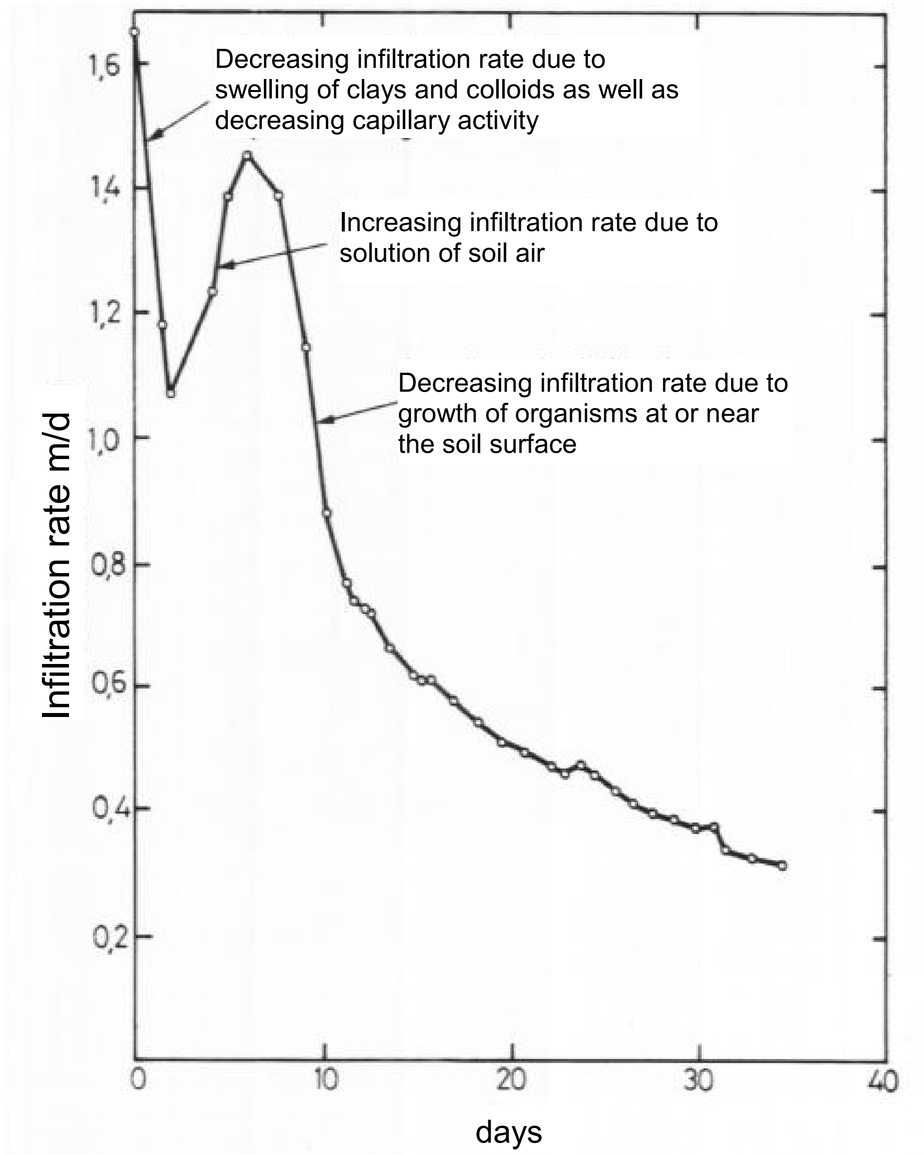

Figure 2: Long-term infiltration experiment at a soil column that has been flooded for more than a month (Matthess and Ubell, 2003, cited in Schack-Kirchner, 2006)

3.1.6 Relationship between water content and water tension

The graphical display of the relationship between water content and water tension is called soil-water characteristics or retention curve. This relationship reflects pore size distribution which is also elementary for estimating the unsaturated hydraulic conductivity. The drainage starts with emptying large pores and progresses to smaller pores consecutively. In smaller pores water is bound stronger, equal to a higher water tension. A certain water tension corresponds therefore to an equivalent average pore diameter. There is a variety of approaches to describe the relationship between water content and water tension as closed function. The model of van Genuchten (Genuchten, 1980) is widely spread. This model can be applied on different soil types and allows to integrate measured data in a flexible way. Equation 4 shows the mathematical relationship between water tension and volumetric water content. θ_s and θ_r are parameters with a physical background, nevertheless they are frequently considered as pure fitting parameters like α and n. The assumption m=1-1/n is frequently met and enables an analytical evaluation of Mualem's formula.

Equation 4

$$\theta \ \Psi = \begin{cases} \theta_r + \dfrac{(\theta_s - \theta_r)}{\left[1 + (\alpha |\psi|)^n\right]^m} & for\ \psi > 0 \\ \theta_s & for\ \psi \le 0 \end{cases}$$

$\theta \ \Psi$ = volumetric water content at certain water tension

θ_s = saturated water content

θ_r = residual water content

α, n = fitted parameter

$m = 1 - \dfrac{1}{n}$

Figure 3 shows typical shapes of the water retention curve for clay, sand and silt (ordinate with logarithmic scale). The parameters α, n, (θ_s, θ_r) are fitted through adjustment to measured data pairs. Mangels, 2000 explains the influence of the different parameters on the curve shape.

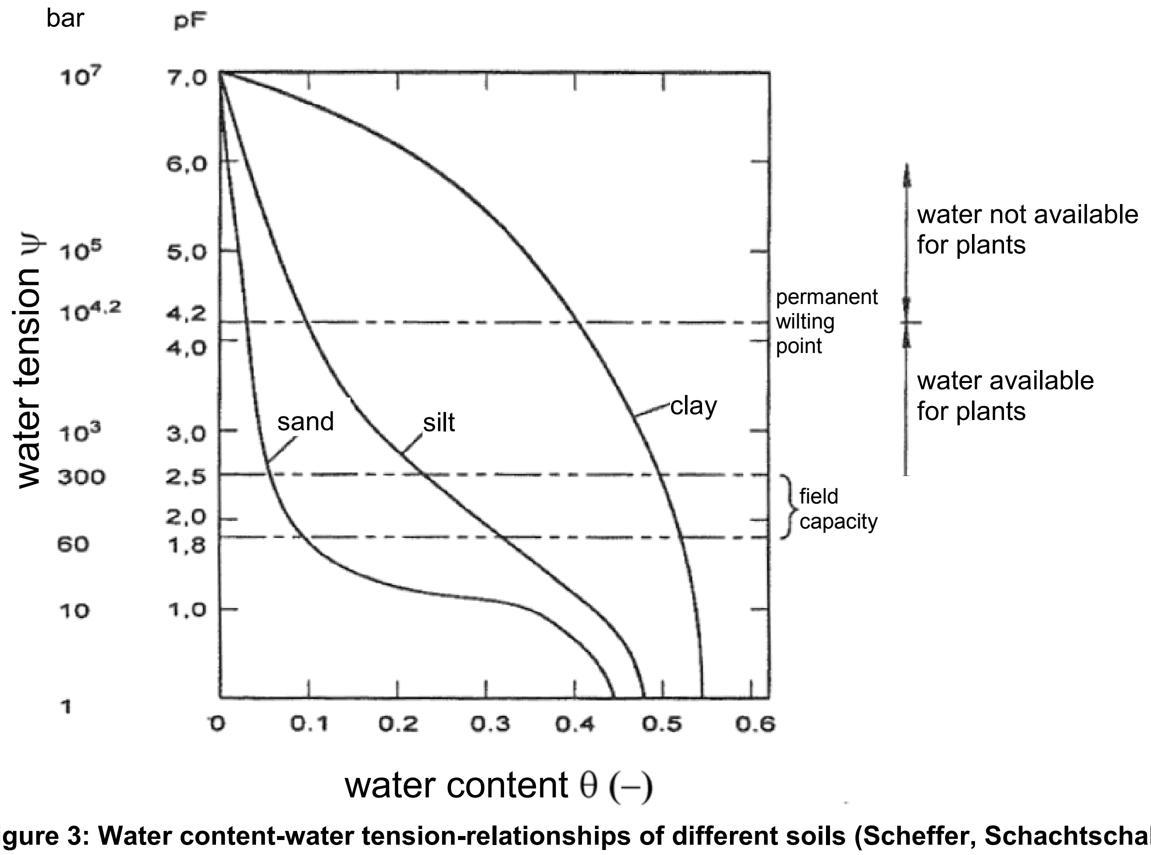

Figure 3: Water content-water tension-relationships of different soils (Scheffer, Schachtschabel and Fischer, 1992)

3.1.7 Relationship between water content and hydraulic conductivity

The hydraulic conductivity is the most important soil property for issues linked with water balance. The experimental determination of the unsaturated hydraulic conductivity is elaborate. An easier way is to derive the function from the retention curve.

The model of Mualem (Mualem,1976) (Equation 5) is frequently used for this purpose. The parameters are identical with the model of Genuchten. The relative hydraulic conductivity is calculated using effective saturation (Equation 6) and the empirical factor m from the Genuchten-model (chap. 3.1.6). The tortuosity factor τ is 0,5, according to Mualem,1976. If the saturated conductivity k_s is known, Equation 7 allows the calculation of the unsaturated conductivity k_u.

Equation 5

$$k_r = S_e^{\tau}(1-(1-S_e^{1/m})^m)^2$$

k_r : relative conductivity

S_e : effective saturation

t : tortuosity (according to Mualem: 0,5)

m : empirical parameter

Equation 6

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r}$$

S_e : effective saturation

θ : water content

θ_r : residual water content

θ_s : water content at saturation

Equation 7

$$k_u = k(\theta) = k_r * k_s$$

k_u : unsaturated conductivity

k_r : relative conductivity

k_s : saturated conductivity

3.2 Calculation of percolating water from measurement of water content

Since capacitive probes for measuring water content in soils have been introduced, several methods were developed to model the movement of soil water without referring to the elaborate measurement of water tension.

The application of those methods is diverse. Brandelik, Schuhmann and Köninger, 2004 used water content sensors in a specified soil layer to detect and quantify percolating water underneath the cover layer of a landfill. Mangels, 2000, Scheuermann, 2005 and Haselsteiner, 2007 tried to quantify soil water movement within dykes. Schindler, Fank and Müller, 2009 developed a method for estimating percolating water in open land and tested it at different lysimeter stations. The methodology for all approaches is more or less identical.

a) Exclude influence of unknown water movement components e.g. evaporation

The measurement of the volumetric water content should take place in zones, where the movement of soil water is directed towards the groundwater. If this is the case, the change of the measured volumetric water content is caused solely by percolating water. Schindler, Fank and Müller, 2009 propose to measure water content in soil depths below the water divine where there is no rising water caused by plants or capillary action. If the total potential gradient in the measuring depth is known, this data can be used for verification: A positive total potential gradient indicates a downward water movement. According to Schindler, Fank and Müller, 2009 the hydraulic divine is usually situated permanently in depths above 3 m under grassland and above 5 m under forests. In laboratories or lysimeters such depths can hardly be achieved. Here plastic covers on top of the soil column prevent evaporation which would cause rising water (Brandelik, Schuhmann, Köninger, 2004). In contrast to the instantaneous profile method (Hillel, Krentos and Stylianou, 1972) this cover does not prevent further irrigation.

b) Establish functional relationship between water content and water tension

To model water tension depending on water content, in many cases the model of Genuchten is used.

c) Establish functional relationship between water content and relative hydraulic conductivity

The model of Mualem is used to derive the relationship between water content (or rather effective saturation) and relative hydraulic conductivity, using the parameters of the Genuchten-curve. If the saturated hydraulic conductivity k_s is known, the unsaturated hydraulic conductivity k_u can be calculated.

d) Verify the calculated conductivities by measured data

If rates of percolating water are known, those can be used to verify the calculation model. For field trials the percolating water has to be calculated from water balance (percolating water = precipitation – evaporation – change of water content in soil – surface runoff)

e) Use of correction factor

Schindler, Fank and Müller, 2009 first calculate a theoretic relative hydraulic conductivity for a time interval of one day using the model of Mualem. Buckingham's law combined with a theoretical saturated hydraulic conductivity k_s and constant total potential gradient results in a daily theoretic amount of percolated water. Summation of these daily amounts over a certain period delivers a theoretic cumulative water volume per area.

A correction factor is calculated as quotient of this calculated outflow water sum and the observed amount of percolated water during the same period. Multiplication of the above Buckingham-equation with this correction factor resulted in many cases in accurate predictions of the amount of percolated water.

4 Data basis, materials and methods

4.1 The experimental set-up

According to Kammerer and Cepuder, 2007 the soil column consists of a PVC sewer pipe, which stands vertically on a balance. The pipe measures 1 m in length and 38 cm in diameter. In a height of 45 cm a wooden support plate was installed, on this plate 6 suction cups were laid out in a star shaped way. They are connected with bottles for water collection and a vacuum tank via connector pipes. In the center of the column there is an access tube for the Sentek device. The suction cups were covered with 50 cm of air dry loamy soil from Groß-Enzersdorf. Great importance was paid to fill the pipe in a homogenous way. The particle size distribution of the soil is characterized by mass fractions 34% sand, 44% silt and 19% clay (for grading curve see appendix 11.1). In natural stratification the soil showed a dry density of ρ_d = (1,45 ± 0,05) g/cm³. In the soil column by manual compaction a density of ρ_d = 1,40 was achieved. In total 78,40 kg or 55,47 dm³ of air dry soil mass with a volumetric water content of 1,2% was filled 50 cm high into the soil column.

A carrier board with 5 EnviroSCAN-FDR-Sensors were inserted into the access tube. The measuring depth of the sensors is 5 cm, 15 cm, 25 cm, 35 cm and 45 cm below the soil surface. The tensiometers are inserted directly into the soil in circular form with pressure transducers in depths of 8 cm, 18 cm, 28 cm, 38 cm and 48 cm.

The irrigation of the soil column is made through a microporous pipe on top of the soil column. To prevent evaporation the soil was covered with a plastic foil during experiments.

Figure 4: Test equipment (soil column, tensiometer shaft, carrier board for FDR-probe, recording module, vacuum tank and water collection bottles)

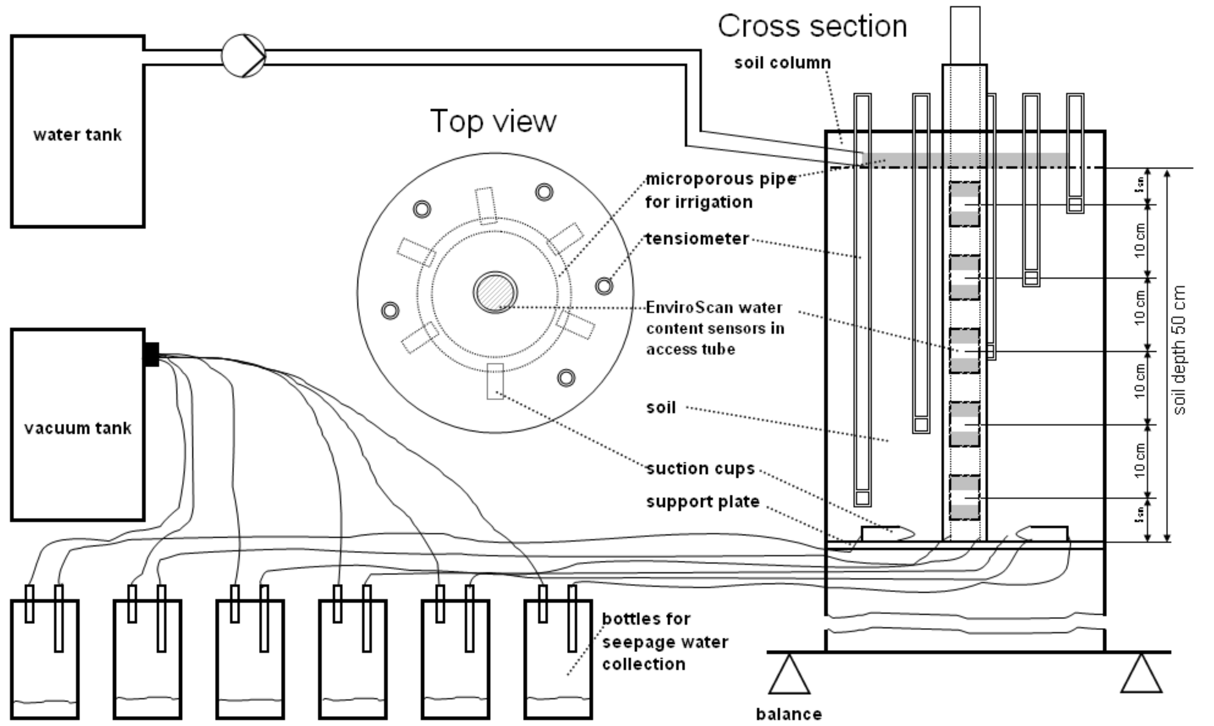

Figure 5: Top view and cross-section of the soil column with measuring devices, irrigation and sorption installations

4.2 Measuring devices

The amount of irrigated and percolated water was measured by weighing the water tank and the bottles for seepage water collection. In the soil column volumetric water content and water tension was recorded in a fine time resolution.

4.2.1 Weighing

The soil column stands on a wooden decimal balance. The balance was tared before the first irrigation. So the balance reading is identical with the mass of water that is instantaneously stored in the soil minus the initial water content (air-dry).

The amount of irrigation water was measured by weighing the storage container, percolated water was determined by weighing the water bottles that were connected to the suction cups and to the vacuum tank.

The weighing and the documentation of the vacuum in the tank was done every 1 to 3 days.

4.2.2 Tensiometer

Tensiometers equipped with pressure transducers serve the continuous measuring of water tensions in soils. The dryer the soil, the higher the potentials of the adsorption and capillary forces. Those forces bind the water in a soil. Tensiometers are designed for measuring water tensions from 0 to 850 mbar. The used tensiometers consist of a tube with a porous ceramic tip (maximal pore diameter 1 µm), a pressure measuring device at the opposite end and a closure cap (Figure 6). Water can enter or exit via the pores. When the soil is drying out, minimal amounts of water move into the soil, which cause an underpressure in the tensiometer tip that is registered by the manometer and the connected data logger. Watering of the soil lowers the underpressure in the tensiometer tip. 5 tensiometers type T6 (UMS) were installed in the soil column.

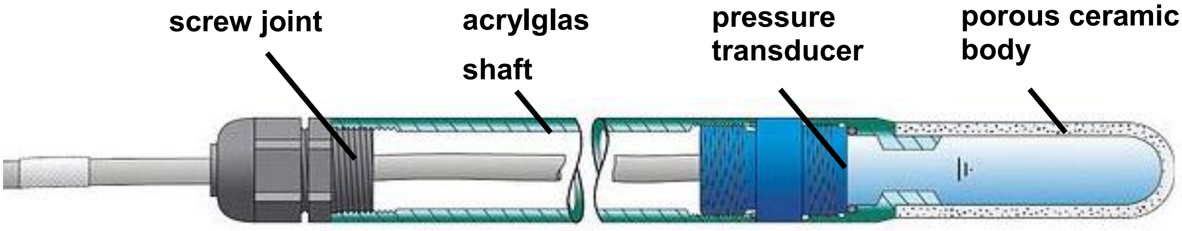

Figure 6: Scheme of a tensiometer (Source: www.ums.de)

4.2.3 Capacitive humidity sensor

The measuring principle relies on „Frequency Domain Reflectometry“ (FDR). The two metal plates of a sensor use the soil as capacitor. When connecting this capacitor together with an oscillator to form an electrical circuit, changes in soil moisture can be detected by changes in the circuit operating frequency. The oscillator frequency is swept under control within a certain frequency range to find the resonance frequency (at which the amplitude is greatest), which is a measure of water content in the soil.

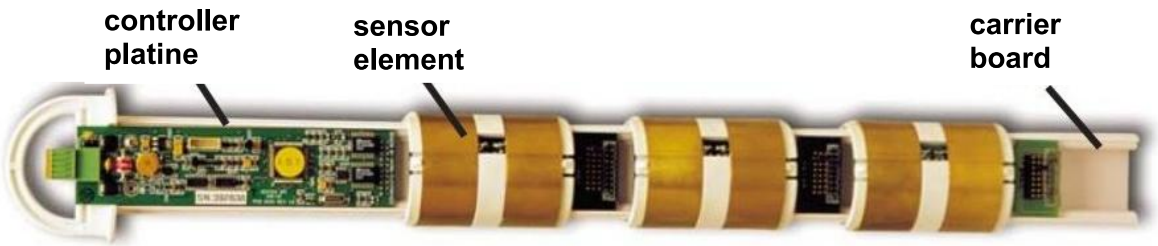

Figure 7: EnviroScan profile probe with 3 sensor elements, without measuring tube (Source: www.ums-muc.de)

For recording the humidity in the soil column the Sentek – EnviroSCAN measuring system was used. This system allows the continuous measurement of the volumetric water content in 5 different depths .

5 Experiment

During the course of the experiment irrigation rate varies as well as the vacuum in the tank supplying the suction cups (Figure 8).

Records begin on 2008-04-11 at 12:00. The soil column is irrigated continuously via the porous tube. The water application rate is on a higher level (1,45 declining to 1,24 mm/h) from the beginning till May 15. After a short rise irrigation is reduced at rates between 0,62 and 0,65 mm/h. From April 18 vacuum amounts 0,4 bar. On 23.05 the vacuum in the vacuum tank drops from 0,375 to 0,2 bar. From May 26 to May 30 vacuum rises on a constant level of 0,3 bar being followed by a drop to 0,2 bar on June 1. The volumetric water content in 5 depths is logged continuously during the experiment. Tensiometer data are recorded from May 7. The experimental protocol notes “water leakage” from soil column on the following days: 15.05, 6.06, 16.06, 17.06, 18.06

Table 2 shows the time series of recorded data during the experiment. Evaluation focuses mainly on the period between May 7 and June 18.

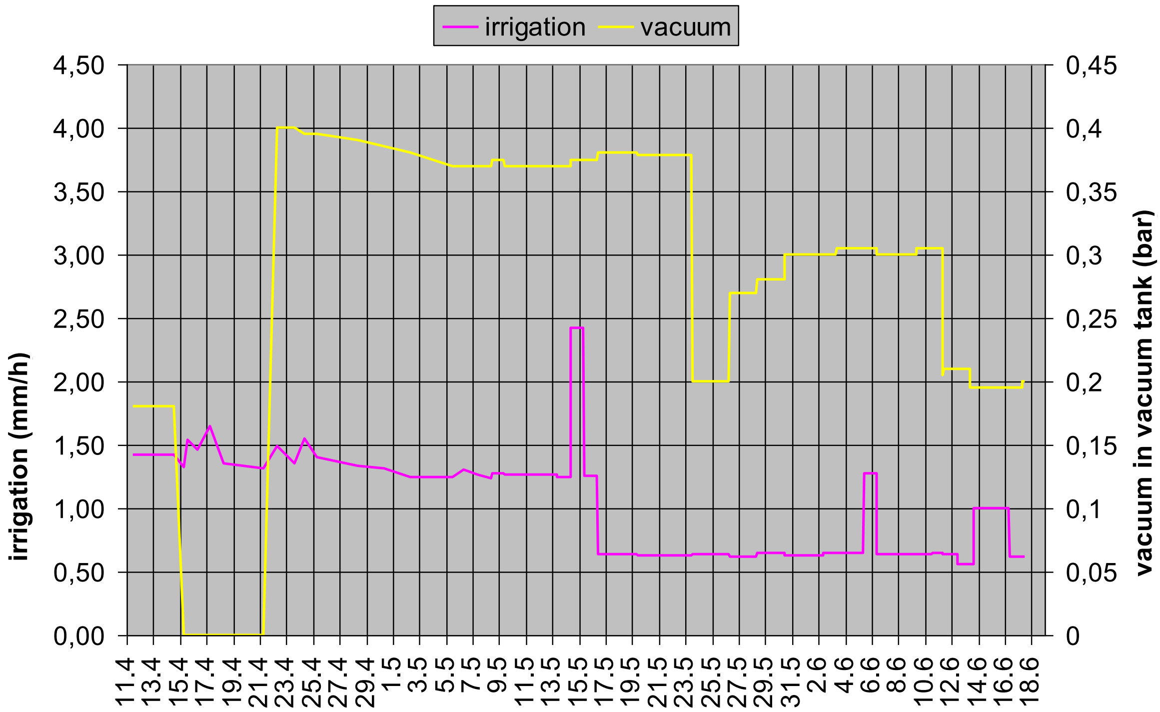

Figure 8: Course of irrigation rate and course of vacuum in the vacuum tank that is connected to the suction cups

Table 2: Measured state quantities, interval of recording during the experiment and the way of collecting the data

Measured data	Interval of recording	Way of collecting data
water contents in 5 depths	hourly	logged automatically
water tension in 5 depths	hourly (from May 7)	logged automatically
irrigation	1 to 3 day intervals	weighing of water tank
outflow	1 to 3 day intervals	weighing of the bottles for seepage water collection
mass of water in soil column	1 to 3 day intervals	weighing of the soil column, balance reading corresponds to mass of soil water
vacuum in vacuum tank connected to the suction caps	1 to 3 day intervals	reading of pressure gauge

6 Results

6.1 Determination of total water content in the soil column by weight

The soil column was weighed every one to three days during the course of the irrigation experiment. Due to the taring in the beginning the balance reading automatically returns the actual weight or volume of water stored within the soil column. Dividing „volume of stored water“ and „soil volume“ results in the average volumetric water content. Soil volume was calculated according to Equation 8

Equation 8

soil volume **=** *vol. of column (soil height 50 cm) – vol. of access tube– vol. of 5 tensiometers*

On May 8, tensiometers were changed, thereby the taring went wrong. A one time addition of 14,19 kg (assumption: water content in soil column between May 8 and 9 is identical) could compensate the mistake. (Figure 9, blue curve: wrong taring, rose curve: corrected taring).

6.2 Test of different calibration functions for EnviroScan-sensors

The EnviroScan sensors deliver a raw signal which has to be conversed by means of a calibration function into volumetric water content. Equation 9 is used to normalise the raw signal and Equation 10 converts the normalised signal into water content.

Equation 9

$$SF(F_{Soil}) = \frac{F_{Air} - F_{Soil}}{F_{Air} - F_{Water}}$$

SF: scaled frequency

F_{Air}: oscillation frequency in air

F_{Soil}: oscillation frequency measured in the soil

F_{Water}: oscillation frequency in water

Equation 10

$$\frac{\theta(SF)}{\%} = \left(\frac{SF - c}{a}\right)^{1/b}$$

3 different sets of calibration parameters for the FDR-sensors are compared in this chapter. To avoid confusion they are labelled as:

Set 0: Unknown parameter set, different from standard parameter set, applied to the raw signal by the EnviroScan logger device during the experiment

Set K1 to 6: 6 parameter sets, proposed by Kammerer, 2005 as an alternative for standard parameter set

Set S: Standard parameter set for EnviroScan FDR-Sensors

Different parameter sets were tested with the objective to match profile water content determined from FDR-readings and by weighing. According to Kammerer and Cepuder, 2007 it was assumed that each sensor represents a profile of 10 cm. As the soil volume in each layer is identical, the profile water content in the soil column is calculated from the arithmetic mean of the five individual water contents Equation 12.

Equation 11

$$\theta_{av\_bal} = \frac{m_{w\_bal}}{\rho_W \cdot V_{column}}$$

θ_{av_bal} : volumetric water content calculated from column weight

m_{w_bal} : weight of soil water in column

ρ_W : density of water

V_{column} :

Equation 12

$$\theta_{av\_FDR} = \frac{1}{\sum \Delta z_i} \cdot \sum_{i=1}^{k} \Delta z_i \cdot \theta_i$$

for $\Delta z_i = const.$:

$$\theta_{av\_FDR} = \frac{1}{k} \cdot \sum_{i=1}^{k} \theta_i$$

θ_{av_FDR} : volumetric water content calculated from FDR signal

z_i : depth of profile represented by FDR signal

k : number of profiles/sensors in soil column

6.2.1 Parameter set 0 compared to set K1 to K6

Parameter set 0 is not known, however the raw signal was logged. That allows to test different calibration functions. Table 3 shows parameter sets K1 to K6 that Kammerer et al., 2005 found for a clay silt. Each of the 6 sets of parameters was tested with the raw signals of the EnviroScan sensors. Despite the considerable divergence of the parameter sets the resulting water contents for the sets K1 to K6 are corresponding. For this reason the results of set K1 are shown as an example.

Figure 9 displays average water content calculated from column weight (rose line), water content calculated upon parameter set 0 (red line) and water content calculated by using the parameter K1 set (green line). Figure 10 shows the water contents for each sensor using set 0 and set K1.

Table 3: Parameter sets for a calibration function of EnviroScan FDR-Sensors, determined in a clay silt (Kammerer et al., 2005)

	New Values F Air	New Values F Water	a	b	c
Set K1	36.078	24.919	2,1480	0,0682	-1,8289
Set K2	36.424	24.936	0,8027	0,1595	-0,5231
Set K3	36.519	25.098	5,5157	0,0294	-5,2225
Set K4	36.457	24.923	2,9008	0,0532	-2,6048
Set K5	36.209	24.945	1,0364	0,1258	-0,7252
Set K6	36.190	25.109	0,1957	0,4040	0,0285

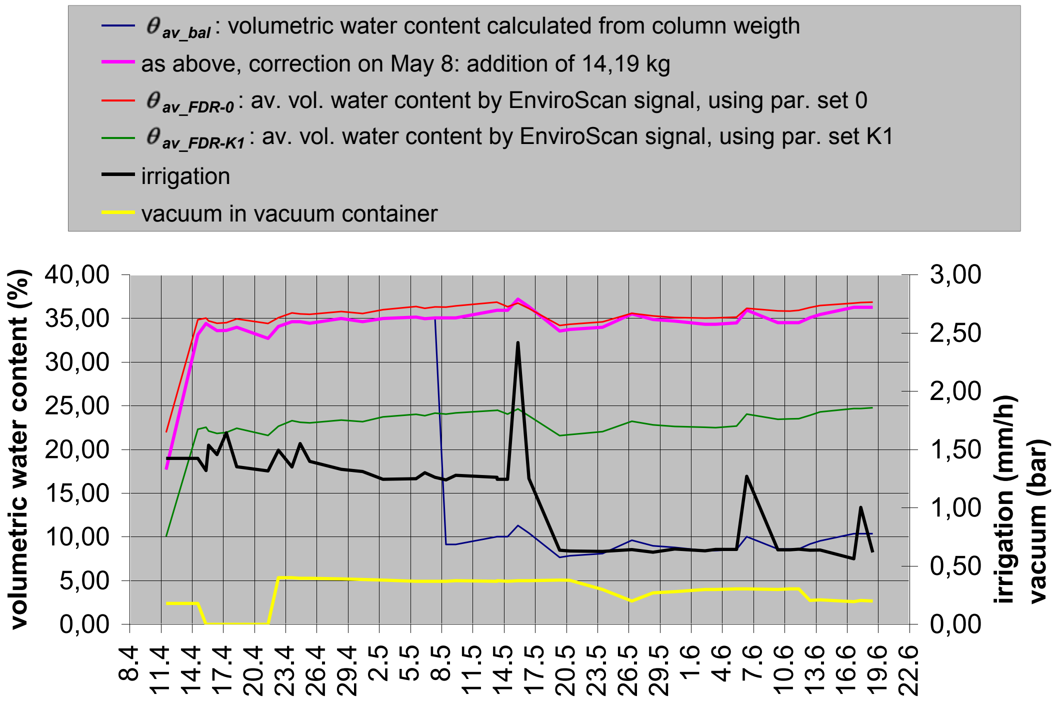

Figure 9: Comparison of water content determined from balance reading θ_{av_bal} (rose line) and water content by EnviroScan measurement with parameter set K1 (green line)

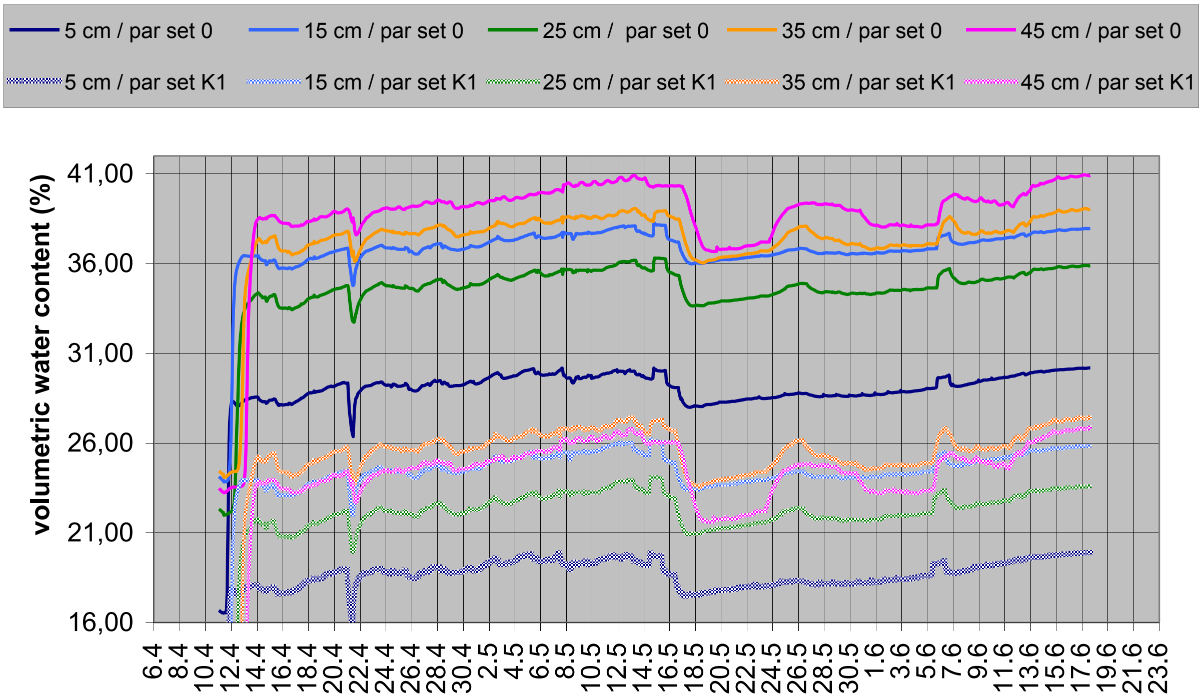

Figure 10: Comparison of the water contents by EnviroScan using parameter set 0 and parameter set K1

The parameter sets K1-6 did not result in a better match between θ_{av_bal} and θ_{av_FDR}.

θ_{av_FDR-0} corresponds to θ_{av_bal} whereas θ_{av_FDR-K1} is clearly too low.

The reason for the low level of correspondence is probably the difference in soil type. Kammerer, 2005 developed the parameter sets in a clay silt, whereas the soil type in the soil column is a sandy loam.

6.3 Test of standard calibration for EnviroScan-sensors

For the sake of completeness the EnviroScan parameter set for standard calibration (Table 4) was applied (Set S). In contrast to the results of Kammerer and Cepuder, 2007 set S led to an unexpectedly good matching of the calculated volumetric water content θ_{av_FDR-S} (green line) with water content determined from balance reading θ_{av_bal} (rose line) demonstrated in Figure 11.

Table 4: Standard calibration parameters of EnviroScan FDR-Sensors (Zupanc et al., 2006)

a	b	c
0,1957	0,4040	0,0285

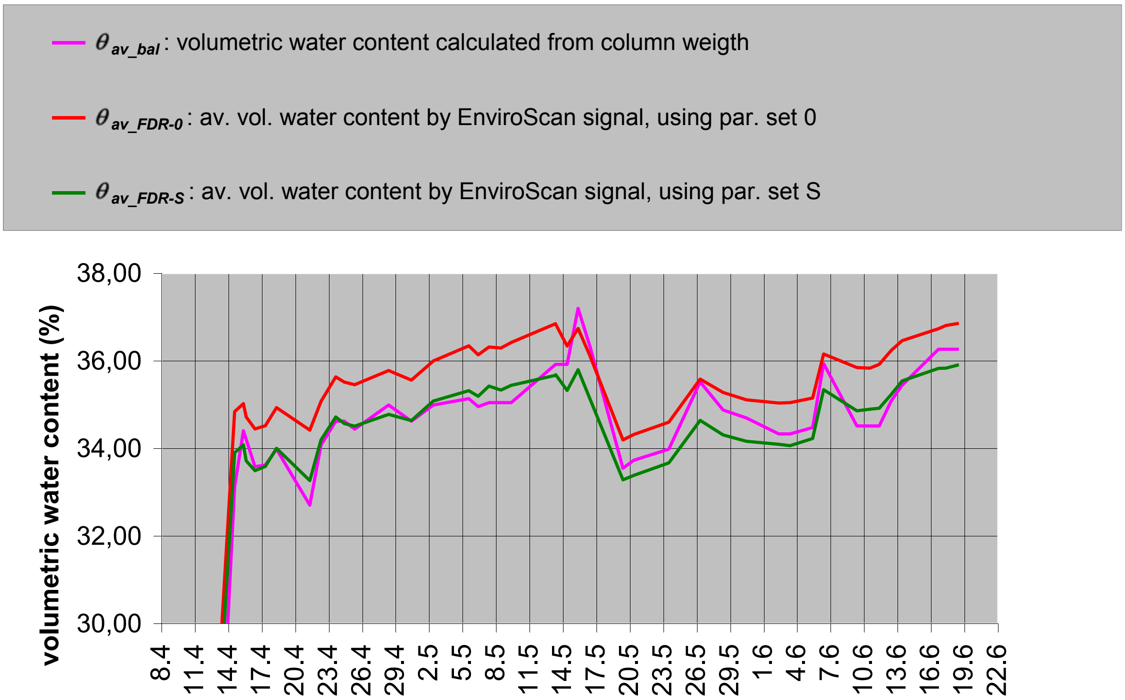

Figure 11: Comparison of water content by weight (rose curve) and water content by EnviroScan measurement using standard calibration (green curve)

Until May 11 the curves are matching more or less exactly. From May 11 to June 6 θ_{av_FDR-S} (green line) stays below θ_{av_bal} (rose line).

It is remarkable that the difference between the two lines decreases with falling water content and increases with rising water content. It might be that during higher irrigation or low vacuum at the suction cups water could flow past the support plate and reached the wooden board of the decimal balance.

This wooden board absorbed the water, so that by drying the surface with a cloth the water could not be removed totally (Kammerer, 2010). The consequence is an overestimation of θ_{av_bal}, because there is additional water on the balance, which is not inside the soil column. Slow drying of the wood could then lead to a rapprochement of both curves. The following observations confirm this hypothesis.

As already mentioned the experimental protocol noted “water leakage” from soil column on the following days: 15.05, 6.06, 16.06, 17.06, 18.06

- On May 15 and on June 6 the difference between the two curves is maximal. The total potential gradient at the bottom of the soil went positive due to irrigation maxima (Figure 14).
- On May 26 and on June 16-18 it was the pressure conditions that led to water leakage (Figure 14). A vacuum of 0,2 bar in the vacuum tank apparently was not sufficient to keep gradient of total potential at the bottom of the soil negative.

Figure 12 shows that until May 15 the irrigation sum and the outflow sum only differ by the water stored in the soil column V_{w_bal} (Equation 13): From these findings it can be deduced that evaporation can be neglected. At the days with water leakage the recorded amount of percolated water is too low, because water that leaves via the support plate can not be counted. As a result the curve “outflow sum + V_{W_bal}” deviates more and more from the irrigation sum after May 15.

Equation 13

$$V_{W\_bal} = m_{W\_bal} \cdot \rho_W$$

V_{W_bal} : Volume of water, stored in soil column

m_{W_bal} : Mass of water, stored in soil column

ρ_W : Density of water

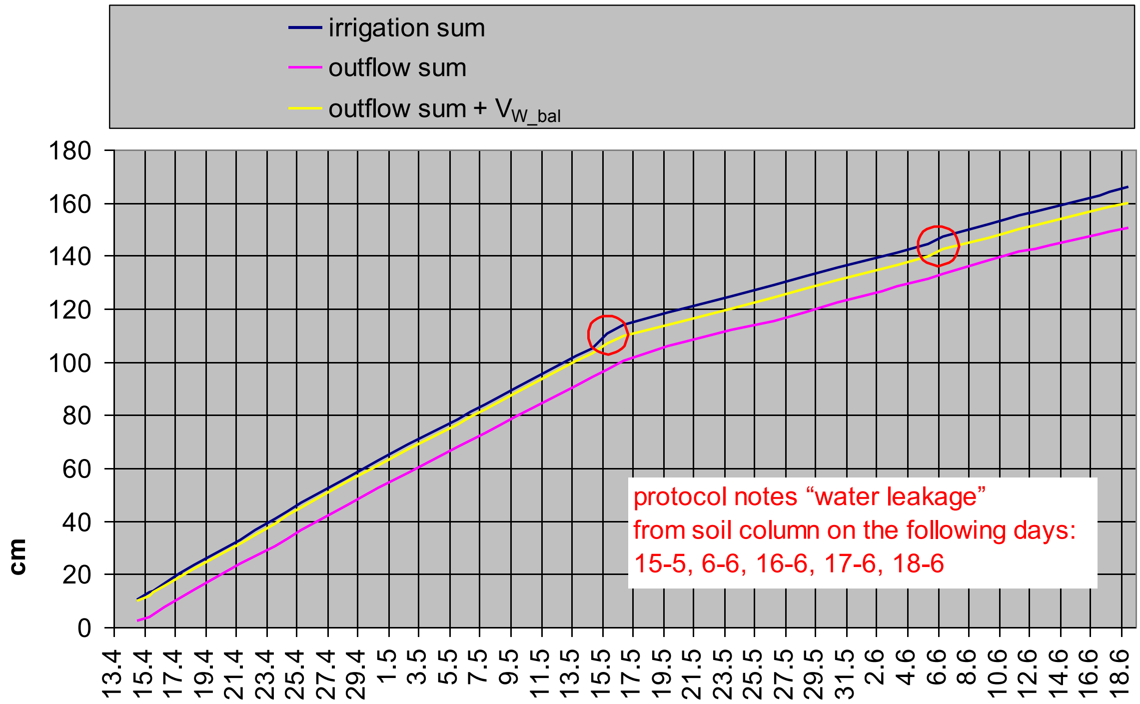

Figure 12: Cumulative curves of irrigation, outflow and outflow + volume of soil water in column V_{W_bal}

In Figure 13 the water contents that result in the different depth using parameter set 0 in and the standard calibration parameter set S are compared. The main difference is the change of the order of the water contents. Whereas with initial calibration the layer from 40 to 50 cm is the wettest, this changes with standard calibration. Now the layer between 30 to 40 cm reaches the highest water contents.

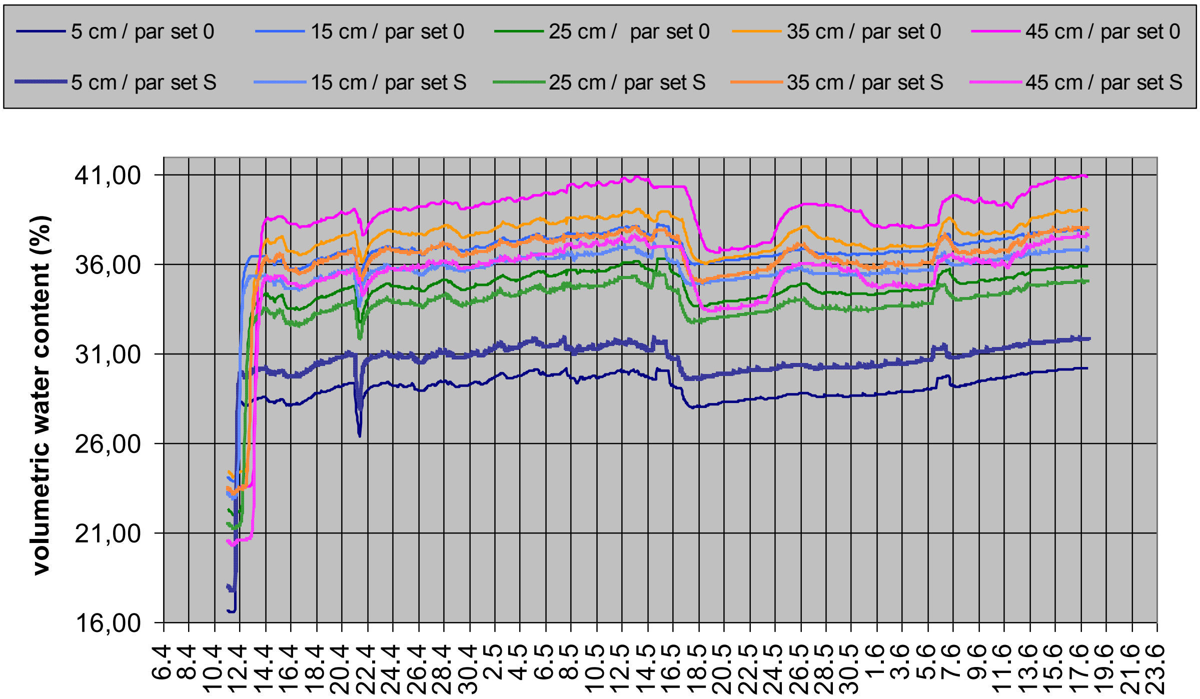

Figure 13: Comparison of the water contents calculated by sensor using the initial calibration (broad lines) versus standard parameter set (thin lines)

6.4 Time series of measured data

The time series of measured data are displayed in Figure 14 from May 7 to June 18.

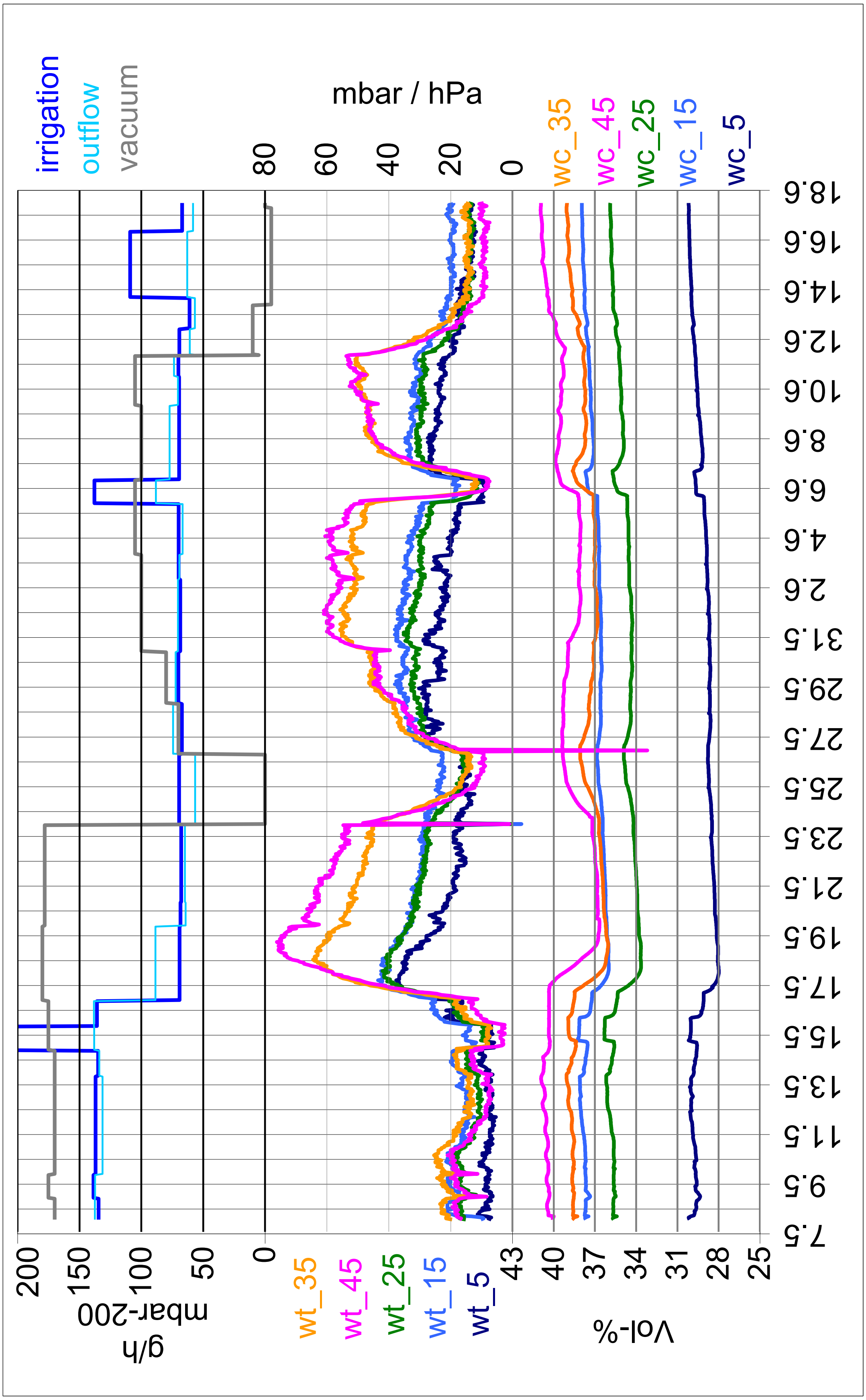

Figure 14: Time series of water content (Vol%) and water tension (mbar/hPa) in different
e 14: Time series of water content (Vol%) and water tension (mbar/hPa) in different depths,

6.5 Requirements for a model to derive soil water flow from measured water content

The following requirements should be met by a model that determines soil water flow from data consisting of volumetric water content:

a) Functioning of the assumption without water tension data
This requirement results from the assignment of the work. It is the goal to predict soil water flow only using data of water content only.

b) Using proven methodology
The requested model should take account of existing, proven approaches.

c) Minimize soil parameters to be determined and small number of fitting parameters
A high number of parameters increase the complexity and the error of the method. The number of fitting parameters should therefore be reduced to the necessary number.

d) Direct calibration on cumulative curve of outflow
By direct calibration on the cumulative curve of outflow modelling errors can be minimised.

6.6 Creating a model based on established methods

As mentioned in chapter 3.1.4 Buckingham's law ( ) applies to water flow in unsaturated soils. Water flow correlates to the total potential gradient (ψ_t) and to the unsaturated hydraulic conductivity k_u. k_u is related to the water content ($k_u=k(\theta)$).

$$q = k(\theta) * grad\ (\psi_t)$$

Since the method should work without data on water tension a constant potential gradient is assumed. The total potential gradient is set to 1:

$$q = k(\theta)$$

The model of Mualem (Equation 8) establishes a relationship between effective saturation S_e and relative hydraulic conductivity k_r of a soil. Fitting parameters are the water content at saturation θ_s and the empirical factor m. It was found, that an additional constant fitting factor (fitting factor c) improves the model. The quantity of θ_r had no significant impact in the region of observed data and is set to 0. The tortuosity factor τ is fixed at 0.5. Equation 7 describes the unsaturated hydraulic conductivity as product of relative hydraulic conductivity k_r and saturated hydraulic conductivity k_S.

Taking into account all assumptions the soil water flow, expressed as specific discharge, is calculated as follows (Equation 14):

Equation 14

$$q = \left(\frac{\theta}{\theta_S}\right)^{\tau} \cdot \left(1 - \left(1 - \left(\frac{\theta}{\theta_S}\right)^{1/m}\right)^{m}\right)^{2} \cdot k_S \cdot c$$

q : specific discharge

c : constant correction factor

6.7 Saturated conductivity

There are numerous approaches for the determination of k_s using particle size distribution (Szymczak, Wassiliew and Behnke, 2009). However, only few are suitable for the calculation of k_s at loamy soils. A better solution is the use of pedotransfer functions, estimating hydraulic properties from data such as soil texture data. The software Rosetta (Schaap, 1999) returned a k_s of 7,8 cm/d (3,2 mm/h) for the given soil texture.

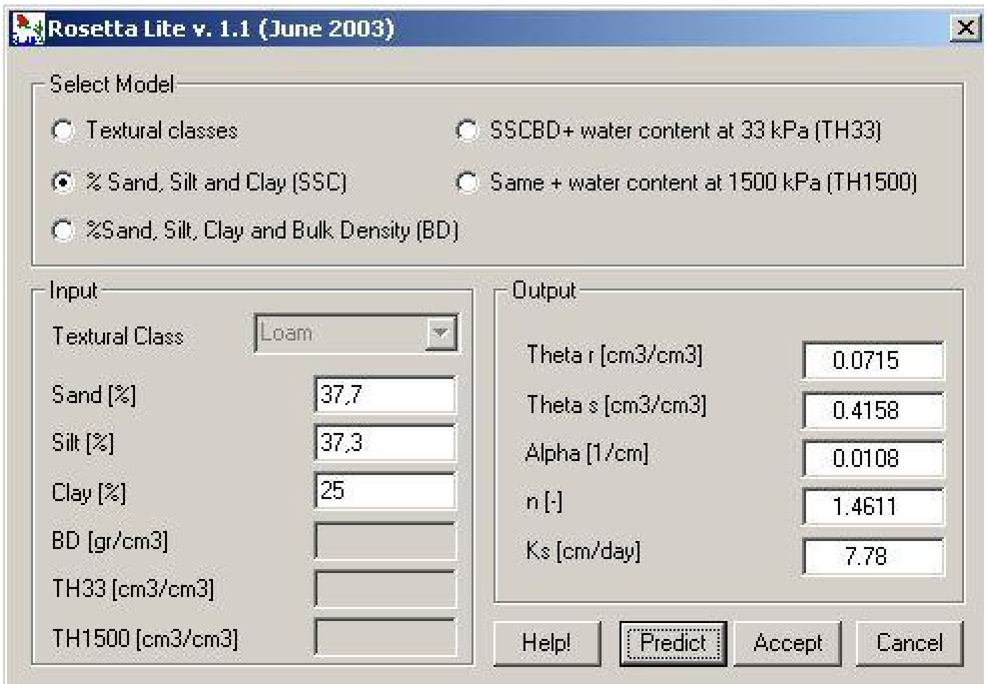

Figure 15: The pedotransfer function Rosetta returns a k_s of 7,8 cm/d for the given soil texture

6.8 Correction of outflow

In section 6.3 it was shown that the recorded outflow is too low due to leakage. It was also shown that Evaporation can be neglected and that the average water content by EnviroScan sensors (θ_{av_FDR-S}) corresponds to the average water content calculated from column weight (θ_{av_bal}). As there is no evaporation, the outflow can be calculated from the irrigation flow corrected by water content stored in or released from the soil column (Equation 15). The change of soil water is calculated every hour. The resulting corrected outflow improves the temporal resolution of the outflow, observable during periods of changing irrigation. The cumulative curve of the corrected outflow only shows slight differences compared to the cumulative irrigation because summation leads to eradication of the effect of changing soil water. Figure 16 shows the irrigation and the resulting calculated outflow.

Equation 15

$$Outflow_{corr} = Irrigation + \Delta V_{W\_bal}$$

$Outflow_{corr}$: corrected outflow

$Irrigation$: water inflow of soil column

ΔV_{W_bal} : change of soil water, measured by EnviroScan sensors

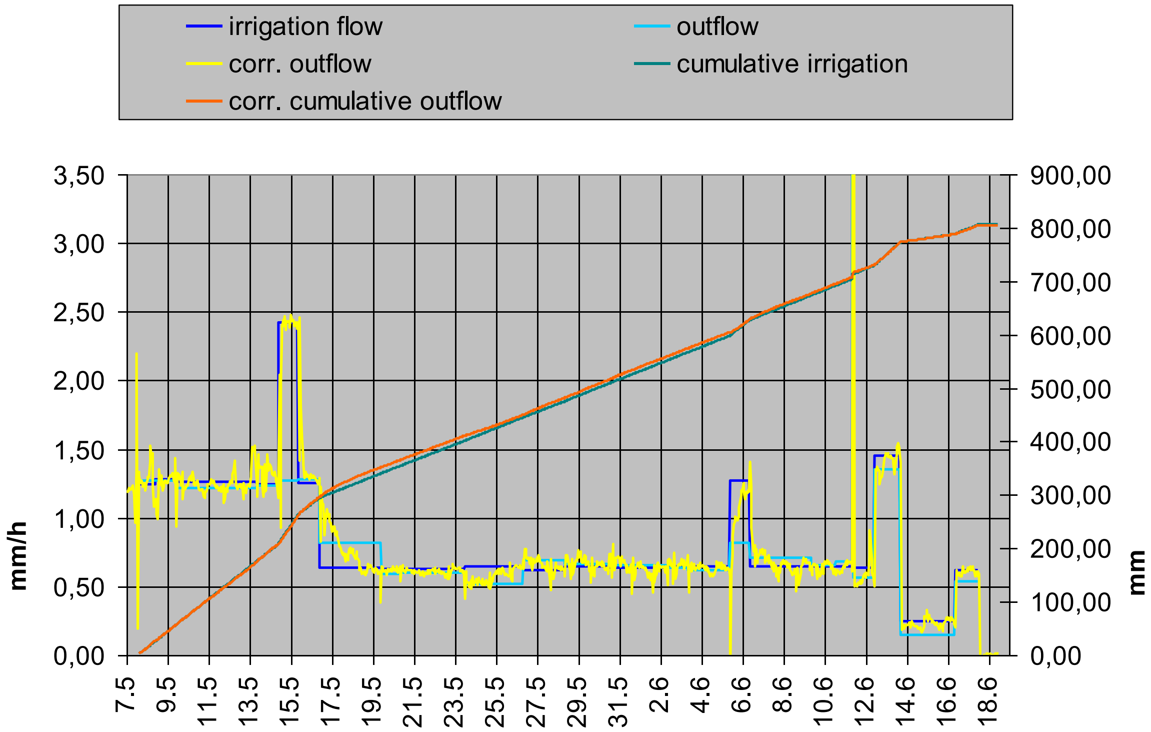

Figure 16: Calculation of percolating water as difference of “irrigation” and “change of water content in soil column”

6.9 Modelling of cumulative soil water flow using water content data

The parameters θ_s, m and k_s were chosen to maximise matching of the model curves with the outflow sum (Figure 17). Each model curve is a cumulative curve of hourly flow calculated using Equation 14. There are specific sets of parameters for each of the five sensors (Table 5). Each model curve is calculated based on the data from one sensor.

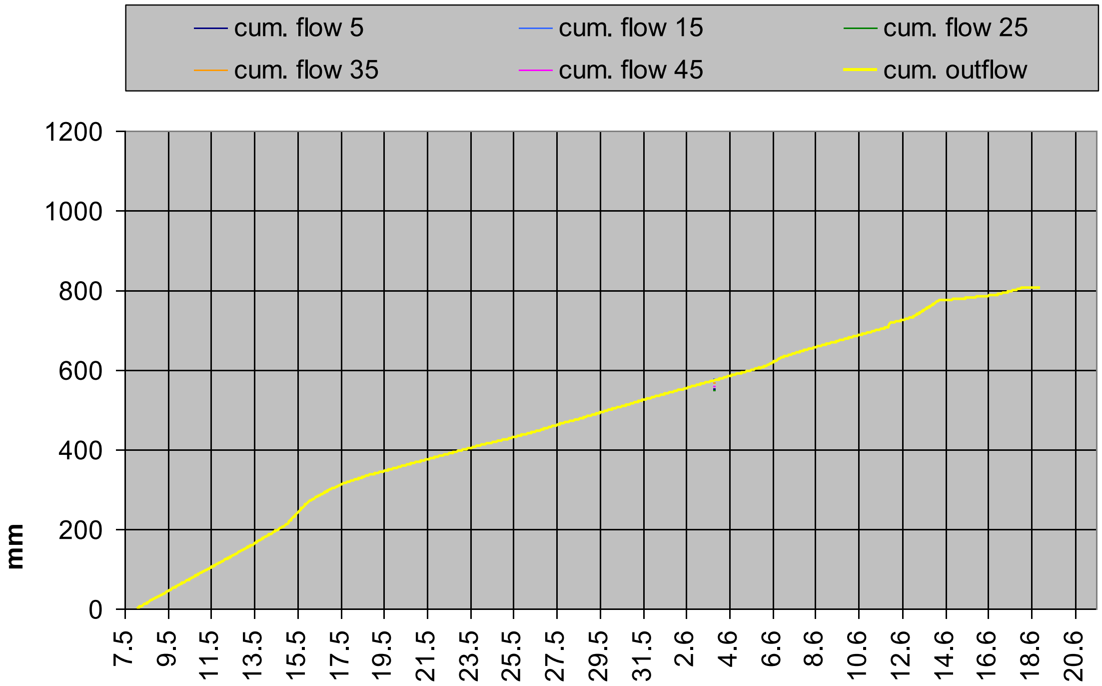

Figure 17: Modelled cumulated outflow for each sensor and observed cumulative outflow (yellow)

Table 5: Choice of fitting parameters and k_s-values, used for modelling the water flow from volumetric water content of the 5 different EnviroScan FDR-sensors.

Sensor depth	**5**	**15**	**25**	**35**	**45**	cm
τ	0,50	0,50	0,50	0,50	0,50	-
k_s	3,24	3,24	3,24	3,24	3,24	mm/h
θ_s	32,00	37,20	35,50	38,10	37,70	Vol%
θ_r	0,00	0,00	0,00	0,00	0,00	Vol%
m	0,32	0,31	0,34	0,33	0,39	-
c	1,13	1,08	0,93	0,93	0,80	-

At the beginning the observed and the calculated cumulative curves of soil water are in good agreement. From 06.06 however, the modelled values exceed the measured values increasingly. Overall, the modelled curves show a slight increase compared to the observed cumulative outflow. This effect could not be adjusted by the choice of the parameters.

Based on the parameters now the soil water flow can be modelled using Equation 14 (Figure 18). Here as well the curves show a upward movement after June 8. The slight upward trend during the experiment can also be observed. The modelled curves correspond better with the corrected outflow (Figure 18) than with measured irrigation or outflow (Figure 19).

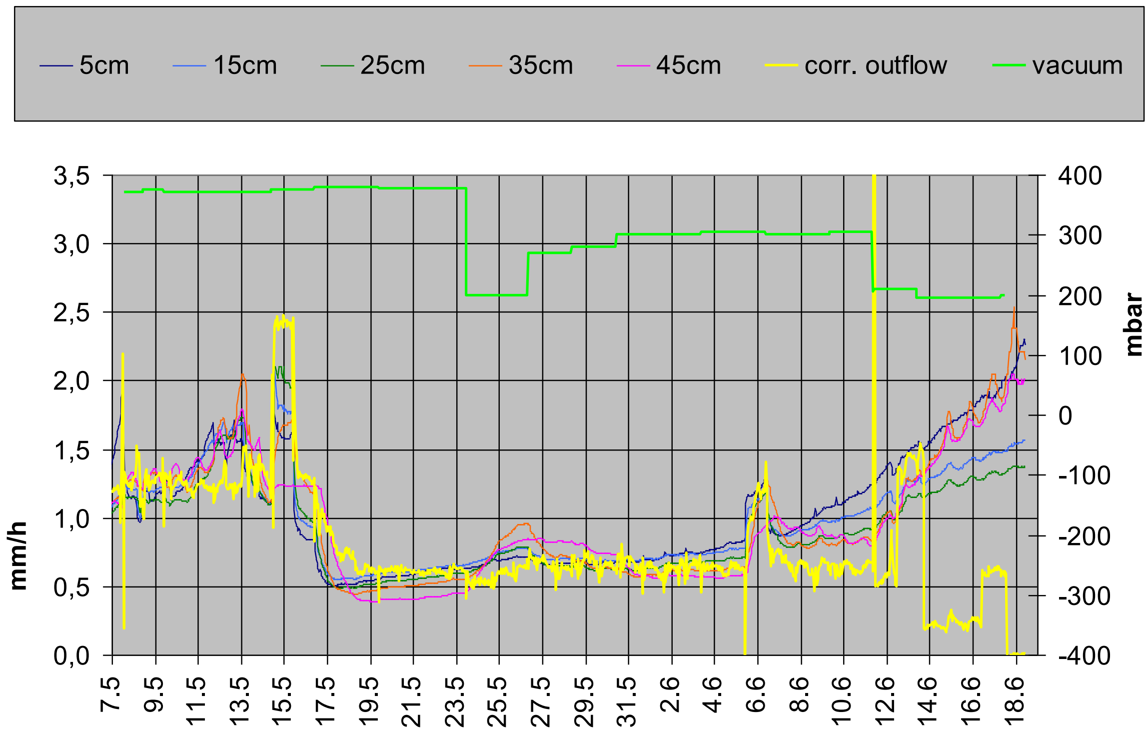

Figure 18: Modelled outflows for each sensor and corrected outflow (yellow)

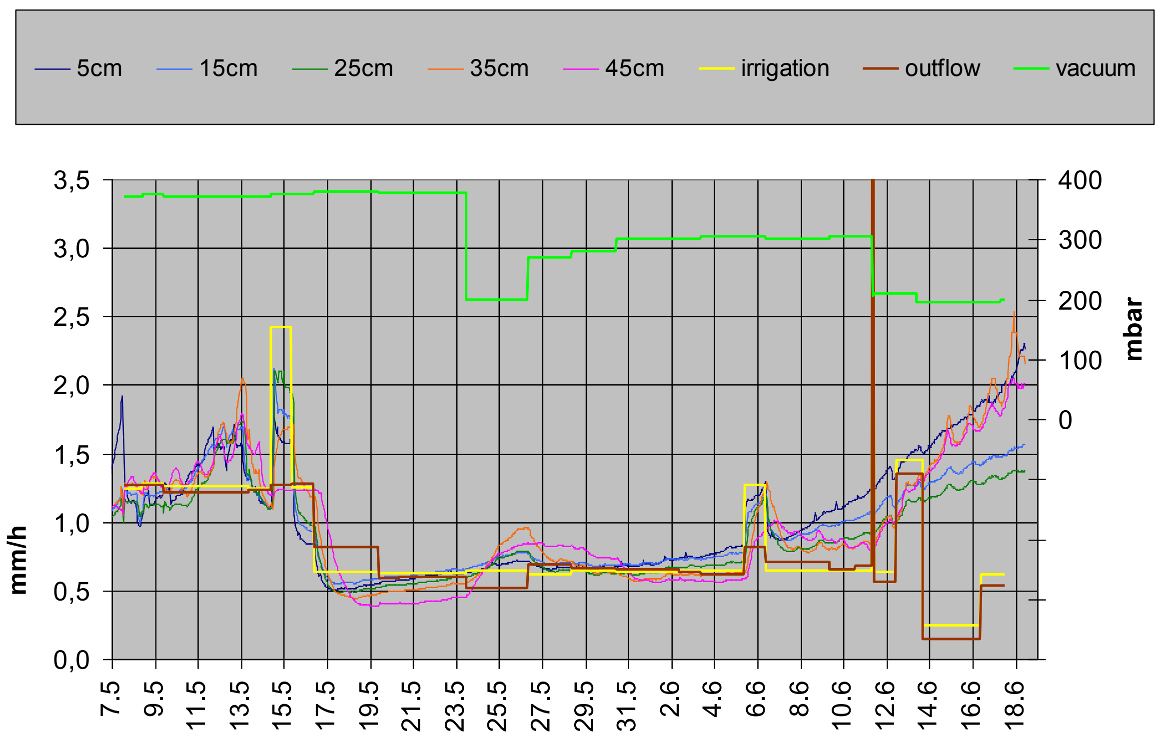

Figure 19: Modelled outflows for each sensor and observed irrigation and outflow

7 Discussion

Looking at Figure 21, a steady increase of water content in all depths can be observed. The trend seems to be independent from irrigation rate, as the effect is visible at high and low rates. As the measured water contents agree with water contents calculated from column weight the effect is not caused by a drift of sensors or temperature effects but is a real physical effect. The first assumption of reduced ambient water tension exerted by the suction cups can not be responsible for the effect. Reduced tension should have an effect first on the lower part of the soil column and this effect is supposed to extend with an attenuated amount up to the surface. The observed increase however is independent of soil depth. The effect of rising water contents at unvaried irrigation rate has negative effects on the modelling, because in the model a certain hydraulic conductivity is linked to a certain volumetric water content. Water contents in different depth, observed flow and modelled flows show that for the period between the beginning of the experiment and the start of the calibration period of the model (May 7) modelled flows do not match the observed flows (Figure 21). The deviation of modelled cumulative flow and the observed cumulative flow during the same period are obvious. From beginning of May the curves run parallel, due to corresponding modelled flow and observed flow (Figure 22). The reasons for this behaviour are not clear and further discussion is necessary.

The total potential at the bottom of the soil column was probably not kept constant over the entire experimental period. The fluctuating vacuum in the vacuum tank led to a fluctuating matric potential and a changing total potential. Mainly after May 20 and June 11 the vacuum in the vacuum tank drops greatly (c.f. Figure 20, vacuum-curve). How this affects the vacuum at the tips of the suction cups is not known, but possibly 200 mbar is close to the pressure loss inside the pipes and suction cups. The consequence is a very low hydrological gradient at the bottom of the soil column or even a positive gradient. The flow into the suction cups was less then the incoming flow. This lead to hydrostatic conditions at the bottom of the soil, water was able to leak through the inadequately sealed gap between support plate and sewer pipe. Probably this effect also caused a restricted outflow from June 7 or 8 until the end of the experiment. In the model increasing water contents are associated with increased hydraulic conductivity. Restricted flow in the soil column leads to errors because high water content is not associated with high hydraulic conductivity any more. This explains the upward trend of the model curves toward the end of the experiment.

The factor c was used as an additional fitting parameter in the model, which was set constant with time. It can be regarded as a correction factor to the assumption, that the total potential gradient equals 1. c varies between 1,13 and 0,8 and decreases with increasing soil depth. A temporarily variable factor c would probably further minimize the deviations between modelled and observed flow.

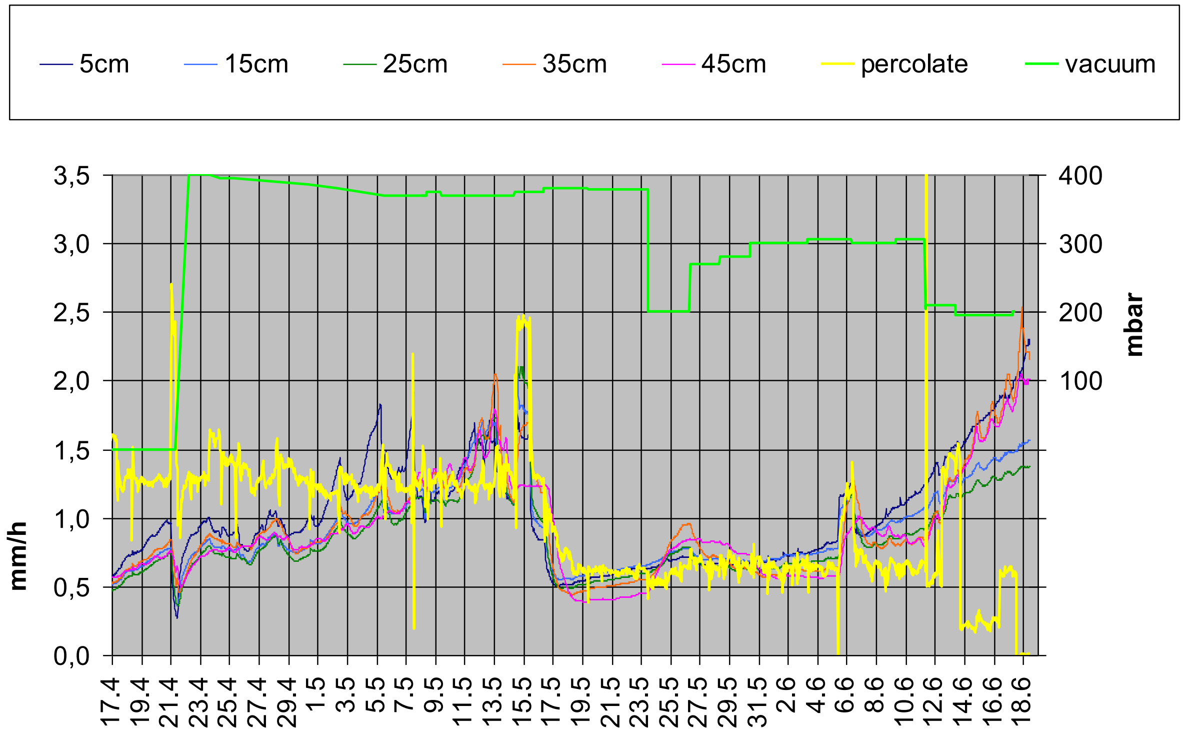

Figure 20: Deviation of modelled flow and observed flow between 17.04 and 07.05 due to a decreasing infiltration rate

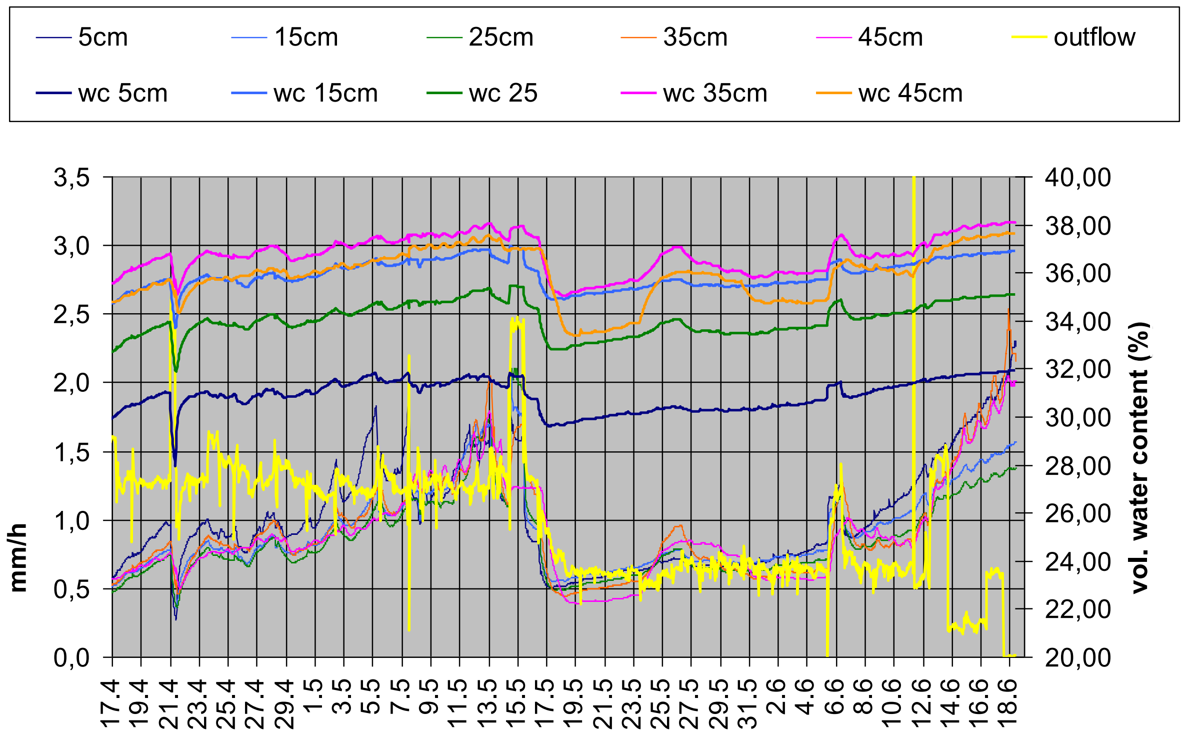

Figure 21: Water contents in different depth, observed flow and modelled flow

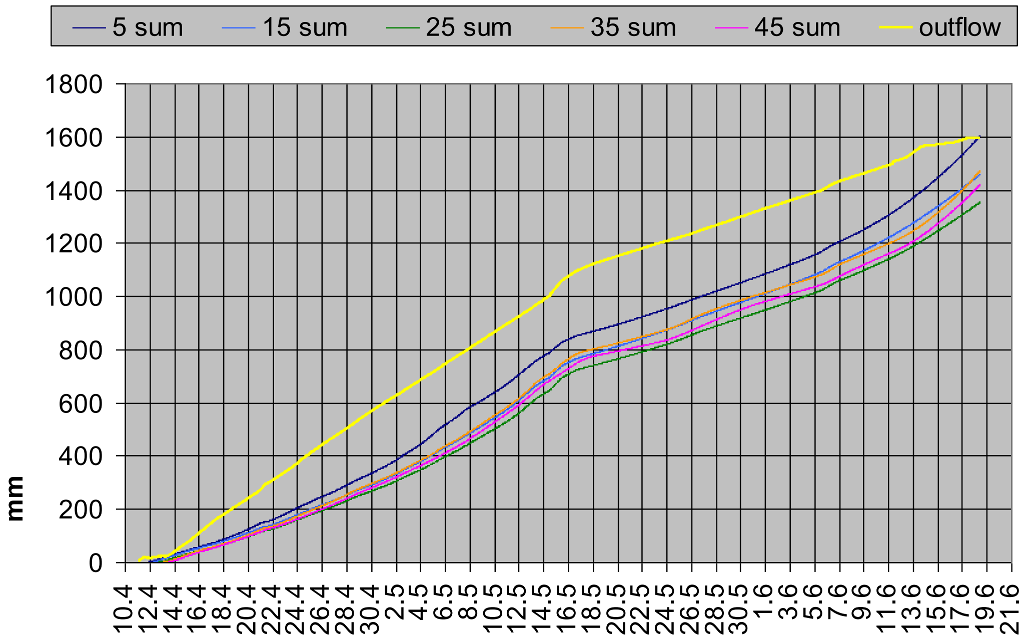

Figure 22: Modelled cumulative flows and observed cumulative flow

8 Conclusions

Despite the limitations described above, the modelled flow matches the observed flow surprisingly well. The modelling could possibly be improved by looking at the water tensions and using a more flexible retention curve model.

The applied method should deliver reliable results, if the following points can be fulfilled:

- constant infiltration rate

- constant unit gradient

- free drainage at the bottom of the soil column / soil

In the present experiment the sensors in depth of 15 and 25 cm delivered the most reliable model curves. The sensors in greater depth were influenced by the fluctuating vacuum of the suction cups.

9 Summary

Water content, water tension and hydraulic conductivity in soils are related. Usually hydraulic conductivity is derived from the relation of water content and water tension. Hydraulic conductivity of a soil is the most important property for calculations concerning the water movement and further water balance components. Since the measurement of water content is less elaborate than the measurement of water tension, it would be advantageous to predict soil water movement only from water content, not needing data on water tension. Main task of this laboratory experiment was to investigate whether automatic FDR-Systems measuring volumetric soil water content in access tubes are suitable for estimation of seepage water rate. A air-dry sandy loam soil was filled 50 cm high into a column with 38 cm diameter and equipped with tensiometers and water content sensors in 5 depths. An irrigation water depth of 1600 mm was applied on the surface in varying rates for 68 days from April to June 2008. During this time the top of the soil column was covered to prevent evaporation losses. At the bottom of the column, lower boundary condition was controlled with suction cups. To model the flow based on volumetric water content measurement the model of Mualem was combined with the law of Buckingham for unsaturated flow. The observed cumulative water flow was used for calibration. Basically it was possible to conclude from soil water content to soil water flow. During the experiment rising water content and a partly blocked water flow prevented a total match between modelled and observed seepage.

10 Literature

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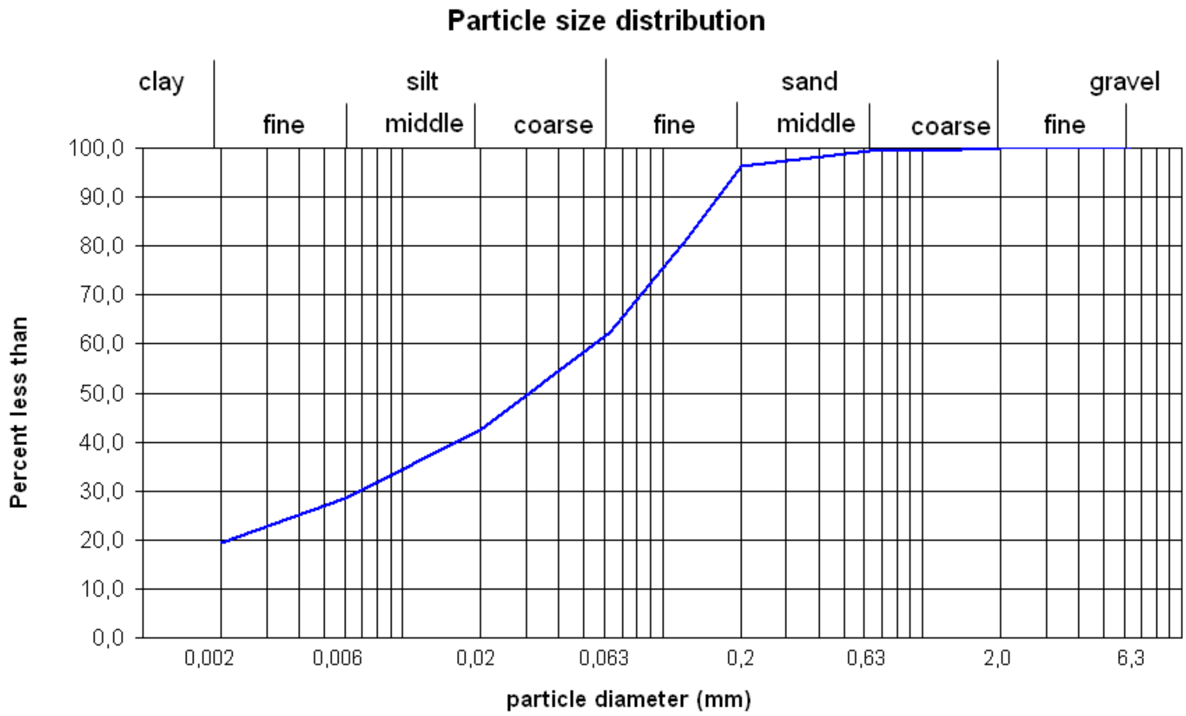
11 Appendix

11.1 Particle size distribution of the soil in column (analysed 03/2010)



11.2 Documentation of the experiment

	soil weight = water in soil column					Comments
	(10 g)	corrected weight. (10g)	Vol% from uncorrected weight	Vol% from corrected weight	Vol% EnvScan with Standard calibration	
11.4.08 12:00	970	970	17,70	17,70	22,56	Tensiometer filled; Start experiment: 2 pump strokes/min, 5 % Stroke length
14.4.08 13:00	1815	1815	33,13	33,13	34,75	Vacuum dropped to 0,18
15.4.08 8:00	1885	1885	34,41	34,41	34,72	Vacuum stopped
15.4.08 14:00	1874	1874	34,21	34,21	34,49	
16.4.08 9:00	1840	1840	33,58	33,58	34,45	Tensio filled
17.4.08 7:00	1842	1842	33,62	33,62	34,62	
18.4.08 7:00	1862	1862	33,99	33,99	34,97	
21.4.08 7:00	1792	1792	32,71	32,71	33,87	pump empty, pump filled up at 9:30; Tensio filled
22.4.08 7:00	1867	1867	34,08	34,08	35,26	0,4 bar
23.4.08 14:30	1897	1897	34,62	34,62	35,60	
24.4.08 9:10	1897	1897	34,62	34,62	35,54	0,395 bar
25.4.08 7:30	1887	1887	34,44	34,44	35,55	
28.4.08 8:15	1917	1917	34,99	34,99	35,75	0,390 bar
30.4.08 9:30	1897	1897	34,62	34,62	35,64	0,385 bar
2.5.08 8:30	1917	1917	34,99	34,99	36,11	0,38 bar
5.5.08 13:00	1925	1925	35,14	35,14	36,26	0,37 bar
6.5.08 9:00	1915	1915	34,95	34,95	36,15	
7.5.08 8:30	1920	1920	35,04	35,04	36,39	12:00 new tensiometer built in ; new weight 501 (due to modification)
8.5.08 10:00	501	1920	9,14	35,04	36,28	0,37 bar
9.5.08 8:30	501	1920	9,14	35,04	36,39	0,375 bar
13.5.08 7:50	549	1968	10,02	35,92	36,62	0,37 bar
13.5.08 8:00	549	1968	10,02	35,92	36,63	0,375 bar, at 10:00 pump to 10 % stroke length

	soil weight = water in soil column					Comments
	(10 g)	corrected weight. (10g)	Vol% from uncorrected weight	Vol% from corrected weight	Vol% EnvScan with Standard calibration	
14.5.08 8:20	549	1968	10,02	35,92	36,27	0,370 bar; at 10 % stroke length same amount of water as with 5% change to 5% and 4 strokes
15.5.08 8:15	619	2038	11,30	37,20	36,75	0,375 bar, water leakage during night, reduction at 2 pump strokes
16.5.08 9:15	572	1991	10,44	36,34	36,09	0,375 bar, reduction at 1 pump stroke
19.5.08 8:30	419	1838	7,65	33,55	34,23	0,38 bar
20.5.08 8:00	429	1848	7,83	33,73	34,33	0,375 bar
23.5.08 11:20	443	1862	8,09	33,99	34,61	0,375 bar, change at 0,3 bar
26.5.08 7:00	527	1946	9,62	35,52	35,59	0,2 bar
28.5.08 8:00	492	1911	8,98	34,88	35,26	0,27 bar
30.5.08 10:15	482	1901	8,80	34,70	35,11	0,28 bar
2.6.08 8:00	462	1881	8,43	34,33	35,04	0,3 bar
3.6.08 8:20	462	1881	8,43	34,33	35,01	0,3 bar; data export; 0,34bar at closed valve (for later pressure change)
5.6.08 8:45	470	1889	8,58	34,48	35,17	0,305 bar; change at 2 pump strokes
6.6.08 8:20	550	1969	10,04	35,94	36,29	0,305 bar; water leakage, reduction at 1 pump stroke
9.6.08 8:15	472	1891	8,62	34,52	35,81	0,3 bar
10.6.08 12:10	472	1891	8,62	34,52	35,84	0,305 bar
11.6.08 8:20	472	1891	8,62	34,52	35,87	0,305 bar; reduction at 0,2 bar
12.6.08 10:10	503	1922	9,18	35,08	36,18	0,205 bar
13.6.08 9:30	523	1942	9,55	35,45	36,49	0,21 bar
16.6.08 15:45	568	1987	10,37	36,27	36,78	0,195 bar; balance is wet
17.6.08 7:30	568	1987	10,37	36,27	36,79	0,205 bar; balance is wet -->not enough time for drying?
18.6.08 11:30	568	1987	10,37	36,27	36,86	0,2 bar; balance is wet + Water underneath the balance, change to 0,25 bar