Int. Agrophysics, 1997, 11, 5-41

INFLUENCE OF SOIL STRUCTURAL PARAMETERS ON HYDRAULIC FUNCTIONS FOR SOIL-WATER BALANCE MODELLING*

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Accepted February 14, 1997

Abstract. The investigations were conducted to prove the application of different methods for measuring soil hydraulic properties. Estimations of unsaturated hydraulic conductivity with different models were compared to measurements. The sensitivity of the computer model on soil structure parameter was tested.

Keywords: soil strucutre parameters, soil hydraulic properties, soil-water balance modelling, tension infiltrometer, Guelph permeameter.

INTRODUCTION

The goal of this project was defined in the following question: How does soil structure influence biomass production and are existing computer models an appropriate tool for answering this question?

The soil structural status has among others a high influence on soil hydraulic properties and on the soil water balance. Therefore the influence on plant growth should be relevant as well. This study deals with the measurement of soil hydraulic properties, how they can be used for modelling the soil water balance and how sensitive computer models react on soil structural differences.

The investigations at the site Fuchsenbigl were conducted to prove the application of different methods for measuring soil hydraulic properties. Especially the sensitivity of the tension infiltrometer was tested. Estimations of unsaturated hydraulic conductivity with different models were compared to measurements.

The soil water balance of the site Großenzersdorf was simulated with a computer model applying several methods for determining soil hydraulic input data. The sensitivity of the computer model on soil structur parameter was tested.

The measurements of the meteorological parameters were done by the Departement of Meteorology and Physics, University of Agriculture, Vienna. The measurements of plant related properties were done by the Departement of Plant Production and Plant Breeding, University of Agriculture, Vienna.

MATERIAL

Investigated areas and soil sampling

Site Fuchsenbigl

The soil ‘Fuchsenbigl’ is a Chernozem. It is situated about 20 km east of Vienna in the ‘Marchfeld’ region, Lower Austria. It consists of a tilled Ap-horizon (0-25 cm), an Ah-horizon (25-45 cm), an AC-horizon (45-60 cm) and a C-horizon (deeper than 60 cm). The grain size distribution of the A-horizon is

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* This work was partly supported by the Project AKTION-SENVIRAC in collaboration with Prof. Dr. S. Matula, Department of Soil Science and Geology, Faculty of Agronomy, Czech University of Agriculture.

about 33 % sand, 40 % silt, 27 % clay; the organic matter content is 1.5 %.

The tension infiltration measurements were conducted in the center of wheel trafficked and untrafficked interrows at a depth of 3 cm. For each interrow seven replicates were taken in a distance of 5 m. Within a distance of 15 cm from each infiltration plot soil cores were taken in a depth from 3 cm to 9 cm for the measurement of saturated conductivity and the soil water retention curve and from 3 cm to 13 cm for the measurement of unsaturated hydraulic conductivity.

All the measurements were performed after harvesting of wheat within 2 weeks (second half of July).

Site Großenzersdorf

The soil in Großenzersdorf is situated about 5 km east of Vienna in the 'Marchfeld' region, Lower Austria and is also a Chernozem type soil consisting of a tilled Ap-horizon (0-25 cm), an Ah-horizon (25-40/45 cm), an AC-horizon (40/45-55/120 cm) and a C-horizon. The depth where the C-horizon starts varies from 55 cm to more than 120 cm. The grain-size distribution for the A-horizon is 30 % sand, 48 % silt, 22 % clay and for the AC-horizon 37 % sand, 45 % silt, 18 % clay. The grain-size distribution of the C-horizon varies in a wide range (e.g., clay content from 10 % up to 26 %). Besides a clay content of the top soil of only about 20 %, in dry summer periods cracks were found to go deeper than 60 cm.

There was no phosphorus and no potassium fertilization since the content of plant available phosporus and potassium in the A - horizon was found to be high. The content of potassium and phosphorus in the AC horizon was low.

On a field of the size 100 x 50 m soyabean (variety 'Ceresia') was planted. In autumn the field was ploughed, on 4th of May seedbed preparation to a depth of 6 - 8 cm and sowing was done. Before, the depth of the C-horizon was investigated using a small auger (120 cm length, 2 cm inner diameter). The augering was done over the whole field in a regulary grid of 7 x 7 m. Based on these results 8 subplots (size: 10 x 10 m) were chosen which all have more or less the same depth of C-horizon (70 cm) for taking soil and plant samples on places with quite homogenous soil conditions.

The soil cores for measuring the soil water retention curves (SWRC), saturated and unsaturated hydraulic conductivity were taken in April before sowing. Additionally 12 soil cores for measuring saturated hydraulic conductivity of the Ap-horizon were taken again in September. For the SWRC 8 soil cores (one from each subplot) were taken from the Ap- and Ah-horizon, respectively and 4 soil cores were taken from the AC-horizon in 60 cm depth (subplot 1, 3, 5, 7). For the saturated hydraulic conductivity 2 soil cores were taken from each subplot for the Ap- and the Ah-horizons and from the AC-horizon 2 soil cores were taken from subplots 1, 3, 5, 7, respectively. Samples for measuring unsaturated hydraulic conductivity were taken from subplots 1, 3, 5, 7 from Ap-, Ah- and AC-horizons.

The GUELPH - permeameter measurements were made at three depths (8-25 cm, 28-45 cm, 50-67 cm) for all 8 subplots during August 1995. The tension infiltrometer measurements were made directly at the soil surface and at depth 10 cm for the subplots 1, 2, 3, 4.

4 of the subplots (subplot 1, 2, 5, 6) were irrigated on 13th, 18th, 25th of July and on 18th of August to maintain optimal water condition for plant growth. At each irrigation event about 30 - 40 mm of water were applicated. For the continous recording of volumetric soil water content two TDR probes were installed at the irrigated 'subplot 2' at depths 15 cm and 35 cm and three TDR probes were installed at the non irrigated 'subplot 3' at depths 15 cm, 35 cm and 60 cm. Soil temperature was measured at 'subplot 2' in 5 cm and 15 cm depth and at 'subplot 3' in 5 cm, 15 cm and 35 cm depth.

An agrometeorological station for measuring precipitation, air temperature, relative humidity, wind speed and global radiation was installed near 'subplot 3'. For the exact arran-gement of the 8 subplots and for the situation of TDR probes and the agrometeorological station see Fig. 1.

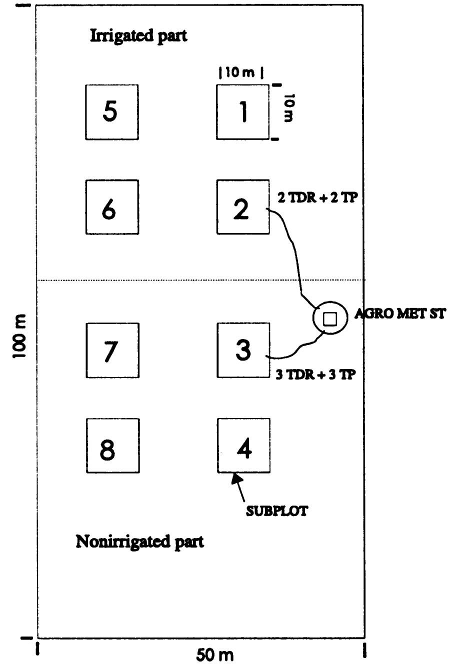


Fig. 1. Experimental field with 8 subplots, an agrometeorological station and situation of the TDR and temperature probes (TP).

METHODS

Soil chemical analysis

The analysis of chemical soil parameters (pH - value, carbonate content, total and organic carbon content) are described in the final report of the foregoing project (Assessment of Soil Structure in Agricultural Soils).

Plant extractable phosphorus and potassium

P and K were extracted with a calciumlactat-Calciumacetat solution. K was measured with an AAS. P was coloured with ammoniummolybdat and measured by UV-Vis-Photometer.

Soil physical analysis

Saturation of soil cores

All soil cores for the different laboratory methods except for measuring the saturated hydraulic conductivity (laboratory method) were saturated by capillary rise of 0.005 m $CaSO_4$ solution at a suction of 3 cm water column. The soil cores were ponded for saturated hydraulic conductivity method.

Soil-water retention curve (SWRC)

The SWRCs were determined according to the DRAFT INTERNATIONAL STANDARD 11274 (Soil quality - Determination of the water retention characteristic - Laboratory method, 1992) by using pressure plate extractors. Up to gas pressures of 1000 hPa undisturbed soil cores of 200 cm^3 size were used. Extracting water by gas pressures higher than 1000 hPa small rings (about 3 cm^3) containing disturbed soil were used.

Saturated hydraulic conductivity

A falling head method was used for determination of saturated hydraulic conductivity in the laboratory. The size of soil cores was 200 cm^3.

Saturated hydraulic conductivity in the field was measured in boreholes with the 'Guelph permeameter' (manufactured by the Department of Irrigation, Drainage niversity, Prague). Ks was measured in 3 depths at the site Großenzersdorf. The constant ponding in the boreholes was for the first depth 8-25 cm of soil depth, for the second depth 28-45 cm and for the third depth 50-67 cm. For each depth a separate borehole was drilled. The walls of the holes were roughened before the measurement with a steel brush. The calculation the hydraulic conductivity from the steady state infiltration rate was performed by Laplace-analysis [9].

The saturated conductivity was also calculated using the tension infiltration method applied tension during the infiltration of 3 hPa and ponded infiltration measurements with an infiltration ring of the same diameter as the base plate of the tension infiltrometer (see unsaturated conductivity in the field - tension infiltrometer).

Unsaturated hydraulic conductivity

Laboratory Evaporation Controlled Instantaneous Profile Method [8]

Saturated soil cores of 10 cm height and 5.5 cm diameter were equipped with 5 TDR-miniprobes and 5 or 4 minitensiometers helically at equal distances (1, 3, 5, 7, 9 cm from bottom of the soil core - if 4 tensiometers were used the tensiometer at 3 cm was omitted). 4 tensiometers proved to give the same results as using 5 tensiometers. After sealing the bottom of the soil core, evaporation was induced by opening the top of the soil core to the atmosphere causing onedimen-sional upward water flux. Water potential and water content were recorded automatically till water potential of the top tensiometer showed more than 850 hPa. The calculation of water potential gradients (dH/dz) was done by fitting an exponential function ($y = ae^{(bx)}+c$) to the data for each time step.

Fluxes (q) were calculated by fitting a second order polynomial function ($y = ax^2+ bx+c$) to the measured water content as a function of time [10]. The hydraulic conductivity is obtained for each depth increment from $q(t_i)$ and $dH(t_i)/dz$. A mean hydraulic conductivity function for the whole soil core is obtained by calculating the weighted geometric mean for certain water content or water potential classes.

Laboratory Multistep Outflow Method [11]

After weighting a saturated soil core is placed in a pressure cell. First the soil is brought to equilibrium at an air pressure of 30 hPa since the conductivity of the porous ceramic plate is much lower than the conductivity of the soil near saturation. Then the pressure is increased stepwise up to a pressure of 600 hPa. Normally 5 pressure steps were used and the duration of one pressure step was one day. The outflow was measured continously in a burette. The last pressure step was maintained until equilibrium was reached, so that it could serve as an independent point of the retention function. After the experiment the soil samples were dried at 105 °C and weighted. The soil hydraulic function of the Mualem - Van Genuchten - model [7,12] was optimized by minimizing the differences between measured and calculated outflow and water content data using the MARQUARDTS-maximum neighbourhood algorithm.

Field Method

Unsaturated hydraulic conductivity values can be obtained in field conditions by tension infiltration measurements [1]. A 20 cm diameter base plate connected to the tension infiltrometer is placed on a layer of fine silica sand (grain size: 0.1 - 0.3 mm) at the soil surface. Water was infiltrated at supply - suctions of 15, 6 and 3 hPa and the infiltration rate was observed by eye or automatically recorded with two pressure transducers and a data logger till steady state conditions were reached. With the help of the transducer installed at the base plate the supply - suction was recorded. Exemplary data are shown in Fig. 2.

Since the measurement of tension infiltration could be influenced by temperature fluctuation (sensitivity of pressure transducers) an umbrella was used during sunny conditions.

After infiltration measurement at supply suction of 3 hPa the tension infiltrometer was removed and a metal ring with the same diameter as the base plate of the tension infiltrometer (20 cm) was carefully inserted to a depth of 1-2 cm into the soil at exactly the same place. Water was ponded to a depth of about 3 cm and the infiltration rate was measured till steady state conditions were reached.

The infiltration rate is obtained by linear regression of steady state infiltration data (usually reached within 30 min of infiltration).

Unsaturated hydraulic conductivity is calculated using Wooding's-approximation [14].

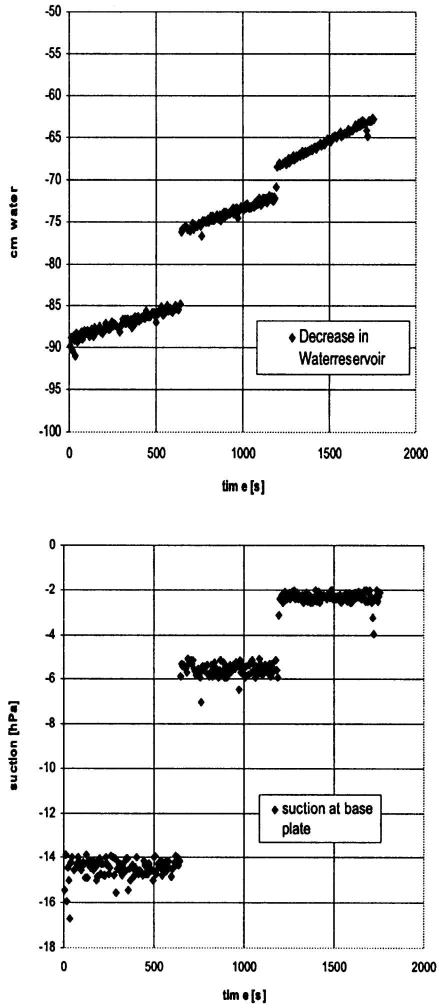


Fig. 2. Exemplary data of tension infiltration measurement.

$$Q=\pi r_2 K\left[1+\frac{4}{\pi r\alpha}\right] \tag{1}$$

where Q is the volume of water entering the soil per unit time, K is the hydraulic conductivity, r is the radius of the base plate and is a parameter.

Unsaturated hydraulic conductivity is described as proposed by Gardner [4]:

$$K(h)=K_{\text{sat}}\exp(\alpha h) \tag{2}$$

where h is matric potential at the source and K_{sat} is saturated hydraulic conductivity. For this case K_{sat} must not be seen as the real ‘Saturated hydraulic conductivity’ of the soil but more as a parameter for the calculation procedure.

Simulation model for soil water and heat conditions - the SOIL model [5]

The SOIL model represents, in one dimension, water and heat dynamics in a layered soil profile covered with vegetation. The central part of the model are two coupled differential equations for water (Darcy’s Law, Richards equation) and heat flow (Fourier’s law). The potential transpiration is calculated from the Penman-Monteith’s combination equation. The reduction of the water soil potential to actual transpiration is dependent on current water tension and soil temperature conditions. Evaporation from the soil surface can be calculated from a Penman-type-equation or from an iterative solution of the energy balance method. As driving variables meteorological data (precipitation, mean daily temperature, wind speed, relative humidity, global radiation) and plant related properties (leaf area index, surface resistance, roughness length, displacement height, root depth and root distribution) are serving. The input of soil hydraulic properties (SWRC, hydraulic conductivity) is realized by estimating coefficients of the function proposed by Brooks and Corey [2] from experimental data. To account for the contribution of macropores, an additional equation of the hydraulic conductivity is considered when water content exceeds θ_s - 4 (θ_s - saturated water content). Bybass flow can be considered using a simple empirical approach.

Parameter estimation of soil hydraulic properties

Experimental data of SWRC and unsaturated hydraulic conductivity were quantified using the model of Mualem-Van Genuchten [7,12], with the help of the computer program RETC [12] and an extended version of the Brooks and Corey model [2,5], with the help of the computer program PLOTPF [6]. The coefficients of the Brooks and Corey-model were obtained from SWRC data whereas the model of Mualem-Van Genuchten could be fitted to SWRC data, to unsaturated conductivity data or simultaneously to both kind of data.

Determination of root distribution

The root system was determined using the 'Profil Wall Method' [3]. A soil profil was dug 1.5 m wide to a depth of 1.2 m. After preparing a vertical working face the roots were exposed using a hand sprayer (10 l, 4-6 bar pressure) by washing away 5 mm of soil. With the help of a gridded counting frame the root units per 5x5 square cm were recorded. A root length of 5 mm was defined as 1 root unit. For the root distribution picture the roots counted in one grid were dotted randomly in the appropriate grid area of the map. Calculation of absolute root density (cm root length/cm^3 soil) from the profil wall method should be done carefully using an empirical conversion factor. From comparison with auger methods Böhm [3] recommends to double the calculated root density.

RESULTS AND DISCUSSION

Providing soil hydraulic functions for the site Fuchsenbigl for an untrafficked and a trafficked soil

With all methods the differences in soil structure of trafficked and untrafficked interrows were clearly obtained. Bulk density ranged from 1.71 to 1.65 for the trafficked and from 1.52 to 1.58 for the untrafficked interrow (Table 1). Saturated conductivity of the soil cores are shown in Table 2.

Table 2. Saturated conductivity (cm/day) - soil core method (laboratory)

	Wheel trafficked	Untrafficked
Geom. mean	2.8	150.5
Arith. mean	3.8	928.6
Stand. dev.	3.54	2459
Maximum	12.9	8309
Minimum	0.94	22.95
Numb. of observ.	12	11

Results and comparison of the tension infiltration measurements are shown in Figs 2 and 3. Infiltration rate was lowest for the trafficked interrow site at 15 hPa and highest for the untrafficked interrow site at 3 hPa suction. The reduction of infiltration of the trafficked compared to the untrafficked interrow was highest at a measurement suction of 3 hPa, that means that wheel traffick destroys in a higher degree the macropores than the micropores.

From tension infiltration measurements at 2 different measurement suctions, hydraulic conductivity values in a range near saturation were calculated (Table 3). No unique -value (Gardner-equation: $k(\psi) = k_{sat}(\alpha\psi)$) was found over the suction range from 15 to 3 hPa. The same is valid for the k_{sat}-parameter. Compared to the soil core method, the calculation from tension infiltration measurements resulted in lower saturated conductivity values.

Soil water retention curves (pF curves) are shown in Figs 5 and 6. The mean pF curve of the trafficked soil has a slightly lower water retention near saturation but a higher water retention in the drier range from

Table 1. Bulk densities of trafficked and untrafficked interrows sites (g/cm^3)

	From sat. cond. meas.		From pF measurements		From unsat. cond. meas.	
	wheel traff.	untrafficked	wheel traff.	untrafficked	wheel traff.	untrafficked
Arit. mean	1.71	1.56	1.68	1.52	1.65	1.58
Stand. dev.	0.05	0.12	0.14	0.15	0.06	0.05
Maximum	1.78	1.8	1.77	1.66	1.71	1.64
Minimum	1.64	1.36	1.47	1.33	1.55	1.49
Number of Observ.	14	14	4	5	8	7

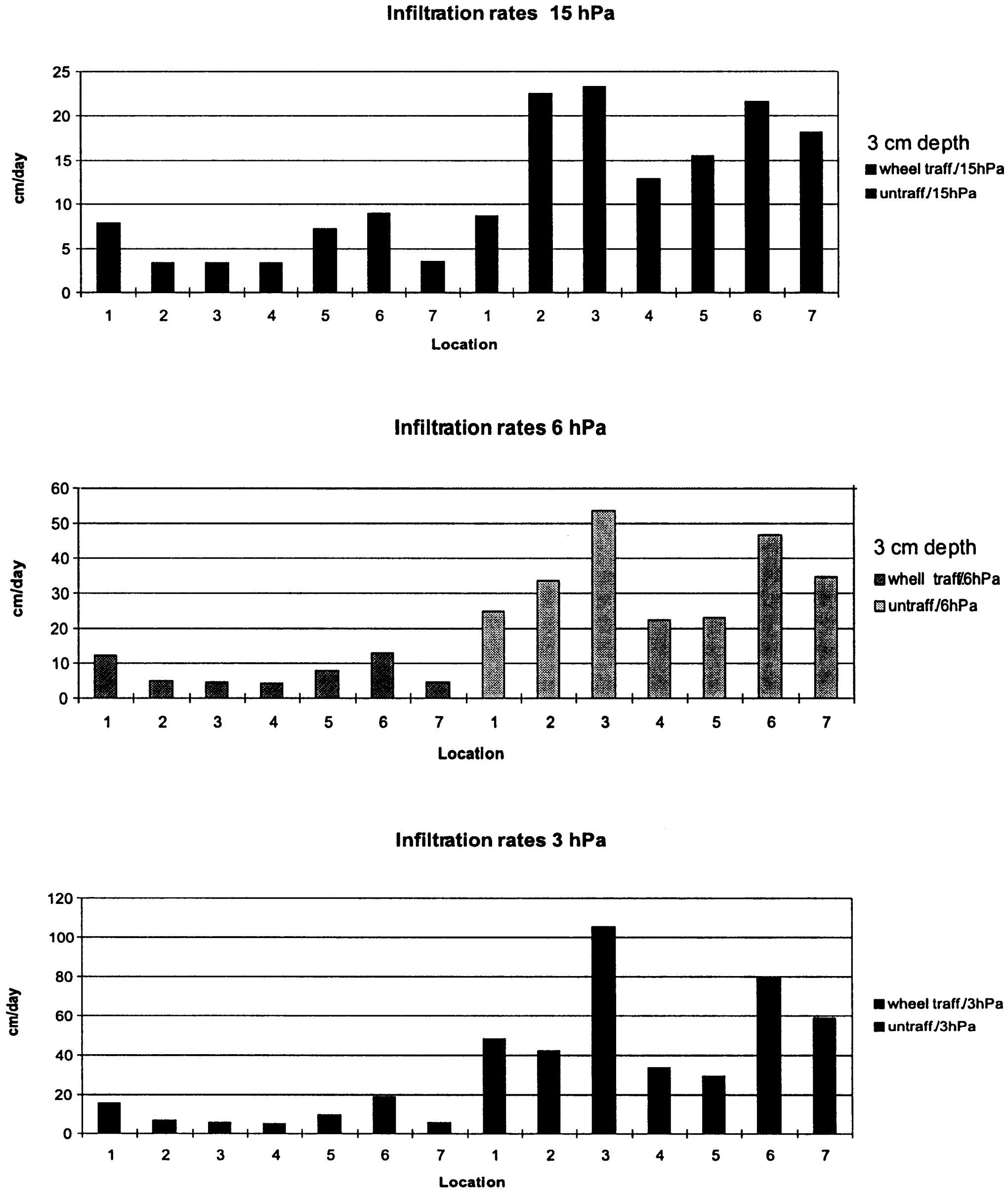


Fig. 3. Comparison of trafficked and untrafficked tension infiltration rates at three different suctions.

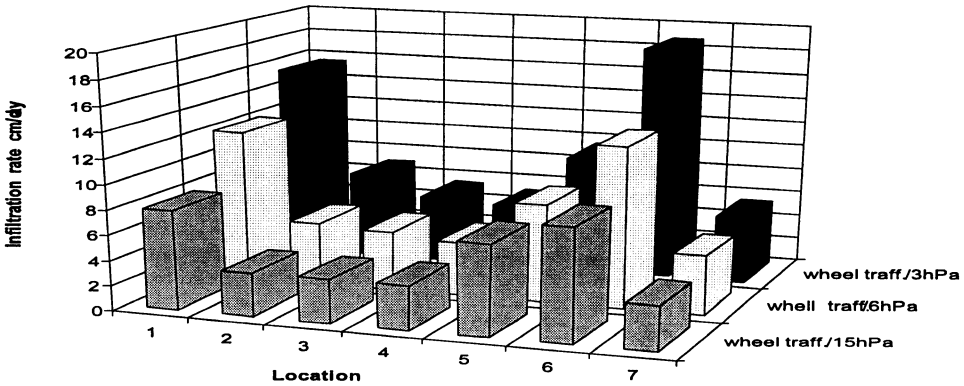
100 to 15000 hPa. The reason for this could be the higher proportion of fine pores in the compacted soil with higher bulk densities.

The pF curves obtained by the instantaneous profil method (Fig. 7) have the same characteristics (lower water retention of the trafficked interrow near saturation - higher retention in the dry range) as the pF curves measured by the pressure chamber method. The different pF curves which resulted from these two methods might be caused by the different measurement conditions. For the pressure chamber method equilibrium of the water content has to be reached. The evaporation

Table 3. Hydraulic conductivity (COND), α-value (ALPHA) and k_{sat} (KSAT) calculated from tension infiltration

	Mean	Std Dev	Geo. Mean	Min	Max	Nb o Ob
COND 15 traff	1.09	0.77	0.9	0.48	2.26	7
COND 6 traff	2.14	1.62	1.71	0.82	4.80	7
COND 3 traff	3.61	3.01	2.73	1.22	9.36	7
COND 15 untraff	6.17	2.34	5.81	4.08	9.84	7
COND 6 untraff	15.19	7.14	14.61	7.44	28.08	7
COND 3 untraff	32.33	20.18	27.05	10.56	67.20	7
ALPHA traff 15 6	0.03	0.01	0.028	0.01	0.05	7
ALPHA traff 6 3	0.07	0.04	0.065	0.04	0.13	7
ALPHA traff 15 6	0.07	0.03	0.07	0.05	0.12	7
ALPHA traff 6 3	0.16	0.06	0.14	0.07	0.23	7
KSAT traff 15 6	1.93	1.68	1.44	0.65	4.807	7
KSAT traff 6 3	4.81	4.49	3.39	1.37	13.68	7
KSAT traff 15 6	20.33	11.49	17.6	8.16	38.40	7
KSAT traff 6 3	56.40	42.42	43.0	13.20	134.40	7

Tension Infiltation - wheel trafficked



Tension Infiltation untrafficked

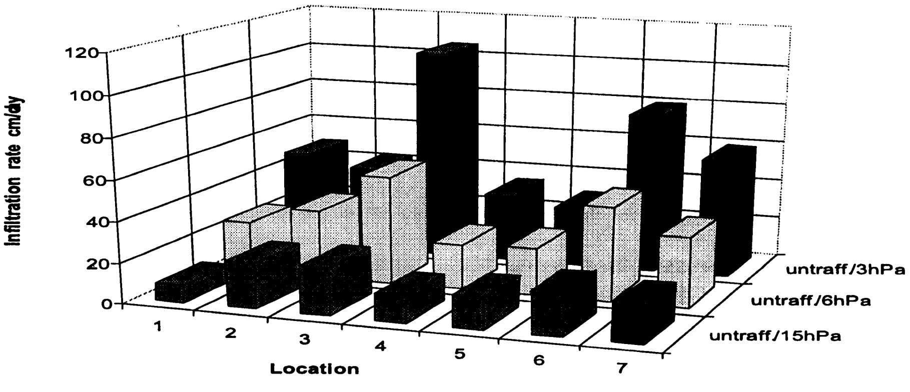


Fig. 4. Steady tension infiltration rates (cm/day) of the trafficked and untrafficked interrows.

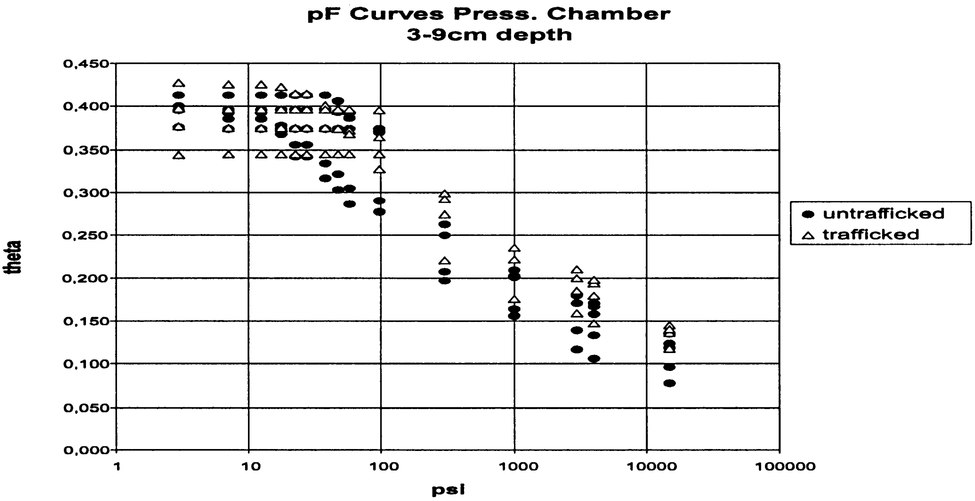


Fig. 5. pF curves (pressure chamber) for trafficked and untrafficked sites.

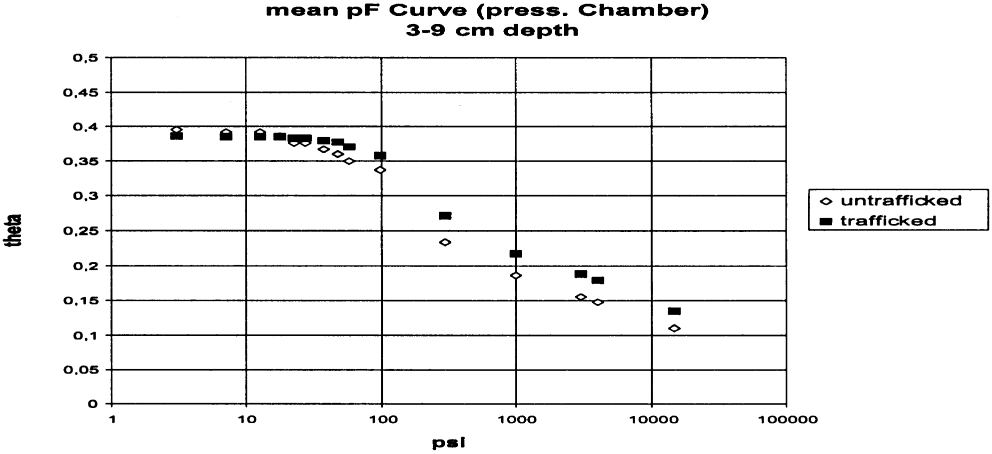


Fig. 6. Mean pF curves (pressure chamber).

during the measurement of the unsaturated hydraulic conductivity is a dynamic process (Fig. 8).

The results of the unsaturated hydraulic conductivity measurements are shown in Fig. 9. Combining the results of saturated and unsaturated conductivity measurements, the functions for hydraulic conductivity are obtained for a suction range from 0 to 850 hPa (Fig. 10).

For the numerical solution of water balance simulations, a parametrisation of the hydraulic conductivity function is needed. For this study it was done by the model of Mualem-Van Genuchten [7,12] and by an extended version of the Brooks and Corey-model [5] which was subsequent used for modelling the soil water balance.

There are 3 possibilities to obtain the parameters of the Mualem - Van Genuchten - model:

- Fitting the model to the retention data; the hydraulic conductivity function is estimated;
- Fitting the model to the hydraulic conductivity data; the water retention curve is estimated;

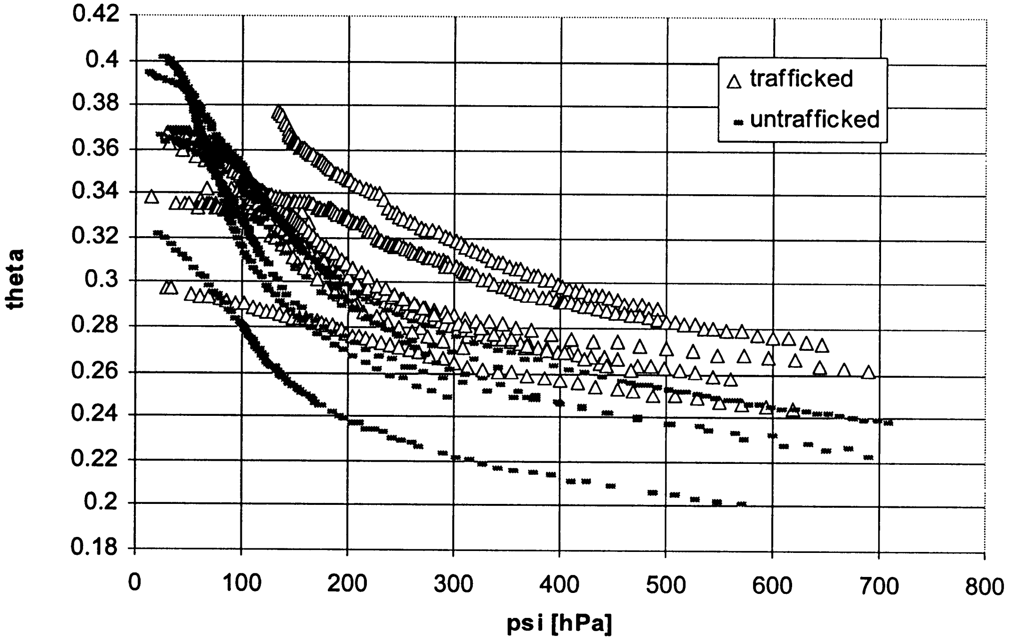


Fig. 7. pF curves (instantaneous profil method).

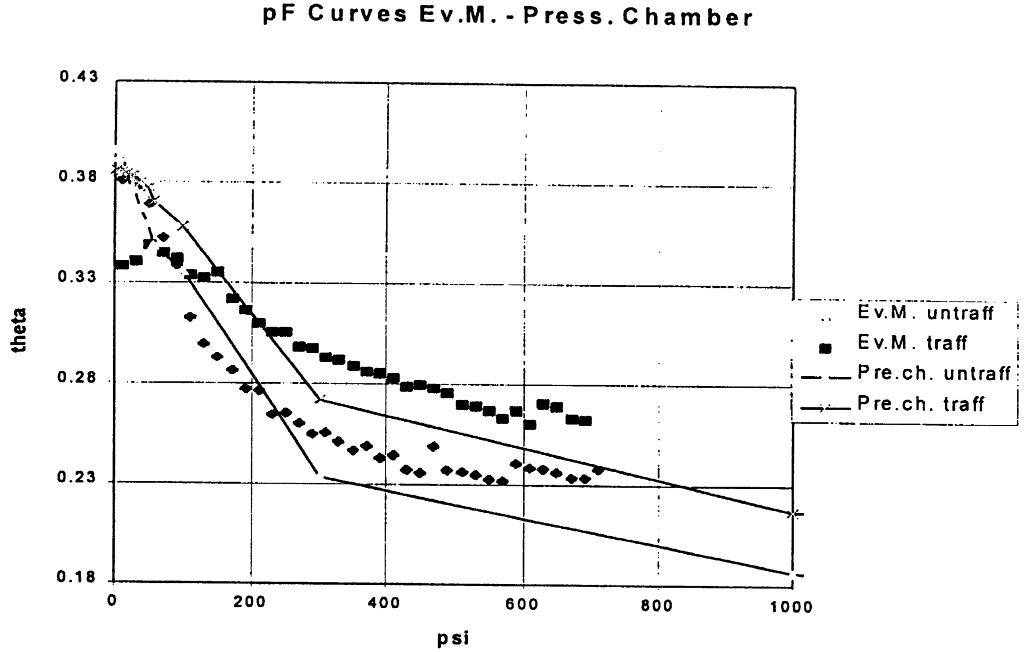

pF Curves Ev.M. - Press. Chamber

Fig. 8. Comparison of pF curves from instantaneous profil method and pressure chamber.

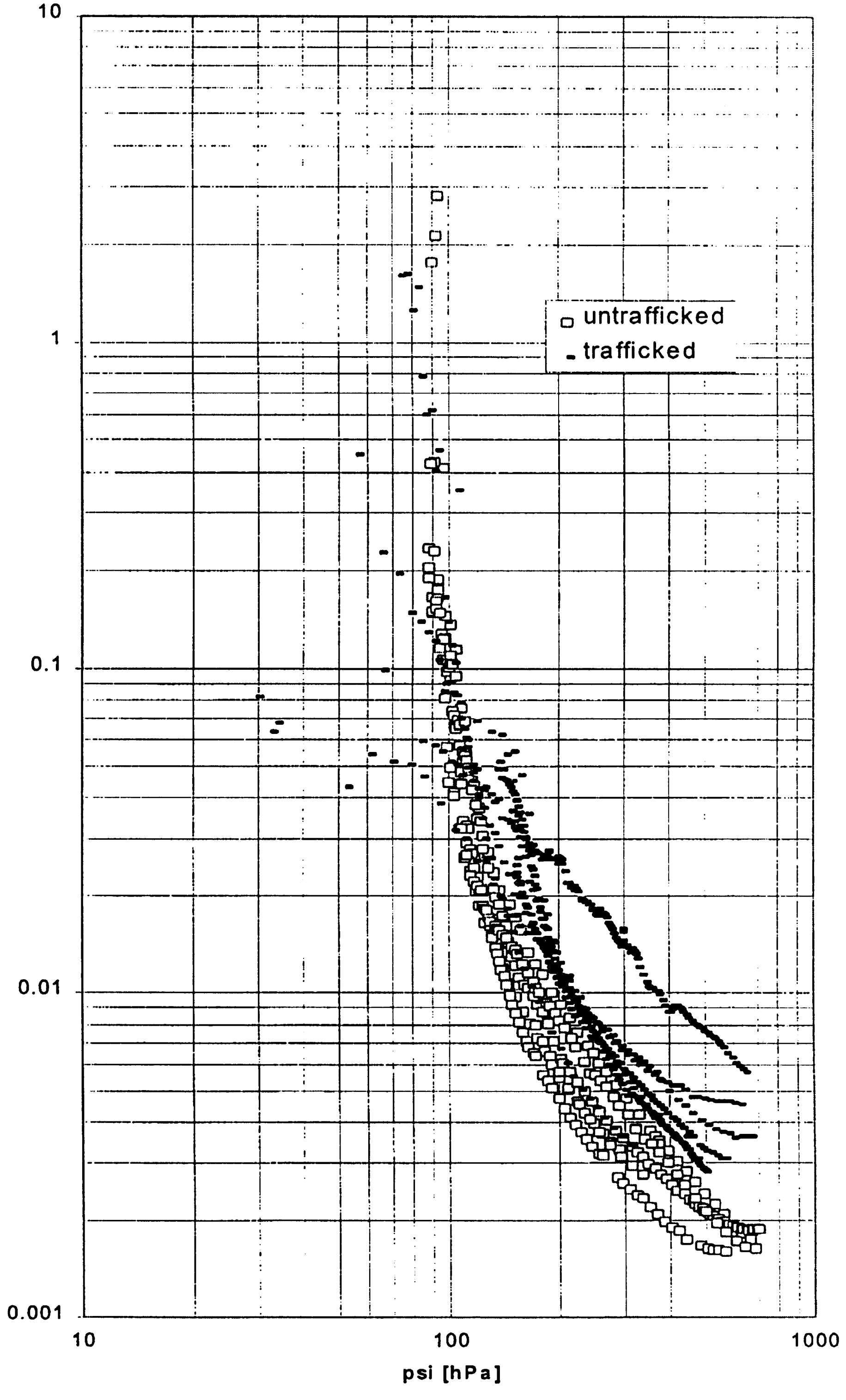


Fig. 9. Hydraulic conductivity for trafficked and untrafficked interrows.

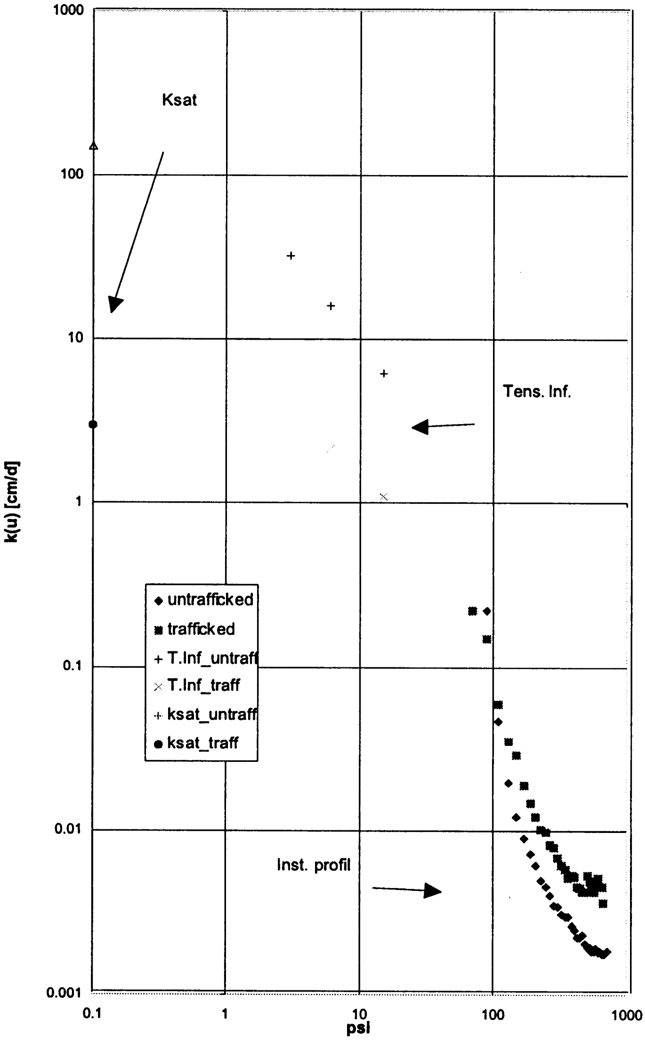


Fig. 10. Combined hydraulic conductivity values measured by 3 different methods.

- Simultaneous fit to retention and hydraulic conductivity data;

There are 3 possibilities to obtain the parameters of the Mualem - Van Genuchten - model:

- Fitting the model to the retention data; the hydraulic conductivity function is estimated
- Fitting the model to the hydraulic conductivity data; the water retention curve is estimated
- Simultaneous fit to retention and hydraulic conductivity data;

The fitting of the Mualem - Van Genuchten - model to retention data obtained by the pressure chamber method and the instantaneous profil method was for both cases satisfying (Figs 11 and 13) but the consequent estimation of the hydraulic conductivity function was bad (Figs 12 and 14). On the other hand the inverse is valid for fitting to the conductivity data and estimating the retention curve (not presented). No unique parameters for the Mualem-Van Genuchten-model could be found. The best result was found by fitting the Mualem- Van Genuchten model simultanously to water retention (pressure chamber) and conductivity data (Figs 15 and 16).

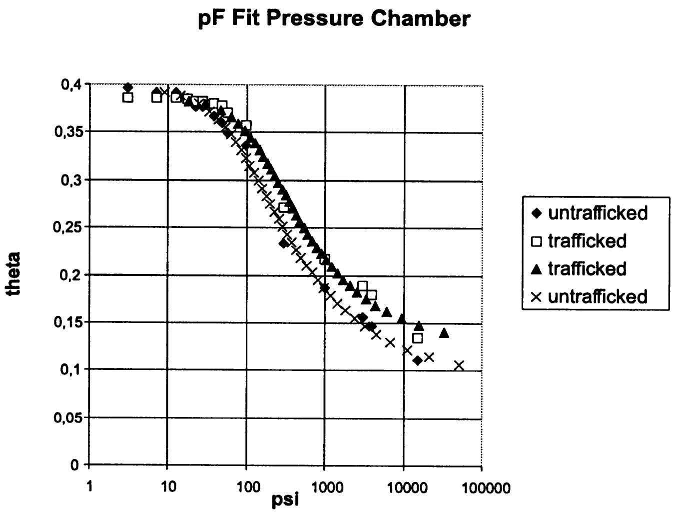


Fig. 11. Fitting the Mualem/Van Genuchten model to pF curve (pressure chamber).

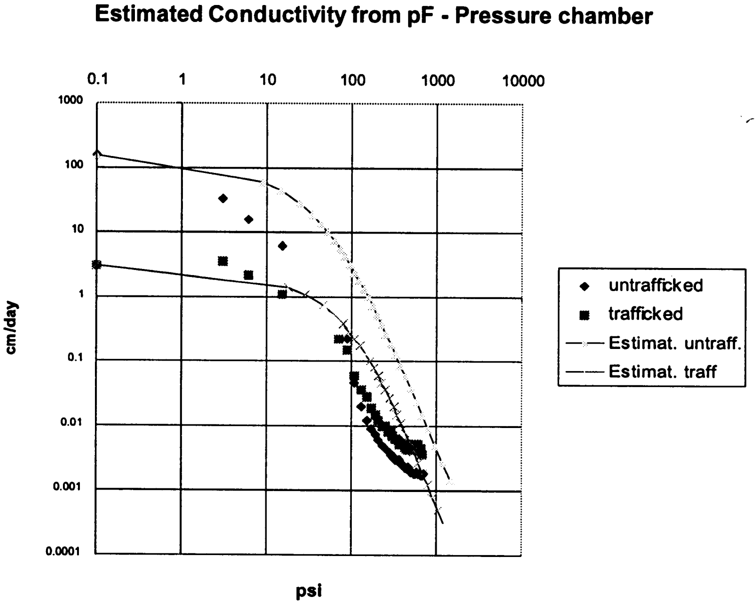


Fig. 12. Estimation of the hydraulic conductivity from pf curves (pressure chamber).

Two preliminary model runs were performed with the computer model ‘SOIL’ for the vegetation period 1992. To obtain the required parameters of the soil hydraulic properties an extended version of the Brooks and Corey-model was fitted to the pF curve. The hydraulic conductivity was estimated from these parameter (Figs 17 and 18). For the first run the soil hydraulic functions for the trafficked interrow; for the second run the soil hydraulic functions of the untrafficked interrow were chosen to model the water movement of the top soil (0-10 cm depth). The soil profil below (10-100 cm depth) was the same for both cases.

Figure 19 is shows the water balance of the top soil for the trafficket and untrafficked site.

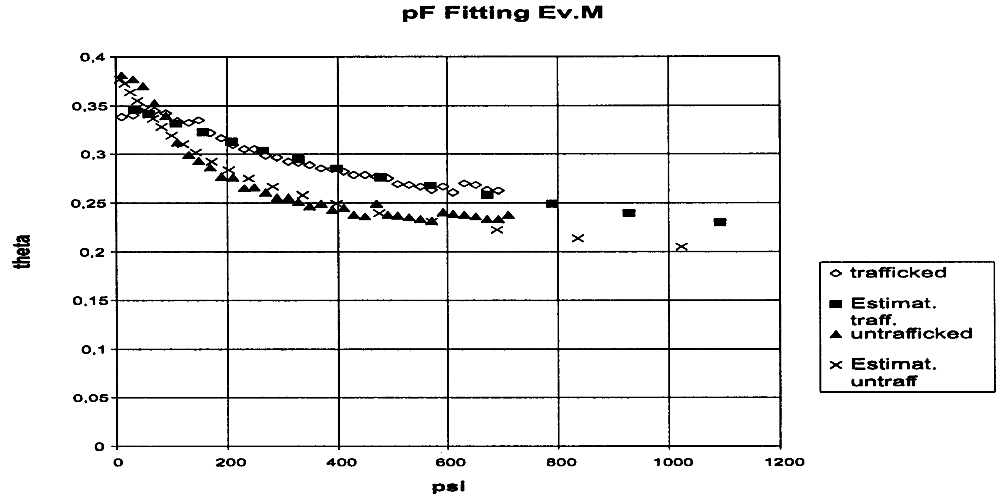


Fig. 13. Fitting the Mualem/Van Genuchten model to pF curve (instantaneous profil method).

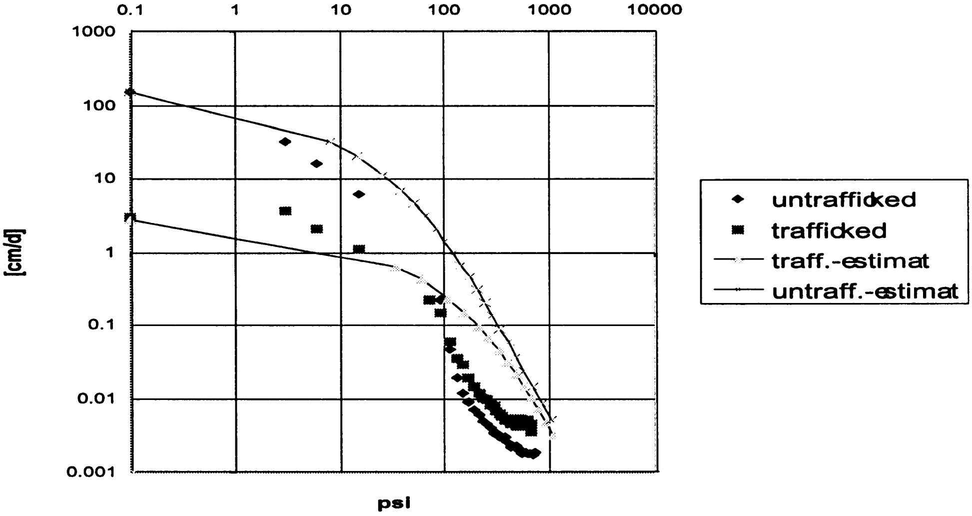


Fig. 14. Estimation of the hydraulic conductivity from pF curves (instantaneous profil method).

The higher water content for the trafficked interrow more or less throughout the whole vegetation period must be the result of the higher water retention capacity (see Figs 6 and 8). A deterioration of the water balance becauseof soil compaction was not found from this model run. There is no evidence from computer simulations that soil compaction has significant influence on the water balance of the deeper horizons (Fig. 19).

Providing soil hydraulic functions for the site Großenzersdorf and water balance simulation of a soybean field with and without irrigation

Almost all of the SWRCs of the soil Großenzersdorf are showing a very distinct air entry pressure at 30 hPa (Fig. 20). The variability of water content belonging to one pressure step is about 5 vol. % for the Ap-and the

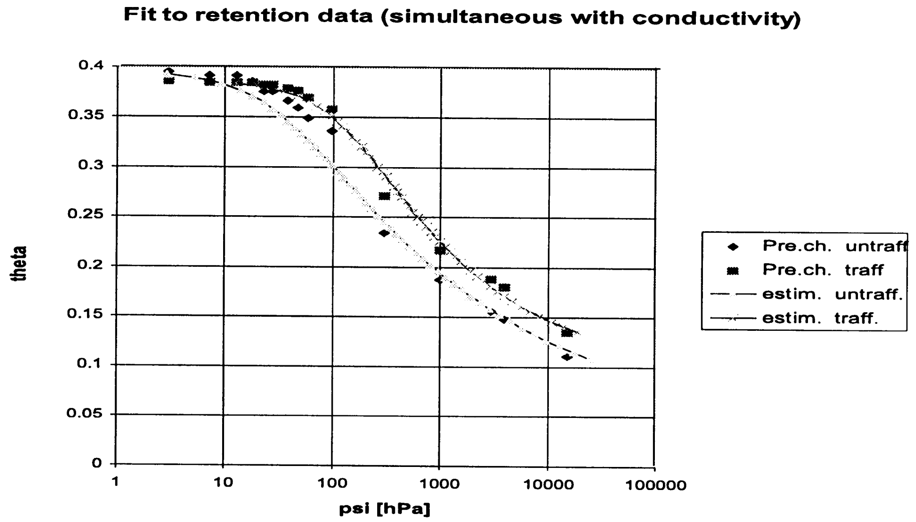


Fig. 15. Fitting the Mualem/ VanGenuchten model to pF curve (pressure chamber) and conductivity data simultaneously.

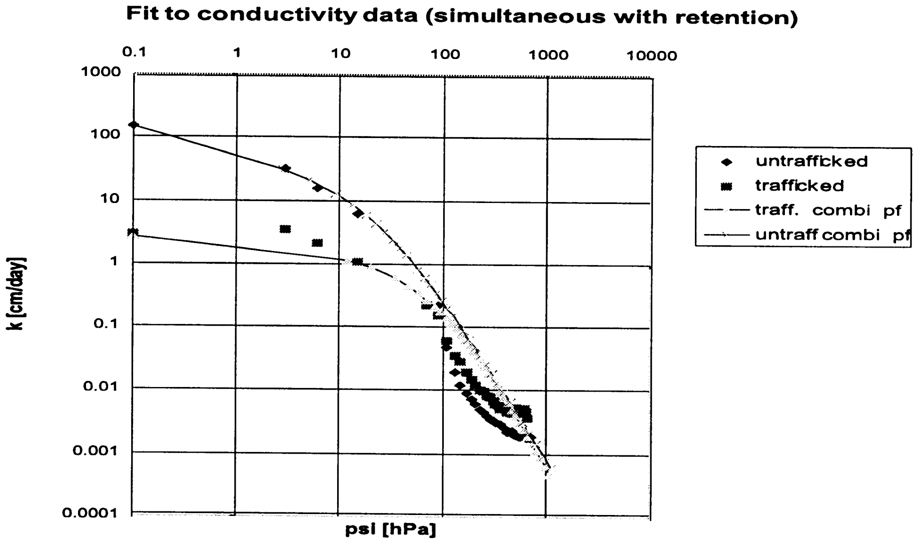


Fig. 16. Fitting the Mualem/Van Genuchten model to conductivity data and pF curve (pressure chamber) simultaneously.

Ah-horizons whereas for the AC-horizon (60 cm) it is much higher (about 10 vol. %). This is due to the higher variability of the grain size distribution at the depth of 60 cm.

The mean SWRCs of the different horizons and the fitting results using the modified Brooks & CoreY-model are shown in Fig. 21. Because of a linear expression used in the range from saturation (qs) to a water content of saturation minus 4 vol. % it is not possible to get a good fit also for the near saturation range and it is not possible to describe the distinct air entry value adequately.

The results of the saturated hydraulic conductivity (= K_{sat}) for the different horizons are shown in Table 4 and in Fig. 22. No statistics were stated

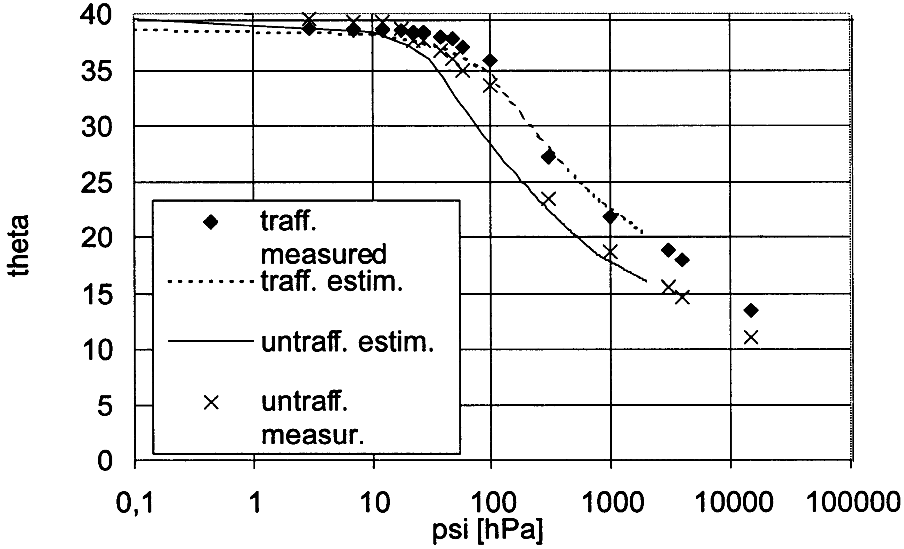


Fig. 17. Retention curve of trafficked and untrafficked top soil as used for modelling the water balance.

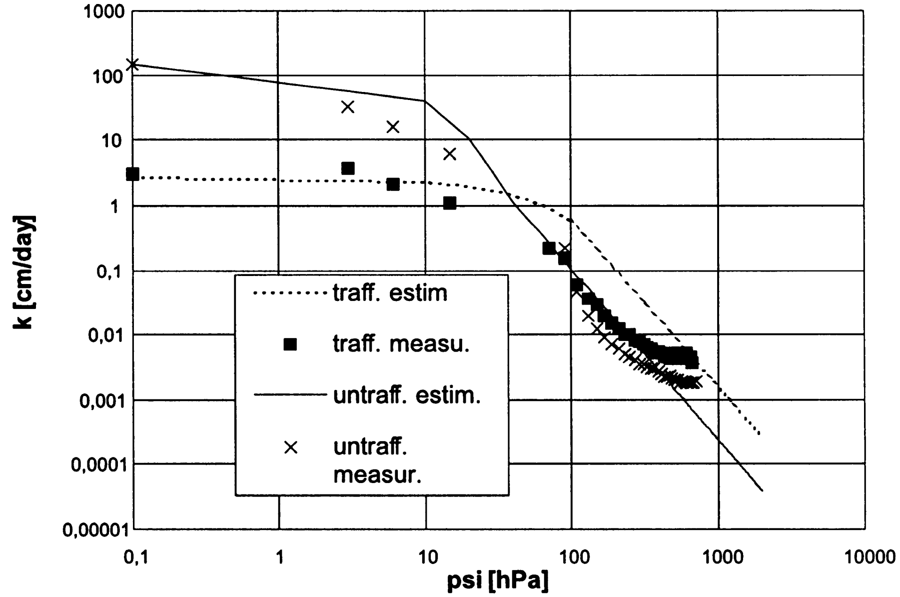


Fig. 18. Hydraulic conductivity functions of trafficked and untrafficked top soil as used for modelling the water balance.

for the saturated hydraulic conductivity calculated from tension infiltration measurements at 10 cm depth and at the tilled surface because of the low numbers of samples.

The highest values of the saturated hydraulic conductivity were obtained by the falling head method in the laboratory. This might be due to the tillage of the Ap horizon and the high density of rainworm furrows in the upper horizons which affect the measurement of K_{sat} by the laboratory method with soil cores of only 6 cm length in a higher degree compared

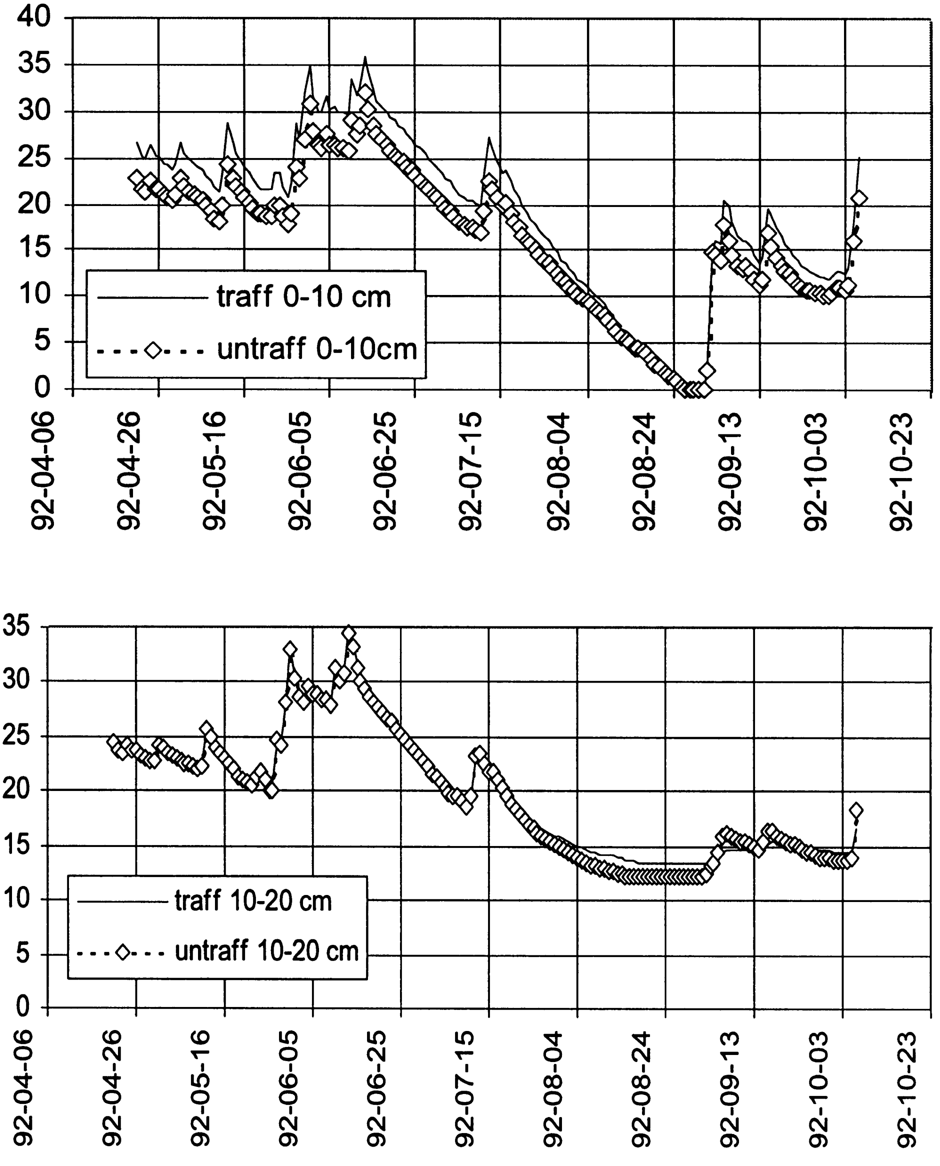


Fig. 19. Simulated water content for the depths 0-10 and 10-20 cm for trafficked and untrafficked topsoil.

to the GUELPH-permeameter method. It was experimentally proved that a GUELPH-permeameter measurement directly on a crack will lead to a high infiltration rate at the beginning of the infiltration but after filling of the crack it results in a similar steady state infiltration rate (which is used for calculating K_{sat}) compared with measurements conducted on a place without cracks. Comparing GUELPH-permeameter with the soil core method, the measurements at 60 cm depth resulted in most similar values of K_{sat} because the primary pore system of the soil is of higher importance than in the upper horizons but differences were still substantial between the two methods. Concerning the specific modelling approach of the 'SOIL' - model K_{sat} measured by soil cores are used as input for the macropore velocity of the defined soil layer and the results of the GUELPH-permeameter mea-surements reflect the saturated hydraulic conductivities of the soil matrix.

Because of the high silt content and low aggregate stability the structure of the soil Großenzersdorf is very susceptible for compaction due to rainfall impact and settlement after soil tillage. This resulted in an increase of bulk density and a strong reduction of the K_{sat} of the Ap-horizon during the vegetation period (Table 4). This was considered for the modelling of the water balance by splitting the vegetation period in a first (from 4th of May to 15th of August) and a second half (from 15th of August to 4th of October) using the corresponding K_{sat} value as input of macropore velocity for the two periods. Since GUELPH-permeameter measurements were performed in August and do therefore not represent K_{sat} of the soil matrix during the first half of the vegetation period, K_{sat} was mea-sured with the tension infiltrometer on a freshly tilled soil.

The calculated K_{sat} values from tension infiltration measurement in september on the soil surface and in 10 cm depth resulted in nearly the same saturated hydraulic conductivity values compared to the measurement of soil cores taken in September (Table 4).

Figure 23 is showing the unsaturated hydraulic conductivity functions (K_u) in the range of -60 hPa to -850 hPa of the Ap-, Ah- and AC - horizons for the subplot 3 measured with the instantaneous profile method. For the whole measurement range K_u of the AC-horizon is highest and K_u for the Ap-horizon is lowest. The comparison of results of the instantaneous profil method and the multistep outflow method is showing an acceptable agreement of the K_u functions obtained by these different methods (see appendix - Figs 48-50) except for the samples of 60 cm depth. This might again be due to the high variability of grain size distribution of the AC- and C-horizon.

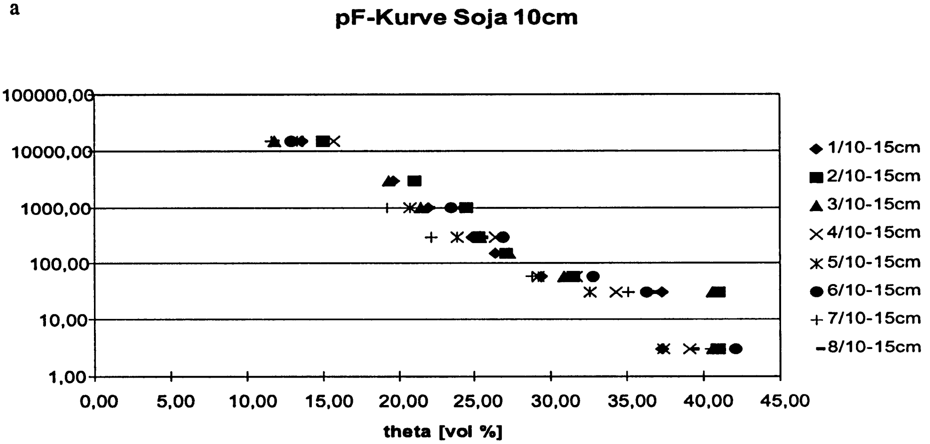
The unsaturated hydraulic conductivity functions which are used as input for the water balance model 'SOIL' were estimated from fitting the Brooks & Corey-model to the SWRC and calculating the K_u function after Mualem [7]. For the A_p-horizon two different Ku functions are estimated for the first and the second half of the vegetation period using the corresponding K_{sat} values (Fig. 24). The higher saturated hydraulic conductivity values (macropores and soil matrix) produced a more or less parallel shift of the K_u function. The estimated K_u for the second half of the vegetation period was in high agreement with the measured values.

Also the estimation of K_u for the Ah-horizon fits very well to the measured data points of the unsaturated conductivity (Fig. 25).

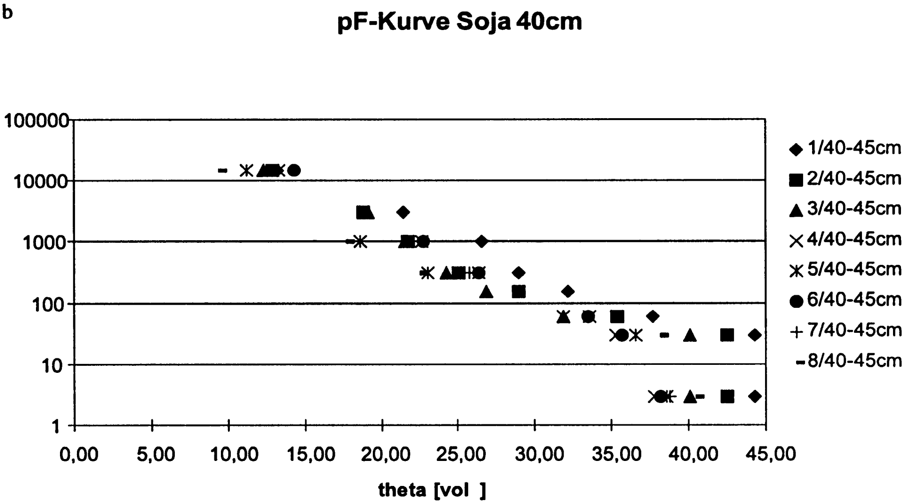
Table 4. Saturated hydraulic conductivity in cm/day of the soil Großenzersdorf measured by different methods (SC = soil core - laboratory method; Guelph = Guelph permeameter method; TI = tension infiltrometer method; TI-til = measurement on surface of freshly tilled soil; per = percentile; n = number of samples)

	SC 10 cm April	SC 10 cm Sept.	SC 40 cm	SC 60 cm	Guelph 8-25 cm	Guelph 28-45 cm	Guelph 50-67 cm	TI surf.	TI 10 cm	TI-til surf.
Geo. mean	3286	79	887	753	26	56	219	108	70	720
Arit. mean	5953	310	2431	827	32	66	231	126	77	-
St. dev.	5883	708	6209	446	27	39	83	64.8	-	-
25 per.	768	24	362	555	15	41	166	71	-	-
75 per.	8880	221	1353	868	34	101	287	165	-	-
Maximum	21640	2513	25598	1788	96	137	382	240	-	-
Minimum	274	14	279	455	10	41	123	32	-	-
n	15	12	16	7	8	8	8	8	3	1

a



b



c

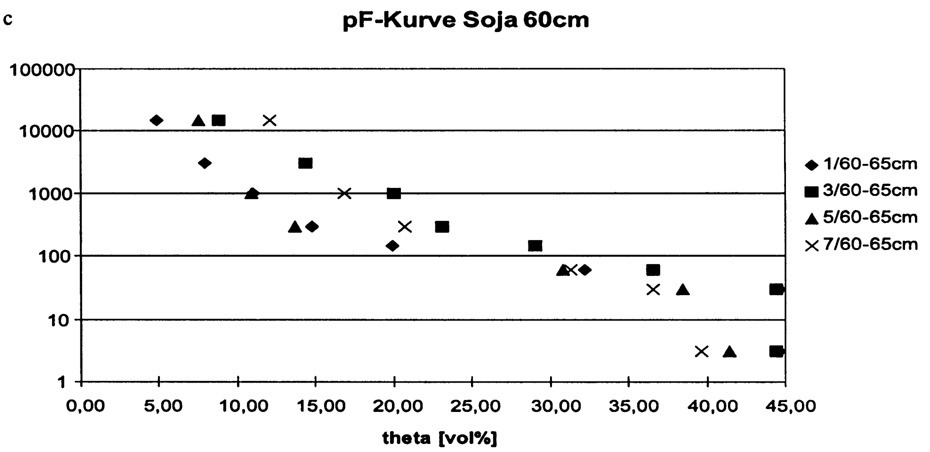


Fig. 20. SWRC of the 8 subplots for the Ap (a) and A_h (b) horizons and of the 4 subplots for AC horizon (c).

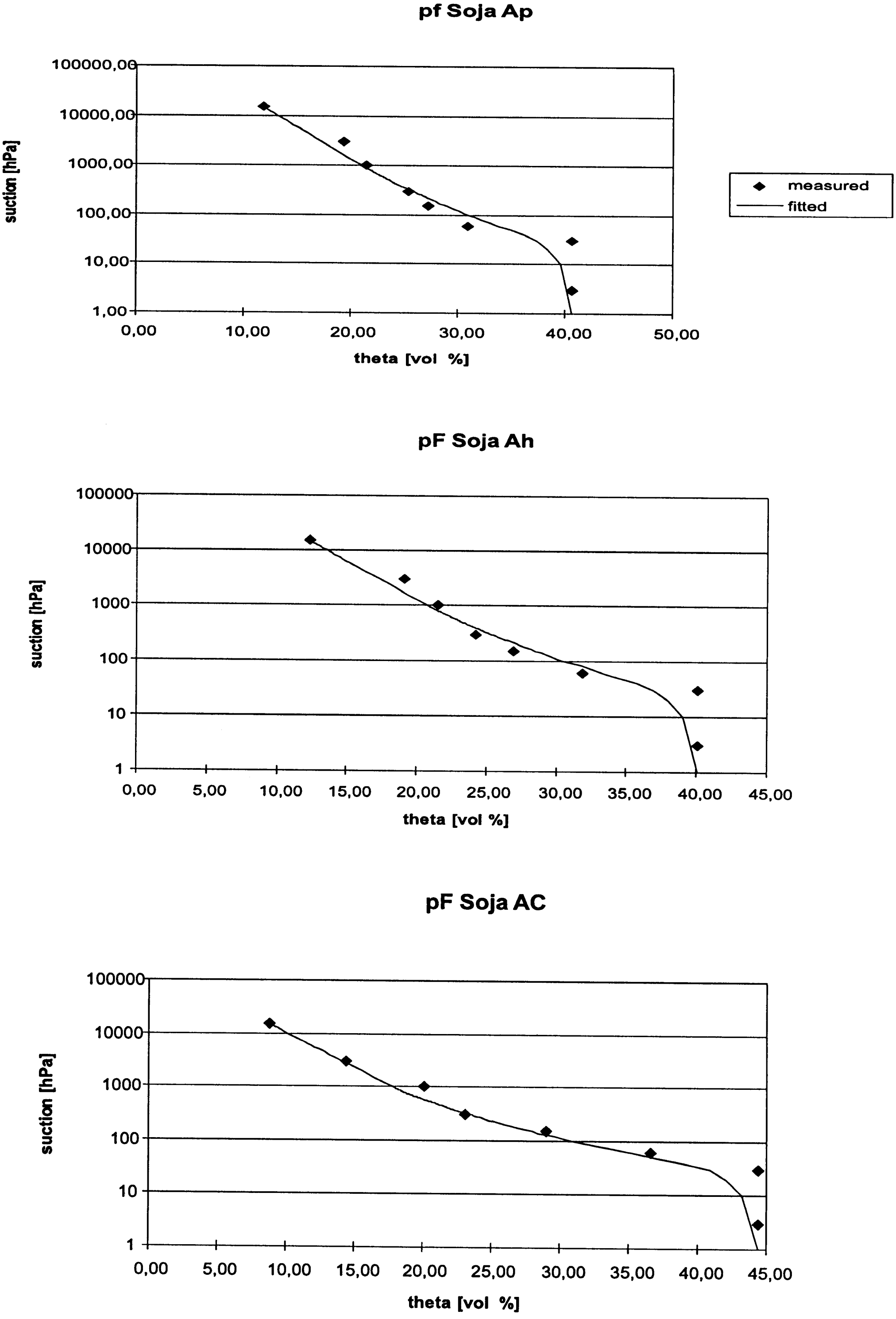


Fig. 21. Mean SWCR for the Ap, A_h and AC horizons and fitting results.

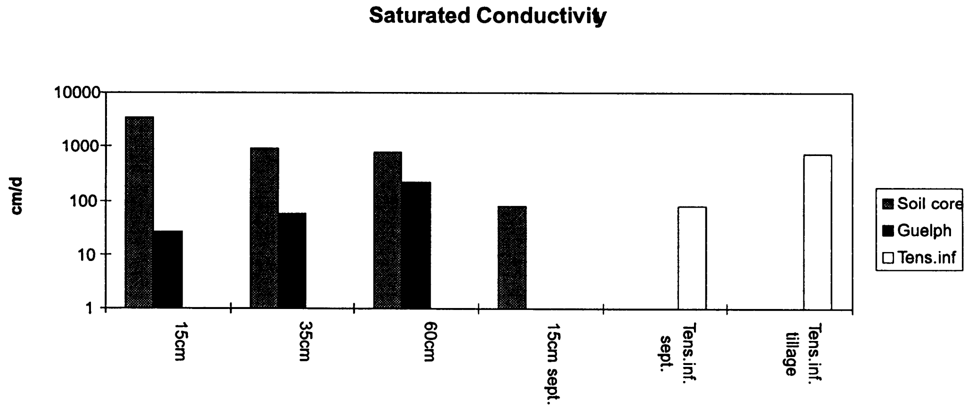


Fig. 22. Saturated hydraulic conductivity measured by different methods.

The unsaturated hydraulic conductivity functions which are used as input for the water balance model 'SOIL' were estimated from fitting the Brooks and Corey-model to the SWRC and calculating the K_u function after Mualem [7]. For the A_p-horizon two different Ku functions are estimated for the first and the second half of the vegetation period using the corresponding K_{sat} values (Fig. 24). The higher saturated hydraulic conductivity values (macropo-res and soil matrix) produced a more or less parallel shift of the K_u function. The estimated K_u for the second half of the vegetation period was in high agreement with the measured values.

Also the estimation of K_u for the Ah-horizon fits very well to the measured data points of the unsaturated conductivity (Fig. 25).

Using the first estimation of the Ku function for the AC-horizon for modelling the water balance, the modelled water content for this horizon resulted in a generally too high water content during the vegetation period (appendix, Fig. 51. first model run - 60 cm depth). In this case the model was calibrated by decreasing the water content of each pressure step of the SWCR for 2 % vol. and estimating the unsaturated conductivity using this new SWRC. This calibrated K_u function was in better agreement with the measured unsaturated conductivity and produced a better fit of the modelled water content to the measured water content data for the AC horizon (Fig. 26).

For modelling of the soil water balance climatic and plant data are needed as driving variables (daily input) or as function over time. Mean daily temperature and daily precipitation of the vegetation period 1995 are shown in Fig. 27. During June the precipitation was high. From the beginning of July up to the 28th of July was a dry and hot period. On 28th of July there was a remarkable thunderstorm with rain intensity of 30 mm within 1 hour. Precipitation was again higher in September with an optimum of 60 mm on 15th of September.

The remaining climatic driving variables (wind speed, relativ humidity, global radiation) and plant variables (leaf area index, rooting depth, root distribution) are shown in the appendix, Figs 28-30. The leaf area index was measured several times during the vegetation period while the root growth during the vegetation period and maximal rooting depth was estimated assuming that the maximal rooting depth is reached at flowering. The root distribution within the soil profile was recorded at the end of the vegetation period.

To compare model results with the reality and to conduct calibration of a model independently measured data are needed. In this case the water content was recorded with TDR probes during the vegetation period. Additionally the volumetric soil water content of the experimental site was occasionally measured with soil cores (weighting and oven drying in the laboratory) to prove the accuracy of the

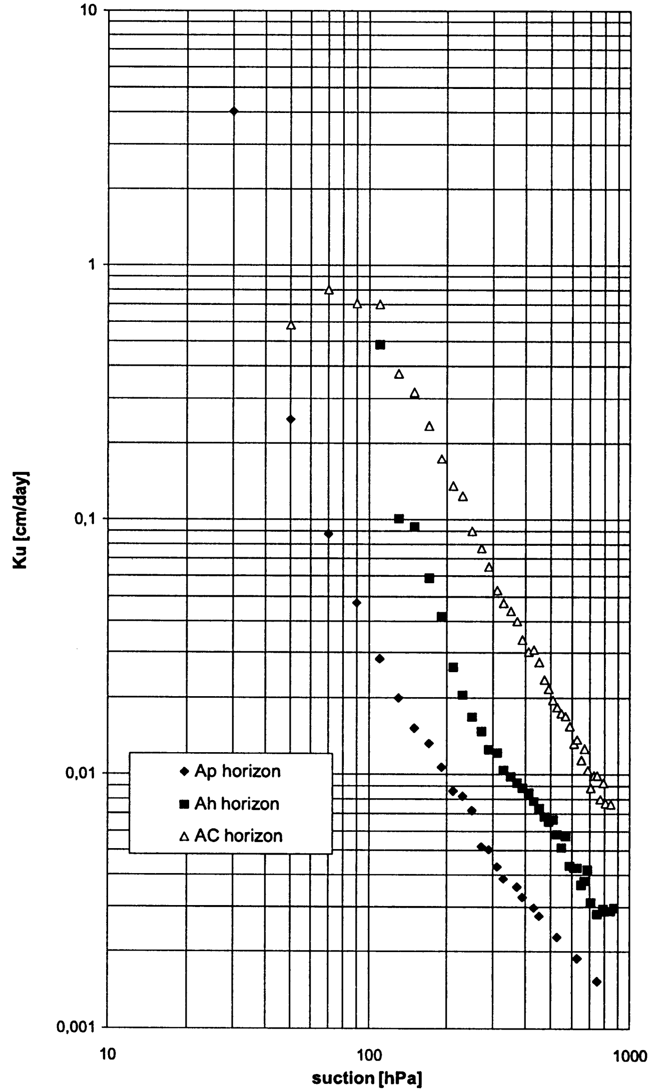


Fig. 23. Unsaturated hydraulic conductivity of the A_p, A_h and AC horizons (subplot 3).

TDR system. Water content data of subplot 2 (irrigated) and subplot 3 (non irrigated) are shown in Figs 31 and 32.

The water content data measured with soil cores corresponds satisfying to the water content data measured with the TDR-system. The deviation is in most of the cases smaller than 5 % vol. and can be interpreted as normal variability of the water content data. That means that the confidence in the TDR measured water content data is high.

The TDR data of the Ap-horizon are showing in both cases - irrigated and non irrigated - a steady increase of the highest water content peaks after extensive precipitation events from 30 % vol. at the beginning of the vegetation period to 35 % vol. at the end of the vegetation period and also an increase of the field capacity level. Two reasons could be responsible for this behaviour:

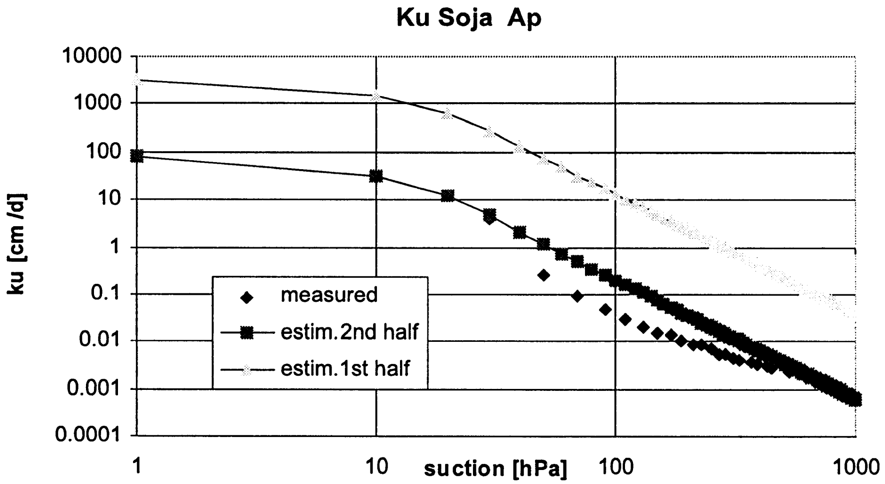


Fig. 24. Measured unsaturated hydraulic conductivity and estimations after Brooks and Corey with K_{sat} (soil matrix) of first and second half of vegetation period for the A_p-horizon.

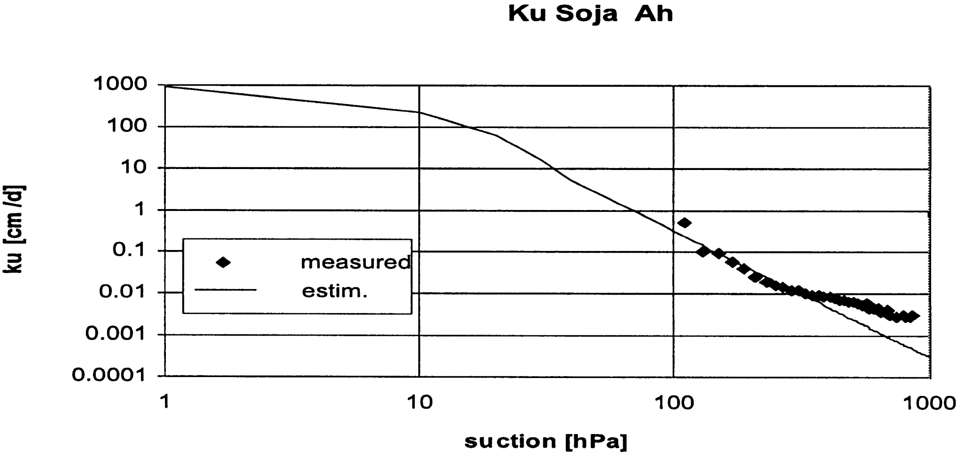


Fig. 25. Measured unsaturated hydraulic conductivity and estimation after Brooks and Corey for the Ah-horizon.

- during the vegetation period the pore size distribution is changing in this way that field capacity is increasing,
- the changing bulk density during the vegetation period is changing the relationship between the dielectric constant measured with the TDR system and the water content [8].

From the beginning of May to the 11th of September the bulk density of the Ap horizon was increasing from 1.33 g/cm^3 to 1.56 g/cm^3. Using a matrix sensitive calibration function for calculating water content from TDR measurements [8], it can be realized that the error caused by using a calibration function without considering the change of bulk density during the vegetation period is less than 3 % vol. in the water content range from 30 to 35 % vol. From this, it can be concluded that at least partially the increase of the field capacity level and highest peaks of water content is caused by the changing pore size distribution. Of course, if the bulk density of the Ap-horizon is changing also the hydraulic properties of the soil must change which was taken into account for modelling the

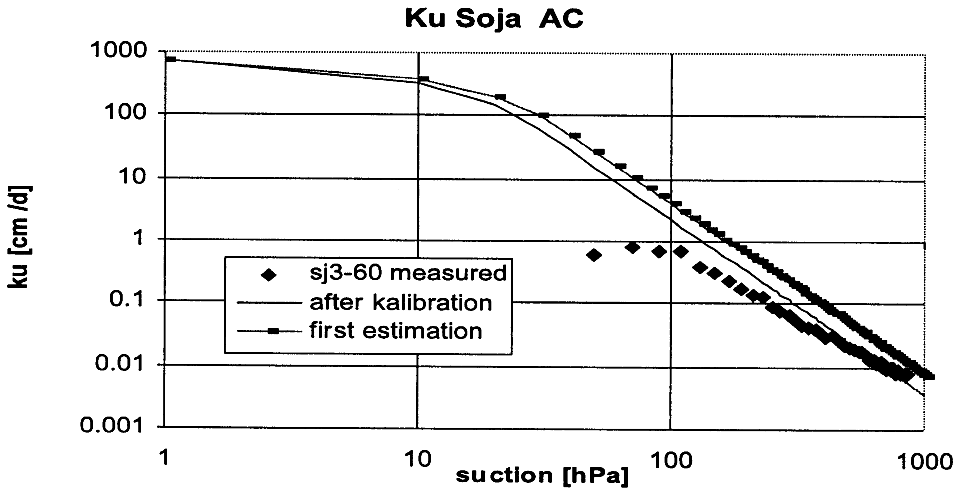


Fig. 26. Measured unsaturated hydraulic conductivity, estimation of Ku after Brooks and Corey and calibrated K_u function for the AC-horizon.

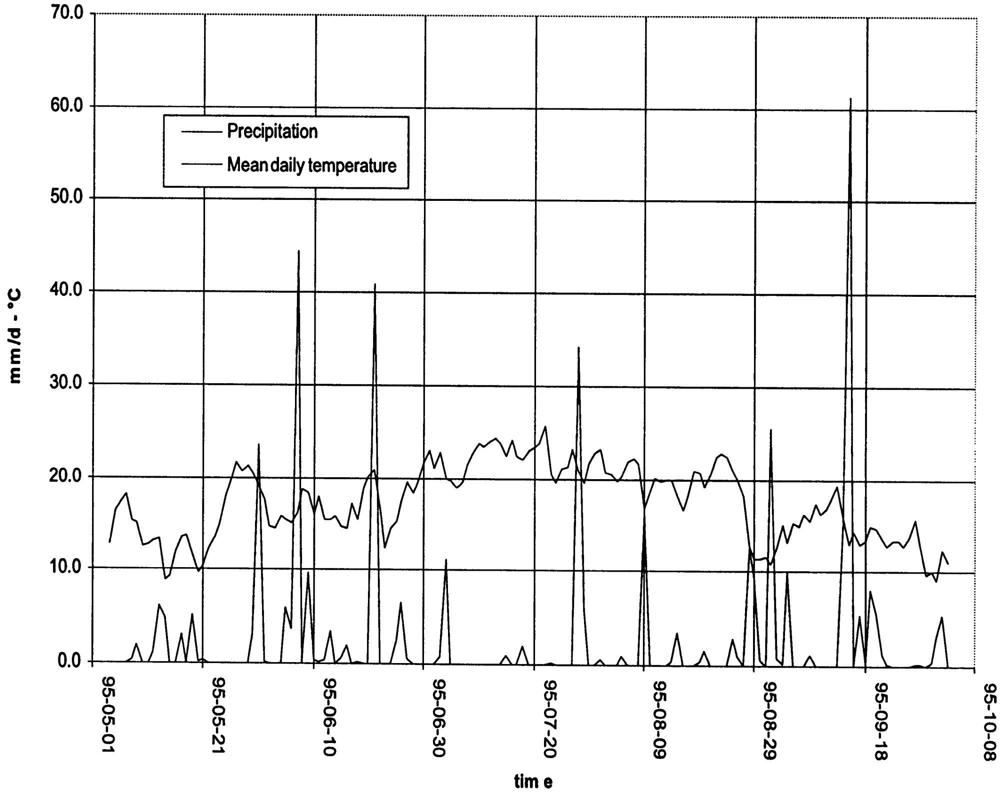


Fig. 27. Mean daily temperature and precipitation during the vegetation period 1995.

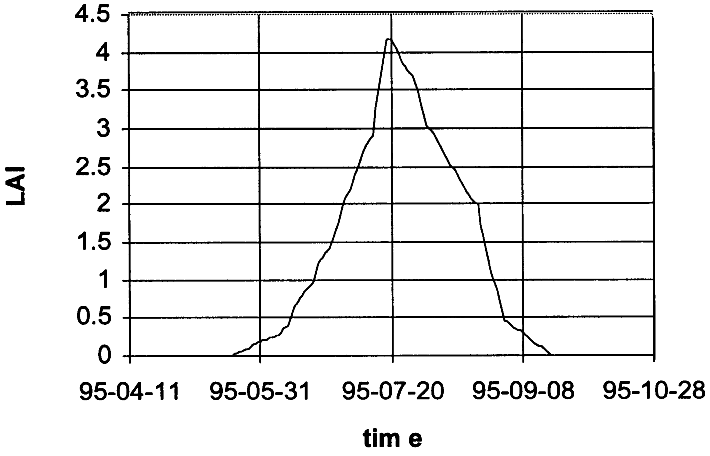


Fig. 28. Leaf Area Index of the soyabean used as driving variable for modelling the water balance.

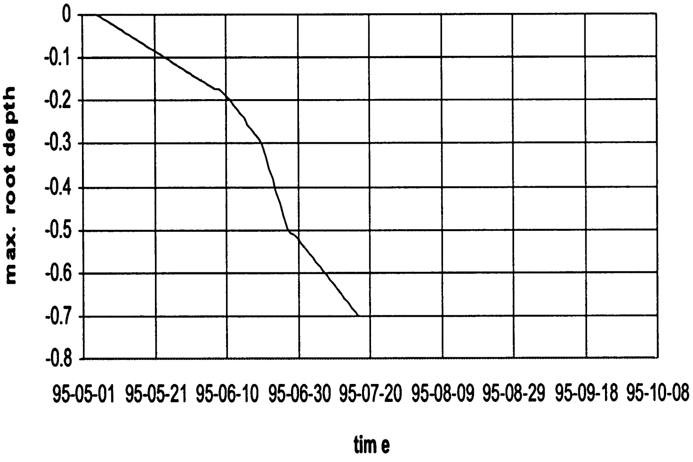


Fig. 29. Developement of maximal rooting depth used as driving variable for modelling the water balance.

water balance by using different saturated and unsaturated hydraulic conductivity values for the first and second half of the vegetation period.

There is no explanation why the TDR probe at 35 cm depth of subplot 2 is not showing the distinct water content peaks after precipitation during the months May and June as this is the case for all the other TDR probes. From beginning of July also this TDR probe seems to work properly till the end of the vegetation period.

Figure 33 shows the measured soil temperature data during the vegetation period of subplot 3 at depths 5 cm, 15 cm and 35 cm.

Using all the described hydraulic conductivity functions, SWRCs and climatic and plant related driving variables the modelling of water balance for subplot 3 is resulting in calculated water content data which are in high agreement with the measured data (Figs 34 and 35).

Applying different hydraulic conductivity functions for the first half and the second half of the vegetation period results in a better fit of the modelled water content to the measured

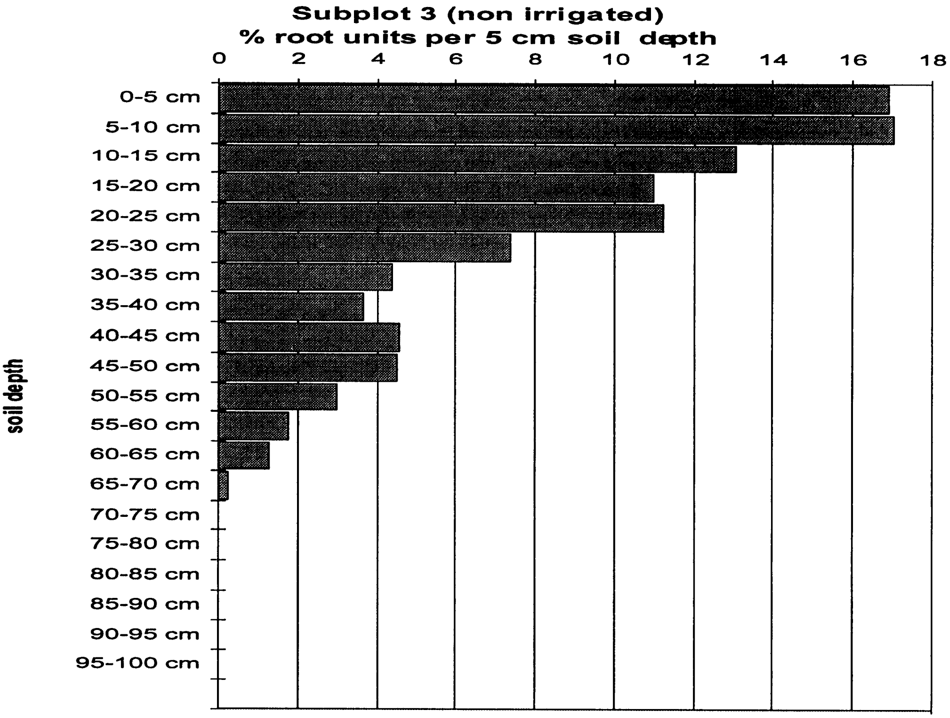


Fig. 30. Root distribution (in % root units per 5 cm soil depth) as used for modelling the water balance.

data as using only one data set for the whole time. In this case the compaction and increase of the bulk density during the vegetation period should be taken into account for modelling of the water balance.

The model ‘SOIL’ is using the saturated hydraulic conductivity of the top layer and daily precipitation data for calculating the infiltration rates. Therefore if there are precipitation events with high rainfall intensity the model cannot detect a restriction of infiltration and ponding of water on the soil surface. Summing up the water content change of the whole soil profil on the 28th of July, it can be realized that at least 50 mm of water is necessary to cause this increase of water content down to a depth of 60 cm and probably deeper. The measured precipitation on 28th of July was only 34.2 mm. This explains why the model cannot fit the TDR measured water content peak during the end of July. The excess water had to flow to the place where the TDR probes were installed because of ponding and a not absolutely flat soil surface.

The next step to improve the model fit to the measured data was to increase the precipitation amount on 28th of July up to 50 mm. This did not improve the modelling result because the higher precipitation only increased the water content on 28th of July of the depth 15 cm and 35 cm but the water content increase in 60 cm depth was still meaningless. Therefore it was concluded that only bypass flow can describe this situation accuratelly. This is confirmed by the observation of a distinct crack system on the experimental site during the second half of July. Cracks are observed to develop down to a depth of 60 cm and deeper.

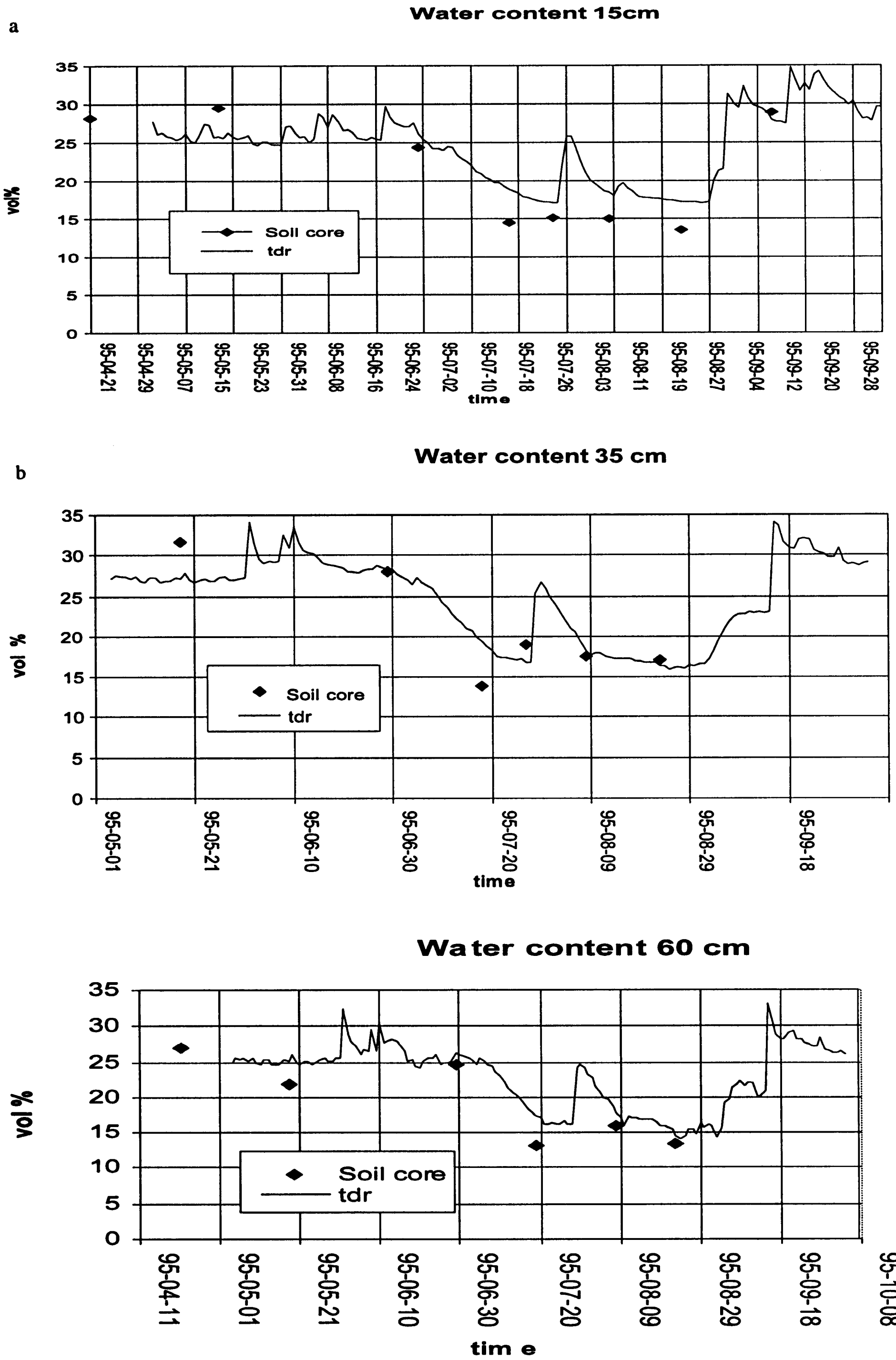
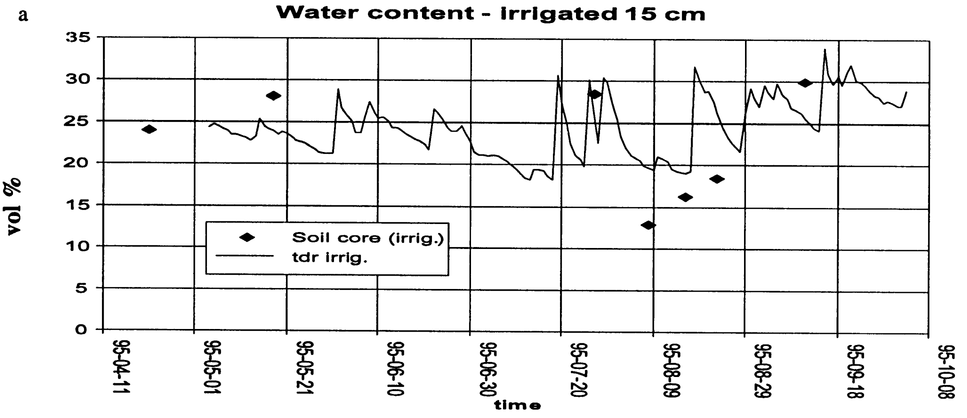


Fig. 31. Water content during the vegetation period of the non irrigated subplot 3 at 15 (a), 35 (b) and 60 (c) cm depths measured with TDR and soil cores.



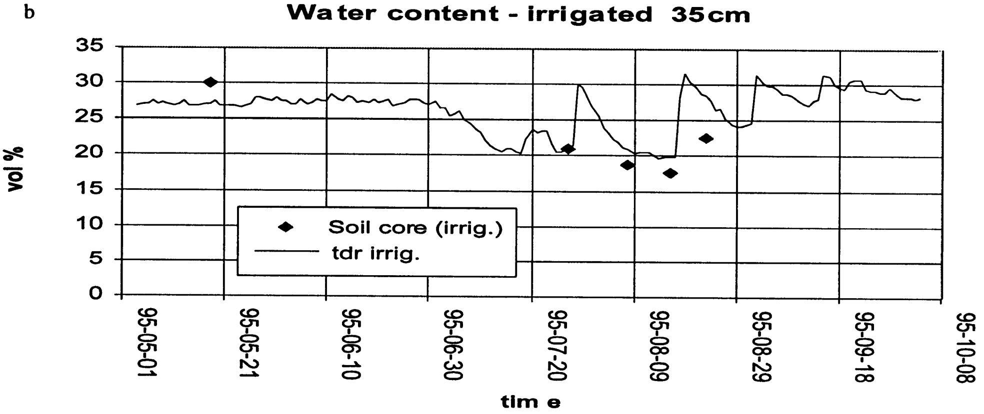


Fig. 32. Water content during the vegetation period of the non irrigated subplot 2 at 15 (a) and 35 (b) cm depths measured with TDR and soil cores.

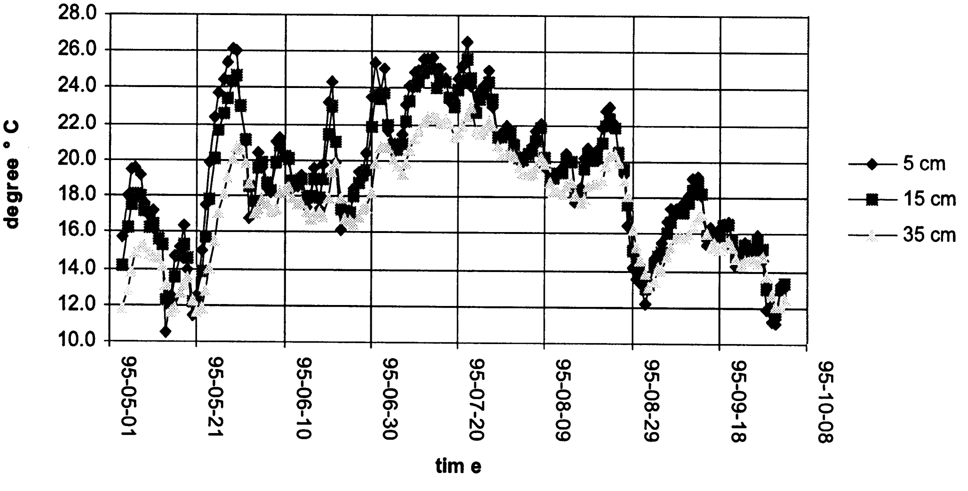


Fig. 33. Soil temperature data during the vegetation period 1995 of subplot 3 (non irrigated) at depths 5, 15 and 35 cm.

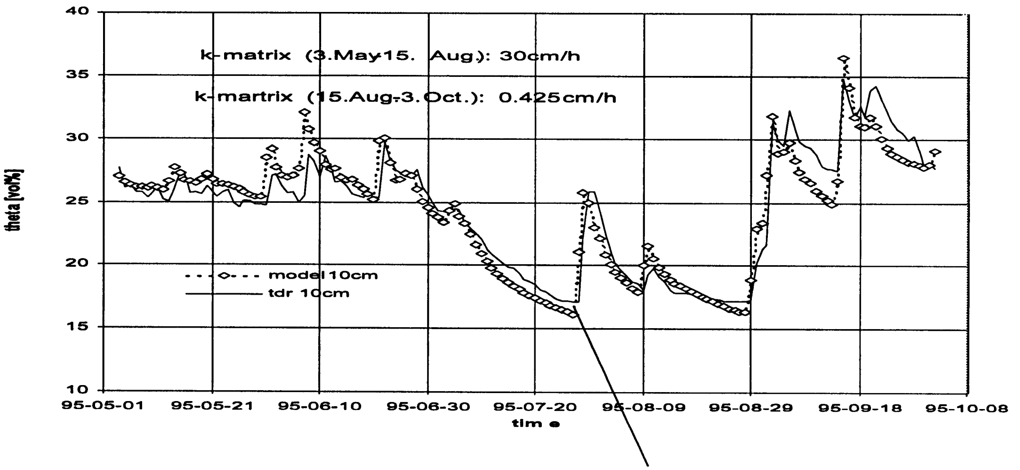


Fig. 34. Measured and modelled water content of the A_p-horizon of subplot 3 using different hydraulic conductivity functions for the first and second half of the vegetation period.

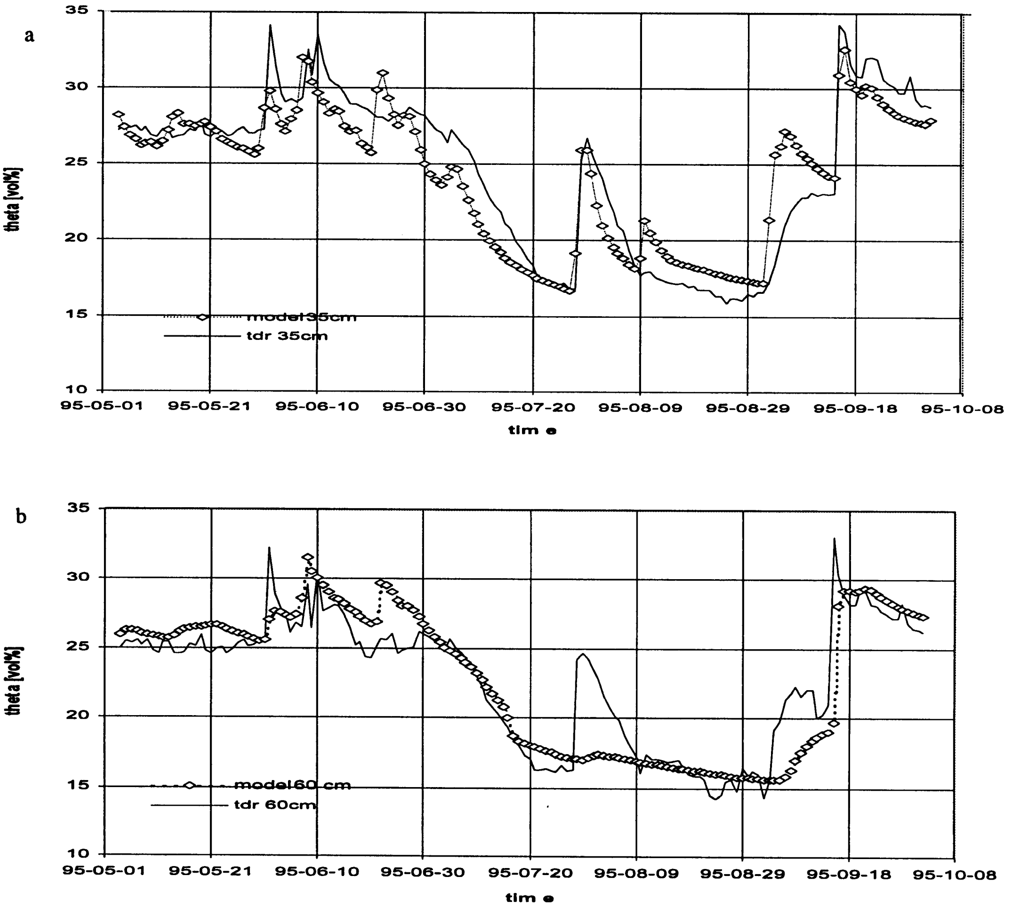


Fig. 35. Measured and modelled water content of the Ah-horizon (a) and AC-horizon (b) of subplot 3.

Also Wilson *et al.* [13], pointed out that preferential flow is occurring at extreme water conditions of the soil that means under wet or very dry conditions which was the case for the soil Großenzersdorf before the thunderstorm on 28th of July occurred.

The model 'SOIL' provides for this situation an empirical procedure with which bypass flow can be modelled. After some trials the water content during the period from 30th of June to the 19th of August could be modelled satisfying with the help of the optional crack procedure (Figs 36 and 37).

The strong rise of tension beginning in the first half of July was caused by root water extraction (Fig. 38). The tensiometer results and the modelled tension at subplot 3 at depth 60 cm are correlating in a high degree, therefore, it can be concluded that the moment when the roots were reaching the depth 60 cm (at 7th of July) is estimated properly.

Irrigation at one half of the experimental site was conducted to keep optimal water content conditions for the plants, that means equal actual and potential evapotranspiration of the plants throughout the vegetation period. A reduction of water uptake by roots is considered to start in a tension range between -600 hPa and -3000 hPa, depending on the plant species and also weather conditions. Taking into account that the corresponding water content value of the SWRC to -3000 hPa tension is about 20 % vol. (Fig. 21) and considering that TDR data of subplot 2 showed water content values lower than 20 %vol only for a few days (Figs 31 and 32), it can be concluded that the water content conditions for the soyabeans at the irrigated part was optimal most of the time during the vegetation period and that the irrigation was from that point of view successful.

The water balance of subplot 2 was modelled using again the measurements of hydraulic and plant properties at this subplot. Again, different saturated hydraulic conductivity values of the Ap-horizon were used for modelling during the first and the second part of the vegetation period. Two calibration steps were necessary to obtain modelling results, as shown in Fig. 39:

- the SWRC of the A_p-horizon was reduced for 2 % vol. of water content at each corresponding tension step except for water content at saturation.
- the amount of irrigated water was reduced to 10 mm at the 13th of July and to 30 mm at the 18th and 25th of July instead of using 40 mm of precipitation per irrigation event, as it was used for the first modelling attempt. This seems to be an inevitable calibration step as far as an irrigation system is used, which is not distributing the water homogeneously over the whole field.

The total amount of irrigated water calculated after the model calibration was therefore 110 mm of water. This increased the model calculated accumulated deep percolation compared to the non irrigated subplot from 123 mm to 154 mm, but the accumulated total evapotranspiration was increased from 310 to 389 and the transpiration from 169 mm

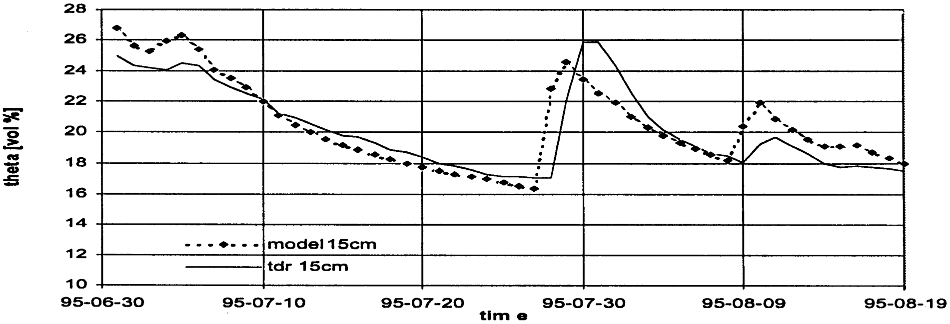


Fig. 36. Measured and modelled water content of the Ap-horizon using bypass flow in the period from 30th of June to 19th of August.

to 241 mm (Table 5). Most of the irrigation water was therefore used to raise the transpiration of the plants, which is highly correlated to plant production.

The non irrigated situation without plant growth was also calculated with the model 'SOIL'. The accumulated deep percolation and evaporation are shown in Table 5.

This situation would result in doubling the deep percolation, a higher soil evaporation but of course in a lower total evapotranspiration.

Some comparative results are shown in Figs 40-42.

Table 5. Accumulated deep percolation, evapotranspiration and transpiration of different model runs (in mm) for one vegetation period (4th of May - 4th of October)

Model run	Deep percolation > 1 m	SET$_{tot}$	S transpiration
Non irrigated (subplot 3)	123	310	169
Without plants non irrigated	266	168	-
With irrigation of 110 m (subplot 2)	158	389	241

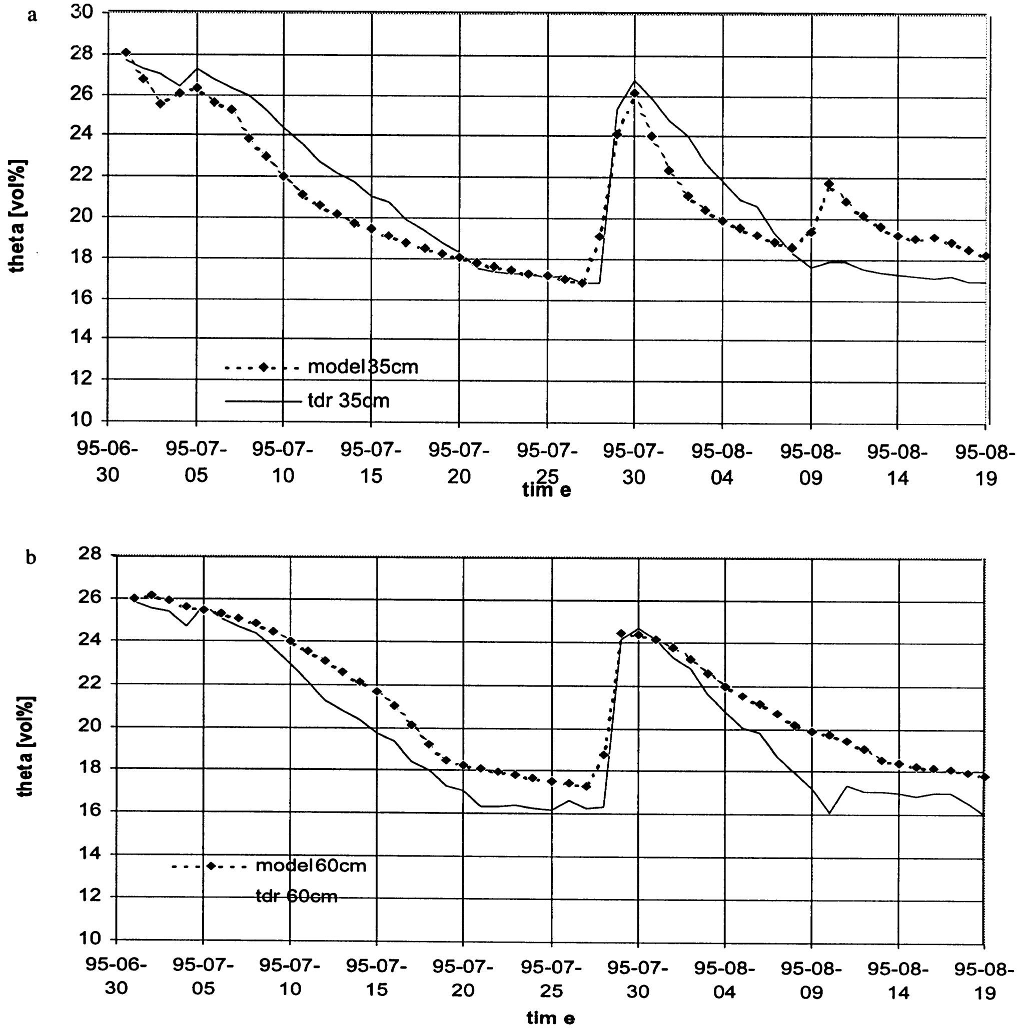


Fig. 37. Measured and modelled water content of the A$_h$-horizon (a) and AC-horizon (b) using bypass flow in the period from 30th of June to 19th of August.

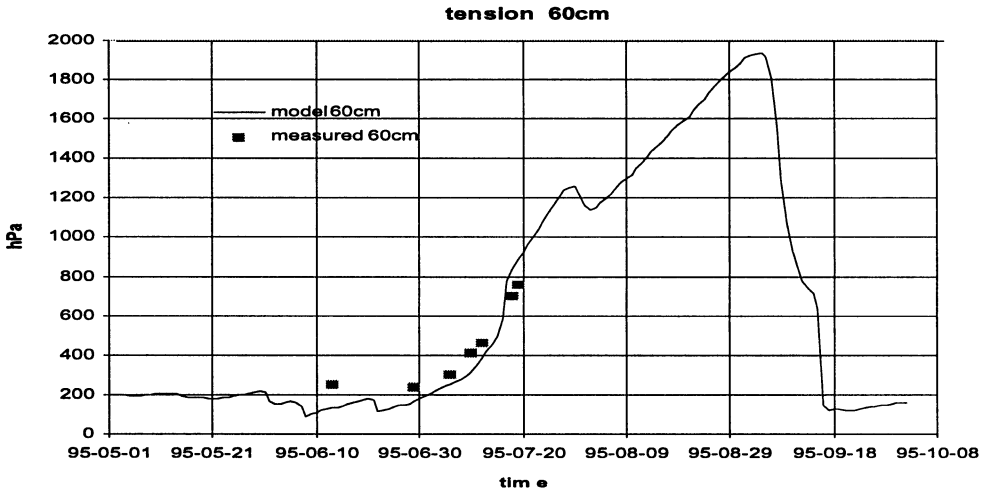
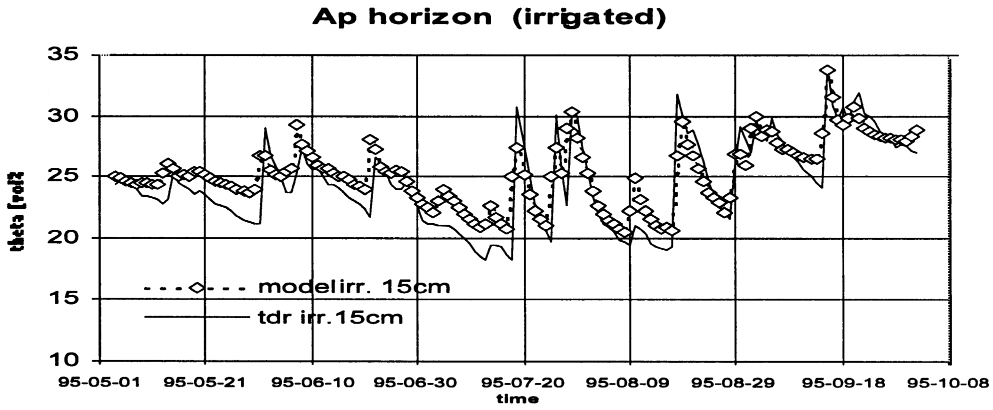


Fig. 38. Measured and modelled tension at 60 cm depth for subplot 3.



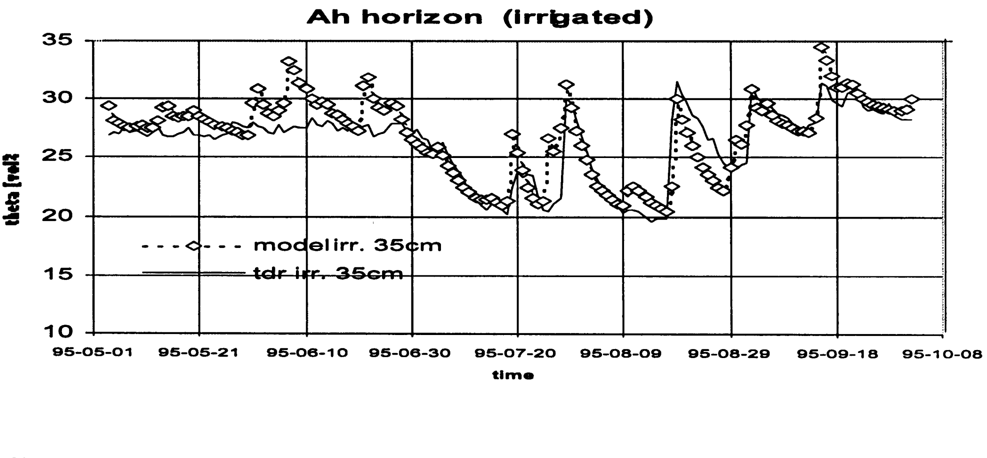


Fig. 39. Measured and modelled water content of the Ap-horizon (a) and Ah-horizon (b) of subplot 2 (irrigated).

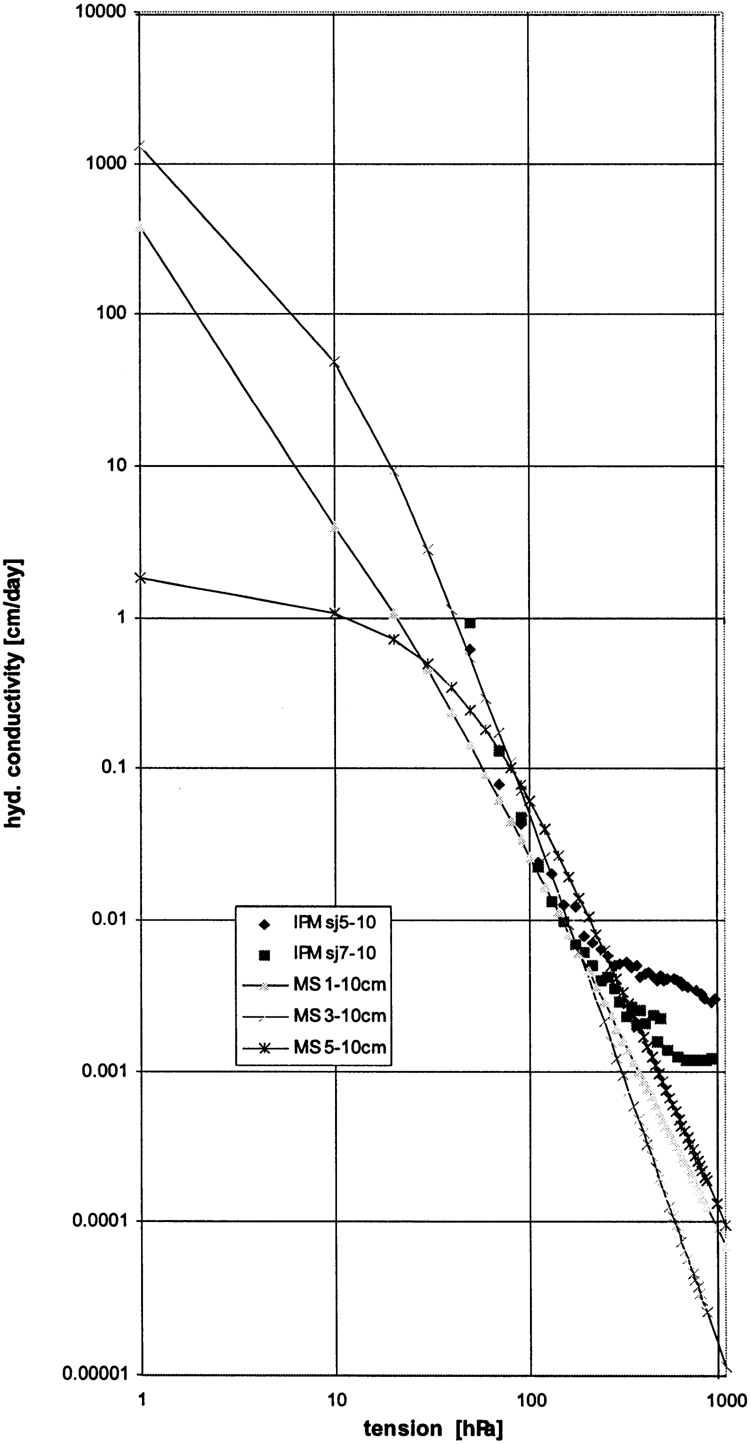


Fig. 40. Comparison of the unsaturated conductivity functions of the A_p horizon measured with the instantaneous profil method (IPM) and the multistep outflow method (MS).

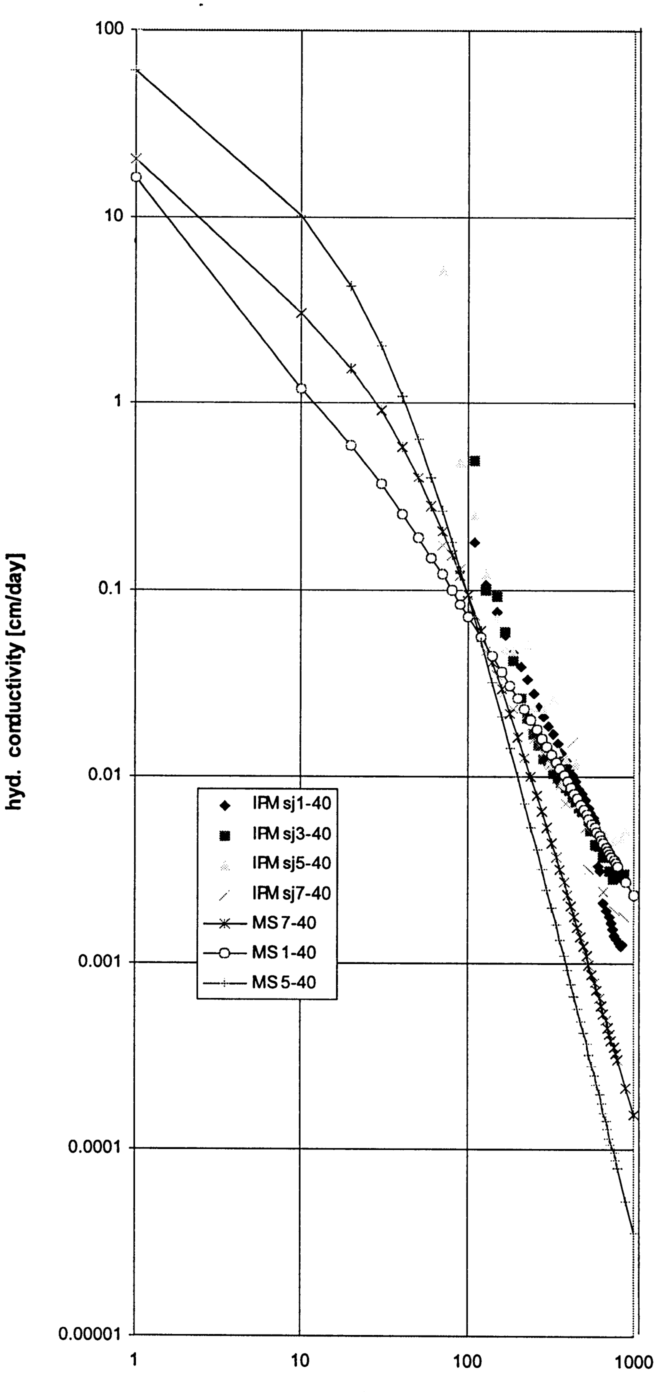


Fig. 41. Comparison of the unsaturated conductivity functions of the A_h-horizon measured with the instantaneous profil method (IPM) and the multistep outflow method (MS).

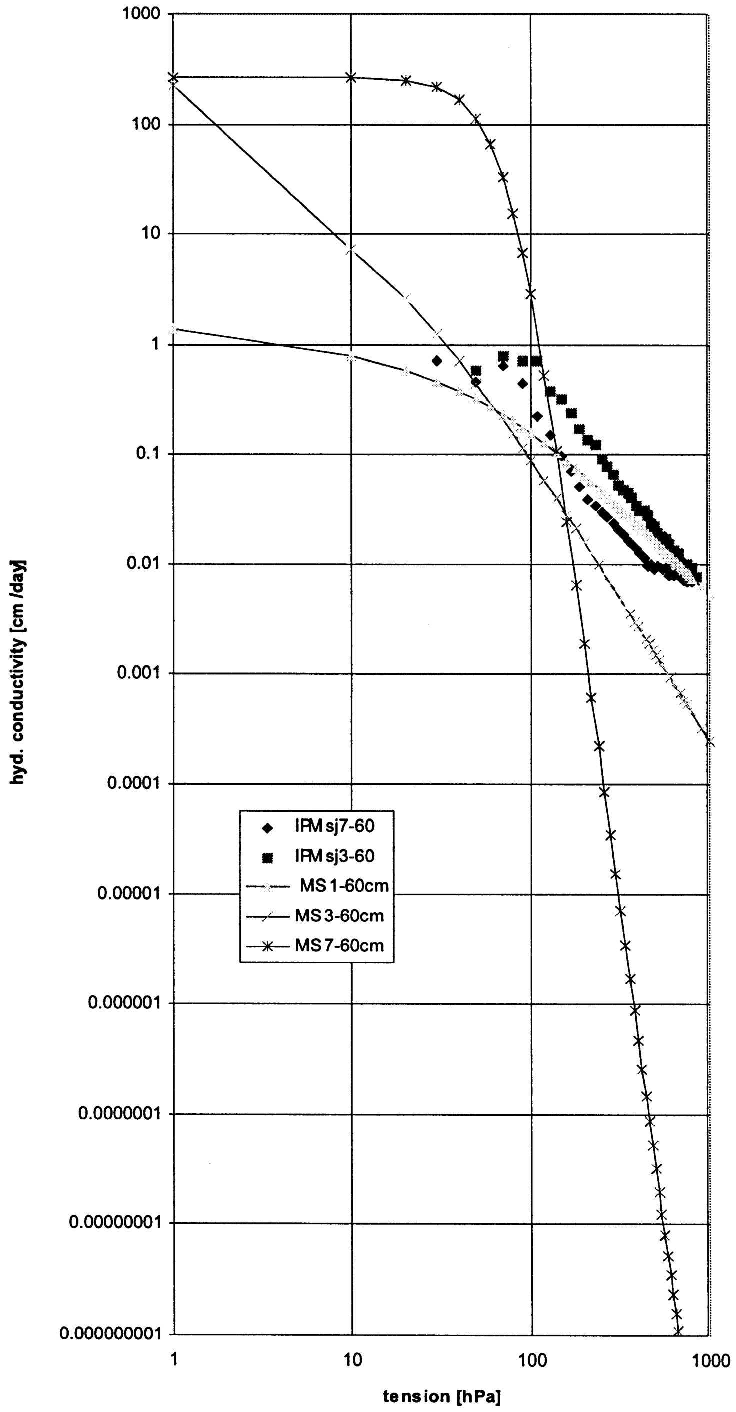


Fig. 42. Comparison of the unsaturated conductivity functions of the AC horizon measured with the instantaneous profil method (IPM) and the multistep outflow method (MS).

CONCLUSIONS

A large number of methods for the assessment of soil structural status concerning the hydraulic properties of a particular soil exists. To get a complete overview about the water transport phenomena, a combination of different field and laboratory methods should be used especially considering the wide soil moisture range from saturation to dry conditions and also considering time variability of soil hydraulic properties.

The tension infiltrometer in combination with ponded infiltration can be used for measuring infiltrability, saturated conductivity and unsaturated conductivity in the near saturation range of the soil surface and the top soil. Applying the tension infiltrometer in deeper soil layers, it is too labourios for routine analysis of hydraulic properties. The tension infiltration measurement can detect fine soil structural differences especially taking into account the measurement of macropores.

The GUELPH-permeameter is best suitable for obtaining the saturated conductivity of different soil layers as input for soil water balance simulations. Because of the big measurement volume dead ending macropores are not extremely influencing the results and therefore the variability of results is quite low. This method is recommended for obtaining the saturated hydraulic conductivity of the soil matrix.

Macropores, as produced by rainworms or cracks, can cause a high variability of saturated conductivity measurement with soil cores in the laboratory and therefore many replicates have to be taken. This method cannot reproduce the field situation in a realistic way if many of the continuous macropores penetrating through the whole length of the soil core are dead ending within the next few centimeters of the underlying soil layer. If the density of macropores is high, this method can give information of saturated conductivity including macropores of distinct soil layers for simulating the soil water balance. For the case Großenzersdorf during the vegetation period 1995 the simulation of soil water balance was not sensitiv on the saturated conductivity including macropores since the near saturation moisture range (saturation minus 4 % vol.) was only rarely occuring. This might be the opposit for simulation models which are using input data of a shorter time scale but not mean daily input data as for the model 'SOIL'.

Using accurately measured soil hydraulic parameters which are highly sensitiv to soil structure as input for the model 'SOIL', the simulated water balance of the site Großenzersdorf was in high agreement with measured water content data.

Exact unsaturated conductivity data as input for simulating the soil water balance are most important in the moisture range from saturation to about 200 to 300 hPa (so called field capacity) since water movement is significant only within this moisture range but can more or less be neglected for drier moisture conditions compared to root water extraction. The instantaneous profile method as well as the multistep outflow method are both suitable for measuring the unsaturated hydraulic conductivity within this moisture range.

The estimation of the unsaturated hydraulic conductivity functions using different models approaches, which are necessary as input for many soil water balance and solute transport simulation models should always be compared and supported with measured results, especially if the effect of soil structural differences caused by different tillage systems are studied. It is not recommended to rely on estimated unsaturated conductivity functions although many times the estimation proved to be satisfying compared to measured data.

The model results are not showing a negativ influence of soil compaction on the soil water balance of the soil Fuchsenbigl and Großenzersdorf and therefore no reduction of plant growth can be expected. On the contrary, the model results showed a higher water retention capacity if the bulk density is increased and the saturated conductivity is decreased.

The influence of soil structure on root growth could not be tested with the chosen computer model since root properties are needed as input parameters. But in many cases a reduction of root growth and rooting depth will significantly influence biomass production. Answering this question will need future activities using different simulation models.

Since only mean daily input data are used as driving variables and the precipitation is uniformly distributed over the whole day, the infiltration of water into the soil cannot be simulated exactly. Therefore ponding of precipitation water and subsequent surface flow of water caused by compaction or crusting of the soil surface (which will also occure under so called flat conditions) could not be detected by the chosen simulation model at situations with high rainfall intensity.

ACKNOWLEDGEMENTS

We should acknowledge Federal Agency and Research Centre for Agriculture for the disposition of the research site 'Fuchsenbigl', Institute of Plant Production and Plant Breeding, University of Agricultural Sciences, Vienna, for the disposition of the research site 'Gross Enzersdorf' and Mrs. Ulla Reithmayr, Institute of Soil Science of the University of Agricultural Sciences, Vienna, for the continuous support in field and laboratory during the whole project.

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