# Retention Curves of Soil from the Liz Experimental Catchment Obtained by three Methods

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**Abstract**: The retention curves were measured in the soil from the Liz experimental catchment (Šumava). The sand table and pressure extractor methods were used to obtain a 13-point retention curve for undisturbed soil samples taken from 6 depths. The data points of the individual retention curves were fitted in with the analytical expression of and the reference retention curves were calculated for each depth by scaling. For the same soil, the retention curves were estimated by the artificial neural network method by and the use of the empirical Pedotransfer function. The numerical experiment, which represented the infiltration and redistribution processes, was conducted using of all three sets of retention curves. Simulated water storages and pressure fields obtained using two sets of estimated parameters produced similar results, however they did not approximate well the modelling results obtained with the use of the measured reference parameter set. Of the two sets of pedotransfer functions (PTFs), which have been tested in this study, the empirical PTF of showed a slightly better agreement with the measured retention curves. The results give a guideline for the application of the retention curves estimation by the pedotransfer function for the soil from the Liz catchment.

**Keywords**: retention curve; hydraulic properties; numerical experiment; pedotransfer functions; neural networks

Modern methods of the hydraulic characterisation of soils, based on the combination of the transient infiltration of the outflow experiment and the parameter estimation by means of inverse modelling, represent a promising tool for a rapid parameter estimation. One of the requirements for the successful prediction of hydraulic properties by parameters optimisation is an appropriate initial guess of the parameters. When the initial set of parameters is too far from the actual values, the optimisation often cannot yield correct values (Dirksen 1991). With a well-posed problem, the initial guess theoretically does not affect the final estimates but the parameter estimation is faster when the guess is close to the actual values (Zhang *et al.* 2003). The influence of the initial estimate increases with the number of the parameters optimised (Simunek & vanGenuchten 1996). More complex parameterisation of the preferential flow models (Vogel *et al.* 2000) often faces problems related to the improper initial estimates of the soil hydraulic parameters. The retention curves parameters obtained by standard static methods of measurement are often taken as the initial parameter estimate for the inverse modelling. However, obtaining the hydraulic characteristics by standard

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static sand table and pressure experiments (Klute 1986) is rather time consuming and costly. An alternative means would be obtaining the retention curve parameter by one of the pedotransfer functions (PTFs), which had been developed during the last decades in order to estimate the retention curve on the readily available soil data e.g. texture, bulk density, and organic matter content. The PTFs are used in such applications where the complete measurement of the retention curves is not economical or possible. The early approaches to the estimation of the retention characteristics from particle size distribution, organic matter content (OM), and bulk density were established by Gupta and Larson (1979), who developed regression equations for the prediction of soil water contents for 12 matric potential in the range from –0.04 to –15.0 bars. Regression coefficients were obtained from the series of retention curves measured on the artificially packed samples of 43 soil materials. The method showed reasonable accuracy when used for the prediction of the retention curves of 61 soils. An overview of the most of PTFs which are currently in use was given by Guber *et al.* (2006), who used an ensemble of 22 PTFs to predict the water contents and pressure heads by means of a model based on Richards equation and compared it to the water contents and pressure heads measured in an experimental trench. The same was done with the directly measured retention curves. Surprisingly, the PTFs based simulations gave a better fit with the measured data, however, the overall fit was not perfect.

This study was targeted on the hydraulic properties determined in the experimental catchment Liz (Šumava) (Tesař *et al.* 2006). The retention curves were measured to support the intensive hydrological research which is conducted within this watershed. A set of undisturbed soil samples were taken to characterise the soil of one of the heavily instrumented sites in the catchment and to help to interpret the data from the tensiometer and soil moisture probes installed in this experimental site. In addition to standard direct measurements of the retention curves, the two PTFs were employed to test their applicability for the soil under study. From a number of the concepts available, one empirical PTF by Wösten *et al.* (1999) was selected. The second PTF under study was the widely used method of retention curve prediction based on artificial neural network model (Schaap *et al.* 1998). The agreement of the predicted and measured retention curves was estimated by testing their correlation and by means of a simple infiltration numerical study.

## MATERIAL AND METHODS

### Retention curves

The soil was sampled in the experimental catchment Liz (Tesař *et al.* 2006). The catchment is located in the Šumava Mts. (Southern Bohemia). This small mountainous forested experimental catchment is a part of the metamorphic complex – Moldanubicum, formed by paragneiss. The mean annual precipitation is 825 mm, the mean annual temperature is 6.3°C. The soil was sampled at the site Liz 1, which is the experimental site instrumented with water content sensors and tensiomenters with automatic data acquisition. The site Liz 1 is a hillslope location in the lower part of the catchment. The soil is mainly Eutric Cambisol. The content of gravel sized particles is high, stones larger then 50 mm are estimated to occupy at least 10% of the soil volume in first 80 cm of the soil profile, the content of stones increasing with increasing depth. The ground water level is mostly absent from in the soil profile unless it is elevated in response to rain events. Based on the extrapolation of the tensiometer data (Tesař *et al.*, unpublished data 2007–2008), the ground water table occurs in the depths ranging from 80 cm to several meters bellow the soil surface. The soil was sampled in three pits about 5 m apart. The soil profiles in all three pits were very similar. The samples for the retention curve measurements were taken from the depths of 10, 30, 40, 50, 60, and 65 cm. Three to nine undisturbed samples ($d$ = 5.8 cm, $h$ = 6.0 cm), were taken from each depth. Fewer samples were taken from greater depths due to the increasing content of large stones, which made the collection of more samples impossible. The soil samples collected were refrigerated to prevent bacterial and fungal growth. Grab samples for the particle size distribution and measurements of organic matter content were collected from the depths of 10, 30, 50, and 60 cm. Due to the high content of large stones, the soil samples must be considered to represent only the continuum in between stones.

The 6-cm high undisturbed samples were used to obtain the water retention at the pressure heads of 0, –1 –3, –5, –10, –30, –102, –204, –1020, –3059, –7138, and –15296 cm. The sand table method was used in the range from –1 to –30 cm. The pressure plate extractor (Soilmoisture Equipment Corp., USA) was used for the pressure head range from –102 to –15296 cm (0.1 to 15 bars).

The curve was fitted in with the measured pressure head – water content values. Non-linear least square method was used to optimise the parameters of the van Genuchten expression (van Genuchten 1980).

$$\theta = \theta_r + \frac{(\theta_s - \theta_r)}{\left[1 + (\alpha|h|)^n\right]^m} \tag{1}$$

$$m = 1 - \frac{1}{n} \tag{2}$$

where:

$\theta$, $\theta_r$, and $\theta_s$ – actual, residual, and saturated volumetric water contents, respectively

$\alpha$, $n$, and $m$ – are the shape parameters of the retention curve

The reference retention curve parameters were calculated using a scaling approach (Vogel *et al.* 1991) for each depth.

The grab samples were air dried, mixed with water and sodium hexametaphosphate and after boiling the suspension, clay and silt were carefully separated from the sand fraction by rinsing with water. The particle-size distribution curve was then determined by sieving for the sand fraction and by Casagrande hydrometer method for the silt and clay fractions.

In the grab samples, organic matter content was estimated by measuring total organic carbon. The wet acid oxidation method was used. The soil bulk density was determined using undisturbed soil samples along with the retention curve measurements, and the mean value was calculated for each horizon.

The parameters of the retention curves were estimated using the two PTFs. The prediction was made for three soil horizons.

The artificial neural network model Rosetta by Schaap *et al.* (2001) was employed to obtain van Genuchten parameters of the retention curves for soils from three depths. The mass fractions of sand, silt, and clay, and bulk density were used as the parameters of the prediction.

Second pedotransfer function tested in this study was the method developed by Wösten *et al.* (1999). The following empirical expressions were used to calculate van Genuchtens parameters:

$$\begin{aligned}\theta_s = {} & 0.7919 + 0.001691C - 0.29619D \\ & - 0.000001491S^2 + 0.0000821OM^2 + \\ & 0.02427\ C^{-1} + 0.01113\ S^{-1} + 0.01472\ \ln(S) - \\ & 0.0000733\ OM\ C - 0.000619\ D\ C - \\ & 0.001183\ D\ OM - 0.0001664\ \text{topsoil}\ S\end{aligned} \tag{3}$$

$$\begin{aligned}\alpha^* = {} & -14.96 + 0.03135\ C + 0.0351\ S + 0.646\ OM \\ & + 15.29\ D - 0.192\ \text{topsoil} - \\ & 4.671\ D^2 - 0.000781\ C^2 - 0.00687\ OM^2 + \\ & 0.0449\ OM^{-1} + 0.0663\ \ln(S) + \\ & 0.1482\ \ln(OM) - 0.04546\ D\ S - 0.4852\ D\ OM + \\ & 0.00673\ \text{topsoil}\ C\end{aligned} \tag{4}$$

$$\begin{aligned}n^* = {} & -25.23 - 0.02195\ C + 0.0074\ S - 0.1940\ OM + \\ & 45.5\ D - 7.24\ D^2 + \\ & 0.0003658\ C^2 + 0.002885\ OM^2 - 12.81\ D^{-1} \\ & - 0.1524\ S^{-1} - 0.01958\ OM^{-1} - 0.2876\ \ln(S) - \\ & 0.0709\ \ln(OM) - 44.6\ \ln(D) - 0.02264\ D\ C + \\ & 0.0896\ D\ OM + 0.00718\ \text{topsoil}\ C\ D\end{aligned} \tag{5}$$

where:

C – mass fraction of clay (0–2 μm) (%)

S – mass fraction of silt (2–50 μm)

OM – organic matter content (%)

D – soil bulk density (g/cm)

Topsoil/subsoil is a qualitative parameter having values 1 or 0. Van Genuchtens parameters are then obtained as $\alpha = \exp(\alpha^*)$, $n = 1 + \exp(n^*)$.

### Numerical experiments

A numerical experiment on infiltration and redistribution was conducted to asses the impact on the flow of the method of hydraulic characterisation, where the indicators were the simulated water storages and pressure fields. The model of the soil water flow used in this numerical study was based on one-dimensional Richards' equation:

$$\frac{\partial \theta(h)}{\partial t} = \frac{\partial}{\partial z}\left(K(\theta)\left(\frac{\partial h}{\partial z} + 1\right)\right) \tag{6}$$

where:

$\theta$ – water content ($cm^3/cm^3$)

$h$ – pressure head (cm), negative under unsaturated conditions

$z$ – vertical spatial coordinate, positive upwards (cm)

$t$ – time (s)

$K$ – unsaturated hydraulic conductivity (m/s)

The Richards equation is numerically solved by S1D code (Vogel 1999, Documentation of S1D code – version 2.0, CTU Prague, Internal Report), which is an improved version of the HYDRUS 5 code (Vogel *et al*. 1996).

The hydraulic properties of variably saturated soil were described by a set of closed-form analytical expressions similar to those of van Genuchten (1980). The original expressions were modified to add extra flexibility to the description of the hydraulic properties near saturation. It was shown that the modified approach provides a more adequate prediction of the unsaturated hydraulic conductivity function (Vogel *et al.* 2001). For the pressure heads larger than the air entry value $h_s$, the water content becomes equal to the saturated water content $\theta_s$.

The following air entry values $h_s$ were used in our case: (1st layer, 2nd layer, 3rd layer, 4th layer, 5th layer, 6th layer) = (–0.5, –0.65, –0.7, –0.8, –0.9, –1.0) cm, respectively.

The flow domain is 80 cm deep and consists of 6 layers with depths according to the measured retention curves. In the case of retention curves from PTFs, the parameters of the 2nd and 3rd layers were identical as well as for the 5th and 6th layers, because the resolution of the measured data was smaller. The computational mesh is finer near the soil surface where a steep wetting front develops. At the beginning of the simulation period, the equilibrium with the groundwater table at 400 cm below the soil surface was applied as the initial condition.

Synthetic rainfall was used as the upper boundary condition (Figure 1). The rainfall intensity was set at the values which do not cause ponding. Total amount of water applied in the rainfall was 43 mm. The upper boundary condition was set at the no-flow condition in a period from 10 to 72 h. The free drainage boundary condition is at the lower end of the flow domain.

For the matter of simplification the evapotranspiration process was neglected. Despite the preferential flow being a known effect with the soil under study, it was neglected in the current study. The synthetic rainfall intensities were set at the levels not increasing the water contents in the soil profile to the close-to-saturation levels. This made a single domain (non preferential) flow assumption possible. The point must be made that the aim of the modelling was to compare the impact of the hydraulic properties obtained by different methods and not necessarily to simulate the flow at the experimental site in full complexity.

## RESULTS

The reference retention curves obtained with 6 soil layers are shown in Figure 2. Except the depths of 50 and 60 cm bellow the surface, the retention curves show an overall shift toward lower water content values with increasing depths. The shape of the curves is very similar with those representing the depths of 10, 30, 40, and 65 cm. The shape of the retention curves from the depths of 50 and 60 cm does not completely fit into this scheme having either higher water contents or less retention space, but the overall shape is very similar.

The retention curves estimated by two PTF methods were compared with the reference re-

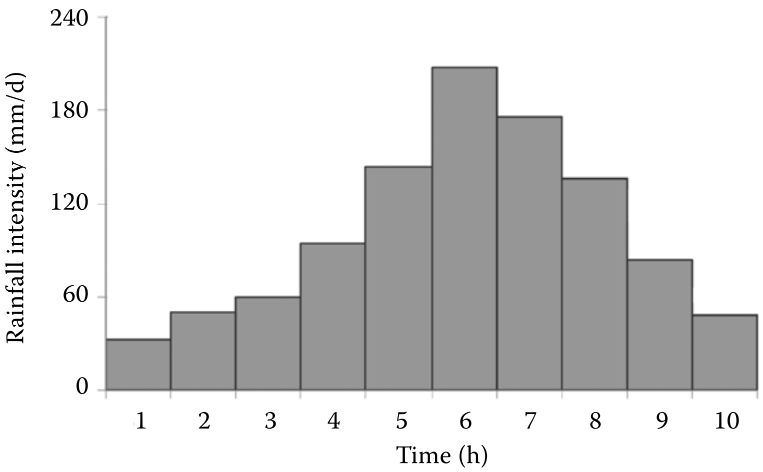


Figure 1. 10-hour synthetic rainfall event; during the first 10 h of simulation period, the synthetic extreme rainfall event is applied as a top boundary condition

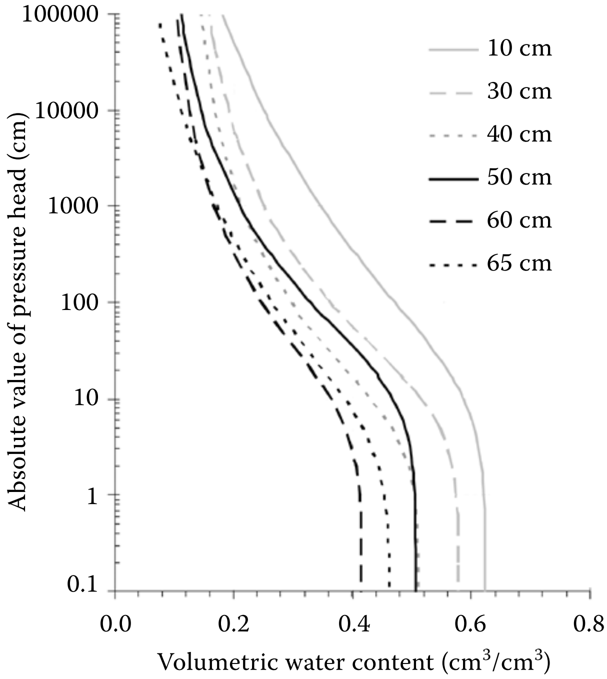


Figure 2. Reference retention curves determined for 6 depths

tention curve (see Figure 3). The parameters of the retention curves are shown in the Table 1. Generally, with the soil from the site Liz 1, both methods produced a reasonable fit with the reference retention curves measured. For all depths, the coefficient of determination $R^2$ ranged from 0.957 to 0.985 with Rosetta method and from 0.946 to 0.998 with Wosten method. Both methods seem to underestimate the water contents at highest tensions. For soil from the depth 30 cm, both methods underestimated the water content in the whole range of pressure, while the same effect was observed for the retention for the depth of 10 cm and Rosetta method. Water contents according to the retention curves are mostly overestimated by both Wösten and Rosetta methods for the depths of 60 and 65 cm and underestimated for the soils from 10 and 30 cm. Wösten *et al.* (1999) method provided a good correlation with the soil from the depth 50 cm.

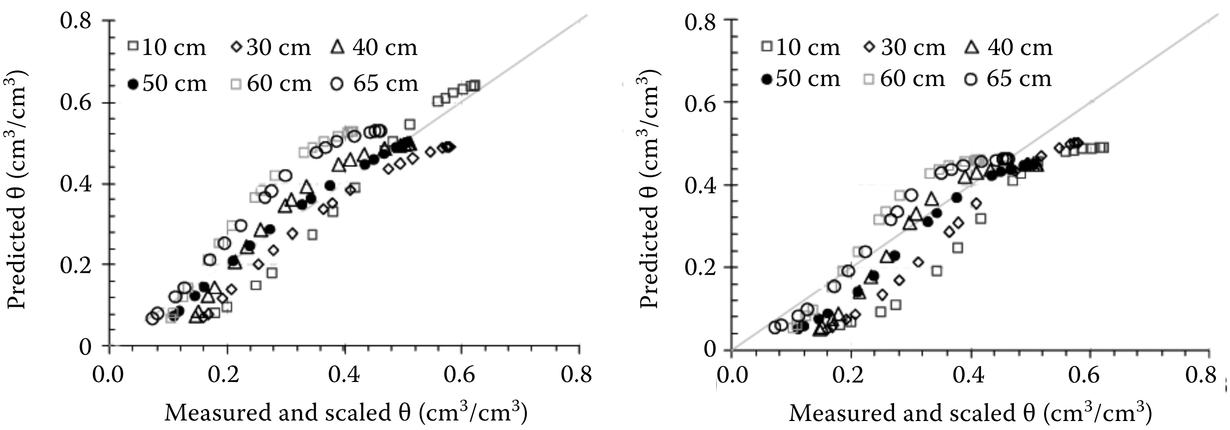


Figure 3. Comparison of the measured reference retention curves and the retention curves predicted by PTFs; graph on the left: measured vs. retention curve predicted by PTF of Wösten *et al.* (1999); graph on the right: measured vs. retention curve predicted by PTF of Schaap *et al.* (1998)

Table 1. Parameters of van Genuchten expression of retention curves for six depths

| Depth (cm) | | $\theta_r$ | $\theta_s$ | α | $n$ |
|---|---|---|---|---|---|
| | reference | 0.000 | 0.634 | 0.0112 | 1.122 |
| 10 | Rosetta | 0.046 | 0.488 | 0.0084 | 1.522 |
| | Wösten | 0.000 | 0.563 | 0.0300 | 1.230 |
| | reference | 0.134 | 0.580 | 0.0969 | 1.293 |
| 30 | Rosetta | 0.038 | 0.501 | 0.0390 | 1.427 |
| | Wösten | 0.000 | 0.491 | 0.0446 | 1.236 |
| | reference | 0.132 | 0.522 | 0.1596 | 1.296 |
| 40 | Rosetta | 0.038 | 0.501 | 0.0390 | 1.427 |
| | Wösten | 0.000 | 0.491 | 0.0446 | 1.236 |
| | reference | 0.088 | 0.521 | 0.0494 | 1.272 |
| 50 | Rosetta | 0.038 | 0.449 | 0.0196 | 1.465 |
| | Wösten | 0.000 | 0.498 | 0.0422 | 1.232 |
| | reference | 0.095 | 0.431 | 0.1241 | 1.296 |
| 60 | Rosetta | 0.038 | 0.460 | 0.0222 | 1.423 |
| | Wösten | 0.000 | 0.529 | 0.0388 | 1.251 |
| | reference | 0.007 | 0.474 | 0.1817 | 1.187 |
| 65 | Rosetta | 0.038 | 0.460 | 0.0222 | 1.423 |
| | Wösten | 0.000 | 0.529 | 0.0388 | 1.251 |

$\theta_r$ and $\theta_s$ – residual and saturated volumetric water contents; α, $n$ – shape parameters of the retention curve

The numerical simulation of the rainfall infiltration was conducted using all three sets of parameters. The hydraulic conductivity $K_s$ was set at the value 126 cm/h for all layers, which was the value obtained from the ponded experiment done in the laboratory on a large undisturbed soil sample.

Pressure head fields are shown in Figure 4. The graphical comparison is illustrated for the change in water storage in the soil profile in Figure 5. It is clearly visible from the graph, that the simulation results for the set of reference retention curves showed a slower draining of the soil profile as compared to the simulations done with the PTF estimated sets of parameters.

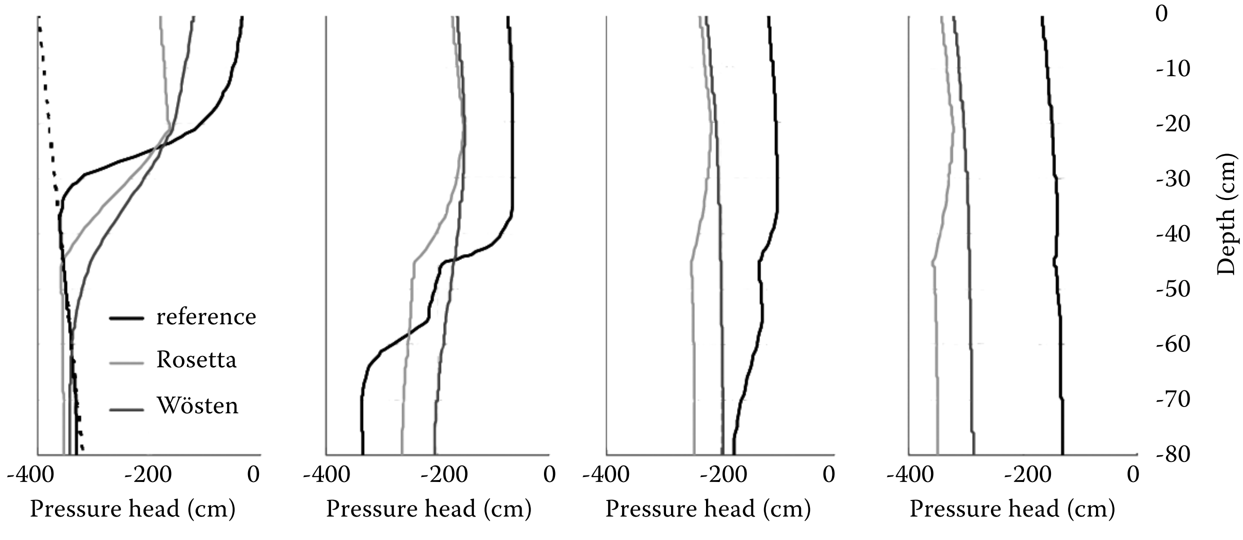


Figure 4. Simulated pressure head profiles for times 6, 12, 24, and 72 hours; initial distribution of pressur (dashed line) is shown in the graph on the left

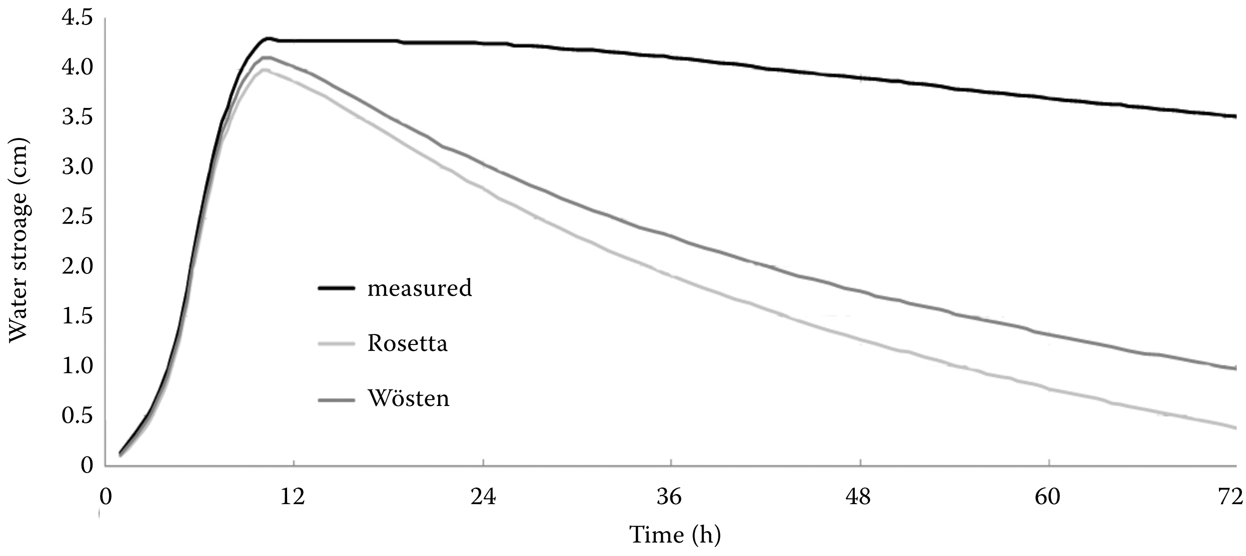


Figure 5. Relative total water storage change in the whole soil profile obtained by simulation using reference and two parameter sets predicted by PTF of Wösten *et al.* (1999) and PTF by Rosetta software (Schaap *et al.* 1998)

## CONCLUSIONS AND DISCUSSIONS

The soil water retention curves estimated by pedotransfer functions approximated relatively well the shape of the directly measured retention curves. However, when used as the parameters of numerical simulations of infiltration and redistribution in the soil profile, the model outputs were considerably different from those obtained with the use of the retention curves measured, especially when the changes of water storage were compared. Overestimation of the retention curve water contents for lower depths by both PTFs was probably responsible for this effect, since it led to a faster draining of the domain during the redistribution. From two PFTs used in this study, Wösten's PTF produced simulation results which were closer to those calculated using the reference set of parameters. Pedotransfer functions, which were tested in this study, should be treated with reasonable care for the soil from the Liz catchment. However the limited dataset does not allow making more general conclusions about the methods.

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