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Effects of simulated rainfall intensity on water flow through soil in two tillage systems

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Abstract

Diffuse losses of phosphorus from agricultural land to freshwater reservoirs have gained increasing interest in later years. Resent research suggests that phosphorus is mainly transported from the fields through macropores, and that soil under reduced forms of tillage can develop a higher macroporosity and thus an increased risk of phosphorus leaching compared to conventionally tilled soil, because of the more rapid flows of water through the soil. In this study field measurements of flow responses to variations in rainfall and laboratory measurements of soil dry bulk density, soil porosity and soil water retention characteristics were compared for a heavy clay soil subject to reduced and conventional tillage respectively. In the field, rainfall with intensities of 10 or 33 mm/h were simulated and percolating water was collected from a cavity dug out at 40-45 cm depth and the collected volume was measured at given times. A simple dual-permeability model was also made and its ability to describe flow responses to changes in rainfall intensity was evaluated through comparison with the field measurements. Flow responses to variations in rainfall intensity were rather similar between the two tillage treatments. Stabilized outflow rates were also very similar between the treatments; between 4 and 8.5 mm/h under the lower rainfall intensity and between 22 and 28 mm/h under the higher. Neither of the parameters measured at the lab showed any clear differences between the two tillage treatments. The model was able to describe the timing of changes in outflow in response to changes in rainfall intensity, but the simulated outflow rate was higher than what was measured and the model also described different final soil water contents after rainfall from those that were measured. Overall, the measurements did not show any effect of tillage treatment on soil hydraulic properties on the profile scale; flow showed dependence mainly on rainfall intensity and soil moisture conditions. The model would need to account for water flow from macropores to matrix to better be able to describe the total outflow from the profile.

Innehållsförteckning

1 Introduction

In later years focus for actions aimed at reducing eutrophication and algal bloom in surface waters has come to shift from nitrogen to phosphorus leaching as a main controlling factor. The mechanisms of phosphorus leaching are not as well understood as those of nitrogen. Losses of phosphorus from agricultural land was up until recently thought to occur mainly through surface run-off and erosion (Jarvis, 2007) and attempts at modeling phosphorus leaching have mainly focused on surface run-off losses though resent research suggests that the major transportation pathway of phosphorus is through soil macropores (Larsson et al., 2007). Whether a particular soil is prone to strong macropore flow or not is dependent on both the properties of the soil itself, such as soil structure, and external factors like climate and precipitation patterns. Soil structure is to a great extent determined by its composition, but can be affected by human activities such as tillage.

The aim of this project has been to measure and compare flow responses to variations in rainfall intensity between soil subject to conventional tillage on the one hand, and reduced tillage on the other. A second aim was to create a simple model of hydraulic flow through a macroporous soil based on parameters that are relatively easy to measure in the field or in the laboratory, to evaluate its ability to predict flow responses to variations in rainfall intensity and identify its weaknesses and possible improvements. The measurements from one of the field experiment runs were chosen for input data for the model and for comparison with the simulation results. This project is conducted as a part of a research project aiming to investigate the effects of tillage system and rainfall intensity on the vertical transport of soil particles and phosphorus through cultivated soil.

2 Background

Soil structure to a large extent determines the hydraulic properties of a soil. Structure is in part dependent on texture, mineralogy and general composition of the soil, but is also affected by land use and operations conducted in the field. What crops are grown, whether the soil is artificially drained or not and the way the soil is tilled, if it is tilled, all affect soil structure. Tillage reduces the stability of soil aggregates and in general the effect is more pronounced the more intense and frequent the tilling is (Logan et al., 1991). Thus, weaker development of structural elements can be expected under intense tilling systems than under reduced ones. Compared to conventional tillage, usually involving moldboard plowing and various secondary tillings, conservation tillage, defined by the U.S. Soil Conservation Service as a tillage system that leaves a minimum of 30% of the soil surface covered by crop residues, usually have more macropores (Logan et al., 1991). Strudley et al. (2007) reviewed tillage effects on soil hydraulic properties. They found that research results show a tendency for macroporosity and macropore connectivity to increase when the soil is not tilled at all compared to when it is conventionally tilled. Saturated hydraulic conductivity and ponded or near saturated infiltration rates also generally increase, while there are no consistent results for the effect on total porosity and bulk density from tillage treatment. Reduced forms of tillage have often resulted in hydraulic properties that are intermediate of the ones in conventionally tilled and non-tilled systems. The authors also state that the effects of tillage treatment can vary in both space and time, and that results are not consistent across soil types. Effects directly caused by the tillage system are also often difficult to distinguish from natural variations (Strudley et al., 2007).

A review of water flow and solute transport through macropores made by Jarvis (2007) concludes that pores with a diameter of about 0.3 mm, i.e. pores that drain at tensions of 10 cm (soil water pressure potential of -10 cm H_2O), can be classified as functional macropores regarding water flow and solute transport. When the tension of the soil decreases below this critical tension the macropores will start to fill with water. The flow through the soil can then no longer simply be described under the assumption of a homogeneous soil with respect to soil water tension and hydraulic conductivity. Water flow through macropores is rapid compared to flow through the soil matrix and mainly driven by the force of gravity as capillary forces decrease with increasing pore size. Thus, a small decrease in tension when the soil is close to saturation will dramatically increase the rate of flow. Macropore flow is more likely to occur when the intensity of rainfall widely exceeds the infiltration capacity of the soil matrix (Jarvis, 2007).

Vertical transport of solutes is also affected by how water flows through the soil. Macropores usually show smaller retardation of solute transport compared to the soil matrix, which can be attributed both to the smaller surface area compared to volume of macropores, and the relatively short transition time of solutes compared to the time required for sorption equilibrium to occur. The potentially fast transportation of solutes through the soil when macrorores are conducting water is cause for worry as both nutrients and pesticides may quickly reach a receiving body of water. If application of surface-applied substances is followed by heavy rainfall, a large part of it may escape through macropores (Jarvis, 2007). Gächter et al. (1998) found much higher phosphorus concentrations in the walls of macropores than in the soil matrix, suggesting that a large portion of phosphorus enriched water bypasses the matrix and is rapidly transported from field to recipient. The authors also refer to previous measurements showing high correlation between peaks in phosphorus concentrations of discharge water and discharge peaks occurring after surface runoff would be expected to have ceased (Gächter et al., 1998).

There are models of water flow and solute transport that account for the effects of macropore flow. Approaches to this and the complexity of the resulting models vary. A review by Šimůnek et al. (2003) on models that in some way include a description of macropore or preferential flow groups these models into single porosity models, dual-porosity models, dual-permeability models, fine-textured soil models and multi-porosity/permeability models. Single porosity models, e.g. Ross and Smettem (2000), differ from dual-and multi-porosity models, e.g. Germann and Beven (1985), as they consider both matrix and macropores as one region and not two or more separate regions of the soil profile for which expressions for flow and transport differ. Fine-textured soil models are models that account for swelling and shrinking of fine-textured clay soils. The difference between dual-/multi- porosity and permeability models is that the former considers water to be stagnant in the soil matrix, while the latter allows convective transport through both the matrix and the macropore regions. The dual permeability approach has for example been used in the model MACRO by Jarvis (1994). The authors appoint the accurate coupling of the matrix and macropore region with regard to water flow and solute transfer as the biggest challenge in constructing this type of model. The authors also conclude that the biggest limitation to the use of these models lies within the parameterization, as most of these models include many parameters which are difficult to measure or parameters for which there are no developed measurement techniques (Šimůnek et al., 2003).

3 Methods

3.1 Study site

The experiments were carried out within a long-term soil tillage trial in a field at Vipängen (59°48'N; 17°39'E), three kilometers south of Uppsala, between May 24 and June 22, 2011**.** The tillage trial (R2-4007) was started in 1974 and has a randomized block-plot design with four blocks and five plots. The plots measure 13 by 20 meters and are subject to one of the following five treatments:

A. Moldboard plow used every year
B. Moldboard plow used some years, shallow cultivation remaining years
C. Moldboard plow used some years, cultivation to plowing depth remaining years
D. Moldboard plow never used, only shallow cultivation
E. Moldboard plow never used, cultivation to plowing depth

Treatments are randomly spread within each block. Plots with treatments A and D were used to run the experiment.

The soil is a clay soil of glacial and post-glacial origin. Measured clay contents at 10-15 cm (upper value) and 30-35 cm (lower value) from the soil surface in treatments A and D are shown in figure 1. Clay content in the field varies between 39 and 59% in the layer 10 to 15 cm from the soil surface, and between 39 and 63% 30 to 35 cm from the soil surface. In most plots the clay content is higher at the lower depth than above, but in treatments D in blocks I and III it is lower at the lower depth.

		I					II		
A	B	C	D	E	E	D	C	B	A
38.9			47.0			51.9			54.0
53.9			38.8			59.0			62.9

		III					IV		
E	C	A	B	D	D	B	A	C	E
		45.7		48.9	51.8		58.6		
		59.2		42.6	59.2		61.0		

N ←

Figure 1. Clay content (%mass) at depths 10-15 cm (upper values) and 30-35 cm (lower values) for treatments A and D in each block.

3.1.1 Climate

The climate is cold temperate, with an annual mean precipitation of 551,5 mm based on daily observations made at the Ultuna climate station during the 30 year period 1980 to 2009. Average daily rainfall during May and June is about 1.5 - 2 mm for both months and average air temperature is 10.5 and 14.5 °C, respectively.

3.2 Experimental design

A 120 cm deep pit was dug out for both treatments A and D in every plot. At a depth of 40-45 cm two 80 cm deep and wide cavities with a height of 40 cm were dug into the pit wall. The bottom of the overlying soil column was carefully prepared with a knife to avoid clogging of the natural pore system. A collecting tray with a drain pipe, 50 cm deep, 50 cm wide, 5 cm high, was placed in the cavity with the upper rim against the bottom of the soil column. The bottom of the collector was filled with a layer of plastic marbles designated at aiding the water flow from the soil column through the collector and covered with a fine-meshed net on top. Net was also placed at the opening of the drain pipe to keep the marbles in place. A rainfall simulation device, 50 cm deep, 50 cm wide, was placed on a stand on the soil surface vertically over the cavity, at least 10 cm from its outer walls, at a height of 100 cm from ground level. The sides of the stand were of solid plastic, to avoid interference from wind on droplet distribution and energy. To avoid having water flowing laterally out of the investigated part of the soil profile, a trench was cut out with a chainsaw around the area subject to rainfall and filled with bentonite, to a depth of approximately 40 cm. The rainfall simulator was provided with water from a 20 liter container placed on top of a balance. Water and sediment from the collection tray was allowed to flow out of the tray through the drain pipe that was reared at the side of the tray facing the pit. Before each run, except for the first one in block IV under treatment A, the soil surface was sprayed with a total amount of one liter of lithium bromide solution to study flows of soil particles and water separately. These results were used for another project and will not be dealt with here, but the addition of the lithium bromide solution wetted the soil surface before starting the experiment, approximately to a depth of five centimeters, and this had to be regarded when analyzing the results of the measurements.

After termination of the simulations, soil cores were taken out using a 25 mm in diameter auger. Samples were collected at 0-5, 5-10, 10-15, 15-20, 20-30 and 30-40 cm, both inside the experimental plot after terminating the experiment for determination of final water contents, and also right outside of the area subject to rainfall. The latter samples were taken to determine initial soil moisture conditions. Inside the experimental plot an additional sample was taken from the bottom of the soil column with a spade, representing an approximate depth of 40-45 cm. All samples, except those at 40-45 cm where one large sample was taken, were taken in four replicates and all samples were stored at 5° in closed plastic bags until they were analyzed, less than 12 hours after sampling. Undisturbed soil cores were sampled using cylinders, 72 mm in diameter and 50 mm high, for measurements of soil water retention characteristics and dry bulk density. A total of 6 cylinders were sampled for each treatment in every plot, three cylinders at 10-15 cm depth and three cylinders at 30-35 cm depth. Disturbed soil samples for measurement of particle density were also taken at these depths, using a spade.

3.3 Field measurements

Two different rainfall intensities were used; 10 mm/h and 33 mm/h. These two intensities were run after one another, in one experiment starting with the low intensity and switching to the higher after a steady outflow from the former had been established. The experiment was terminated when a new steady outflow occurred.

The intensities were then run in the opposite order for the other experiment. These two strategies will here be referred to as Low to High and High to Low respectively. The experiments were conducted starting in block IV followed by block III, II and finally I. During runs the amount of water applied by the rainfall simulator was measured continuously as the difference between readings on the balance. The flow out from the collector tray was measured volumetrically at time intervals of 5, 10 or 20 minutes depending on flow rate.

3.4 Laboratory measurements

Measurement of gravimetric water content was performed on a subsample of every sample, weighing approximately 10 g. In some cases samples were very small and therefore a subsample of 5 instead of 10 g was taken out for analysis. All subsamples were weighed at field moisture content within a few hours after sampling and then oven-dried at 105°C for at least 24 hours. After drying, samples were weighed again and the water content was calculated for each sample according to equation 1, see below. The obtained gravimetric water content values were later used to calculate volumetric water content from the values of dry bulk density according to equation 2.

Dry bulk density was determined by dividing the weight of soil cores that had been dried at 105°C by the fixed volume of the cylinder. Three replicates in each plot and depth were used.

Soil particle density was measured on disturbed soil samples that had been oven dried at 105°C for 24 hours, ground and passed through a 2 mm sieve. The coarser fraction was discarded. 30 grams of soil from each sample was put in a 50 ml flask, together with a first volume of ethanol that was noted, approximately 35 ml. The samples were mixed with a magnetic stirrer for about 30 seconds until samples appeared homogenized. They were then left to settle until the next day, sealed with a plastic top to avoid evaporation. The following day samples were once again stirred and a second volume of ethanol was added to the samples, enough to make the total volume 50 ml. The required ethanol volume was also noted. Based on the total added volume of ethanol a pre-calculated particle density was obtained from a table. The analysis was done with two replicates for each block and plot, for levels 10-15 cm and 30-35 cm. Particle density for each sample was calculated as the mean value of the two replicates. Porosity, assumed to be saturated volumetric water content, was calculated from values of dry bulk density and particle density by equation 3.

Soil water retention characteristics were measured using a tension plate at tensions of 5, 50 and 100 cm. Sampled cores were wetted until saturated for two weeks. Before applying suction, saturated samples were left standing in a few centimeters of water for about 30 minutes to avoid air bubbles between samples and the tension plate. After applying suction, samples were left to equilibrate for seven days. They were then weighed separately. In cases where the soil cores swelled over the rim of the cylinder, the height increase was measured and noted to adjust the volume and calculated bulk density of the cores. Water contents at each tension were calculated by equation 2.

3.4.1 Calculations

Gravimetric water content, w

$$w = \frac{(m_t - m_s)}{m_s} \quad \textbf{(1)}$$

where m_t (g) is total sample mass and m_s (g) is solid mass.

Volumetric water content, θ

$$\theta = w \cdot \rho_b \quad \textbf{(2)}$$

where ρ_b (g cm^{-3}) is soil dry bulk density.

Porosity, f

$$f = 1 - \frac{\rho_b}{\rho_s} \quad \textbf{(3)}$$

where ρ_s (g cm^{-3}) is soil particle density.

Statistical analysis was not performed on the obtained data. The initial conditions in the different plots varied too much for the different runs of the experiments to be considered replicates of the same experiment. The data has been analyzed in a qualitative manner.

3.5 Modeling

3.5.1 Model description

Soil water flow

Powersim 2.5d was used to create a dual-permeability model describing the flow of water through the soil profile. A schematic picture of the model can be seen in figure 2.The model divides the soil profile into a matrix and a macropore domain, with different expressions to describe the flow of water through them.

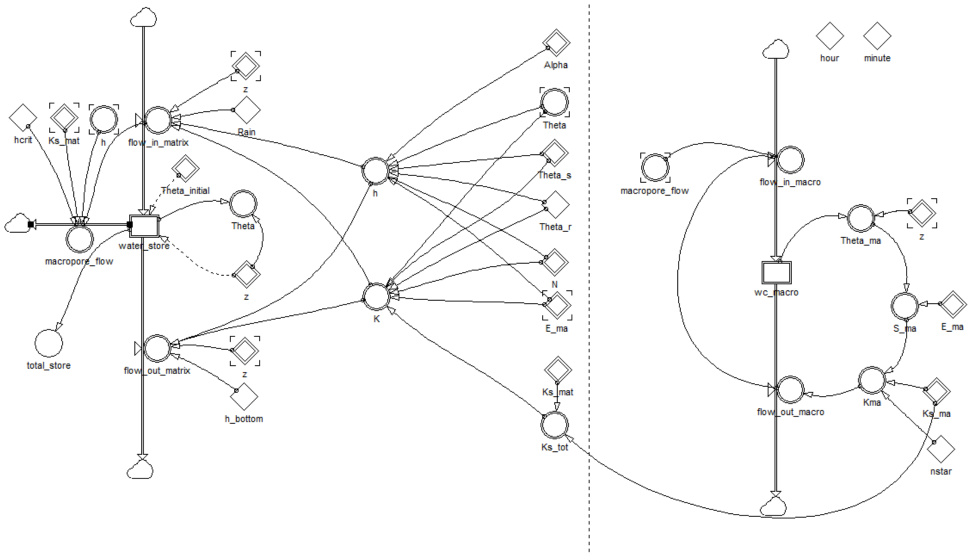

Figure 2. The model created in Powersim 2.5d. The left part of the model simulates flow through the matrix region, and the right part simulates flow through macropores.

Flow through the soil matrix only holding micropores (here defined as pores that are drained at tensions >10 cm) is described by Richard's equation

$$\frac{\delta\theta}{\delta t} = \frac{\delta}{\delta z}\left[K\left(\frac{\delta h}{\delta z} + 1\right)\right] \pm \Sigma Si \qquad \textbf{(5)}$$

where $\delta\,\theta/\delta t$ ($m^3\ m^{-3}\ s^{-1}$) is the change in water storage with time, K ($cm\ s^{-1}$) is the unsaturated hydraulic conductivity, $\delta h/\delta z$ ($cm\ cm^{-1}$) is the pressure potential gradient and S_i (cm ^{3}) is a source-sink term. In this model this is a sink term accounting for the portion of water that is redirected into macropores. In all layers except the top one the flow into one layer is defined as the flow out from the layer immediately above it.

Flow through meso- and macropores (pores drained at tensions <10 cm), hereafter only referred to as macropores, is described by the kinematic wave equation (Germann, 1985)

$$\frac{\delta\theta ma}{\delta t} = \frac{\delta Kma}{\delta z} \pm \Sigma Si \qquad \textbf{(6)}$$

where $\delta\theta ma/\delta t$ (m^3 m^{-3} s^{-1}) is the change in water storage in the macropores with time, $\delta Kma/\delta z$ (cm s^{-1} cm^{-1}) is the difference in macropore hydraulic conductivity between two points. S_i is here a source term accounting for water flowing into the macropores from the matrix. Flow through macropores is described as unaffected by matric suction and exclusively driven by gravity. Flow in to one layer is defined in the same way as described for matrix flow.

The partitioning of water flowing in to a layer between matrix and macropores is modeled through assuming that water is starting to flow into macropores when the inflow is greater than the saturated hydraulic conductivity of the matrix $K_{s\ matrix}$ and the tension is lower than 10 cm ($h_{critical}$). Flow in to the matrix is then defined as $K_{s\ matrix}$ and flow in to the macropores as the difference between the flow out of the overlying layer and $K_{s\ matrix}$. When flow in is smaller than $K_{s\ matrix}$ flow in to macropores is 0. For the upper five layers flow was assumed to occur only in the matrix, since 0-5 cm is the harrowed layer where macropores can be assumed to be absent or flow paths broken. Therefore macropore flow for these layers was initially set to be 0.

Hydraulic properties

Soil water tension h is calculated for each layer and time step using the van Genuchten model describing an S-shaped water retention curve

$$h = \frac{1}{\alpha}\left(\frac{\theta-\theta_r}{\theta_s-\theta_r}\right)^{-\left(\frac{N}{N-1}\right)^{\frac{1}{N}}} \qquad \textbf{(7)}$$

where θ ($cm^3\ cm^{-3}$) is soil wetness, θ_r ($cm^3\ cm^{-3}$) is the residual water content, θ_s ($cm^3\ cm^{-3}$) is the saturated water content and α and N are empirical constants. Values of θ_r, θ_s, α and N are obtained by fitting an equation to measured soil water retention data.

The unsaturated matric hydraulic conductivity K is given by Mualem-van Genuchten's model

$$K = K_s\left(\frac{\theta-\theta_r}{\theta_s-\theta_r}\right)^{0,5}\left(1-\left(1-\left(\frac{\theta-\theta_r}{\theta_s-\theta_r}\right)^{\frac{N}{N-1}}\right)^{1-\frac{1}{N}}\right)^2 \tag{8}$$

Where K_s ($cm\ min^{-1}$) is the saturated hydraulic conductivity of the entire soil volume.

For calculations of both h and K, θ_s is adjusted by subtracting the macropore volume from the total porosity.

Macropore hydraulic conductivity K_{ma} is calculated from the saturated macropore hydraulic conductivity Ks ma in the same way as described by Larsbo and Jarvis (2003) in the MACRO model, as an exponential function of the degree of macropore saturation S_{ma}

$$K_{ma} = K_{s\,ma} S_{ma}^{n^*} \tag{9}$$

where n* is a kinematic exponent, and Sma ($cm^3\ cm^{-3}$) is calculated as

$$S_{ma} = \frac{\theta_{ma}}{\varepsilon_{ma}} \tag{10}$$

where θ_{ma} ($cm^3\ cm^{-3}$) is macropore wetness and ε_{ma} (cm3 cm-3) is macroporosity.

3.5.2 Boundary conditions

The flow in to the top layer is set as the amount of rain at each time step. Normally, actual evapotranspiration would be added as a flow out of the first layer, adding to the sink term in equation 5. In this case however, it was neglected since the stand over the soil surface holding the rainfall simulator most likely decreased evaporation. Transpiration should have been low if it at all occurred since the surface was cleared of vegetation.

Flow out of the bottom layer is calculated based on the difference in pressure potential between the bottom layer and the cavity, where atmospheric pressure is assumed. Flow cannot occur from the shaft into the overlying bottom layer, and flow out is only assumed to occur when the layer is saturated. Therefore the flow is set to be 0 when the difference in tension between the bottom layer and the cavity is negative, to prevent the model from simulating upward flow.

3.5.3 Parameter values

The measurements from experiments conducted in block III, treatment A, were chosen for comparison with the model simulations, as laboratory test results for this plot seemed reliable. Values of constants in the model could not entirely be based on laboratory and field measurements, as some of the parameters included in the model were not measured. The study site has previously been studied by researchers at SLU, and values from their research have been used for some parameters. Parameter values used in the simulations are shown in table 1 below, together with the source of each value.

Table 1. Parameter values used for the simulations, and source of each value

Parameter	Value	Source of value
K_s	117 mm/h	Larsbo et al., 2009
$K_{s\ matrix}$	0.91 mm/h	Larsbo et al., 2009
$K_{s\ macro}$	116.09 mm/h	Larsbo et al., 2009
θ_s	0.62 between 0 and 5 cm*, 0.50 between 6 and 25 cm, 0.44 between 26 and 45 cm	Laboratory test results
θ_r	0	Pers. com. Jarvis, 2012
α	0.05	Messing, 1993
N	1.6	Messing, 1993
ε_{macro}	0.037 between 0 and 25 cm, 0.003 between 26 and 45 cm	Laboratory test results
h_{bottom}	0 cm	Assumed value
$h_{critical}$	10 cm	Jarvis, 2007
n*	2	Pers. com. Jarvis, 2012

Hydraulic conductivity values are based on the measurements of Larsbo et al. (2009), where K values were measured at 25 cm depth with a tension infiltrometer at 10 cm tension (-10 cm pressure head) and a pressure infiltrometer at 0 cm tension, giving values of matrix conductivity and saturated conductivity respectively. The hydraulic conductivity of the macropores is calculated as the difference between the two. For evaluation purposes, the sensitivity of the hydraulic conductivity parameter was tested using values from Messing (1993), also measured with tension infiltrometer in the same soil tillage trial at Vipängen. The author found a best fit of a two line regression model to the obtained K(h) data, describing a breaking point after which the conductivity increased much more rapidly with decreasing tension than before the breaking point. The tension corresponding to this shift in hydraulic conductivity increase was assumed to be the critical tension separating macro- and mesopores. These measurements suggested a breaking point for the soil surface at a tension of 5.33 cm with a hydraulic conductivity of 0.137 mm/h, and field-saturated hydraulic conductivity being 340.36 mm/h, thus making macropore conductivity 340.233 mm/h. Measurements made at 15 and 25 cm depth showed a breaking point at 4.43 cm, hydraulic conductivity then being 0.419 mm/h and field-saturated hydraulic conductivity 194.42 mm/h, making macropore conductivity 194.001 mm/h. The model was run only changing the initial settings of critical tension hcritical and saturated matrix conductivity Ks matrix corresponding to this tension to the values found by Messing (1993) at first, to evaluate the effect of the assumptions underlying the partitioning of water between matrix and macropores. After completing this simulation, the sensitivity of the saturated macropore conductivity variable was tested by also changing the value of this parameter in accordance with the findings of Messing (1993).

Θ_s for the top five layers corresponding to the harrowed layer was calculated assuming that dry bulk density of this layer was 1 g/cm^3.

n* was given a value of 2, which is a typical value of a structured clay soil like the one at Vipängen (pers.com. Jarvis, 2012). This value is usually found through calibration of the model, but a few initial test simulations with different n* values showed little or no effect on the macropore outflow and it was therefore decided to skip this step.

$\theta_{initial}$ values were calculated for each 1 cm layer as functions of linear gradients between two measuring points, assumed to be located at middle depth of each sample. The value measured between 0 and 5 cm (table 2) was used for the layers above the midpoint. Similarly, the value measured between 30 and 40 cm was used for all layers below the midpoint of the sample. The initial water content values that were used to calculate the gradient are the same as those shown in table 2, with one exception. Initial test runs of the model showed a delay in outflow onset compared to what was observed in the field. This was likely an effect of the assumed dry bulk density being too high in the upper five centimeters. Dry bulk density was therefore given a new assumed value of 1 g/cm^3, rendering a new $\theta_{initial}$ value of 0.04. $\theta_{initial}$ for the top five layers was also adjusted by adding 0.08 to each value, to account for the 1 liter of lithium bromide solution that was added before the start of the experiment.

Table 2. Measured initial and final water content (%vol.) for experiments Low to High and High to Low in block III, treatment A, for each sampling depth

	Water content (%vol.)		
Sampling depth (cm)	Initial	Final Low to High	Final High to Low
0-5	0.136	0.294	0.403
5-10	0.205	0.312	0.420
10-15	0.310	0.325	0.402
15-20	0.343	0.371	0.380
20-25	0.354	0.359	0.406
25-30	0.391	0.396	0.448
30-40	0.341	0.315	0.433
40-45	-	0.289	0.385

3.5.4 Model application

The model was used to simulate the flow resulting from rainfall simulation experiments Low to High and High to Low in Block III, treatment A.

4 Results

4.1 Field measurements

Measured outflow volumes and recorded time intervals between samplings were used to calculate flow rates at specific times during the experiments. The development of the flows in to and out of the soil profile over time in each block for each treatment and intensity sequence are shown graphically in figures 3 through 10.

Due to difficulties in setting the pump at the right speed in the first measurement when running Low to High in block IV, treatment A (figure 3a), much more rain than intended was generated during the first 125 minutes of the experiment. Intensity was raised 271 minutes from start, by mistake too high initially, providing 71 mm/h for 5 minutes before it was discovered and corrected. In both experiments conducted in block IV under treatment A the high rainfall intensity was higher than the intended 33 mm/h. The high intensity was still higher than intended in both experiments Low to High and High to Low when run in Block IV, treatment D (figure 3b).

330 minutes into the experiment when running Low to High in block I, treatment D (figure 10a), there was a stop in the function of the generator providing electricity for the pump. The stop in rainfall made the outflow decrease to less than 1 mm/h during the time it took to get the rainfall simulator working. Once the rainfall started again, the outflow increased relatively rapidly.

About 315 minutes into the experiment when running High to Low in block I, treatment D, (figure 10b) the water tank was refilled. Flow then accidentally increased applying 119 mm/h during 1.5 minutes. Rainfall rate was then 0 for half a minute before the previous rate of about 33 mm/h was resumed. Only a very small response to the entire operation can be seen in the outflow data.

Around the same time as the outflow rate stabilized the second time when running Low to High in block I, treatment A, ponding of the soil surface was noticed. Ponding also occurred when running High to Low, shortly after the outflow rate stabilized the first time.

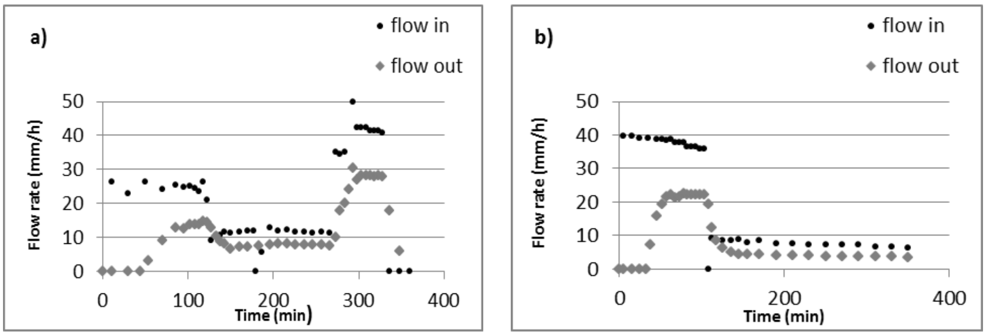

Figure 3. Flow rate in and flow rate out in block IV, treatment A for a) Low to High and b) High to Low.

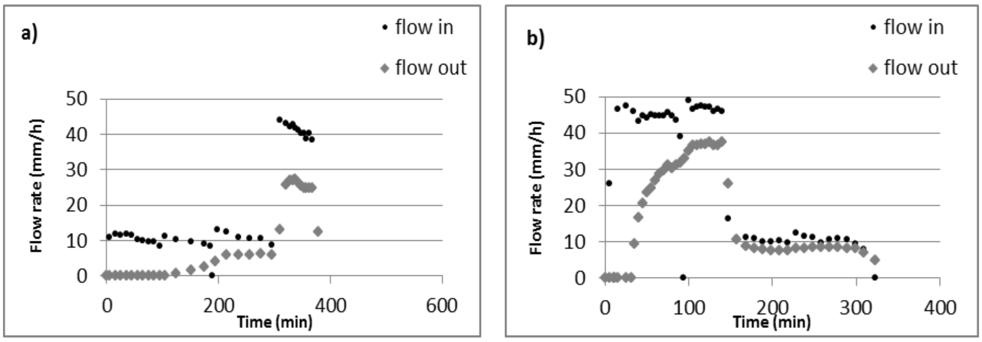

Figure 4. Flow rate in and flow rate out in block IV, treatment D for a) Low to High and b) High to Low.

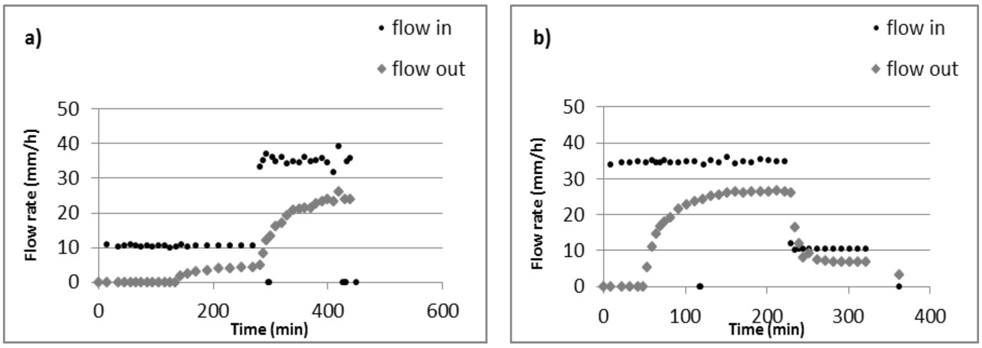

Figure 5. Flow rate in and flow rate out in block III, treatment A for a) Low to High and b) High to Low.

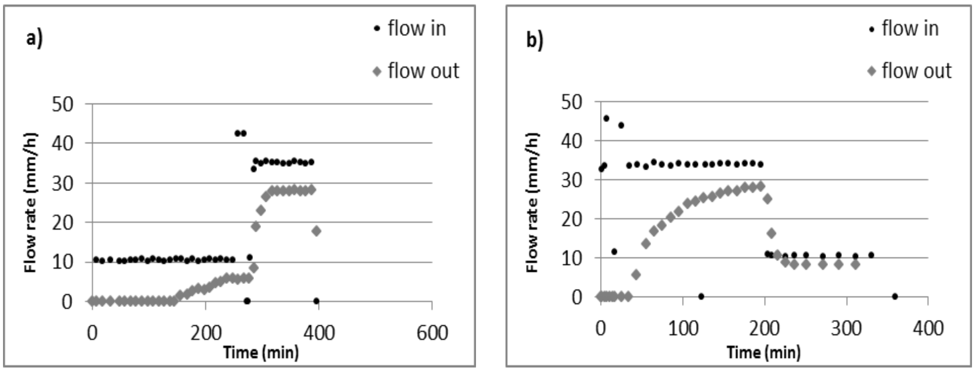

Figure 6. Flow rate in and flow rate out in block III, treatment D for a) Low to High and b) High to Low.

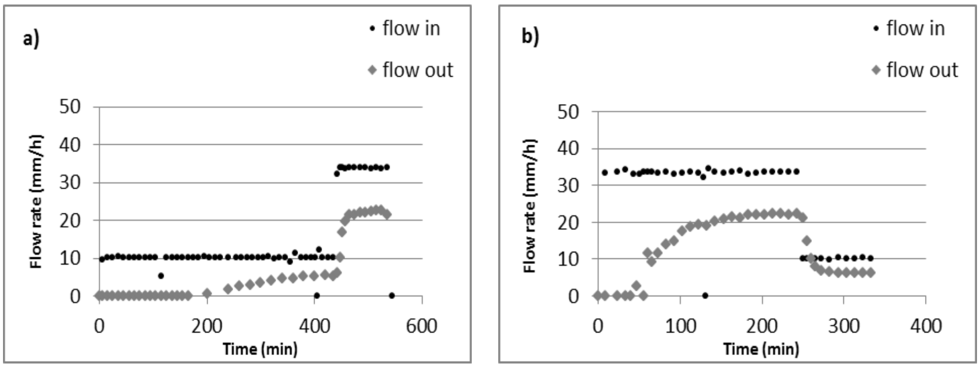

Figure 7. Flow rate in and flow rate out in block II, treatment A for a) Low to High and b) High to Low.

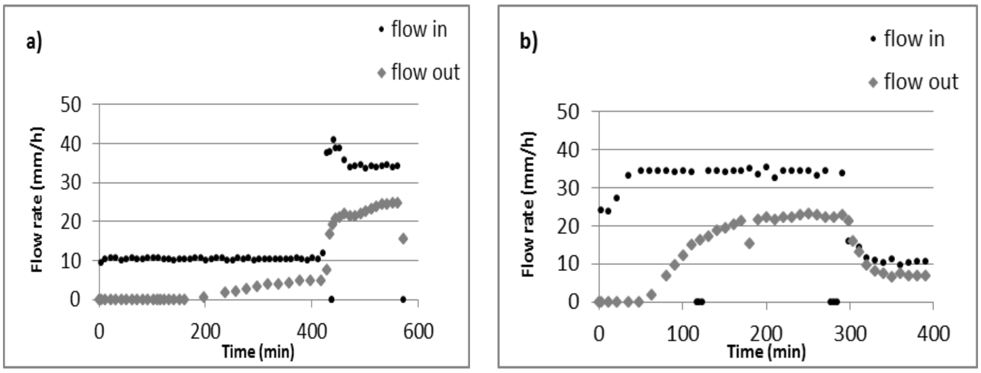

Figure 8. Flow rate in and flow rate out in block II, treatment D for a) Low to High and b) High to Low.

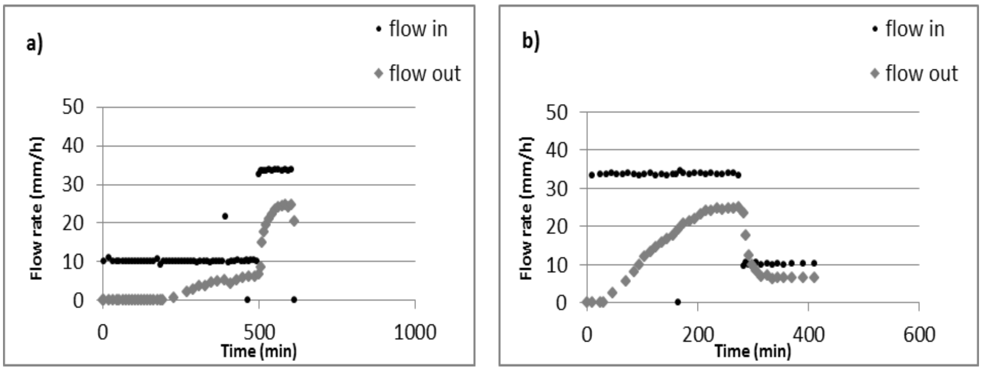

Figure 9. Flow rate in and flow rate out in block I, treatment A for a) Low to High and b) High to Low.

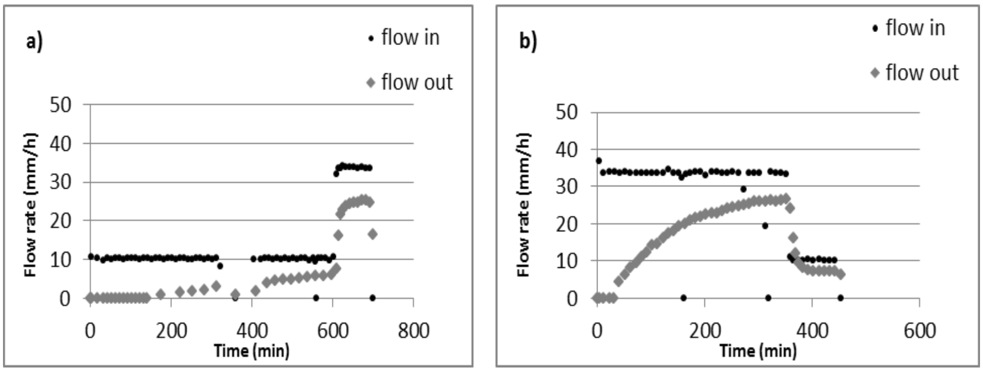

Figure 10. Flow rate in and flow rate out in block I, treatment D for a) Low to High and b) High to Low.

Outflow showed similar development in most blocks in response to the different simulated rainfall intensities in the two experiments. The Low to High run in block IV under treatment A differs from the other runs of the same experiment, as the low rainfall intensity was initially much higher than intended. The timing of changes in outflow rate differed somewhat between runs. Estimates of elapsed time and cumulative amount of rainfall until the start of outflow, stabilization of outflow rate under the first run rainfall intensity and the second respectively can be seen in table 3. Time and rainfall amount are calculated from when the experiment started for outflow onset and the first stabilization of outflow rate, and from when the intensity was changed for the second stabilization. When running Low to High, the required time and amount of rainfall for outflow to start increased when moving from block IV to block I, with the exception of the run in block I under treatment D where outflow started relatively early into the experiment. Outflow started much earlier in block IV under treatment A than in all other plots due to the higher rainfall intensity. Outflow started much earlier in all plots when running High to Low than Low to High, with the exception of block IV under treatment A where the difference between the first run intensities in the two experiments was quite small and the difference in time from start to outflow onset was smaller than in other plots. Required time and amount of rainfall when running High to Low followed an irregular pattern, not indicating any correlation with neither block nor treatment. The amount of rainfall required for outflow to start was larger when running High to Low than Low to High in two plots; block IV under treatment D and block III under treatment A. In all other plots outflow started after smaller amounts of rainfall when running High to Low. Required amounts of rainfall for outflow to start were however rather similar between experiments, blocks and treatments, between 19 and 33 mm. The Low to High run in block I under treatment A required the longest time and amount of rainfall for outflow to start, indicating relatively high infiltration to the soil matrix of this plot where clay content in the upper layers were the lowest of those measured.

Stabilization of outflow rate under the first run intensity occurred after longer time and smaller amounts of total rainfall when running Low to High than High to Low in all plots except block IV under treatment A where stabilization occurred after a larger amount of total rainfall when running Low to High. A tendency for longer time and larger required amounts before stabilization of outflow rate could be seen moving from block IV to block I, implying longer time for stabilization of matric uptake rate in the initially drier plots.

Stabilization of the outflow rate under the second run intensity was naturally faster than stabilization under the first, as the soil was moister at this point. Required amounts of rainfall were also generally smaller, but for two runs; Low to High in block III under treatment A and Low to High in block II under treatment D, relatively large amounts of rainfall and also relatively long time were required for outflow to stabilize under the second intensity. The comparison between runs is impaired by the fact that the intensity was changed after different times and amounts of rainfall in each run, thus with different soil moisture conditions.

Table 3. Time (min) and amount of simulated rainfall (mm) (numbers within parenthesis) between start of the experiment and when water started flowing out of the drain pipe, between start of the experiment and stabilization of the outflow rate under the first run intensity, and between the change of intensity and stabilization of the outflow rate under the second run intensity

Block, treatment and experiment	Start – outflow onset	Start – steady outflow rate 1	Change of intensity – steady outflow rate 2
IV A Low to High	47 (25)	196 (64)	32 (24)
IV A High to Low	35 (23)	58 (38)	80 (14)
IV D Low to High	108 (19)	215 (37)	50 (30)
IV D High to Low	32 (21)	105 (76)	35 (6)
III A Low to High	137 (24)	210 (37)	110 (61)
III A High to Low	49 (28)	162 (92)	50 (9)
III D Low to High	149 (26)	238 (42)	30 (18)
III D High to Low	38 (18)	156 (83)	30 (5)
II A Low to High	169 (29)	400 (68)	25 (14)
II A High to Low	41 (23)	183 (101)	35 (6)
II D Low to High	167 (29)	377 (65)	105 (61)
II D High to Low	51 (25)	201 (105)	75 (15)
I A Low to High	196 (33)	428 (74)	75 (42)
I A High to Low	32 (18)	225 (124)	60 (10)
I D Low to High	141 (24)	458 (67)	40 (23)
I D High to Low	32 (18)	292 (162)	40 (6)

Stabilized outflow rates under the two experiments were rather similar between plots. Values for each plot and experiment are shown in table 4. These values are calculated as averages of the measured outflow rates after the time at which outflow rate appeared stabilized. Steady outflow rates under the lower intensity were between 3.8 and 8.4 mm/h; steady outflow rates under the higher intensity were between 22.1 and 28.1 in blocks III, II and I. In block IV where the high intensity was between 38 and 46 mm/h instead of the intended 33 mm/h, stabilized outflow rates under this intensity were between 22.0 and 36.8 mm/h. Stabilized outflow rates under the lower rainfall intensity were on average 5.9 mm/h for treatment A and 6.6 mm/h for treatment D. For treatment A the average outflow rate was the same for both Low to High and High to Low, for treatment D it was higher in High to Low. Stabilized outflow rates under the higher rainfall intensity, calculated as an average for blocks III, II and I for which the rainfall intensity had been the same, rates were on average 23.9 mm/h for treatment A and higher for High to Low, and 25.7 mm/h for treatment D where average values were almost the same for both experiments.

Steady outflow rates were lower than inflow rates for both rainfall intensities in all experiments. Steady outflow rates during low intensity were on average 63% of the inflow rate in block IV, leaving a difference of 3.6 mm/h. In blocks III, II and I it was on average 60% of the inflow rate, with a difference of 4.2 mm/h. Ratios in these three blocks were also lower when experiments started with low intensity than when they started with high. Steady outflow rates during high intensity were on average 66% of inflow rates in block IV with a difference of 14 mm/h. In blocks III, II and I the steady outflow rates were on average 73% of the inflow rate with a 9.2 mm/h difference. High steady outflow rates were also lower compared to inflow when the experiments started with low intensity, although differences were small.

Table 4. Stabilized outflow rates under the first and second run rainfall intensity (mm/h) for each block, treatment and experiment

Block, treatment and experiment	Steady outflow rate 1 (mm/h)	Steady outflow rate 2 (mm/h)
IV A Low to High	7.9	28.1
IV A High to Low	22.0	3.8
IV D Low to High	6.0	25.0
IV D High to Low	36.8	8.4
III A Low to High	4.1	23.5
III A High to Low	26.4	7.0
III D Low to High	5.9	28.1
III D High to Low	28.1	8.4
II A Low to High	5.6	22.6
II A High to Low	22.1	6.2
II D Low to High	4.8	24.5
II D High to Low	22.4	6.7
I A Low to High	6.1	24.5
I A High to Low	24.5	6.7
I D Low to High	4.8	24.8
I D High to Low	26.3	7.4

Total flows in and out of the soil profile for all experiments can be seen in table 5. Total outflow was between about 40 and 53 % of total inflow when running Low to High. The ratio was higher when running High to Low; total outflow was then between about 47 and 66 % of total inflow. The difference between total inflow and total outflow, which could have been retained in the soil profile, was between

55 and 85 mm when running Low to High, and between 45.5 and 92.5 mm when running High to Low. This amount of water could also to an unknown extent have leaked out of the investigated part of the profile. The difference between total inflow and outflow increased with increasing amount of total inflow. No clear difference in total outflow-inflow ratios can be seen between treatments in experiment Low to High. For High to Low, ratios were higher in all blocks under treatment D than under treatment A, most markedly in blocks IV and I.

Table 5. Total flows in and out of the soil profile (mm), difference between flows in and out (mm) and outflow-inflow ratios for each block treatment and experiment

	Low to High				High to Low			
Block and treatment	Total inflow (mm)	Total outflow (mm)	Difference	Ratio	Total inflow (mm)	Total outflow (mm)	Difference	Ratio
IVA	121.5	64.0	57.5	0.527	98.5	46.0	52.5	0.467
IVD	98.0	43.0	55.0	0.439	136.0	84.5	51.5	0.621
IIIA	137.5	68.0	69.5	0.495	147.0	87.5	59.5	0.595
IIID	124.5	64.5	60.0	0.518	133.5	88.0	45.5	0.659
IIA	131.0	52.0	79.0	0.397	152.0	76.0	76.0	0.500
IID	154.5	69.5	85.0	0.450	174.0	90.5	83.5	0.520
IA	147.0	65.5	81.5	0.446	179.0	86.5	92.5	0.483
ID	142.0	59.0	83.0	0.415	213.0	124.5	88.5	0.585

4.2 Laboratory measurements

Gravimetric water content values before and after rainfall were calculated as an average of the four replicates, and then recalculated into volumetric water content. For samples taken above 25 cm depth, the dry bulk density measured at 10-15 cm was used; for samples taken under 25 cm depth, the dry bulk density of 30-35 cm was used. 0.08 was added to all values from 0-5 cm sampling depth, to account for the applied lithium bromide solution. Average volumetric water contents in relation to saturation for each block is illustrated in figures 11 through 14. The soil was initially rather dry in the upper 10 cm of all blocks with more moist conditions underneath, except in block I where the upper 10 cm had higher initial water content than other blocks, and the profile underneath was rather dry compared to other blocks (figure 14). The higher water content in the upper layers was likely the effect of a rainfall event prior to measurements. Block IV under treatment A (figure 11a) had water contents relatively close to saturation below about 20 cm depth already before the start of the experiments.

Final water contents were very similar between experiments in most blocks; notable differences between Low to High and High to Low were only found in block III and block II, both under treatment A (figures 12a and 13a). In both these plots High to Low resulted in higher water content than Low to High. Final water contents were close to saturation in two plots, block IV under treatment A(figure 11a) and block II under treatment D (figure 13b), after both experiments. Block III under treatment A (figure 12a) also reached water contents close to saturation in the bottom 10 to 20 cm of the profile after High to Low, as did block II under treatment A (figure 13a) where water contents were close to saturation also at more shallow depths after running High to Low. Four of the plots resulted in water contents well below saturation after both experiments. Final water contents in the uppermost layers were often high.

The top layers, which were the driest at the beginning of the experiment in all blocks except block I (figure 14), showed large increases in water content at the end of the experiments. In block IV under both treatments (figure 11), and block III under treatment D (figure 12b), the increases in water content at the bottom of the profile were small. They were also small in bottom layers in block III (figure 12) and II under treatment D (figure 13b) when running Low to High but larger when running High to Low. Block I which initially had relatively low water contents at lower depths showed a large increase in water content at the bottom of the profile after rainfall for both tillage treatments (figure 14).

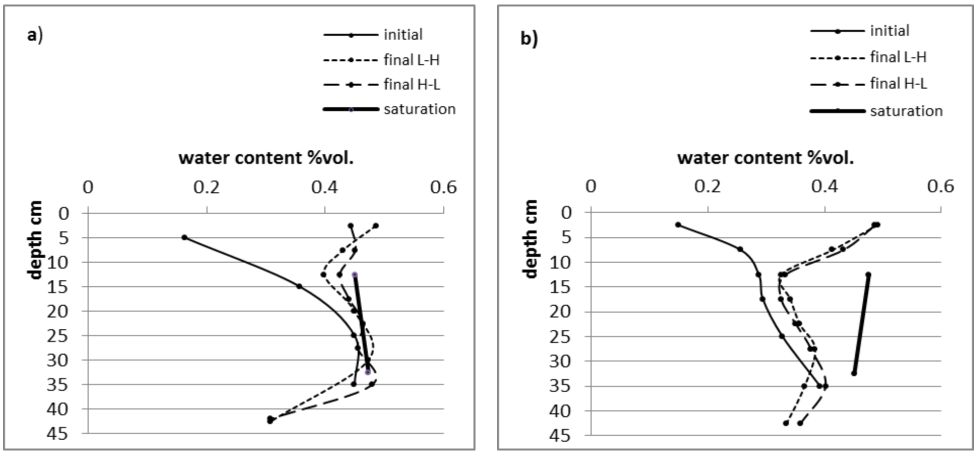

Figure 11. Initial volumetric water content, final water content after runs Low to High and High to Low, and water content at saturation (%vol.) in a) block IV, treatment A and b) block IV treatment D.

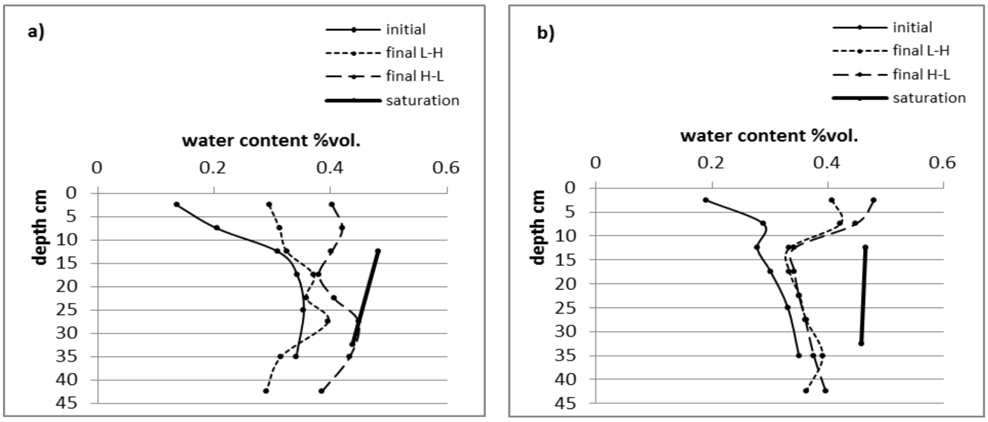

Figure 12. Initial volumetric water content, final water content after runs Low to High and High to Low, and water content at saturation (%vol.) in a) block III, treatment A and b) block III, treatment D.

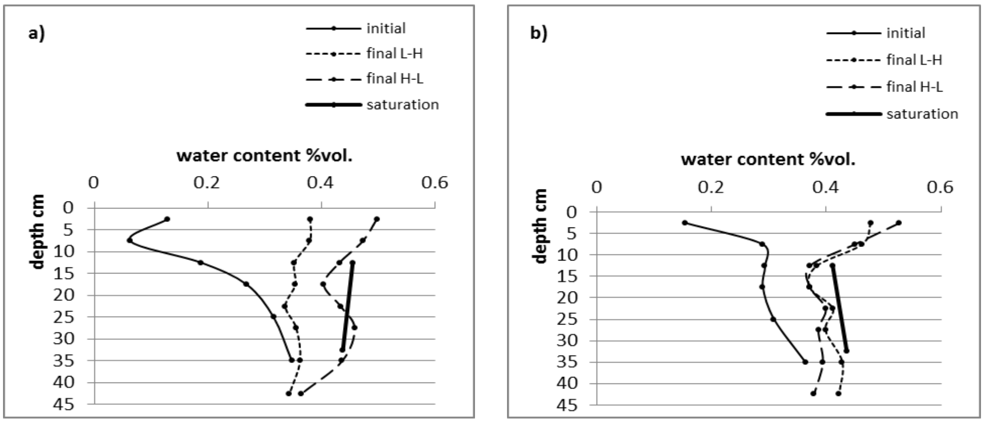

Figure 13. Initial volumetric water content, final water content after runs Low to High and High to Low, and water content at saturation (%vol.) in a) block II, treatment A and b) block II treatment D.

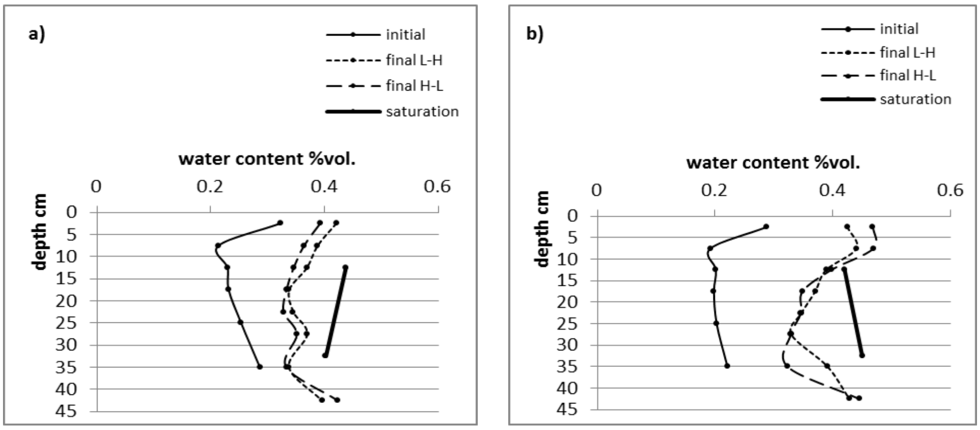

Figure 14. Initial volumetric water content, final water content after runs Low to High and High to Low, and water content at saturation (%vol.) in a) block I, treatment A and b) block I, treatment D.

The calculated water content values were also used to calculate the total amount of water stored in the profile before and after rainfall, and the change in total storage. The results of these calculations are shown in table 6. Initial storage decreased from block IV to block I in the same order as measurements were made. An increasing dryness of the soil during the time period when the experiments were conducted was also noticed during the fieldwork. A tendency towards larger increases in storage after the experiments can be seen moving from block IV to block I. The increase in storage was the highest in block II under treatment A for High to Low. Increases in storage were also high in block I under treatment D, both when running Low to High and High to Low. Storage increased the least in block III, treatment A, when running Low to High, and in block IV, treatment A, when running Low to High.

Table 6. Initial and final storage and change in storage after experiments Low to High and High to Low

Block and treatment	Initial storage (mm)	Final storage Low to High (mm)	Change in storage Low to High (mm)	Final storage High to Low (mm)	Change in storage High to Low (mm)
IVA	172.1	192.9	20.8	197.9	25.8
IVD	142.3	169.0	26.7	173.4	31.1
IIIA	138.1	148.8	10.7	185.5	47.4
IIID	139.1	167.8	28.7	183.2	44.1
IIA	117.1	161.3	44.2	196.8	79.7
IID	136.3	189.0	52.9	183.6	47.3
IA	119.0	165.0	46.0	160.1	41.1
ID	97.0	175.7	78.6	172.6	75.6

When comparing the calculated values of change in storage (table 6) with the difference in total in- and outflow (table 5), the former values were smaller than the latter ones in all cases except for in block II under treatment A after running High to Low when the calculated change in storage was a few mm more than the difference between total inflow and outflow. In two cases calculated change in storage values were just a few mm smaller; in most other cases between 20 and 30 mm differed. In block III, treatment A, the calculated change in storage was 58.8 mm less than the difference between measured in- and outflow for Low to High. For High to Low it was 12.1 mm less.

Average values of dry bulk density from the three replicates were calculated for each block, treatment and sampling depth. Results are shown in table 7. Dry bulk density was the lowest at 10-15 cm in block III, treatment A, and the highest at 30-35 cm in block I, treatment A. No clear patterns of differences could be distinguished between neither treatments nor sampling depths.

Table 7. Average dry bulk density (g/cm^3) for each block and treatment at depths 10-15 cm and 30-35 cm

Depth	IVA	IVD	IIIA	IIID	IIA	IID	IA	ID
10-15 cm	1.463	1.383	1.379	1.406	1.442	1.564	1.491	1.527
30-35 cm	1.433	1.485	1.522	1.450	1.524	1.515	1.596	1.451

Particle density values were between 2.63 and 2.72 g/cm^3. These values were used together with dry bulk density values to calculate the porosity for each plot and treatment at the two sampled depths.

Average values of $\theta(h)$ were calculated from the three replicates for each block, treatment and tension at the two sampled depths. The obtained values together with calculated porosity f, are shown in table 8 below. Most samples obtained greater water contents at tension 5 cm than at presumed saturation, even after porosity was corrected for swelling. The most likely explanation for this is that these samples were very close to saturation at 5 cm tension, and small errors in measurements were enough to affect the calculated values. Variability between samples from the same block, treatment and depth were however large in general. Samples from 10-15 cm depth in block IV, treatment A, and block III, treatment A, showed a steep decrease in water content between saturation and 5 cm tension. In those cases that water content decreased between saturation and 5 cm tension in the samples from 30-35 cm depth, the decrease was much smaller than at 10-15 cm. All samples showed a decrease in water content between 50 and 100 cm tension, in most cases smaller than the decrease between 5 and 50 cm tension.

Table 8. Calculated porosity, corrected porosity (values within parenthesis) and average water content (%vol.) at given tension (cm) for each block and treatment at depths 10-15 cm and 30-35 cm

Depth	Block and treatment	Water content (%vol.)			
		Porosity	5 cm	50 cm	100 cm
10-15 cm	IVA	0.405 (0.458)	0.427	0.393	0.384
	IVD	0.479 (0.486)	0.492	0.427	0.412
	IIIA	0.482 (0.500)	0.471	0.405	0.390
	IIID	0.465 (0.476)	0.478	0.407	0.393
	IIA	0.455 (0.474)	0.506	0.442	0.431
	IID	0.411 (0.419)	0.447	0.421	0.413
	IA	0.437 (0.445)	0.437	0.358	0.343
	ID	0.420 (0.432)	0.462	0.430	0.419
30-35 cm	IVA	0.473 (0.473)	0.479	0.470	0.466
	IVD	0.451 (0.451)	0.462	0.450	0.444
	IIIA	0.438 (0.439)	0.439	0.417	0.411
	IIID	0.458 (0.458)	0.458	0.432	0.424
	IIA	0.438 (0.440)	0.490	0.471	0.465
	IID	0.436 (0.449)	0.481	0.449	0.437
	IA	0.402 (0.406)	0.417	0.362	0.350
	ID	0.450 (0.458)	0.478	0.420	0.409

4.3 Modeling

The model was first run using data from the Low to High experiment in block III, treatment A, allowing macropore flow from layers 6 to 45. The development of the simulated outflow compared to the measured is illustrated in figure 15. The onset of simulated outflow was delayed by 65 minutes compared to the measured outflow. The simulated outflow did not show the same stabilization of the flow rate under the lower rainfall intensity as the measured outflow did. The simulated outflow rate was also higher than what was measured in the field, mainly during the higher rainfall intensity. The simulated outflow however responded to the increase in rainfall intensity and the cease of rainfall more or less at the same time as the measured outflow did. Due to the higher outflow rate during the high rainfall intensity, the cumulated simulated outflow exceeded the cumulated measured outflow, see figure 17. The total simulated outflow was 115.5 mm compared to the measured 68 mm (table 5).

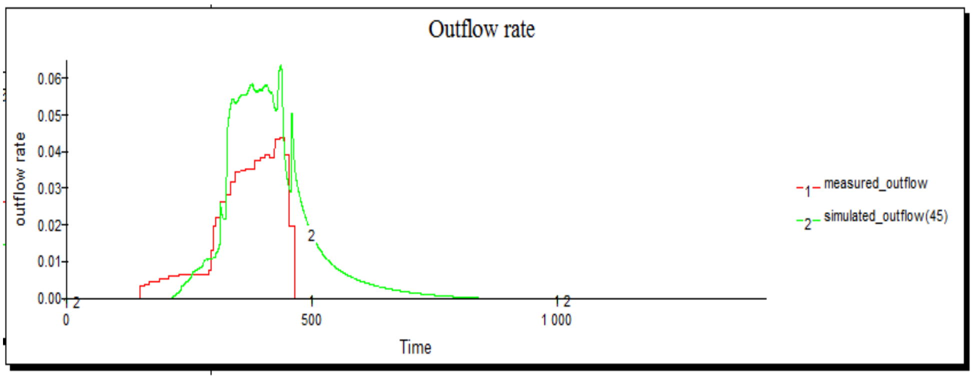

Figure 15. Measured and simulated outflow rate (cm/min) over time (min) for experiment Low to High in block III under treatment A.

When running the model with input data from the High to Low experiment, the simulated outflow started 12 minutes after the measured. The variations in simulated flow rate with time, compared to measured flow rates, are shown in figure 16. Similar to when running Low to High, the model calculated higher outflow rates compared to the field measurements, but simulated and measured flow curves show similar responses to changes in rainfall intensity. Cumulative measured and simulated outflow from the High to Low simulation are shown in figure 18. Total simulated outflow was 125.2 mm compared to the measured 87.5 mm (table 5).

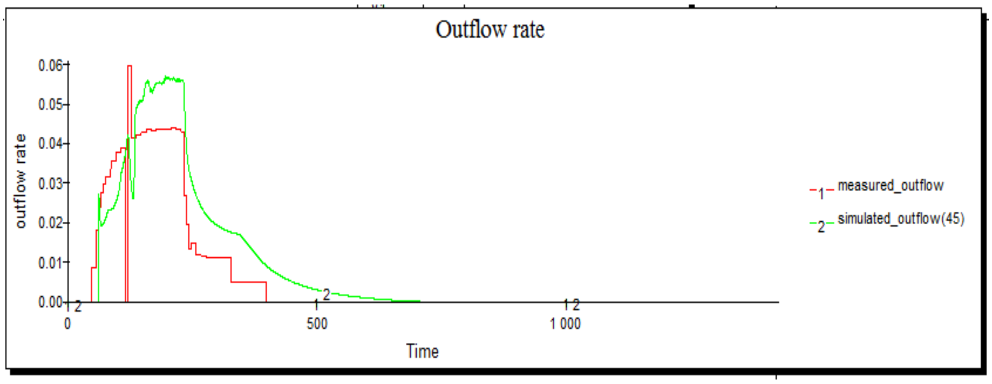

Figure 16. Measured and simulated outflow rate (cm/min) over time (min) for experiment High to Low in block III under treatment A.

Outflow from matrix and macropores respectively, wetting of macropores over time, and variation of tension in layers 6 and 7 over time for the simulation of Low to High are illustrated in figure 17 and in figure 18 for the simulation of High to Low. The simulations showed that the time of outflow onset coincided with the time when water started to be rerouted into macropores in layer 6 below the harrowed upper 5 cm Figures 17 and 18). The tension also decreased to the 10 cm that was the condition for macropore flow around the same time as outflow began. The outflow during the rainfall was dominated by macropore flow. This flow very rapidly decreased after rainfall stopped, and outflow was then completely consisting of matrix flow. This was the case both when simulating Low to High (figure 17) and High to Low (figure 18), the only difference was that wetting of macropores and the decrease in tension occurred earlier after start when simulating High to Low.

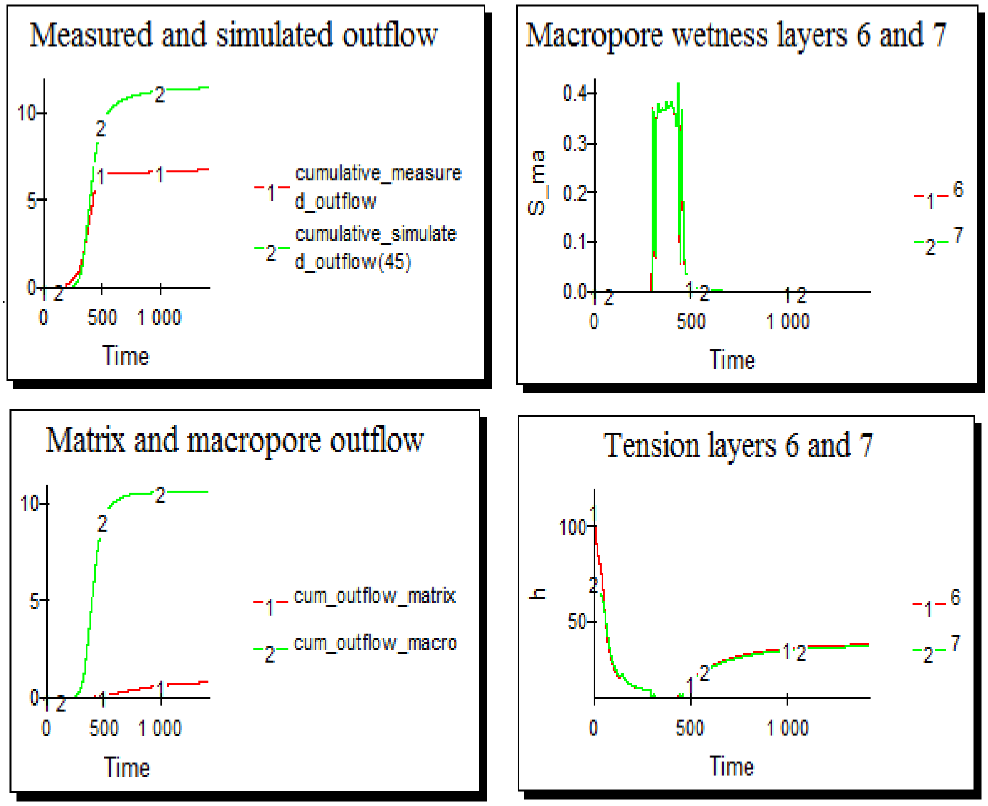

Figure 17. Upper left: Cumulative measured and simulated outflow (cm) over time (min). Upper right: Cumulative simulated outflow (cm) from matrix and from macropores over time (min). Lower left: Simulated macropore wetness at 6 and 7 cm from the soil surface over time (min). Lower right: Tension (cm) at 6 and 7 cm from the soil surface over time (min). All results from simulating Low to High.

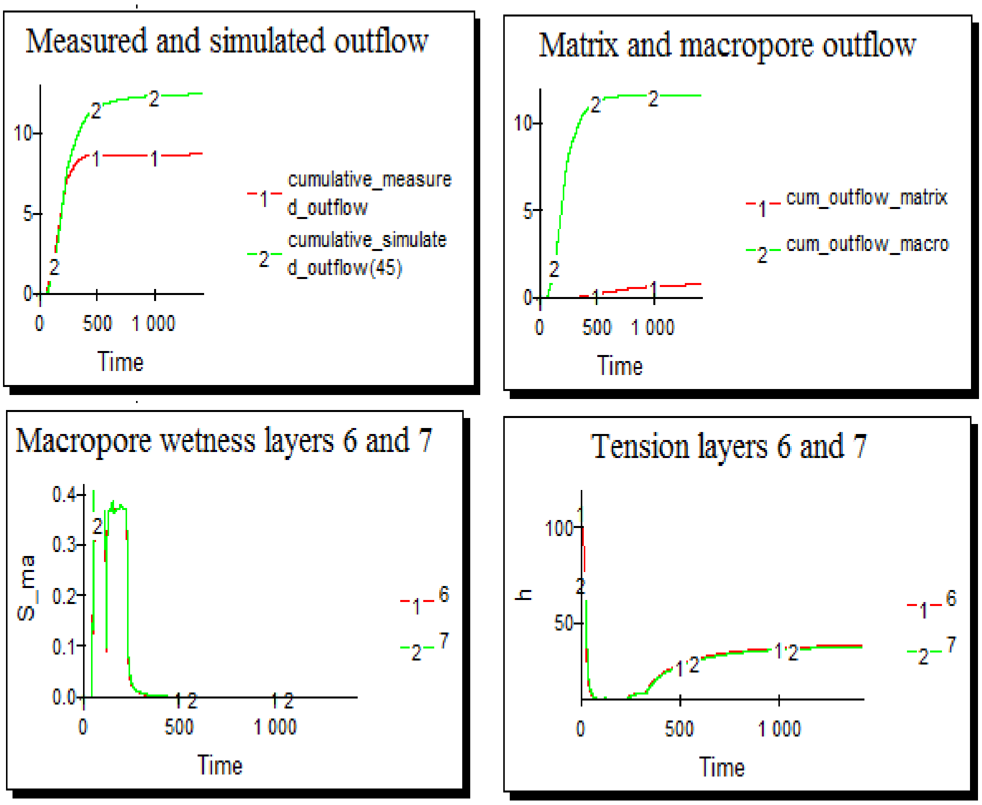

Figure 18. Upper left: Cumulative measured and simulated outflow (cm) over time (min). Upper right: Cumulative simulated outflow (cm) from matrix and from macropores over time (min). Lower left: Simulated macropore wetness at 6 and 7 cm from the soil surface over time (min). Lower right: Tension (cm) at 6 and 7 cm from the soil surface over time (min). All results from simulating High to Low.

The model simulated the same final water contents for both Low to High and High to Low, while the measurements showed higher final water contents after running High to Low than Low to High. After checking the tension in each layer at the end of the simulation it was concluded that the simulated final water contents corresponded to drainage equilibrium for the entire soil profile. Measured final water contents after both experiments run in block III under treatment A compared to simulated final water content are illustrated in figure 19.

The simulated change in water storage for the soil profile under Low to High was higher than the change calculated from the measurements (table 6); 21.8 mm compared to 10.7 mm. For High to Low the simulated change in storage was smaller than the 47.4 mm that were calculated from the measurements. Final simulated water contents in layers corresponding to measurement depths deviated from measured values with between 2.7 and 7.5 % down to 35 cm for the Low to High run. The main deviation between measured and simulated values was the water content in the bottom of the profile, where the simulated water content was 13.8 % higher than the measured. For High to Low the simulated values were between 4.3 and 13.9 % lower than measured values down to 35 cm. At the bottom of the profile the simulated value was slightly higher than the measured.

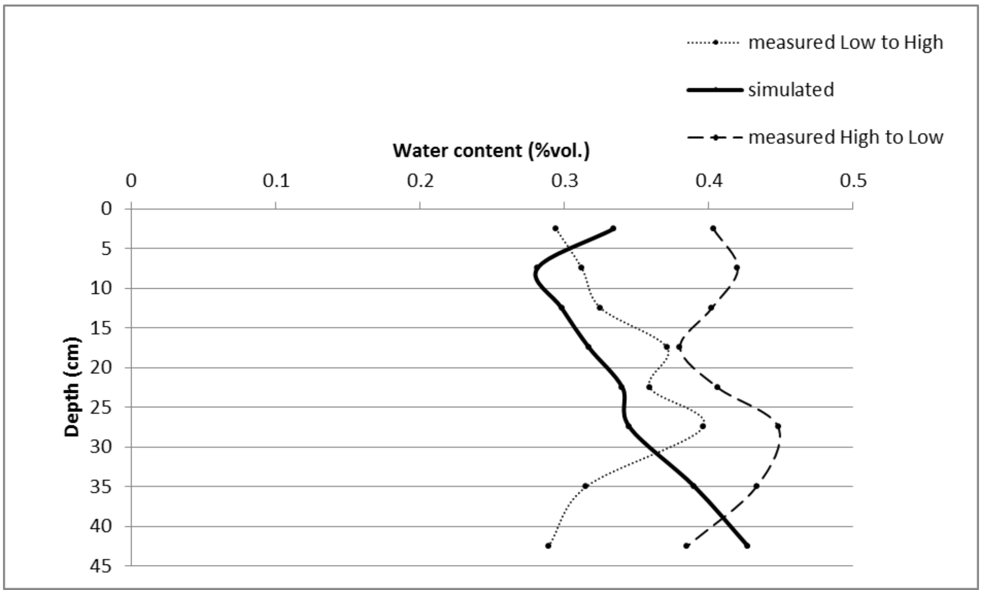

Figure 19. Simulated and measured final water contents (%vol.) for Low to High and High to Low in block III under treatment A.

The simulations that were made with different values of critical tension $h_{critical}$ and hydraulic conductivity of matrix $K_{s\ matrix}$ and macropores $K_{s\ ma}$ showed small effects on the simulation results. Both when only changing the values of $h_{critical}$ and $K_{smatrix}$, and also changing the value of K_{sma}, the simulated outflow rate followed a somewhat smoother curve than before, responding a little more slowly to changes in rainfall intensity. Simulated outflow rate was still much higher than what was measured. Final simulated water contents were exactly the same as before.

5 Discussion

5.1 Field and laboratory measurements

The conducted measurements and data analyses do not show any conclusive differences between the two investigated soil tillage systems. Time and required amount of rainfall for start and stabilization of outflow appear to have been more affected by initial water content and rainfall intensity than by tillage treatment. Stabilized outflow rates under both low and high rainfall intensity were on average a little higher in treatment D than in treatment A, but the values are very similar for most runs. The values are also a bit inexact as there was no clear point at which outflow rate stabilized and one had to be estimated for each run. Increases in water storage after termination of the experiments appear to have been mostly dependent on initial storage with larger increases in plots that were initially drier. Dry bulk density and total porosity displayed irregular variations between both plots and depths. Ratios between total out- and inflow (table 5) were higher in treatment D than in treatment A in all blocks when running High to Low, but the pattern was not repeated for Low to High.

Messing (1993) conducted measurements of hydraulic conductivity in the same soil tillage trial and experimental plots as those that were investigated in the present study and found that differences between treatments were small (Messing 1993). Larsbo et al. (2009) also conducted measurements of hydraulic properties and solute transport in the same experimental plots. They found average rates of both total saturated hydraulic conductivity in the top 5 cm of the profile, and infiltration at 0 cm tension measured at 25 cm depth to be higher in plots subject to reduced tillage compared to those that had been plowed. Differences were however not statistically significant. Dye tracer experiments conducted in the field showed larger dye coverage below 20 cm depth, interpreted as greater macropore connectivity, in plots subject to reduced tillage than in those that were plowed. They did also find that leaching patterns differed between soil subject to reduced tillage and soil that was plowed when conducting tracer experiments on sampled soil columns, although differences in total leaching of the tracer were not significant. Concentrations in the percolating water were initially higher in the soil under reduced tillage, and then rapidly decreased, whereas leaching from the plowed soil was more constant, suggesting stronger macropore flow in soil under reduced forms of tillage (Larsbo et al., 2009). The same patterns were found by Shapitalo et al. (2000) when applying $NO3^-$ and Br^- to plowed and untilled soil respectively in a 2 year column lysimeter experiment. They also found that total loss was unaffected by tillage. When applying Sr^{2+}, a reactive tracer binding to soil particle surfaces, losses were larger from the untilled soil. The authors hypothesized that the unreactive solutes were probably washed into the soil matrix to a greater extent in the plowed soil than in the untilled soil, from which more of both the reactive and unreactive solutes were rapidly transported through macropores (Shapitalo et al., 2000). The current study did not show any clear differences between tillage treatments in flow responses to rainfall, and the above mentioned studies of hydraulic conductivity by others in the same experimental plots resulted in similar findings. It is possible that the disruption of macropores in the top layers resulting from cultivation, or creation of preferential flow paths in-between large cohesive aggregates formed by the plow in the upper layers occurred and evened out any differences. Also, heavy clay soils displaying swelling and shrinking have been found to reverse the effects of soil disturbance such as tillage to some extent, through formation of cracks at the soil surface when the soil dries and self-healing of cracks (Strudley et al., 2008). The soil at Vipängen showed swelling when wetted, and could be a type of soil where the effects of tillage are not stable over time. This would help explain the lack of differences in hydraulic properties between the two tillage treatments.

Ratios of stabilized outflow rates (table 4) and inflow rate were higher under the higher rainfall intensity than under the lower. Also, when comparing total outflow to total inflow (table 5) the ratios were higher after High to Low where the higher intensity was run for a longer time than in Low to High. This indicates that a larger portion of the infiltrating water was transported through larger pores or cracks when the rainfall intensity was higher. Although outflow-inflow ratios were higher under the higher rainfall intensity, the rate at which the soil matrix appears to have been absorbing water was also higher under the higher intensity. This may be the result of a larger pressure gradient formed between aggregate surfaces and the soil matrix under higher rainfall intensity.

Shapitalo et al. (2000) investigated the effect of rainfall intensity on water flow and solute transport and found much larger total percolation and vertical solute transport when 30 mm of rain was applied in 15 minutes than when the same amount was applied at lower intensity. They also found that transport of freshly applied solutes was reduced when high rainfall intensity was preceded by low intensity rainfall but that the amount of percolation was not (Shapitalo et al., 2000). The former of these findings is in line with what was observed in the current study. Macropore flow appears to have been more pronounced under higher rainfall intensity.

Final water contents after running the experiments were in most cases rather far from presumed saturation (figures 11 through 14). This would support the idea that the matrix was not completely wetted and that a large portion of the infiltrating water flowed through larger pores and cracks. The relatively short amount of time that elapsed between start and outflow onset, and the small amount of rain that was required, also show that water, at least in the initial stages of the experiments, flowed along preferential flow paths rather than through the entire profile.

Calculated increases in water storage were in most cases smaller than the differences between total in- and outflow, which ideally should not be the case. This sink term in the water balance could be an effect of water content not being correctly determined. The sampling method that was used may have resulted in unrepresentative samples, as the soil core was compacted when the auger was pushed through the sticky soil, and this caused some uncertainty regarding the depth corresponding to the samples that were taken. Also affecting representativity of the samples that were taken is the fact that the soil was most likely not homogenously wetted laterally. Samples from inside large aggregates ought to have had lower water content than samples taken between these aggregates. Samples for determination of final water content were collected the day after running the experiment, and due to percolation and redistribution of soil moisture did therefore not reflect conditions at the time when the experiment was terminated. Volumetric water contents were not measured directly but calculated from the measured dry bulk density values. As dry bulk density was only measured at two depths in the soil profile, and dry bulk density at other depths was estimated from these, there is a possibility that dry bulk density of one or more of the layers were higher in reality than what was assumed and that the calculated water contents therefore were lower than they actually were in the field. The depth of the soil column above the trench was assumed to have been 45 cm when calculating storage values, but might not always have been the case. There is also a possibility that the sink term of the calculated water balance was due to leaking of water out of the investigated part of the profile. The sealing trench surrounding this part of the profile did only go down to about 40 cm depth, leaving a few centimeters at the bottom unsealed. Thus, some of the applied water may have leaked out laterally from the profile and did therefore not reach the collector.

5.2 Modeling

When using the model to simulate the outflow from the Low to High run (figure 15), the simulated outflow started about an hour later than what was observed in the field. When simulating High to Low (figure 16), the simulated outflow onset was less delayed compared the measured than when simulating Low to High but there was still a delay. This could be an effect of the assumption that there were no macropores in the top five centimeters and that macropore flow could only occur below this depth. This did probably not reflect the situation in the field. The rainfall intensity was much higher than the matrix conductivity and had the water not been able to flow into larger pores and be transported downward, the soil surface would have been ponded at an early stage of the field experiments. Ponding in the field occurred only twice; the first time towards the end of the experiment when running Low to High in block I, treatment A, and the second time after about two hours of high rainfall intensity when running High to Low in the same plot. There is also a possibility that the calculated values of water contents were not correct. If the soil was initially wetter in reality than what was simulated, the simulated outflow would naturally start later compared to what was observed in the field.

The model simulated higher outflow rates for both rainfall intensities in both experiments than what was measured in the field. This was only slightly affected by changing input values of matrix and macropore conductivity. Rather than being an effect of incorrect parameter values for the conductivities of the matrix and the macropores, this is likely due to the simplified reality that the model describes. It does not account for lateral transfer of water from the macropores to the soil matrix. Substitution of water between macropores and matrix could be added to the model but it would require a different modeling program than the one that was used, and the addition of new parameters with unknown values, such as the conductivity of the matrix-macropore interface and macropore geometry.

The final water contents were identical after simulating Low to High and High to Low. This result is due to the long simulation period, and in particular the long time that the profile is draining after the cease of rainfall. Tensions throughout the profile correspond to drainage equilibrium at the end of the simulations. As all soil parameters were set identically for the simulations of both experiments, final water contents were naturally the same. Worth mentioning is that the simulated water contents at drainage equilibrium were lower than what the measurements of soil water retention characteristics (table 8) would suggest. The simulated values were calculated using parameter values for the van Genuchten equation (equation 7) found in the literature as these parameters were not measured in this study. As these values affect the water holding characteristics of the modeled soil, and thereby the overall water balance of the simulation, more care should be taken to their determination.

6 Conclusions

Neither measurements made in the field nor at the laboratory show any conclusive differences between the two investigated tillage treatments. Development of flow appears to be affected mainly by soil moisture conditions and rainfall intensity, masking any effects of structural difference. A smaller portion of the infiltrating water was retained in the soil, even though the rate of matric uptake appears to have been higher under the higher rainfall intensity. The model that was built managed to describe the timing of changes in outflow, but simulated higher outflow rates than what was measured. The main reason for this was likely that the model did not include a description of flow from the macropore to the matrix region, which also affected its ability to describe development of water content stored in the soil.

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