Refined Modeling of Infiltration Processes into the Upper Soil Layer

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1. Abstract

The deterministic and lumped rainfall-runoff models in general make use of a linear approach to model the infiltration rate. To get more realistic results, the computation of infiltration has to be modeled in a more complex way. This paper describes the estimation of infiltration based on a dual-porous media scheme (micro and macropores). Laboratory experiments have being carried out and compared with different theoretical approaches. Richard equation and the Van Genuchten method for determining the unsaturated hydraulic conductivity were found to describe the infiltration in micropores properly. However, in reality infiltration is affected also by macropores. This paper shows the effect of worms on the infiltration and the possibility to model this impact on a macro-soil structure introduced by Bronstert.

2. Introduction

Hydrological models use different approaches to estimate the infiltration rate. They can be mainly linear, exponential or empirical (Jeníček 2007). More complex infiltration methods consider the different porosity stages of the soil matrix (Jeníček 2007; Bronstert & Plate 1997). At the Institute of River and Coastal Engineering at University of Technology Hamburg-Harburg (TUHH) there is good experience with a theoretical concept based on the method of Ostrowski (Hübsch 2006; Ostrowski 1982). By using a 1D water balance equation and simple linear empirical equations the infiltration rate in dependence on the soil moisture and rain intensity can be quantified. However, the main drawbacks are the linear behavior of infiltration with respect to soil moisture conditions, which simplifies the reality too much, and the saturated hydraulic conductivity used for infiltration computations in the unsaturated zone. This requires further calibration, resulting in a generation of non physically based parameters. This study intends to enhance the simulation of infiltration by a non-linear approach using Richard equation for the infiltration in micropores and a volumetric pore concept for the infiltration in micropores (Bronstert 1994).

3. Methods

<u>The non-linear approach based on principle of dual-porous media</u>

The theoretical (linear) approach regards the vertical processes as a chain of reservoirs (layers) with constant soil characteristics. Each soil layer is partitioned in two fractions, one containing macropores and the other containing a homogeneous soil matrix (Figure 1b). First, infiltration through the micropores is calculated (Figure 1a). Each layer is discretized in small sub-layers of length *dz*. At the surface, the rate of infiltration for the layer is determined *(I_{mic})*, whereas the vertical infiltration in each sub-layer describes the water movement and enables the water contribution to the next soil layers ($Imic_i$). In each sub-layer the fraction of water which percolates *($Percc_i$)* will be the infiltration for the next sub-layer (if the next sub-layer does not have less permeability). The vertical flow movement is driven by the gradient produced between the soil moisture boundaries in terms of their pressure head *(ho* and *hx),* and the transport rate is driven by the unsaturated hydraulic conductivity. The potential infiltration rate into the soil matrix is calculated from (Feddes et al. 1978):

$$I_{mic\_pot}(t) = k(\theta)\cdot\left(\frac{dh}{dz}-1\right), \quad (1)$$

where *k(θ)* is the unsaturated hydraulic conductivity [L/T], and *dh/dz* is the hydraulic gradient [-]. The actual infiltration $I_{mic\ actual}$ is the minimum between the water available at the soil surface *(Imax)* and the potential infiltration.
The infiltration rate into the macropores is enabled when precipitation exceeds the soil matrix capacity (Figure 1b). Even though macropores are distributed along the total soil layer, the model recognizes both pore domains as equivalent volume of the total layer. Therefore, the depth of the equivalent volume of macropores is given by the root depth (*Hz*). Infiltration into the macropores is determined as follows (Bronstert 1994):

$$I_{mac\_pot}(t) = \frac{(vtmac(t) - wcmac(t))}{dt} \quad , \tag{2}$$

with *vtmac* being the equivalent volume of macropores in the soil layer [L], *wvmac* the water content in macropore volume [L] and *dt* the change of time [T]. The actual macropore infiltration I_{mac} will be dependant on the water available at the surface and the water infiltrated into the soil matrix (Bronstert 1994):

$$I_{mac_{actual}}(t) = \begin{cases} \frac{vtmac(t) - wcmac(t)}{dt} & for\ I_{\max}(t) - I_{mic_{actual}}(t) > \frac{vtmac(t) - wcmac(t)}{dt} \\ I_{Max}(t) - I_{mic_{actual}}(t) & for\ 0 < I_{Max}(t) - I_{mic_{actual}}(t) < \frac{vtmac(t) - wcmac(t)}{dt} \\ 0 & for\ I_{Max}(t) - I_{mic_{actual}}(t) = 0 \end{cases} \quad , \tag{3}$$

The potential exfiltration of water into the soil matrix *(Imac_mic)* enhances the soil moisture conditions (Bronstert 1994):

$$I_{mac\_mic_{pot}}(t) = k(\theta(t))_{mac-mcc} \cdot \frac{dh_{mac-mic}(t)}{r_{mac-mic}} \, , \tag{4}$$

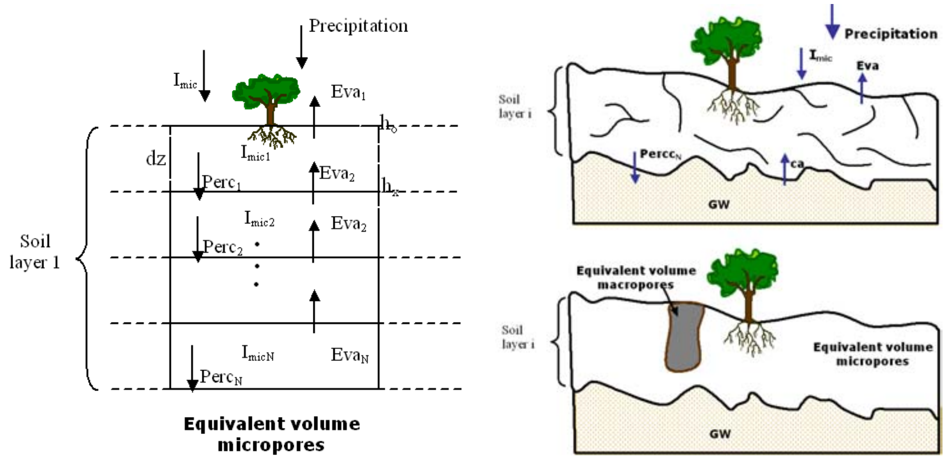
where $k(\theta)_{mac-mic}$ is the average conductivity between the both pore systems [L/T], $dh_{mac-mic}$ is the average soil tension of both pore systems [L], and $r_{mac-mic}$ is the radial average distance between the micro-macropores [L].
Total infiltration rate *I* [L/T] is the combination of the water flowing through the soil matrix and macropores:

$$I = I_{mic} + I_{mac} \quad . \tag{5}$$

Finally the moisture condition for a soil layer *SM [L/T]* will be computed as:

$$\frac{d(SM(t))}{dt} = I_{mic}(t) + I_{mac\_mic}(t) - (Percc(t) + Intf(t)) - Eva(t) + ca(t) + q_B(t) \tag{6}$$

with *Intf* the interflow [L/T], *ca* the capillary uprise [L/T], and q_B the groundwater recharge [L/T].



(a) **(b)**

Figure 1 Definition sketch: (a) micropore approach (b) normal pore distribution and equivalent volume for infiltration into micropores and macropores

<u>*Experimental setup*</u>

Three disturbed soil layers were collected, analyzed in the laboratory and packed in a column of 30 cm diameter and 80 cm height. At the bottom, the cylinder was perforated and a paper filter was placed to prevent washing out of soil material. Layers were classified as fine-middle sand *mSfs* (I layer: 95% sand, 5% gravel; II layer: 97,5% sand, 1,3% gravel, 1,2% silt, III layer: 96% sand, 1,5% gravel, 2,5% silt). The saturated hydraulic conductivity was obtained from soil analysis, and the soil hydraulic properties were obtained and compared by two methods: by experimental verification and applying the RETC code from (Van Genuchten et al. 1991), and from the table provided by the Federal Institute for Geosciences and Natural Resources (BGR 2008).

Before packing, the soil layers were dried up to low moisture conditions to increase the range of data collection of soil-water content and soil tension during the simulation of the rain event. The second and third layers were used as buffer. Three pairs of TDRs-Tensiometers were installed in the first layer at 5, 30 and 40 cm, one set in the second layer at 50 cm, and two sets in the third layer at 56 and 72 cm. A micro-drip system in spiral form was used as rain simulator, placed 20 cm over the soil surface. Rain was generated through 19 needles spaced at 10 cm approximately. Infiltration rate was determine indirectly by determine the soil moisture changes collected from the pairs of TDRs-Tensiometers.

The experiments were divided into two parts: 1) Experiment I: infiltration into a homogeneous soil matrix without macropores, with initial moisture conditions for layers I, II and III of 7.9, 13.6 and 6.7 Vol-% respectively. 2) Experiment II: infiltration as in experiment I and addition of macropores, performed after experiment I and after layer 1 drained to field capacity. Earthworms were added and after two weeks the experiment started. The initial moisture condition for layers I, II and III were 18.5, 31.1 and 26.36 Vol-% respectively. An average rain intensity of 52 mmh^{-1} ±2% was applied along the whole experiment (4 hours).

4. Results and Discussion

The concept explained in section 3 was implemented in the Rainfall-Runoff Model KalypsoNA (Hübsch 2006) to verify it. Experimental results of the first layer were compared to the linear approach (Ostrowski) and dual-porous system approach. For both experiments four simulation runs were performed, with soil parameters experimentally verified and obtained from literature (Table 1) for the non-linear and linear approaches, respectively. Parameters used by experimental verification obtained by laboratory tests and without calibration were: wilting point, field capacity, maximum water content, saturated hydraulic conductivity. By using the RETC code (Van Genuchten et al. 1991) the pF-curve shape parameters n and α were calculated. For both methods macropore fraction and pore distance were determined by observation.

Table 1 Main input model parameters

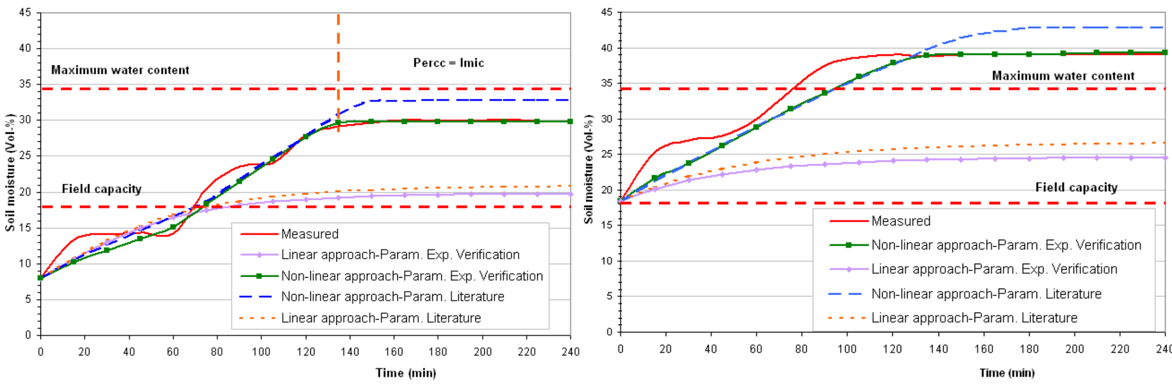
Parameter estimation	Soil type	Wilting point [mm/dm]	Field Capacity [mm/dm]	Max. water content [mm/dm]	n [-]	α [1/cm]	Saturated conductivity [mm/d]	Pore distance [cm]	Macropores [%]
Experimental verification	mSfs	4.0	18.0	34.5	1.94642	0.0560	1250.7	5	20
Literature (BGR 2008)	mSfs	4.85	18.0	38.45	1.63898	0.0687	1250.7	5	20

Total soil moisture for layer 1 was obtained by discrete integration of individual sub-layers, being infiltration rate derived from soil moisture values. To discretize the layer a resolution of 0.02 m was found to be the most appropriate, generating better simulation results in this study.

Two different experiment series are discussed. Experiment I tested the infiltration into a homogeneous soil matrix without macropores (Figure 2a). Measurements show a wavy shape before it reaches the saturated conditions. Since soil moisture instruments were placed at three different depths, the measured values here presented are weighted averages giving a uncertainty in measurement of ±2% confidence interval. At saturation the wavy curve become constant indicating a balance between infiltration and percolation rates. The non-linear approach using experimental verified parameters fits 10% better than the non-linear approach using input parameters from literature. This indicates a certain amount of error when soil data is not proved experimentally; in this particular case simulations demonstrated high sensitivity with respect to maximum water content parameters. Differences between non-linear and Ostrowski approaches are evident due to the non-linearity of parameters. In Richard equation, hydraulic gradient and unsaturated hydraulic conductivity are adjusted linearly as the soil is being moisturized. On the other hand, in the Ostrowski approach the saturated hydraulic conductivity is not adapted to changes in moisture conditions, keeping a constant soil permeability along the whole infiltration process. Therefore, in this experiment Richard equation shows to be appropriate to represent the physical infiltration processes within a soil matrix without macropores.

Experiment II tested the first soil layer with a homogeneous soil matrix including the impact of macropores (Figure 2b). The increase of infiltration capacity with macropores enhanced the holding moisture capacity of the soil 30% with respect to the soil matrix capacity without macropores. Even though Richard equation demonstrated to perform very well in a homogenous soil matrix, with macropores some empirical parameters are necessary to include, such as the volume of macropores and spatial distance between them. Thus, calibration of this parameters is necessary.

The approach suggested by Bronstert (1994) for the computation of macropores is a good solution to model the effect of these pores in the soil system, however calibration is necessary as long as the correlation between macropores and environmental and farming conditions are unknown. Further experimental tests will be oriented to study the influence of soil texture on infiltration and to determine flow patterns by changing vegetation and soil surface characteristics. These considerations are expected to be an useful tool for improving the decision making process on sustainable water management, for instance, to quantify better the effects of landuse on flood generation process, or to improve the assessment of sustainable farming and sustainable drainage.



(a) **(b)**

Figure 2 Measured and simulated results considering (a) only micropores and (b) micro and macropores

6. Acknowledgments

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