IMPACT OF FOREST SOIL INTERFACE DEPTH ON VALUE OF SATURATED HYDRAULIC CONDUCTIVITY OF SUPERIMPOSED ORGANIC HORIZON

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The paper examines the impact of the interface depth between the superimposed organic horizon and the organomineral A-horizon of forest soil on the water infiltration from the Guelph infiltrometer into forest soil. The superimposed organic horizon forms the surface layer of forest soil and it has specific physical properties such as high porosity, low bulk density, released structure and high values of hydraulic conductivity. The decomposing organic matter of the superimposed organic horizon causes the water repellency of organomineral A-horizon lying under it. In model Hydrus 2D/3D simulations with different interface depths between the superimposed organic horizon and the organomineral A-horizon of forest soil a slowdown of vertical component of infiltration from the Guelph infiltrometer and a preference of horizontal component of infiltration was detected in the case when the interface was in the bottom of borehole in which the Guelph infiltrometer was located, or when the interface has been moved higher than the bottom of borehole. By the increase of interface above the bottom of borehole, the increase of saturated hydraulic conductivity value from $K_s=0.0041$ cm s$^{-1}$ to $K_s=0.109$ cm s$^{-1}$ was detected.

KEY WORDS: forest soil, saturated hydraulic conductivity, superimposed organic horizon, model Hydrus 2D/3D

Introduction

The climatic conditions largely impact on the amount of water in the soil but also by the physical and chemical properties of the soil. These properties are impacted by the type of plant cover, especially in the top of forest soil layers. The forests (deciduous, coniferous), meadows and pastures, vegetation of spring areas, tree strips and groves in agricultural land, etc. impact the development of soils under these stands. Priority for the development of superimposed organic horizons of forest soils are dead underground and above ground (litter) organs of plants and animals. Dead organisms change over time, subject to the interaction of microbial soil component (bacteria, actinomycetes) through various degradation and synthetic processes of mainly biochemical nature. The composition, properties and amount of organic matter are constantly changing, the degree of decomposition is varies. Organic material of superimposed forest soil is very specific in terms of its physical properties. Several authors report mainly high porosity of this material, low bulk density, released structure and high values of hydraulic conductivity (Butorova and Bedrňa, 2012; Lauren and Manerrkoski, 2001; Kosugi, 1997). These specific physical properties would logically predetermine the superimposed organic horizons of forest soils to stimulate rainwater infiltration and prevent surface runoff. However, the hydraulics of these materials is not really trivial. Dead organic matter can cause an increase in the contact angle between water and the solid phase of soil matrix, especially in the organomineral A-horizon. The soil material then behaves as water repellency, which is caused mainly by waxes from biological litter, by the presence of fungi, mosses, lichens and other types of organic matter (Neris et al., 2013). The research of soil organic matter is a demanding discipline due to various continuous and parallel transformation processes that cause their very variable overall biochemical composition and habitus across a range of spatial scales. Water repellency and cohesion of soil particles are the key factors in soil hydrological processes. Even in the soil species with generally high infiltration capacity and low runoff generation, the litter accumulation and leaching can lead to significant changes in the values of these parameters. Organic water repellency limits water infiltration into the soil matrix, while superimposed organic horizon aggregation limits the presence of preferential flows that allow rainwater to reach subsurface soil horizons. Water infiltration into soil is the most important initiation process in the distribution of rainwater among the components of the hydrological cycle; surface and subsurface runoff, evapotranspiration, soil water supply regime and replenishment of deep water reservoirs in the river basin. Despite the relatively great interest in these processes in the scientific literature of the last decades (Capuliak et
al., 2010; Ritsema and Dekker, 2000; Jury and Horton, 2004), our ideas of water infiltration, especially in mountainous areas are many times very simplified and not seldom unrealistic. It is caused by historical development of hydrological models, which did not take into account the real physical properties of the soil, with a large number and variability of relevant factors that determine these soil properties. The infiltration of water into the soil is usually not uniform, the water transfer is heterogeneous and uneven, and the water flow rate is very spatially and temporally variable, even when is saturated. Among the other factors influencing the infiltration of water into the soil are two very important characteristics: the vegetation cover and the pedogenic substrates resp. the maternal rocks from which the soil cover was evolved (Orfánus et al., 2018). The saturated hydraulic conductivity ($K_s$) is a quantitative characteristic of the ability to transfer water in a water saturated soil or other porous medium. Its value depends mainly on the structure and texture of the soil. Hydraulic conductivity measurements are significantly influenced by the heterogeneity of the soil composition. The spatial variability of hydraulic conductivity is manifested in both horizontal and vertical directions. The higher hydraulic conductivity in the vertical direction than in the horizontal direction was detected in the structural soils. On the contrary, the prevailing horizontal conductivity was observed in layered and compacted soils (e.g. forest roads) (Surda et al., 2013).

The aim of this paper is to examine the impact of interface depth between the superimposed organic horizon and the organomineral A-horizon of forest soil on the water infiltration. The Hydrus 2D/3D model was applied for the modelling of water infiltration into forest soil from the Guelph infiltrometer at a different level of interface between superimposed organic horizon and the organomineral A-horizon.

Material and methods

The research locality with a working name at "Kokava meadows" is located on a wooded slope near the meadow in a typical cultural mountain spruce forest in the Western Tatras near community Liptovska Kokava. The coordinates of the research area are: 49° 6’ 30.8” northern latitude and 19° 51’ 53.4” eastern longitude. The average altitude is 878 m. The measurement places (1–6 in Table 3) were situated in area where the raining experiment was carried out in the past (Orfánus and Fodor, 2011), in a part with more developed superimposed organic horizon. All measurements were performed in an uneven pattern choosing the sites on naturally flat (not inclined) segments of relief and best developed forest floor horizons, without human intervention, within the 15x45 meter plot. The tributary of the Dovalovec stream, which flows near the research locality, is unlikely to have any effect on measurements. The research locality is located at the top of the slope and the tributary of the Dovalovec stream flows at the bottom of the slope, 30 meters below the measurement locality. For saturated hydraulic conductivity measurement by the Guelph infiltrometer method six places was selected at locality and forest soil moisture was measured by the Frequency domain reflectometry method. The average angle of the examined slope is 25°. The observed soil is cambisol modal, acidic with an A-layer (16–25 cm) covered by superimposed organic horizon (0–16 cm deep) which was composed of layer of plant litter (mainly needles) at different degree of decomposition. This superimposed organic horizon in the bottom layer shown a significant degree of water repellency depending on the water content of the forest soil (Orfánus and Bedrna, 2012). The previous research in the year 2010 revealed that the organomineral A-horizon has also significant hydrophobic properties in the dry season. The transition A/B horizon is located at a depth of 25–45 cm with the Bvs horizon below it. The plant cover of soil consists of spruce forest (different age structure) with discontinuous underground growth of blueberries and mosses.

At selected places, the saturated hydraulic conductivity was measured by a Guelph infiltrometer of the upper soil layer, which consisted mostly of the superimposed organic horizon and partially encroached into the organomineral A-horizon. Guelph infiltrometer is an experimental field method applying the principle of Mariotte container which was inserted into the borehole with adjustable level of pond. The measured values of $K_s$ express the integrally vertical and horizontal hydraulic conductivity of saturated soil and by pond influence it includes also the preferential pathways (Steikauerová et al., 2010). The measurements were realized in 6 cm and 11 cm deep of boreholes at six selected places at the research locality. The deep of pond was set to 5 cm and 10 cm. To calculate the steady water discharge ($Q$) and consequently the $K_s$, the equations 1–7 were use. The parameter $a$ was determined according to soil structure and then inserted into the equations together with water head height $H_1=5$ cm and $H_2=10$ cm and than calculated the shape factors $C_1$ and $C_2$ as follows:

$$C_1 = \left( \frac{H_1}{a} \right)^{0.754} \left( 2.074 + 0.093 \frac{H_1}{a} \right)^{-0.254}$$  \hspace{1cm} (1)

$$C_2 = \left( \frac{H_2}{a} \right)^{0.754} \left( 2.074 + 0.093 \frac{H_2}{a} \right)^{-0.254}$$  \hspace{1cm} (2)

where $C_1$, $C_2$ – shape factor, $H_1$, $H_2$ – water head height [L], $a$ – radius of borehole into soil [L].

After inserting $C_1$ and $C_2$ into equations (3) and (4), we calculate $G_1$ and $G_2$.

$$G_1 = \frac{H_2 C_1}{\pi(2H_1H_2(H_2-H_1) + \alpha^2(H_1C_1-H_2C_2))}$$  \hspace{1cm} (3)

$$G_2 = \frac{H_1 C_2}{\pi(2H_1H_2(H_2-H_1) + \alpha^2(H_1C_1-H_2C_2))}$$  \hspace{1cm} (4)
where

\( G_1, G_2 \) – two head, combined reservoir,

\( H_1, H_2 \) – water head height [L],

\( \pi \) – constant (Ludolf number),

\( \alpha \) – radius of borehole into soil [L].

The measurement data of steady flow rate \( R_1 \) and \( R_2 \) obtained from the Guelph infiltrometer we insert into equations \( Q_1 \) and \( Q_2 \):

\[
Q_1 = R_1 \times 35.22
\]

\[
Q_2 = R_2 \times 35.22
\]

where

\( Q_1 \) – steady state infiltration flow rate \([L^3 \times T^{-1}]\) for setting water head height \( H_1 \),

\( Q_2 \) – steady state infiltration flow rate \([L^3 \times T^{-1}]\) for setting water head height \( H_2 \),

\( R_1, R_2 \) – steady flow rate from the Guelph infiltrometer \([L \times T^{-1}]\).

The saturated hydraulic conductivity \( K_s \) we calculate by using \( Q_1, Q_2 \) and \( G_1, G_2 \):

\[
K_s = G_2 \times Q_2 - G_1 \times Q_1
\]

\( K_s \) – saturated hydraulic conductivity \([L \times T^{-1}]\).

Hydru 2D/3D (Šimůnek et al., 2012a) was used to estimate the soil hydraulic parameters via numerical inversion and simulate the observed saturated hydraulic conductivity of forest soil. The Hydru model (Šimůnek et al., 2008, Šimůnek et al., 2012b, Šimůnek et al., 2016) is a mathematical deterministic model that allows the simulation of water movement, heat and solutes transport in porous materials that are variable saturated. Preferably it was designed to simulate the transport of chemicals, but it is possible separately to simulate the movement of water in a one-dimensional or two-dimensional environment by incorporating a double porosity or double permeability model. The model has a very good user interface and is continually improved based on the current demands of its users.

The single-porosity model was used to simulate the hydraulic parameters of the superimposed organic horizon from the cumulative water infiltration into the forest soil measured by the Guelph infiltrometer. We created a network in the Hydru 2D/3D (Šejna et al., 2014) model for an axially symmetrical quasi-three-dimensional runoff domain. The drainage domain contained axially symmetrical holes in a superimposed organic horizon with a radius of 2.5 cm and a depth of 12 cm. The simulated domain is composed of two materials with different values of \( \theta_r \) – residual soil moisture, \( \theta_b \) – saturated soil moisture, \( \alpha \) – alpha parameter, \( n \) – parameter, \( K_o \) – saturated hydraulic conductivity, detected from the retention curve and from the measurements of saturated hydraulic conductivity \( K_s \) (Table 1).

During the infiltration of water into the forest soil, a free drainage was set as boundary condition. The Hydru 2D/3D modelling consisted of changing parameters (the depth of interface of two horizons, the depth borehole and the applied pond). The saturated hydraulic conductivity \( K_s \) of the superimposed organic horizon was calibrated by inverse modelling while maintaining the other parameters as determined by measurements.

Forest soil moisture was measured by the Frequency Domain Reflectometry method. The electrical capacitance of a capacitor that uses the soil as a dielectric depends on soil water content \( \theta \). When this capacitor, which is made of metal plates or rods imbedded in the soil, is connected to an oscillator to form an electrical circuit, changes in soil moisture can be detected by changes in the circuit operating frequency (Bátková et al., 2013). These changes form the basis of the Frequency Domain Reflectometry sensors.

**Results and discussion**

From the measurements of saturated hydraulic conductivity \( K_s \) in two summer seasons (in the year 2015 and 2016) at the locality near Kokava meadows, was detected, that the values of \( K_s \) measured with the Guelph infiltrometer were higher unlike other methods of measuring saturated hydraulic conductivity, when the values of \( K_s \) were lower in the year 2016 (Zvala, 2018). After considering of possible causes of this condition, we decided to verify one of the most likely hypotheses by mathematical model (Hydru 2D/3D). The hypothesis was based on the assumption that in the second year (2016) the depth of boreholes for measurement by the Guelph infiltrometer was near to the boundary of the superimposed organic horizon with a significantly water repellency organomineral A-horizon. The \( K_o \) value of superimposed organic horizon was calibrated by the inverse model. The depth of the interface was changed, all other parameters remained unchanged. By using of Guelph infiltrometer the higher values of saturated hydraulic conductivity in the year 2016 compared to the previous year were measured. It was in average of 0.023 cm s\(^{-1}\), four times more than the previous year (Table 2). How is it possible if the measurements were carried out at the efficacy of the same factors (lower water content, volume changes, water repellency), which in other methods caused the decrease of \( K_o \)? The answer to this question is to be found in one of the other factors which overlaps the effect of the above mentioned parameters in this method and which is not present in disk infiltrometer and single-ring method respectively is much less active. The most likely parameter will be the depth of boundary between the superimposed organic horizon and water repellency organomineral A-horizon. The reason why we decided to simulate the measurement of saturated hydraulic conductivity of forest soil by Guelph infiltrometer was the increase in the value of saturated hydraulic conductivity in year 2016 compared to year 2015. The 2016 simulation provided us with an answer to the beginning of the question. Table 2. contains the average values of saturated hydraulic conductivity calculated from the six measured values for each method. Six measurements for each method correspond to six diffe-
The decrease in moisture content of forest soil in 2016 (Table 3), the volume changes of forest soil and increased water repellency (decrease in forest soil moisture causes the increased water repellency of organomineral A-horizon) and they are therefore the most likely cause of a significant decrease of $K_s$ in 2016 compared to 2015 for single ring method and disk infiltrometer method. The forest soil moisture and their average values on all six places at the research locality of measurement are presented in Table 3. Forest soil moisture were measured before the measurement of saturated hydraulic conductivity by various methods. They are identical to the measurement points for saturated hydraulic conductivity. At each of the six points, the measurement of forest soil moisture was performed five times. From the five measured values was calculated average value for each point. Measured by frequency domain reflectometry method.

The Guelph infiltrometer measurements were apparently installed below or just below the interface between the superimposed organic horizon and organomineral A-horizon. The presence or the proximity of this interface to the bottom of the boreholes for the Guelph infiltrometer caused a much more significant slowdown in the vertical component of water infiltration in 2015. The model simulations using the Hydrus 2D/3D model include various changing parameters: the interface of two materials, the depth of borehole and the height of pond, which are described in each example for water infiltration into forest soil from the Guelph infiltrometer. The soil hydraulic parameters for superimposed organic horizon such as: residual soil moisture, saturated soil moisture, alpha parameter, $n$ – parameter and saturated hydraulic conductivity, were unchanged and their values were: $\theta_r=0.057 \, \text{cm}^3 \, \text{cm}^{-3}$, $\theta_s=0.7 \, \text{cm}^3 \, \text{cm}^{-3}$, $\alpha=0.03 \, \text{cm}^{-1}$, $n=1.6$, $K_s=0.0041 \, \text{cm} \, \text{s}^{-1}$ and for organomineral A-horizon: $\theta_r=0.089 \, \text{cm}^3 \, \text{cm}^{-3}$, $\theta_s=0.43 \, \text{cm}^3 \, \text{cm}^{-3}$, $\alpha=0.01 \, \text{cm}^{-1}$, $n=1.23$, $K_s=0.000019 \, \text{cm} \, \text{s}^{-1}$.

In model simulation no. 1 (Fig. 1) the following model domain was setting: the interface between superimposed organic horizon and organomineral A-horizon was at the borehole bottom for the Guelph infiltrometer, the depth of borehole was 12 cm, the height of pond was 10 cm. The value of saturated hydraulic conductivity of the superimposed organic horizon obtained by inverse modelling was: $K_s=0.04026 \, \text{cm} \, \text{s}^{-1}$.

In model simulation no. 2 (Fig. 2) the following simulation model domain was setting: the interface between superimposed organic horizon and organomineral A-horizon was under borehole bottom in depth of 50 cm, 10 cm.

### Table 1. The soil hydraulic parameters of forest soil

| Soil horizon                | $\theta_r$ [cm$^3$ cm$^{-3}$] | $\theta_s$ [cm$^3$ cm$^{-3}$] | $\alpha$ [cm$^{-1}$] | $n$ | $K_s$ [cm s$^{-1}$] |
|----------------------------|-------------------------------|-------------------------------|----------------------|-----|--------------------|
| Superimposed organic horizon | 0.057                         | 0.7                           | 0.03                 | 1.6 | 0.0041             |
| Organomineral A-horizon     | 0.089                         | 0.43                          | 0.01                 | 1.23| 0.000019           |

### Table 2. The average values of saturated hydraulic conductivity $K_s$ measured in 2015 and 2016 at the locality Kokava meadows (Zvala et al., 2017)

| Year of measurement | Guelph infiltrometer $K_s$ [cm s$^{-1}$] | Single ring method $K_s$ [cm s$^{-1}$] | Disk infiltrometer $K_s$ [cm s$^{-1}$] |
|---------------------|----------------------------------------|----------------------------------------|----------------------------------------|
| 2015                | 0.0056                                 | 0.033                                  | 0.086                                  |
| 2016                | 0.023                                  | 0.0061                                 | 0.0032                                 |

### Table 3. The forest soil surface moistures measured by Frequency Domain Reflectometry method at Kokava meadows locality in the years 2015 and 2016

| Place of measurement at the research locality | Year | Forest soil moisture [%] | Average forest soil moisture [%] |
|---------------------------------------------|------|--------------------------|---------------------------------|
| 1.                                          | 2015 | 8.6                      | 11.2                            |
|                                             | 2016 | 8.8                      | 12.6                            |
| 2.                                          | 2015 | 8.1                      | 16.0                            |
|                                             | 2016 | 11.9                     | 11.3                            |
| 3.                                          | 2015 | 14.6                     | 9.8                             |
|                                             | 2016 | 6.0                      | 7.0                             |
| 4.                                          | 2015 | 26.3                     | 10.2                            |
|                                             | 2016 | 4.0                      | 5.6                             |
| 5.                                          | 2015 | 10.5                     | 9.0                             |
|                                             | 2016 | 6.9                      | 5.8                             |
| 6.                                          | 2015 | 12.6                     | 15.3                            |
|                                             | 2016 | 10.7                     | 13.5                            |
the depth of borehole was 12 cm, the height of pond was 10 cm. The value of saturated hydraulic conductivity of the superimposed organic horizon obtained by inverse modelling was: \( K_s = 0.02566 \text{ cm s}^{-1} \).

In model simulation no. 3 (Fig. 3) the following simulation model domain was setting: the interface between

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Fig. 1. Model simulation of water infiltration into forest soil by use Guelph infiltrometer in Kokava meadows locality (6/15/2016): a) the forest soil before the start of infiltration (0 s), b) the infiltration after 26 s, c) the infiltration after 52 s. (Model simulation no. 1).
superimposed organic horizon and organomineral A-horizon was in a depth of 7 cm, i.e. above borehole bottom, the depth borehole was 12 cm, the height of pond was 10 cm. The value of saturated hydraulic conductivity of the superimposed organic horizon obtained by inverse modelling was: $K_s=0.109$ cm s$^{-1}$. 

**Fig. 2.** Model simulation of water infiltration into forest soil by use Guelph infiltrometer in Kokava meadows locality (6/15/2016): a) the forest soil before the start of infiltration (0 s), b) the infiltration after 26 s, c) the infiltration after 52 s. (Model simulation no. 2).
From the measured and modelled results we detected the differences in the values of saturated hydraulic conductivity. In model simulation no. 1, when the interface between superimposed organic horizon and organo-

Fig. 3. Model simulation of water infiltration into forest soil by use Guelph infiltrometer in Kokava meadows locality (6/15/2016): a) the forest soil before the start of infiltration (0 s), b) the infiltration after 26 s, c) the infiltration after 52 s. (Model simulation no. 3).
organic horizon. In simulation model no. 2., when the interface between superimposed organic horizon and organomineral A-horizon was under borehole bottom in depth of 50 cm, we detected the increase of $K_s$ value from $K_s=0.0041$ cm s$^{-1}$ to $K_s=0.02566$ cm s$^{-1}$, and almost no influence on vertical and horizontal components of water infiltration into forest soil. In model simulation model no. 3, when the interface between superimposed organic horizon and organomineral A-horizon was above the borehole bottom, at a depth of 7 cm, we detected the highest increase of saturated hydraulic conductivity value from $K_s=0.0041$ cm s$^{-1}$ to $K_s=0.109$ cm s$^{-1}$ and the highest preference of horizontal component of infiltration into the forest soil due to the water repellency interface. Simulation model Hydrus 2D/3D revealed a significant impact of the interface depth on the calibrated value of the saturated hydraulic conductivity of the forest soil. The increase of interface above the bottom of borehole, the increase of saturated hydraulic conductivity and preferring of horizontal component of infiltration was detected. Figures 1–3 determine the water content of forest soil from $\theta_{wil}=0.271$ cm$^{-3}$ (dark blue color) to $\theta_{wil}=0.700$ cm$^{-3}$ (dark red color). From the figures we can observe the change in the water content of the soil as a function of time and the movement of water in the soil, which is influenced by the water repellency interface.

Conclusions

The Hydrus 2D/3D model was applied for the modelling of water infiltration into forest soil from the Guelph infiltrometer. The macropores and released structure of superimposed organic horizon create a preferred pathways for water infiltration. In model simulations with different interface depths between the superimposed organic horizon and the significantly water repellency organomineral A-horizon of forest soil a slowdown of vertical component of infiltration from the Guelph infiltrometer and a preference of horizontal component of infiltration was detected in the case when the interface was in the bottom of borehole in which the Guelph infiltrometer was located, or when the interface has been moved higher than the bottom of borehole. The depth of interface between the superimposed organic horizon and the organomineral A-horizon of forest soil significantly impacted the calibrated value of saturated hydraulic conductivity. By the increase of interface above the bottom of borehole, the increase of saturated hydraulic conductivity value was detected.

From the point of view of hydrological processes in forested river basins, a significant slowdown of infiltration at the water repellency interface between superimposed organic horizon and organomineral A-horizon. It can cause the shallow subsurface runoff, which accelerates the runoff during floods and causes significant washing of superimposed organic horizon can be optically observed in the forest after extreme rainfall events. It can be stated that a significantly larger part of the water flows through the macropores and the preferred pathways than the through the soil matrix.

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