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The role of stony soils in hillslope and catchment runoff formation

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Abstract: The role of stony soils in runoff response of mountain catchments is rarely studied. We have compared simulated response of stony soils with measured catchment runoff for events caused by rains of small and high intensities in the mountain catchment of the Jalovecký Creek, Slovakia. The soil water response was simulated for three sites with stoniness 10–65% using the Hydrus-2D single porosity model. Soil hydraulic parameters employed in the modelling, i. e. the saturated hydraulic conductivity and parameters of the soil water retention curves, were obtained by two approaches, namely by the Representative Elementary Volume approach (REVa) and by the inverse modelling with Hydrus-1D model (IMa). The soil water outflow hydrographs simulated by Hydrus-2D were compared to catchment runoff hydrographs by analysing their skewness and peak times. Measured catchment runoff hydrographs were similar to simulated soil water outflow hydrographs for about a half of rainfall events. Interestingly, most of them were caused by rainfalls with small intensity (below 2.5 mm/10 min). The REV approach to derive soil hydraulic parameters for soil water outflow modelling provided more realistic shapes of soil water outflow hydrographs and peak times than the IMa approach.

Keywords: Lateral subsurface flow; Mountain catchment; Soil water flow modelling.

Abbreviations: REV – representative elementary volume; REVa – the REV approach; IMa – the inverse modelling approach; SWRC – soil water retention curve.

INTRODUCTION

Soils play an important role in catchment runoff formation. The response of catchment runoff to precipitation is highly nonlinear due to heterogeneity in inputs and catchment characteristics, threshold behaviour depending on catchment wetness and storage state, varying relative contributions of different landscape units, etc. An excellent state of the art review of the processes and controlling factors affecting runoff formation at hillslopes was recently given by Bachmair and Weiler (2011). Preferential flow in the soils (Beven and Germann, 1982), the instability-driven flow (Tesař et al., 2001) or fill and spill mechanism (Tromp-van Meerveld and McDonnell, 2006) are commonly used to explain rapid formation of the subsurface flow that eventually contributes to catchment stormflow. Soil stoniness can have similar effect (Hlaváčiková et al., 2015, 2016) as the retention capacity of stony soils is reduced. This phenomenon is still not well studied, and it is neglected in runoff formation theories.

Many authors (e.g., Botter and Rinaldo, 2003; Li and Sivapalan, 2011) observed that hillslope processes, mainly the lateral subsurface flow tend to make catchment runoff hydrograph positively skewed. Hillslope lateral subsurface flow is dependent on soil properties such as infiltration capacity, heterogeneity of hydraulic conductivity, soil water retention, thickness of unsaturated zone and preferential pathways.

Stony soils are commonly found in hilly and forested regions of the world. Stoniness, defined as the relative volume of rock fragments, is an important soil property. It can strongly influence water infiltration, movement, retention characteristics and runoff formation (e.g., Al-Qinna et al., 2014; Chen et al., 2012; Hlaváčiková et al., 2015). Correct estimation of the soil hydraulic properties (i.e., hydraulic conductivity and van Genuchten soil water retention functions) is essential to evaluate the water flow (hydrological response) in stony soils. Water flow modelling in a stony soil profile is difficult due to the heterogeneity of rock fragments distribution and quantity. It requires determination of the retention characteristics of fine soil fraction, saturated hydraulic conductivity and stoniness in soil layers. For this, a large representative elementary volume (REV) of soil sample is needed to characterize the bulk characteristics of the stony soil profile (e.g., Hlaváčiková et al., 2015, 2018). Buchter et al. (1994) recommended that the dry mass of a stony soil sample should be at least 100 times the mass of the largest particle. However, there is no rule for how large the REV of a stony soil should be for measuring its hydraulic characteristics. After obtaining the stoniness from REV, the soil water retention curves of the fine soil fraction are corrected to adequately represent the hydraulic characteristics of the studied stony soil profile (e.g., Bouwer and Rice, 1984; Coppola et al., 2013; Ma and Shao, 2008).

An alternative approach to REV, the inverse modelling utilizing measured soil moisture data has been used for the estimation of soil hydraulic parameters (e.g., Šimůnek and van Genuchten, 1996; Šimůnek et al., 1998; Wegehenkel et al. 2017). The inverse modelling uses optimization techniques for the estimation of soil hydraulic parameters from transient flow transport data (Šimůnek et al., 2013). The disadvantage of this approach is that derived soil hydraulic parameters can be applied only to the sample volume around the soil moisture sensors that may be very small (200 cm^3) compared to the REV (1 m^3).

In our knowledge, not a single study addressed the impact of soil hydraulic parameters estimated by both inverse modelling and REV on the lateral subsurface flow simulations in stony soils. The objective of our work was to compare the response of the outflow from stony soils in a small mountain catchment to rainfall events with different intensity to catchment runoff response. To fulfil the objective, the work was divided into two parts. First, soil hydraulic parameters needed for the subsurface water flow modelling for three study sites with moderate to high stoniness (10–65%) were derived by the REV (REVa) and inverse modelling (IMa) approaches. Then, comparison of lateral subsurface flow hydrographs (hereafter also soil water outflow) and catchment runoff was done by analysing the skewness and peak time of the hydrographs.

STUDY SITE

The study is carried out in the mountain catchment of the Jalovecký Creek (the Western Tatra Mountains, Slovakia), shown in Fig. 1. Catchment area is 22.2 km^2, its mean slope is 30° and the altitude ranges from 800 to 2178 m a.s.l. (mean 1500 a.s.l.). The bedrock is dominantly formed by crystalline and metamorphic rocks. Soils are represented by shallow Cambisol, Pozdol, Lithosol, and Leptosol (the soil depth is about 0.7–1 m). Soil stoniness is high and varies from 10–65% or more. Forest (mostly spruce), dwarf pine and alpine meadows, including bare rocks on the steepest slopes, cover 44%, 31%, and 25% of catchment area, respectively. Most of the forest is over 100 years old. Mean annual precipitation is about 1500 mm and mean air temperature is 3°C. Additional catchment characteristics can be found e.g., in Holko and Kostka (2010); the detailed information about the catchment hydrological cycle over the three decades of its monitoring is presented in Holko et al. (2020a, b, this issue).

Simulation of water outflow from the mountain soils was carried out for three sites located at elevations above 1000 m a.s.l. Two of them are in the forest, one is in the open area covered by grass. The main attributes of the sites are:

Site 1: Červenec – open area, 1500 m a.s.l., a flat terrain with slope angle 2.86°, slightly to moderately stony soil classified as a Leptosol with a sandy loam texture is typical for the site. The site is covered by grass and low vegetation.

Site 2: Červenec – forest, 1450 m a.s.l., a moderately steep terrain with slope angle 14°.

Site 3: Pod Lyscom, 1040 m a.s.l., a steep terrain with slope angle 22°.

Moderate to high soil stoniness is typical for sites 2 and 3. The soil type is classified as Cambisol and has a sandy loam texture. A 130-year old Norway spruce forest (*Picea abies*) and a low understorey vegetation of *Vaccinium myrtillus* L. grow at the sites.

DATA

Rainfall, discharge and soil moisture data of the warm seasons (June to September) measured in years 2013–2016 were used in this study. Rainfall and soil moisture data were measured every 10 minutes at all three sites. Hourly discharge data measured at catchment outlet (820 m a.s.l.) were obtained from the 10-min interval pressure transducer water level measurements and the discharge rating curve.

Rainfall data provided the meteorological inputs for the simulation of the soil water outflow. Fifteen rainfall events separated according to rainfall intensity were used (Table 1).

The small intensity rains had maximum intensity below 2.5 mm/10 min. The large intensity rains had maximum intensity above 3.5 mm/10 min. This division was based on the

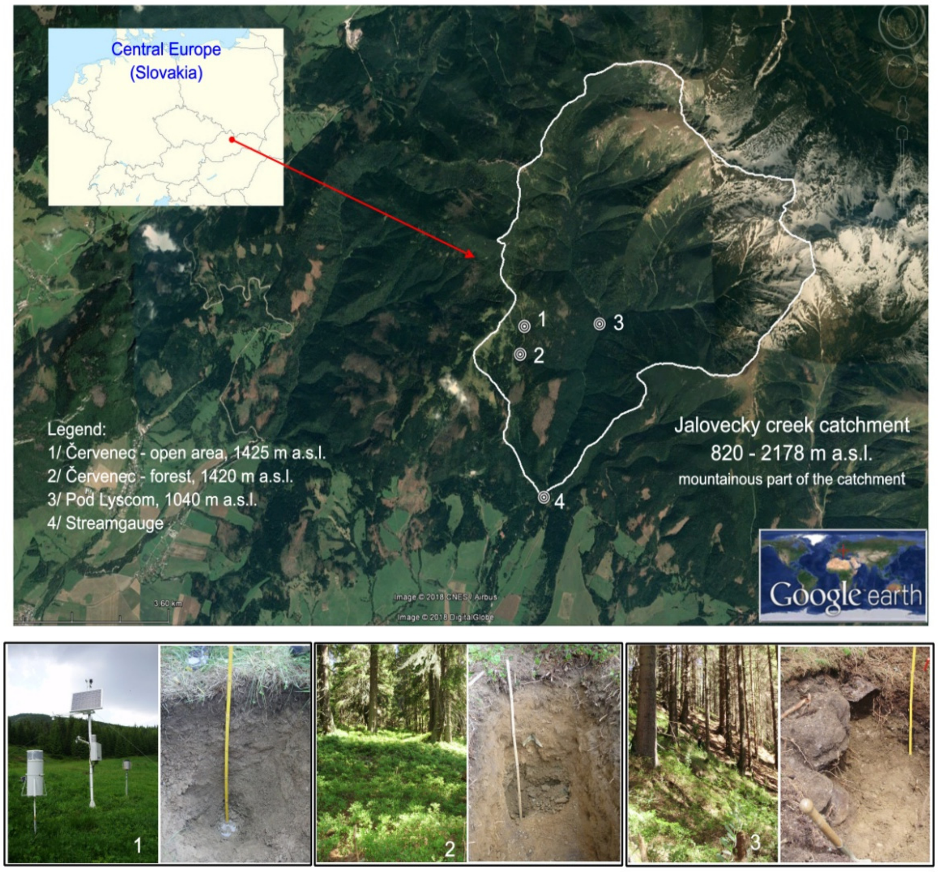


Fig. 1. The Jalovecký Creek catchment, location of the sites for which the soil water outflow was simulated (1, 2 and 3), vegetation and soil profiles at the sites; catchment outlet where catchment runoff was measured is indicated by number 4.

Table 1. Characteristics of the rainfall events and periods used for the lateral subsurface flow simulations at the three study sites; API is total precipitation over the last 10 days, A-I are events with small rainfall intensity, AI-FI are events with large rainfall intensity.

Rainfall event	Study site	Simulation period	Rainfall amount (mm)	10-min maximum (mm)	API (mm)
A	Červenec - open area	22.9.2013–16.10.2013	58.4	1.5	116
	Červenec - forest		72.8	1.4	75
	Pod Lyscom		39.8	1.4	120
B	Červenec - open area	24.6.2014–29.6.2014	19.4	1.6	13
	Červenec - forest		12.8	1.0	8
	Pod Lyscom		14.2	1.4	2
C	Červenec - open area	11.7.2014–14.7.2014	24.4	1.0	103
	Červenec - forest	11.7.2014–18.7.2014	18.4	0.8	66
	Pod Lyscom	11.7.2014–18.7.2014	22.6	1.2	75
D	Červenec - open area	25.9.2014–1.10.2014	38.2	1.5	44
	Červenec - forest		23.6	1.0	25
	Pod Lyscom		27.8	1.0	29
E	Červenec - open area	2.9.2013–9.9.2013	17.3	1.6	31
	Červenec - forest	2.9.2013–11.9.2013	25.4	1.4	14
	Pod Lyscom	2.9.2013–11.9.2013	23.2	1.4	14
F	Červenec - open area	23.8.2014–9.9.2014	39.2	1.7	50
	Červenec - forest		31.2	2.8	24
	Pod Lyscom		18.2	1.0	20
G	Červenec - open area	8.8.2016–14.8.2016	30.4	2.1	14
	Červenec - forest		20.0	1.6	30
	Pod Lyscom		27.2	1.6	40
H	Červenec - open area	5.8.2016–10.8.2016	13.1	1.7	62
	Pod Lyscom	5.8.2016–10.8.2016	12.6	1.6	56
I	Červenec - open area	20.8.2016–4.9.2016	21.2	2.5	25
	Pod Lyscom*	20.8.2016– 5.9.2016	24.6	5.6	22
AI	Červenec - open area	8.8.2013–28.8.2013	28.1	3.8	10
	Červenec - forest	9.8.2013–28.8.2013	15.6	3.8	7
	Pod Lyscom	9.8.2013–28.8.2013	11.6	3.4	6
BI	Červenec - open area	1.7.2014–8.7.2014	51.3	5.7	90
	Červenec - forest		39.6	3.6	55
	Pod Lyscom		36	3.4	62
CI	Červenec - open area	20.7.2014–28.7.2014	40.4	6.3	33
	Červenec - forest	20.7.2014–31.7.2014	38.8	6.0	22
	Pod Lyscom	20.7.2014–31.7.2014	28.0	2.2	27
DI	Červenec - open area	10.8.2014–13.8.2014	50.9	12.0	19
	Červenec - forest		31.4	11.2	17
	Pod Lyscom		35.0	9.4	16
EI	Červenec - open area	3.8.2015–14.8.2015	89.4	12.0	58
	Červenec - forest		71.6	21.2	46
	Pod Lyscom		82.6	19.3	35
FI	Červenec - open area	13.8.2016–21.8.2016	25.3	6.6	43
	Červenec - forest		17.4	4.8	30
	Pod Lyscom		22.2	6.0	40

Pod Lyscom * – event I at the site is classified as large intensity rainfall

unpublished results of the analysis of soil moisture response to rainfall on the study sites. Catchment runoff hydrographs during the rainfall events were used for the comparison of soil and catchment responses. The soil moisture measurements helped to obtain the hydraulic parameters of the soils (i.e. the saturated hydraulic conductivity and parameters of the soil water retention curves) used in the lateral subsurface flow simulation (by inverse modelling). Physical characteristics of the soils were measured in the soil pits of 1 m^2 cross section dug to depths 0.7–0.95 m at each site (Hlaváčiková et al., 2015).

METHODOLOGY

Lateral subsurface flow simulation

Lateral subsurface flow hydrographs were simulated by the well-known finite element model HYDRUS 2D (Šimůnek et al., 2008, 2013) as the outflow from the soil through gradient boundary. The 20 m long hillslope segment with 1 m soil profile depth (Fig. 2) and different slope angles corresponding to the slope angles at the three study sites (2.86°, 14°, and 22° for sites 1, 2, and 3, respectively) were schematized for the simulations. Soil layers in the model corresponded to the layers found in the soil pits. The following boundary conditions were used in the simulations (Fig. 2):

- the upper boundary (surface) was set as atmospheric boundary condition.
- the lower boundary (bottom) and upper vertical boundary (left hand side) were set as no flux conditions. No flux condition at the lower boundary was given because the hydraulic conductivity of the bedrock was much smaller than that of the above soil and water table was not present in the soil profile.
- the lower vertical boundary (right hand side) was set as gradient boundary condition.

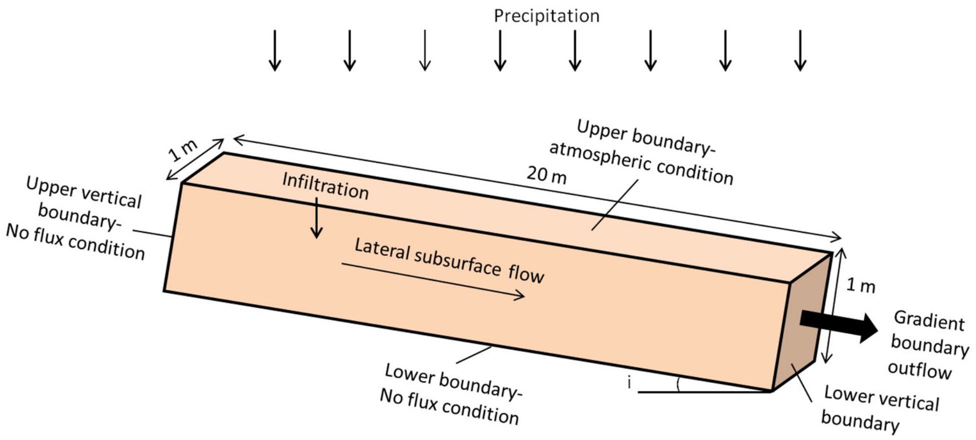


Fig. 2. Schematic sketch of the hillslope section used in simulation of the soil water outflow (lateral subsurface outflow). Boundary conditions are also presented. Gradient boundary outflow is the lateral subsurface outflow. *i* denotes the slope gradient which is 2.86° for site 1 (Červenec – open area), 14° for site 2 (Červenec – forest) and 22° for site 3 (Pod Lyscom), respectively.

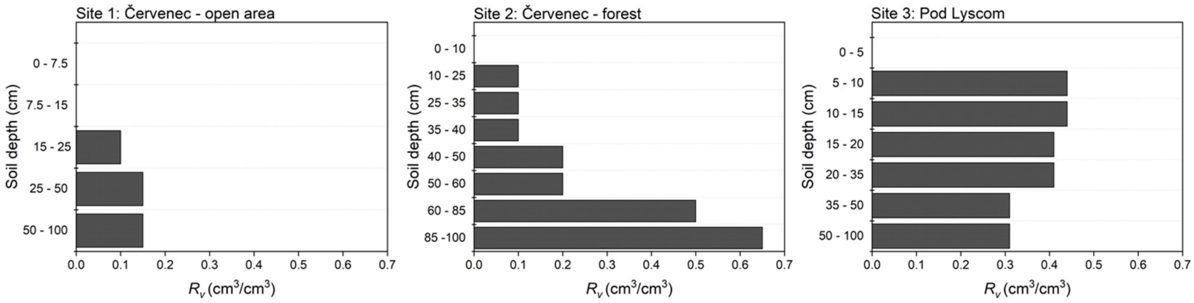


Fig. 3. Stoniness R_v (cm^3 cm^{-3}) in different soil layers on site 1, 2 and 3 measured in the representative elementary volume (REV) of about 1 m^3; modified from Hlaváčiková et al. (2015).

The computation time varied from 40 to 60 minutes for each simulated rainfall event. In total, 86 simulations of the soil water outflow were conducted.

The soil hydraulic parameters required by HYDRUS 2D (i.e. the saturated hydraulic conductivity K_s and parameters of the soil water retention curve θ_s, θ_r, α, n) were obtained by two approaches – the representative elementary volume (REV) and inverse modelling (IM) as described below. The two approaches were used to obtain the hydraulic parameters for the soil depth 0–50 cm. Hydraulic parameters the soil depth 50–100 cm were obtained only from the REV approach.

The REV approach was based on field measurements in soil pits of 1 m^2 cross section dug to depths 0.7–0.95 m at each site (Hlaváčiková et al., 2015). Volumes of stones and boulders were measured directly in the field. Soil stoniness estimated for the soil pits of the REV dimensions is shown in Fig. 3. Additionaly, the disturbed soil samples with volume of 2–3 litres were collected for each characteristic soil layer for the laboratory evaluation of the fine soil fraction and the volume of the gravel part of the stoniness.

Undisturbed and disturbed samples of fine soil with volume 100 cm^3 were collected for each characteristic soil layer at each site to determine the saturated hydraulic conductivity and water retention measurements. The saturated hydraulic conductivity of the fine soil was estimated in the laboratory by the variable hydraulic head method. A small number of field measurements of the saturated hydraulic conductivity was carried out with the single ring infiltrometer as well (Hlaváčiková et al. (2015, 2018)). Drying branches of the soil water retention curves (SWRC) of the fine soil were measured by the pressure plate extractor (Dane and Hopmans, 2002) for pressure heads between –50 and –3000 cm. Drying branches of the soil water retention curves of top soil layer (organic horizon) were measured by the sand tank for pressure heads between –2 and –100 cm, smaller pressure heads were measured by the pressure plate extractor. Measured soil water retention curves were fitted by the analytical model of van Genuchten (1980) and their parameters θ_s (the saturated water content) and θ_r (the residual water content) were corrected for the stoniness using the Bouwer and Rice (1984) equation. The stoniness-corrected soil water retentions curves and measured saturated hydraulic conductivity (an average of the laboratory and field measurements) obtained for different soil layers at all three study sites provided the soil hydophysical parameters needed in the lateral subsurface flow modelling. Stoniness used in the REV approach for the soil water retention correction was determined from the soil pits stoniness measurements shown in Fig. 3.

The IM approach for determination of soil hydraulic parameters was based on the single porosity HYDRUS 1D modelling calibrated against measured soil moisture using the optimization technique available in the Hydrus 1D package. Model parameters were set according to fine soil water retention and the stoniness measurements. Time series of measured soil water contents at three depths (5, 10, 20 cm) at site 1 and two depths (10, 40 cm) at sites 2 and 3 were used in the inverse modelling. Simulated soil profile of all three sites had depth of 50 cm. Soil hydrophysical parameters were determined by the IMa only for the soil depths 0–50 cm because the soil moisture data were not measured at greater depths due to large soil stoniness.

The initial soil conditions for water flow modelling were set for each rainfall event separately according to antecedent soil wetness represented by pressure heads. For this purpose, the soil water potential was estimated from the known soil water retention curves and by taking in account the antecedent precipitation (API). The API was calculated as the sum of 10-day rainfall before the rainfall event. Initial conditions set in the form of pressure heads were chosen because the pressure head can better describe the status of water at the beginning of the simulation. The inverse modelling was done as in Wegehenkel et al. (2017). First, the parameters n and θ_s were calibrated, then K_s and θ_r were obtained, and finally parameter α was calibrated.

Table 2. Soil hydraulic parameters estimated by the REV approach at various soil depths on the three study sites; θ_s is the saturated water content, θ_r is residual water content, α and n are the van Genuchten´s parameters, K_s is the saturated hydraulic conductivity and R_v is the relative volume of rock fragments.

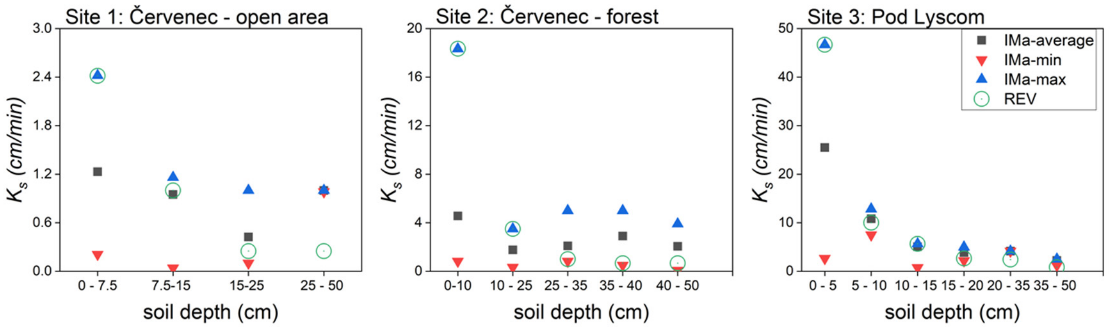
Soil depth	θ_r (cm^3 cm^{-3})	θ_s (cm^3 cm^{-3})	α (cm^{-1})	n (–)	K_s (cm min^{-1})	R_v (cm^3 cm^{-3})□
Site 1: Červenec - open area						
0–7.5 cm	0.1	0.63	0.10	1.27	2.42	0.00
7.5–15 cm	0.05	0.51	0.43	1.13	1.00	0.00
15–25 cm	0.05	0.45	0.43	1.13	0.25	0.10
25–50 cm	0.04	0.43	0.41	1.11	0.25	0.15
50–100 cm	0.04	0.41	0.40	1.10	0.25	0.15
Site 2: Červenec - forest						
0–10 cm	0.05	0.64	0.48	1.22	18.33	0.00
10–25 cm	0.05	0.58	0.05	1.24	3.50	0.10
25–35 cm	0.05	0.57	0.07	1.25	1.00	0.10
35–40 cm	0.05	0.57	0.07	1.25	0.67	0.10
40–50 cm	0.04	0.50	0.07	1.25	0.67	0.20
50–60 cm	0.04	0.50	0.07	1.25	0.67	0.20
60–85 cm	0.03	0.31	0.07	1.25	0.33	0.50
85–100 cm	0.02	0.22	0.07	1.25	0.33	0.65
Site 3: Pod Lyscom						
0–5 cm	0.05	0.63	0.56	1.21	46.67	0.00
5–10 cm	0.03	0.36	0.42	1.24	10.00	0.44
10–15 cm	0.03	0.41	0.13	1.27	5.67	0.44
15–20 cm	0.03	0.49	0.12	1.22	2.67	0.41
20–35 cm	0.03	0.49	0.12	1.22	2.42	0.41
35–50 cm	0.03	0.52	0.06	1.25	0.83	0.31
50–100 cm	0.03	0.52	0.06	1.25	0.33	0.31

Table 3. The Mean values of soil hydraulic parameters estimated by the IM approach; the mean values were calculated from the results of simulations for all 15 rainfall events; θ_s is the saturated water content, θ_r is the residual water content, α and n are the van Genuchten´s parameters, K_s is the saturated hydraulic conductivity and R_v is the relative volume of rock fragments.

Soil depth	θ_r (cm^3 cm^{-3})	θ_s (cm^3 cm^{-3})	α (cm^{-1})	n (–)	K_s (cm min^{-1})	R_v (cm^3 cm^{-3})□
Site 1: Červenec - open area						
0–7.5 cm	0.10	0.59	0.11	1.25	1.61	–
7.5–15 cm	0.11	0.54	0.41	1.12	0.90	–
15–25 cm	0.02	0.42	0.46	1.14	0.42	0.10
25–50 cm	0.05	0.47	0.42	1.10	1.00	0.15
*50–100 cm	0.04	0.41	0.4	1.1	0.25	0.15
Site 2: Červenec - forest						
0–10 cm	0.12	0.61	0.42	1.26	11.37	–
10–25 cm	0.07	0.54	0.05	1.24	1.99	0.10
25–35 cm	0.14	0.57	0.06	1.25	2.15	0.10
35–40 cm	0.14	0.67	0.06	1.24	2.59	0.10
40–50 cm	0.08	0.61	0.07	1.22	1.97	0.20
*50–60 cm	0.04	0.50	0.07	1.25	0.67	0.20
*60–85 cm	0.03	0.31	0.07	1.25	0.33	0.50
*85–100 cm	0.02	0.22	0.07	1.25	0.33	0.65
Site 3: Pod Lyscom						
0–5 cm	0.12	0.68	0.31	1.23	22.22	–
5–10 cm	0.11	0.68	0.41	1.23	11.41	–
10–15 cm	0.05	0.61	0.12	1.26	5.33	0.20
15–20 cm	0.12	0.54	0.10	1.22	3.76	0.20
20–35 cm	0.09	0.83	0.10	1.21	4.01	0.20
35–50 cm	0.09	0.70	0.06	1.20	2.21	0.20
*50–100 cm	0.03	0.52	0.06	1.25	0.33	0.31

*Parameters for the soil depth of 50–100 cm were the same for the REV and the IM approaches and were derived by the REV approach.

a) Small intensity rainfalls



b) Large intensity rainfalls

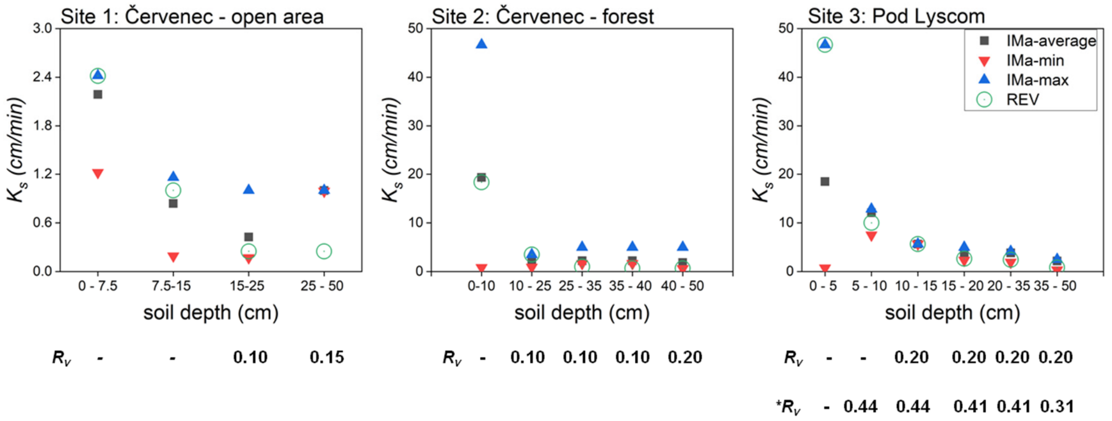
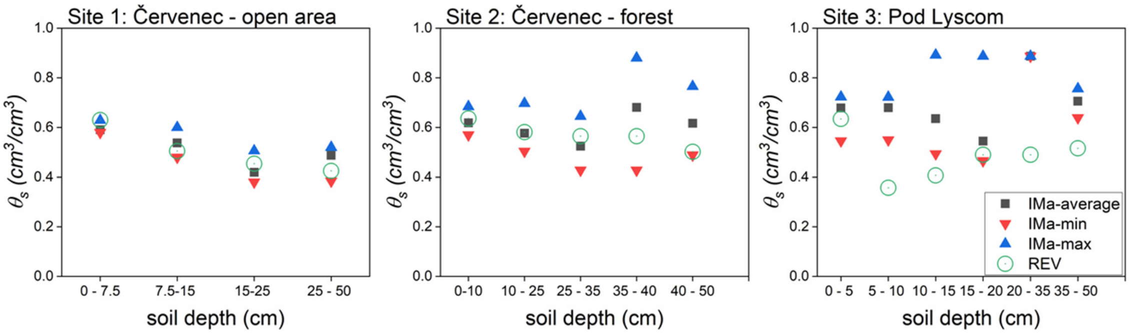


Fig. 4. Saturated hydraulic conductivity K_s estimated by the REV and IM approaches at various soil depths with different stoniness R_v; minimum and maximum K_s values estimated by the IMa are also presented; the asterisk denotes different stoniness at site 3 for REVa.

a) Small intensity rainfalls



b) Large intensity rainfalls

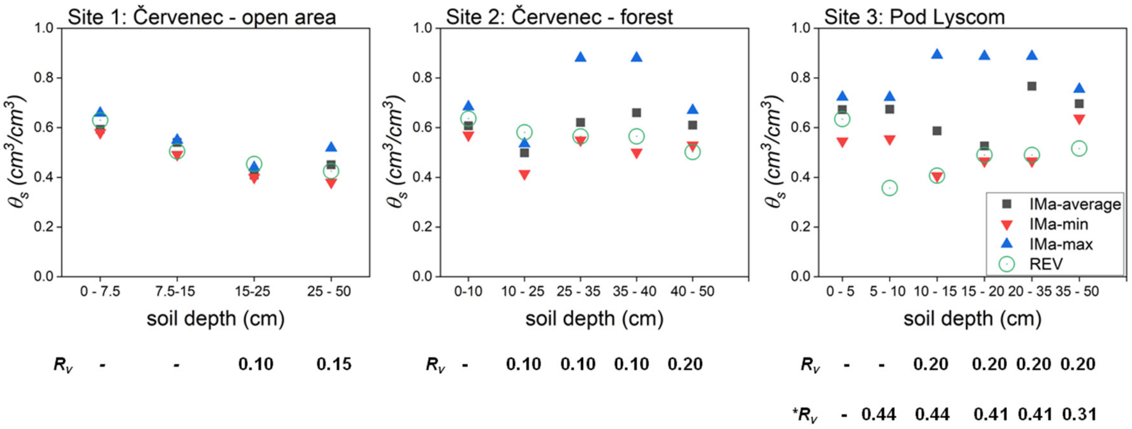


Fig. 5. Saturated moisture content θ_s estimated by the REV and IM approaches at various soil depths with different stoniness R_v of site 1, 2 and 3; minimum and maximum θ_s values estimated by the IMa are also presented; the asterisk denotes different stoniness at site 3 for REV.

Hydrographs comparison

The subsurface lateral flow hydrographs simulated by HYDRUS 2D (with soil hydrophysical parameters from both REVa and IMa) were compared to measured catchment runoff hydrographs. The comparison was based on hydrograph geometry (skewness) and peak times. Skewness as an important characteristic of hydrograph geometry was quantified by the volume before peak (VBP) values (Collischonn et al., 2017). The VBP is the ratio of the flow volume before the peak to total flow volume during an event. Its value ranges between 0 and 1. If VBP is equal to 0.5, the hydrograph is symmetrical. VBP smaller than 0.5 characterizes the positively skewed hydrographs while the negatively skewed hydrograph has the VBP greater than 0.5. Flow volume before the peak was calculated from the discharge data between the rainfall beginning and the hydrograph peak. Total flow volume was calculated from the initiation time of the rainfall until the time when discharge dropped to the value measured before the rainfall. The peak time difference between catchment runoff and lateral subsurface flow hydrographs for every rainfall event at each site was analysed as well. The VBP and peak time difference were used to quantify the geometric similarities of subsurface and catchment runoff hydrographs.

RESULTS

Influence of stoniness on soil hydraulic parameters estimated by the REV and inverse modelling approaches

Soil hydraulic parameters estimated by REVa and IMa which were thereafter used in the soil water outflow simulation are given in Tables 2 and 3. Two out of five parameters, namely the saturated hydraulic conductivity (K_s) and the volumetric saturated soil moisture content (θ_s) were found to be the most sensitive in inverse modelling. Figs. 4 and 5 show the K_s and θ_s values estimated by REVa and IMa at all three sites for different soil depths.

The top soil layers (organic horizons) at all three sites (0–15 cm at Site 1, 0–10 cm at Site 2 and 0–5 cm at Site 3) contained no stones. The highest K_s values were obtained for these layers by both REVa and IMa. The K_s values obtained by both IMa and REVa decreased in the presence of rock fragments at each site for both small and large intensity rainfalls. The largest K_s value difference obtained by inverse modelling for small and large intensity rainfalls was found in the soil depth of 0–7.5 cm at site 1 and 0–10 cm at site 2. Two and four times greater K_s values were obtained for large intensity rainfall at both sites and showed faster water dynamics during large intensity rainfalls. Apart from that, the K_s values obtained by IMa for large rainfalls were 0.7–1.3 times than those for small rainfalls for the remaining corresponding soil layers at all sites.

Soil retention capacity decreased with the increase of stoniness for the REVa at all three sites (Fig. 5). Compared to the top soil, 32%, 15% and 40% reduction in θ_s was observed, on average, at sites 1, 2 and 3, respectively. For the IMa, the retention capacity on site 1 was the highest in the top soil (zero stoniness) for small and large rainfalls. For both small and large rainfalls, the θ_s value was the highest at lower soil layers on site 2 (35–40 cm depth, $R_v = 0.1$) and site 3 (20–35 cm depth, $R_v = 0.2$). The greatest differences in the retention capacity of soils profiles between the REV and IM approaches were found on site 3. These differences correspond to different stoniness related to the particular approach.

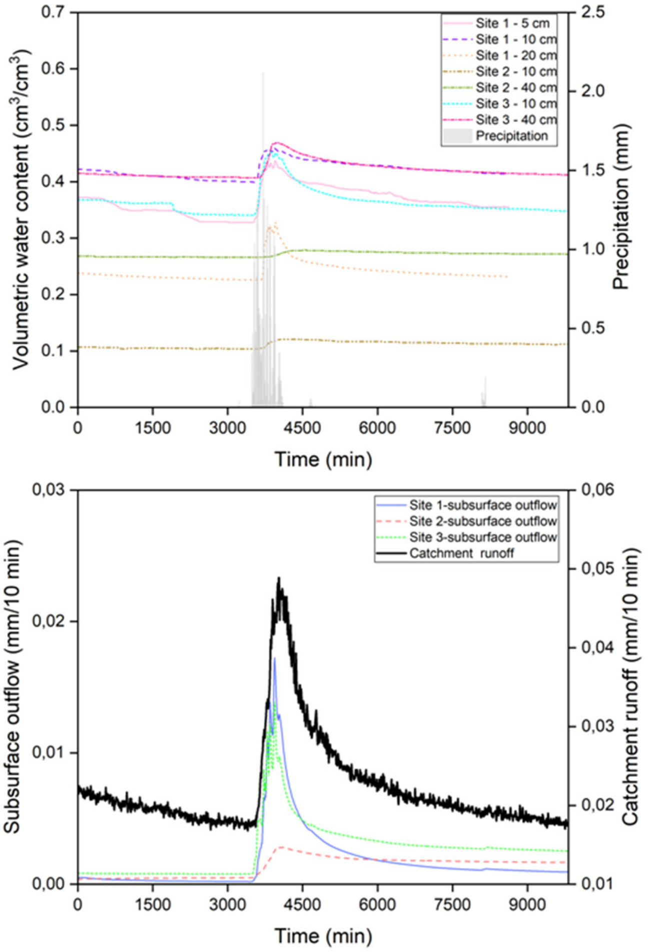


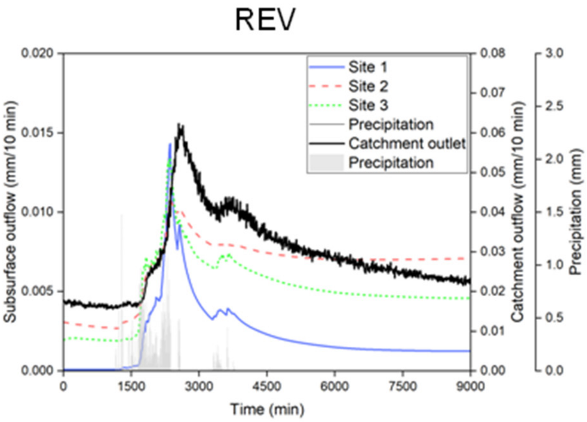
Fig. 6. Comparison of simulated lateral subsurface flow based on the REVa (the bottom panel) and catchment runoff for the small intensity rainfall event G; the soil moisture and rainfall measurements are presented in the top panel.

Comparison of the lateral subsurface flow and catchment runoff hydrographs

Soil moisture of the top soil layer at all three sites significantly increased at the initiation of rainfall and started to decrease slowly when the rain finished (Fig. 6). Patterns of the lateral subsurface flow and catchment runoff hydrographs were similar. An example of the lateral subsurface flow and catchment runoff responses for the small and high intensity rainfalls is shown in Fig. 7. The most pronounced lateral subsurface flow response was simulated for site 1 which is located in the open area. The response at forested sites 2 and 3 was also dynamic, but only for the soil hydraulic parameters estimated by the REV approach. Hydraulic parameters obtained from IMa typically resulted in smaller dynamics of the simulated lateral subsurface flow response on sites 2 and 3.

The VBP (volume before peak) values are given in Table 4. The VBP values for catchment runoff hydrographs varied from 0.11 to 0.4, suggesting positively skewed hydrographs. Among the lateral subsurface flow hydrographs estimated by both REVa and IMa, there were in total 10 hydrographs that were negatively skewed (VBP > 0.5). Table 4 shows that similar skewness of lateral subsurface flow hydrographs and catchment runoff hydrographs was obtained for approximately one half of rainfall events (8 out of 15). The similarity was most often

a) Small intensity rainfall event D



b) Large intensity rainfall event FI

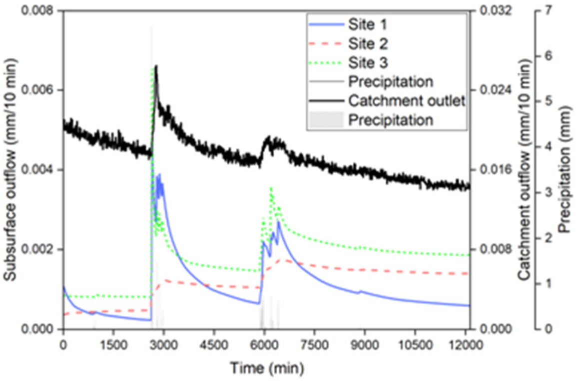


Fig. 7. Catchment runoff and simulated lateral subsurface flow hydrographs estimated by the REVa and the IMa for a small and large intensity rainfalls.

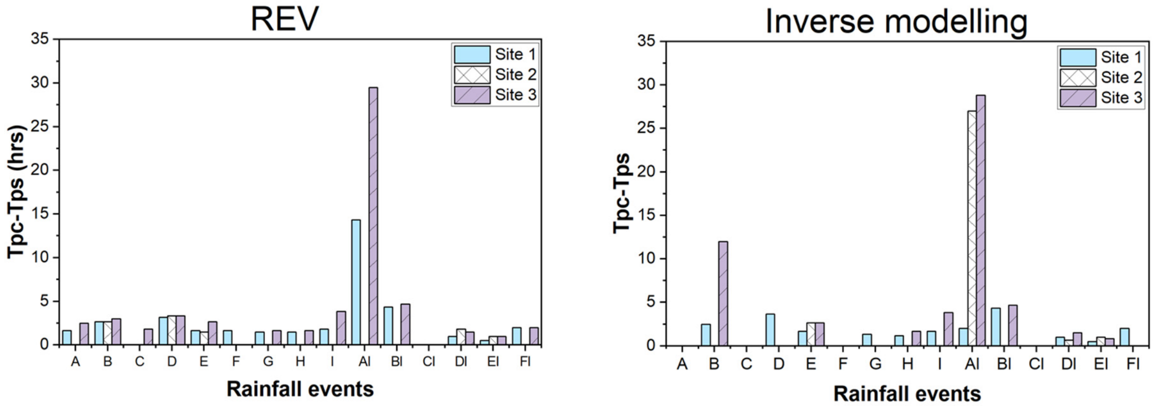


Fig. 8. Peak time difference (in hours) between the lateral subsurface flow (Tps) and catchment runoff (Tpc) hydrographs.

obtained for the small intensity rains and site 3 (and parameters obtained from the IMa) which has the shortest distance to the Jalovecký Creek. The connectivity of that particular site with stream network probably does not develop, but the entire hillslope may be connected to the narrow riparian area existing in that part of the catchment.

The negatively skewed hydrographs were excluded from the peak times comparison. Fig. 8 shows that more realistic results were obtained for simulations with soil hydraulic parameters estimated by the REVa and the time delay between peaks in the lateral subsurface flow and catchment runoff were mostly about 2–3 hours. Three events with the highest rainfall intensities and comparatively higher wetness before the rain (DI, EI, FI) had shorter time delays (about 1–2 hours).

DISCUSSION

Previous studies in the Jalovecký Creek catchment which is representative for the hydrological cycle of the highest part of the Carpathian Mountains, documented the dominant role of the pre-event water, fast runoff response to rainfall and pointed at the importance of the stony soils in catchment runoff generation (e.g., Hlaváčiková et al., 2015, 2018, 2019; Holko and Lepistő, 1997; Holko et al. 2011, 2018; Kostka, 2009).This work indicated that simulation of the lateral subsurface flow in different parts of the catchment and comparison of simulated lateral subsurface flow hydrographs with catchment runoff hydrograph could improve the understanding of the contribution of different parts of the catchment to runoff formation. Comparison of

Table 4. Volume before peak (VBP) values for catchment runoff hydrographs and simulated lateral subsurface flow hydrographs; the bold numbers show the negatively skewed hydrographs (VBP > 0.5), the yellow-marked numbers indicate the lateral subsurface flow hydrographs with skewness most similar to that of catchment runoff hydrograph; A-I are events with small intensity rainfalls, AI-FI are the large intensity rainfalls.

Rainfall event	VBP values for lateral subsurface hydrographs						Catchment's outlet runoff hydrographs VBP values
	Inverse modelling approach			REV approach			
	Site 1	Site 2	Site 3	Site 1	Site 2	Site 3	
A	**1.00**	0.35	0.15	0.02	0.34	0.05	0.11
B	0.13	0.26	0.14	0.10	0.23	0.26	0.40
C	0.39	**1.00**	0.15	0.38	0.15	0.10	0.15
D	0.38	**0.99**	0.18	0.18	0.16	0.18	0.21
E	0.08	0.06	0.08	0.06	0.05	0.08	0.16
F	**0.99**	**0.98**	**0.94**	0.04	0.16	0.18	0.11
G	0.22	0.31	0.34	0.21	0.19	0.21	0.38
H	0.17	–	0.23	0.17	–	0.19	0.37
I	0.05	–	0.04	0.08	–	0.04	0.41
Al	0.05	0.03	0.05	0.01	**0.85**	0.04	0.12
Bl	0.12	**0.98**	0.25	0.11	**1.00**	0.14	0.24
Cl	0.18	**0.99**	0.07	0.12	0.06	0.08	0.11
Dl	0.05	0.18	0.18	0.05	0.11	0.12	0.26
El	0.04	0.02	0.02	0.09	0.01	0.06	0.16
Fl	0.10	0.5	0.49	0.09	0.11	0.11	0.25

Site 1 = Červenec - open area; Site 2 = Červenec - forest; Site 3 = Pod Lyscom.

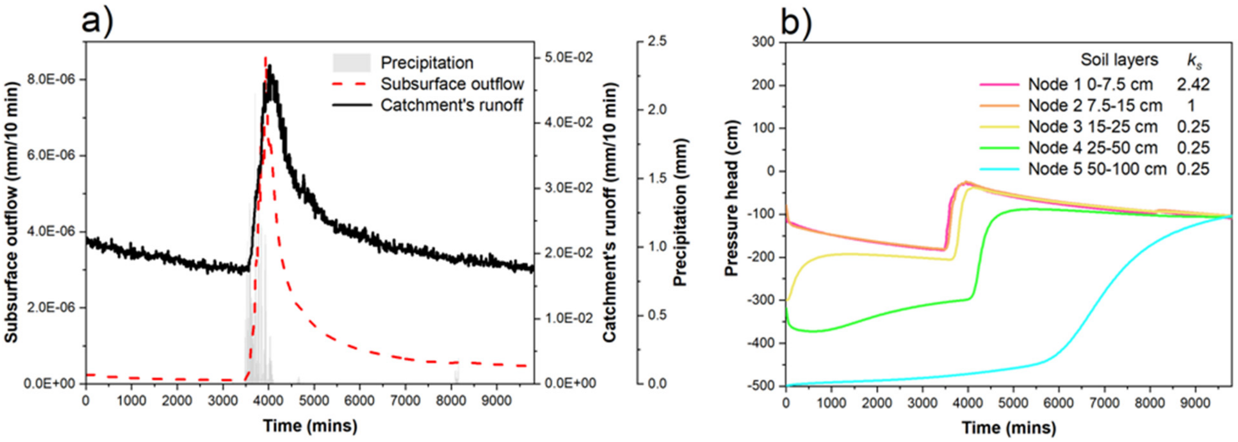


Fig. 9. a) Rainfall, catchment runoff and lateral subsurface flow hydrographs with positive skewness caused by the rainfall event G on site 1; b) temporal evolution of pressure head at the gradient boundary observation nodes at different soil depths estimated by the REVa for the same event and site; K_s is the saturated hydraulic conductivity in cm/min.

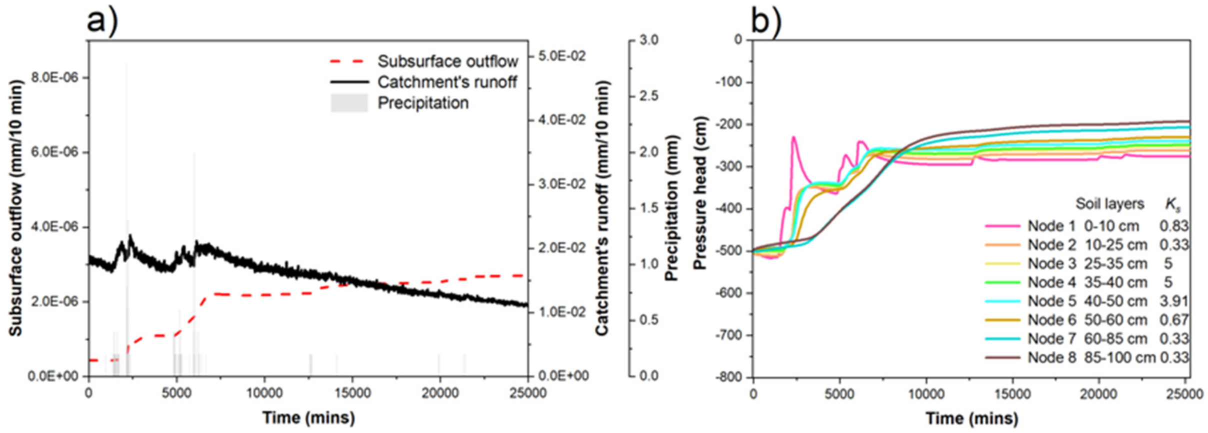


Fig.10. a) Rainfall, catchment runoff hydrograph and soil water outflow hydrograph with negative skewness caused by the rainfall event F on site 2; b) temporal evolution of pressure head with time at the gradient boundary observation nodes at different soil depths estimated by inverse modelling for the same event and site; K_s is saturated hydraulic conductivity in cm/min.

hydrographs shapes based on skewness and peak times was useful to identify the similarity. Additional criteria of hydrograph similarity can be tested when more rainfall events data is available. One of the ultimate aims of such a comparison would be the identification of typical hydrograph shapes related to certain field conditions. An example of the usefulness of such a work was recently given by Brunner et al. (2018) who used flood hydrograph shapes classification to delineate regions of similar flood behavior in Switzerland.

Simulated soil water outflow depends on many factors, e.g. the initial wetness, soil hydraulic properties, rainfall intensity, hillslope inclination, etc. All these factors determine the shape of the lateral subsurface flow hydrographs. Our simulations showed that K_s value of the soil layers played the key role in influencing the hydrograph geometry at different initial soil conditions and rainfall intensities. An example is presented in Figs 9 and 10.

Fig. 9a shows the positively skewed catchment runoff (measured) and lateral subsurface flow (Hydrus 2D simulated) hydrographs that have similar shapes. Temporal evolution of the simulated pressure head at various soil depths is shown in Fig. 9b. The top soil on site 1 had high K_s values and its pressure head hydrograph followed the rainfall pulse pattern. The upper soil layers (0–15 cm) were the dominant contributors to simulated soil water outflow and the obtained hydrograph was positively skewed.

Fig. 10a shows the negatively skewed lateral subsurface flow hydrograph. The lower soil layers on the study site (25–100 cm) had eight times greater K_s value than the top soil layers (0–15 cm) (Fig. 10b). Consequently, the rainfall fed by the top soil layers to lower soil layers resulted in greater outflow from the lower soil layers compared to the top soil layers. The lowest soil profile zone (depth 50–100 cm) was continuously fed by the upper soil layers that significantly increased its water storage. Since, there was no flux condition at the lower soil segment boundary in our numerical simulation (see Fig. 2), the lateral outflow occurred only from the 50–100 cm soil depth layer. The outflow was increasing continuously until the end of the simulation. That resulted in the negative skewness of the simulated soil water outflow hydrograph.

Presence of the rock fragments decreases retention capacity of soil by reducing the soil volume. In case of REVa, it was observed that soil layers with the highest stoniness had the lowest retention capacity at each site. However, it was not like that for the IMa (see Fig. 5).

The IMa optimizes soil hydraulic parameters by simulating moisture content according to observed moisture content. These observed soil moisture data are measured by sensors installed at various soil depths. Soil moisture sensors measure the water content at specific region, without taking in account the entire soil profile, i.e., their sampling area is small. The rock fragments affect the hydraulic characteristics of moderately to highly stony soils by reducing the available soil volume for water flow that increases water dynamics (e.g., Hlaváčiková et al., 2015, 2018). The IMa takes the rock fragments into account, but only in a small area of the sampling volume. On the contrary, the REVa represents the bulk characteristics of the soil profile and changes the soil water retention curves in the soil layers according to variation of stoniness in these layers. The REVa also takes into account field and laboratory measurements of hydraulic conductivity of stony soils that make it more suitable than the IMa.

We assumed constant parameters for each layer over the entire 20 m long section of the hillslope. Future studies are needed to evaluate the performance of REVa for the soil layers which do not have constant soil hydraulic parameters.

CONCLUSIONS

Outflow from stony the soils can contribute to rapid increase of catchment discharge due to small retention of such soils. Comparison of simulated lateral subsurface flow hydrographs with catchment runoff hydrographs indicated that the shapes of both were similar for about one half of the examined rainfall events.

Soil hydraulic parameters obtained from the Representative Elementary Volume approach provided more realistic simulated soil outflow hydrographs than the parameters obtained from the Inverse Modelling approach. The IMa more often resulted in the negatively skewed hydrographs and peaks that occurred after the catchment runoff peaks.

Modelling of water flow in stony soils is rare and we are not aware of studies analyzing subsurface flow and catchment runoff relationships that would consider the stony soils. Future studies could examine the REVa capabilities under different initial soil conditions, soil characteristics, stoniness, rainfall intensities and slope angles.

Limiting factor in a more thorough exploration of the central idea that reduced retention of stony soils can have similar effect on catchment runoff formation as the commonly accepted and more often studied preferential flow, is related to availability of data. While networks of rain gauges supplemented by soil moisture measurements at several depths covering different landscape units of the catchment (e.g., hillslopes, riparian areas) can be established more easily, more effort is needed to obtain good field and laboratory data characterizing soil stoniness and its variability.

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