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Simulation of the influence of rainfall redistribution in spruce and beech forest on the leaching of Al and SO_4^{2-} from forest soils

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Abstract: The aim of this study was to assess the impact of different vegetation on the distribution of rainfall (due to throughfall and stemflow), water regime, and Al and SO_4^{2-} leaching from forest soils. The water flow and Al and SO_4^{2-} transport were modeled using HYDRUS-1D. The study was performed at two elevation transects on the Paličník and Smědava Mountain in Jizera mountains. Podzols and Cambisols were prevailing soil units in this area. It was shown that the effect of the precipitation redistribution on water regime was considerable in the beech forest, while it was almost negligible in the spruce forest. Redistribution of precipitation under trees caused runoff (in one case), increased water discharge through the soil profile bottom, reduction of water storage in the soil, and thus reduction of root water uptake. Simulated Al leaching from the soil profile was determined mainly by the initial Al content in the soil profile bottom. Leaching of SO_4^{2-} was mainly determined by its initial content in the soil and to a lesser extent by redistributed precipitation and SO_4^{2-} deposition.

Keywords: Throughfall; Stemflow; Wet deposition; Soil water regime; Solute transport.

INTRODUCTION

The rainfall intensity and its distribution on the soil surface influence the soil water regime, and consequently, dissolution and migration of various substances in the soil. In forests, rainfall is intercepted by the canopy and partitioned into throughfall and stemflow. Distribution of precipitation depends on the tree species and the age of the trees (Ford and Deans, 1978; Kantor, 1985; Johnson, 1990; Loustau et al., 1992; Levia and Frost, 2003; Van Stan et al., 2011). Stemflow generated between condominant tree species may be highly affected by wind (Van Stan et al., 2011) and the spatial variability of throughfall was also documented (Bouten et al., 1992; Keim et al., 2005; Holko, 2010, 2011). Concentrations of dissolved substances in throughfall and stemflow may be considerably different (Kantor, 1985; Raubuch et al., 1998; Oulehle and Hruška, 2005; Devlaeminck et al., 2005; Levia, D.F., 2011). It was shown that the spatially distributed infiltration under the forest canopy caused a significantly variable water regime (Bouten et al., 1992; Raat et al., 2002; Liang et al., 2007, 2009; Guswa and Spence, 2012; Guswa et al., 2012) and soil solution chemistry (Chang and Matzner, 2000). Stemflow has been considered as a spatially localized input of water into the soil causing preferential flow, which allowed rapid transport of contaminants to greater depths and then into the groundwater (Taniguchi et al., 1996).

Water flow and solute transport in soil can be simulated by many numerical models (Köhne et al., 2009). One of them is the program HYDRUS-1D or HYDRUS 2D/3D (Šimůnek et al., 2008). The HYDRUS-3D was used to simulate spatially distributed drainage fluxes accounting for throughfall and stemflow under banana plants (Sansoulet et al., 2008). The HYDRUS-1D and HYDRUS-2D programs were also used to simulate the soil water regime under a beech tree, where considerably different (due to stemflow and throughfall) infiltration fluxes were found (Nikodem et al., 2010).

The program HYDRUS-1D can simulate either a general solute transport (as 2D/3D) or transport of selected ions (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Cl^{-}, SO_4^{2-}) in soils. In addition, the program HYDRUS-1D was coupled with the geochemical model PHREEQC to create a new simulation tool HP1 (Jacques and Simunek, 2005). Program HYDRUS-1D was recently used for modelling toxic-metals transport: Cd transport (Moradi et al., 2005), Cu mobility (Bahaminyakamwe et al., 2006), Zn, Cu and Pb transport (Ngoc et al., 2009) and modelling of Al transport in forest soil (Nikodem et al., 2010). The HP1 model was used to predict leaching of toxic elements and the transport of the explosive trinitrotoluene and its degradation products (Šimůnek et al., 2006), and Cd transport (Jacques et al., 2008). Program HYDRUS-2D was used to simulate Al transport (Nikodem et al., 2010) and Cd, Cu, Pb and Zn transport and their root uptake (Trakal et al., 2012).

The main aim of this study was to extend the studies performed by Nikodem et al. (2010), which were focused on the simulation of Al transport in Podzol (one soil profile) in a beech forest using the HYDRUS-1D and HYDRUS-2D programs. In this study, spatially distributed precipitation and Al deposition below the tree canopy were assumed. The aim of the present study was to assess the impact of different vegetation cover (grass, spruce and beech) on the precipitation and Al and SO_4^{2-} distribution at the soil surface, and following impact on simulated (using HYDRUS-1D) water regime and Al and SO_4^{2-} leaching from forest soils (Podzols and Cambisols).

MATERIALS AND METHODS

Study site

The study was performed in the Jizera Mts. in the Czech Republic. The Jizera Mts. region is located in the North of Bohemia. The average annual temperature of this area ranges from 3 to 6°C depending on the altitude. The annual rainfall is 1500 mm. The core of the Jizera Mts. is a plutonic area with uniform granite bedrock. Soils were developed from medium-grained porphyric granite to granodiorite of the Upper Carboniferous age (Cháb et al., 2007). Natural soil acidification in this area was accelerated by an anthropogenic acidification. Natural stable forest ecosystems (consisting mostly of beech trees [*Fagus sylvatica* (L.)]) were altered in this region by human impact into a spruce [*Picea abies* (L.)] monoculture (which increased soil acidity). High concentrations of acidificants in the atmosphere (originating mainly from thermal power stations in the Czech Republic, Germany, and Poland, also called the Big Black Triangle) that occurred 30 yr ago damaged the soil and forests and led to the deforestation of the mountain summits (Sucharova and Suchara, 1998). This area was quickly invaded by grass [*Calamagrostis* villosa (Chaix) J.F. Gmel., *Deschampsia flexuosa* (L.) Trin.] as a natural mechanism of ecosystem restoration.

The Jizera Mts. is a region, where the long-term hydrological regime within the experimental catchments has been monitored by Czech Hydrometeorological Institute (Kulasová et al., 2005, CHMI, 1997). Detailed studies of water regime at selected locations were presented by Hrnčíř et al. (2010), Vogel et al. (2010), Šanda et al. (2009), Šanda and Císlerová (2009), Remrová and Císlerová (2010) and Pavelková et al. (2012).

The complex soil studies of the Jizera Mountains region were presented by Mládková et al. (2005), Borůvka et al. (2005), Drábek et al. (2007), Tejnecký et al. (2010) and Nikodem et al. (2013). Prevailing soil types were identified as Cambisols and Podzols. Both soil groups are supposed to have a high Al content, especially in free or labile forms, which may produce toxic effects. This paper deals with two elevation transects in the northern part of this region. New sampling sites were selected within the elevation transect on Smědava Mountain (1,084 m a.s.l.) and Palicnik (944 m a.s.l.). These transects were studied earlier in detail by Pavlů et al. (2007) (10 soil profiles at each transect), and later on, by Borůvka et al. (2009) (5 soil profiles at each transect). However, they measured only some physical and chemical properties of all diagnostic horizons of all soil profiles: pH; effective cation exchange capacity; content of cations in the sorption complex; A400/A600 as humus quality parameter; content of available Ca, Mg, K, P; pseudototal content of Ca and Mg; amount of crystalline forms of Al and Fe, content of two differently extracted Al forms and speciation of potentially dangerous Al forms.

The first transect, Smedava, represents an altitude range from 719 to 1067 m a.s.l. with northern orientation (Table 1). Soil samples were collected from three soil profiles (of 5 soil profiles studied by Borůvka et al., 2009) along this transect. Forest cover changes with decreasing altitude, from an area where spruce forest died in 1980s and early 1990s due to strong acid deposition and was replaced with young (now approximately 10 years old) free-growing spruce and with high grass abundance (mainly *Calamagrostis villosa* (Chaix) J.F. Gmel.) (Smedava 1), to old beech forest at lower altitudes (Smedava 4 and 5). Podzols (Haplic, Gleyic, or Entic) were the prevailing soil types, but in the middle and steepest part of the transect, a Colluvic Regosol was identified (which was not sampled for this study). The second transect, Palicnik, represents an altitude range from 596 to 930 m a.s.l. with south-western orientation. Soil samples were collected from four soil profiles along the transect (Table 1). Three soil profiles were placed in old beech forest (Palicnik 1, 2 and 5); one was dug under spruce forest (Palicnik 4). The soils were classified as Dystric Cambisol at two sites, as Entic Podzol at one site, and as Haplic Podzol at the most elevated site. Grab soil samples were taken from all soil horizons to measure basic soil properties (Borůvka et al., 2009) and to evaluate adsorption isotherms for Al and SO_4^{2-}. Undisturbed 100-cm^3 soil samples were taken from soil horizons, which were thick enough to insure soil material homogeneity (e.g. no impact of neighboring layers).

Table 1. Description of soil sampling sites at the Smedava and Palicnik transects.

Site name	Altitude [m a.s.l.]	Aspect	Soil unit	Forest type	Tree age [years]
Smedava transect					
Smedava 1	1067	N	Gleyic Podzol	grass/spruce	10
Smedava 4	818	N	Haplic Podzol	beech	100+
Smedava 5	719	N	Entic Podzol	beech	100+
Palicnik transect					
Palicnik 1	930	SW	Haplic Podzol	beech	170
Palicnik 2	852	SW	Dystric Cambisol	beech	170
Palicnik 4	638	SW	Entic Podzol	spruce	90
Palicnik 5	596	SW	Dystric Cambisol	beech	170

N – North, SW – South-West.

Simulation of water flow and Al and SO_4^{2-} transport

Water flow and transport of Al and SO_4^{2-} in the soil were simulated using the HYDRUS-1D program (Šimůnek et al., 2008). The study by Nikodem et al. (2010) documented that weighted averages of simulated boundary fluxes for two different precipitation intensities (e.g. stemflow and throughfall) might represent approximately average boundary fluxes in 2D/3D flow system. Water flow in this model is described by the Richard's equation, which is based on the continuity equation and the Darcy's law (Richards, 1931). Transport of dissolved substances in water is described by the advection-dispersion equation, which was extended for nonequilibrium solute transport (Šimůnek and van Genuchten, 1995). In the case of Al and SO_4^{2-} transport, it is assumed that both substances are absorbed on the soil particles.

Most input data for the mathematical modelling of water flow and solute (Al and SO_4^{2-}) transport in the soil profiles were obtained experimentally. Part of the necessary data (daily climatic data and monthly atmospheric deposition) was completed in cooperation with CHMI.

Because the granite bedrock is close to the soil surface and the soil profiles are shallow in this area, the depth of the soil profiles were set to 80 cm. The thicknesses of soil diagnostic horizons were defined based on soil profiles description (Table 2). Three subhorizons (Green et al., 1993) were distinguished within the organic matter horizons. The L subhorizon (the slightly decomposed organic material – leaves or needles) horizon was not considered.

Analytical expressions proposed by van Genuchten (1980) for the hydraulic characteristics, e.g. soil water retention curve, $\theta(h)$, and the hydraulic conductivity function, $K(\theta)$, are used in the HYDRUS-1D model:

$$\theta_e = \frac{\theta(h) - \theta_r}{\theta_s - \theta_r} = \frac{1}{\left(1 + |\alpha h|^n\right)^m}, \quad h < 0 \tag{1}$$

$$\theta_e = 1, \quad h \geq 0$$

$$K(\theta) = K_S\, \theta_e^l \left[1 - \left(1 - \theta_e^{2/m}\right)^m\right]^2, \quad h < 0 \tag{2}$$

$$K(\theta) = K_S, \quad h \geq 0,$$

where θ_e is the effective soil water content (–), K_s is the saturated hydraulic conductivity (LT^{-1}), θ_r and θ_s are the residual and saturated soil water contents (L^3L^{-3}), respectively, l is the pore-connectivity parameter (–), α is reciprocal of the air entry pressure (L^{-1}), n is related to the slope of the retention curve at the inflection point (–), and $m = 1 - 1/n$ (–). Parameters of the soil hydraulic characteristics (Table 2) were evaluated on the undisturbed 100-cm^3 soil samples in the laboratory using the multistep outflow experiment (van Dam et al., 1994). The undisturbed 100-cm^3 soil samples (soil core height of 5.1 cm and cross-sectional area of 19.60 cm^2) were placed in the Tempe cells. Initially, fully saturated soil samples placed in the Tempe cells were slowly drained using nine pressure head steps (a minimum pressure head of −1000 cm) during a 3-week period and cumulative outflow in time was measured. The points of the soil water retention curve were evaluated using the final soil water content and water balance within the soil sample. The single-porosity model in HYDRUS-1D (Šimůnek et al., 2008), which is widely used and tested for inverse modeling (Twarakavi et al., 2010), was then applied to simulate observed water regime within the soil sample (e.g. cumulative outflow in time and points of the retention curves) and to optimize parameters of the van Genuchten (1980) soil hydraulic functions (Eqs (1) and (2)). The procedure was described by Kodešová et al. (2007). The hydraulic properties of the F horizons were not measured because, owing to the small thickness of these horizons, it was not possible to take undisturbed soil samples. Therefore, the hydraulic properties that were measured for the H horizons were used also for the F horizons. It should be noted that plants and biological soil crust might influence water regime in some soils (Lichner et al., 2012). Hovewer, such effects were neglected in this study.

The bulk densities (Table 3) were measured on undisturbed 100-cm^3 soil cores. Longitudinal dispersivities (Table 3) were set to values suggested for the various soil textures, experimental scales, and transport distances by Vanderborght and Vereecken (2007). The molecular diffusion was neglected (the mechanical dispersion played dominant role in our case).

Assuming the equilibrium solute adsorption, the adsorption isotherm relating the adsorbed concentration, s, and liquid concentration, c, may be described using the Freundlich equation:

$$s = K_F c^{\beta}, \tag{3}$$

where K_F (L^{3b} M^{1-b} M^{-1}) and β (–) are empirical coefficients. The parameters that describe the equilibrium adsorption of Al and SO_4^{2-} (Table 3) were obtained using standard batch experiments. Triplicate soil samples (10 g) were shaken with the Al solution ($AlCl_3$, w/v ratio 1 : 10) with concentrations 0, 45, 50, 90, 100, 130, 150, 170, 200, 210, and 250 mg L^{-1} Al, and with the SO_4^{2-} solution (Na_2SO_4, w/v ratio 1 : 10) with concentrations 0, 40, 80, 100, 200 mg L^{-1} SO_4^{2-}. Extracts were separated from suspension by centrifuging and further purified by passing through chromatography disk filters with pore size 0.45 μm. The concentration of Al was determined by ICP–OES (VARIAN Vista Pro, VARIAN, Melbourne, Victoria, Australia) and the content of SO_4^{2-} by ion chromatography(IC) with suppressed conductivity (Dionex, USA). Final equilibrium solute liquid concentrations were paired with the equilibrium adsorbed concentrations, which were evaluated using the solute mass balance. When no Al or SO_4^{2-} sorption occurred in individual soil horizons, the parameter K_F equaled to 0 and the parameter β equaled to 1. The parameters of the adsorption isotherms could not be evaluated relably in the surface horizons due to initially high concentrations of SO_4^{2-} in these soils. Therefore sets of simulations were carried out for SO_4^{2-} with the Freundlich coefficients set to various values (K_F = 5, 10, 20, 30, 40 and 50 ($cm^{3\beta}$ $\mu g^{1-\beta}$ g^{-1}) and $\beta = 0.5$).

A 6 months period in 1997 was chosen for numerical simulations due to availability of climatic data, which are necessary for the definition of the upper boundary condition and root water uptake. Climatic data were measured by the Czech Hydrometeorological Institute (Kulasová et al., 2005). Numerical simulation was performed from 1 May to 31 October.

The initial pressure heads in the soil profiles were set to a constant value of –100 cm, which corresponded to the higher saturation of soil profiles with water after the winter period. The initial concentrations of Al and SO_4^{2-} in soil profiles (Table 4) were estimated based on the data obtained in this transects since 2005 (Pavlů et al., 2007) and the results obtained in the Jizera Mts. since 2002 (Mládková et al., 2005; Borůvka et al., 2005 and Drábek et al., 2007). Initial concentrations were expressed as μg of substance per cm^3 of soil. These values were calculated from the measured values expressed as mg substance per kg of soil accounting for the soil bulk density. The initial concentrations of Al and SO_4^{2-} in the water and in the solid phase was then calculated by the HYDRUS-1D program using the inserted parameters of adsorption isotherms and initial moisture contents (corresponding to the specified pressure heads).

The top boundary conditions were defined using the measured daily rainfall. One scenario was simulated for the site Smedava 1, where the soil surface was mostly covered by grass vegetation at this site. Total rainfall used for the simulation reached 99.81 mm. Three scenarios were simulated for the other sites with beech and spruce trees. Reduced rainfall due to interception of vegetation (forest) was modelled in the first scenario. The other two scenarios distinguish between throughfall and stemflow. The precipitation (e.g. potential infiltration fluxes) used for individual stands (spruce and beech) was calculated on the basis of the measurements made by Kantor (1985). Monthly percentages of rainfall minus the forest interception, throughfall and stemflow for spruce and beech trees were observed under similar conditions in the Orlické Mts. in the Czech Republic during the five-year period between 1977 – 1981

Table 2. Parameters of soil hydraulic functions (van Genuchten, 1980) used for water flow simulation (θ_r and θ_s are residual and saturated water content; K_s is saturated hydraulic conductivity; α and n are empirical parameters, $l = 0.5$.

Site name	Horizon	Horizon depth (cm)	θ_r ($cm^3\ cm^{-3}$)	θ_s ($cm^3\ cm^{-3}$)	α (cm^{-1})	n (–)	K_s ($cm\ d^{-1}$)
Smedava 1	F †	6 – 10	0.568	0.830	0.033	1.591	28.4
	H	10 – 18	0.568	0.830	0.033	1.591	28.4
	Ep	18 – 32	0.112	0.473	0.080	1.194	562.34
	Bhs	32 – 44	0.264	0.598	0.059	1.258	355.3
	Gor	44 – 60	0.380	0.598	0.015	1.593	16.2
Smedava 4	F †	2 – 4	0.404	0.761	0.029	1.200	17.7
	H	4 – 7	0.404	0.761	0.029	1.200	17.7
	Ep	7 – 12	0.112	0.473	0.080	1.194	562.3
	Bhs	12 – 22	0.339	0.720	0.095	1.586	1523.4
	Bs	22 – 55	0.346	0.675	0.030	1.843	245.5
Smedava 5	F †	2 – 3	0.338	0.671	0.026	1.574	31.2
	H	3 – 5	0.338	0.671	0.026	1.574	31.2
	Ae†	5 – 6.5	0.338	0.671	0.026	1.574	31.2
	Bvs	6.5 – 14.5	0.297	0.700	0.038	2.051	1412.4
	Bv	14.5 – 70	0.274	0.609	0.046	1.818	1477.7
Palicnik1	F †	3 – 4	0.435	0.779	0.042	1.743	189.0
	H	4 – 10	0.435	0.779	0.042	1.743	189.0
	Ae	10 – 13	0.363	0.674	0.060	1.736	194.8
	Bhs	13 – 17	0.329	0.688	0.575	1.695	543.5
	Bs	17 – 51	0.304	0.701	0.483	2.223	235.5
Palicnik 2	F †	3 – 6	0.000	0.784	0.352	1.070	1459.6
	H	6 – 9	0.000	0.784	0.352	1.070	1459.6
	Ae	9 – 11	0.363	0.674	0.06	1.736	194.8
	Bv	11 – 61	0.000	0.652	0.113	1.135	834.9
Palicnik 4	F†	4 – 7	1.164	0.598	0.041	1.598	326.9
	H	7 – 13	1.164	0.598	0.041	1.598	326.9
	Ae †	13 – 18	1.164	0.598	0.041	1.598	326.9
	Bvs	18 – 38	0.212	0.559	0.053	1.562	897.7
	Bv	38 – 80	0.097	0.517	0.125	1.515	1305.9
Palicnik 5	F †	3 – 6	0.312	0.739	0.031	1.943	124.3
	H	6 – 10	0.312	0.739	0.031	1.943	124.3
	Ah †	10 – 13	0.312	0.739	0.031	1.943	124.3
	Bv1	13 – 33	0.000	0.642	0.130	1.231	908.0
	Bv2	33 – 63	0.097	0.517	0.125	1.515	1305.9

† Data from H horizon.

(Table 5). The potential daily infiltration fluxes for throughfall precipitation scenarios were calculated as the amount of rainfall multiplied by corresponding monthly percentages (Kantor, 1985) then divided by 100.

The following parameters were also used to evaluate the stemflow potential daily infiltration flux in beech stands: treetop diameter, 390 cm; stem diameter, 35 cm; and width of area around the tree of stemflow infiltration into the soil, 20 cm. The following parameters were suggested for spruce stands: treetop diameter, 440 cm; stem diameter, 37 cm; and width of area around the tree of stemflow infiltration into the soil, 10 cm (relatively small infiltration areas were defined in both cases because of the high hillslope at these areas and consequent expected runoff) (Fig. 1). Data are based on the measurements in the field at the monitored sites. The stemflow potential daily infiltration flux was calculated as rainfall multiplied by the monthly stemflow percentage (Kantor, 1985) and the treetop area, the product then divided by the area of the potential infiltration and 100. Root depth was 20 cm for the site Smedava 1 (grassland) and 80 cm for the spruce and beech stands. The daily potential transpiration rates were calculated using the Penman-Monteith equation (Monteith, 1981; Monteith and Unsworth, 1990), which required the following parameters: solar radiation (4.16–224.45 W m^{-2}), air temperature (maximum, –4.6–27.7°C; minimum, –21.3–12.0°C), air humidity (57.01–100%), and wind speed (0.4–9.0 m s^{-1}). The albedo was set at 0.23 for the grassland, 0.17 for beech and 0.10 for spruce stands (Budikova et al., 2008). The value of leaf area index (LAI) for grass vegetation was defined as 0.24 multiplied by crop height (30 cm) (used in HYDRUS-1D). The leaf area index was set at 5.06 and 5.47 for beech and spruce, respectively (Scurlock et al., 2001). Evaporation at the top of the soil profiles was neglected since the soil surface was covered with grass (Smedava 1) or by a layer of organic horizon L (the other sites). Wet atmospheric depositions of Al and SO_4^{2-} (Table 6), measured during simulated period in rainfall were applied at the surface of the individual soil profiles running the first series of simulations. Then the second run of simulations was performed. The concentrations of Al and SO_4^{2-} in precipitation (e.g. wet atmospheric depositions) were recalculated from the measured values assuming the ratio between concentrations in rainfall, total precipitation under trees, throughfall precipitation and stemflow, which were found by Kantor (1985) (Table 7). It was assumed that the roots did not take up any Al and SO_4^{2-}.

Table 3. Parameters used for reactive solute transport simulations.

Site name	Horizon	Bulk density (g cm^{-3})	Longitudinal dispersivity (cm)	Freundlich adsorption isotherm coefficient Al K_F (cm$^{3\beta}$ μg$^{1-\beta}$ g^{-1})	Al β (–)	SO_4^{2-} K_F (cm$^{3\beta}$ μg$^{1-\beta}$ g^{-1})	SO_4^{2-} β (–)
Smedava 1	F	0.344 †	0.5	279.7	0.230	N.A. ††	N.A. ††
	H	0.344	1	94.7	0.218	N.A. ††	N.A. ††
	Ep	1.358	1.5	0.0	1.000	0.00	1.000
	Bhs	1.054	2	69.1	0.299	0.00	1.000
	Gor	1.029	4	120.3	0.201	1.76	0.628
Smedava 4	F	0.345†	0.5	217.0	0.243	N.A. ††	N.A. ††
	H	0.345	1	65.2	0.233	N.A. ††	N.A. ††
	Ep	1.358	1.2	7.7	0.851	0.00	1.000
	Bhs	0.593	1.5	66.8	0.222	3.07	0.590
	Bs	0.678	4	67.6	0.189	11.83	0.451
Smedava 5	F	0.781†	0.5	200.2	0.212	N.A. ††	N.A. ††
	H	0.781	1	35.0	0.251	N.A. ††	N.A. ††
	Ae	0.781	1.5	69.6	0.222	0.00	1.000
	Bvs	0.698	2	13.9	0.430	11.03	0.577
	Bv	0.952	4	5.1	0.525	19.41	0.473
Palicnik1	F	0.333 †	0.5	387.7	0.218	N.A. ††	N.A. ††
	H	0.333	1	149.0	0.189	N.A. ††	N.A. ††
	Ae	0.708	1.5	51.0	0.430	0.00	1.000
	Bhs	0.727	2	23.0	0.395	11.23	0.431
	Bs	0.813	3.4	67.6	0.189	11.83	0.451
Palicnik 2	F	0.333	0.5	425.5	0.243	N.A. ††	N.A. ††
	H	0.411	1	81.5	0.289	N.A. ††	N.A. ††
	Ae	0.708	1.5	79.7	0.201	0.00	1.000
	Bv	0.830	2	31.1	0.222	17.67	0.451
Palicnik 4	F	1.048 †	0.5	190.6	0.202	N.A. ††	N.A. ††
	H	1.048	1	49.5	0.398	N.A. ††	N.A. ††
	Ae	1.048†	1.5	26.4	0.397	0.00	1.000
	Bvs	1.037	2	1.1	0.894	13.96	0.447
	Bv	1.210	3.4	0.0	1.000	6.62	0.581
Palicnik 5	F	0.565 †	0.5	246.7	0.170	N.A. ††	N.A. ††
	H	0.565	1	0.0	1.000	N.A. ††	N.A. ††
	Ah	0.565†	1.5	0.0	1.000	0.00	1.000
	Bv1	0.848	2	0.0	1.000	0.00	1.000
	Bv2	1.210	3.4	0.0	1.000	6.62	0.579

† Data from H horizon.
†† Not reliable data, variable values of K_F (equal to 5 up to 50) and constant β = (0.5).

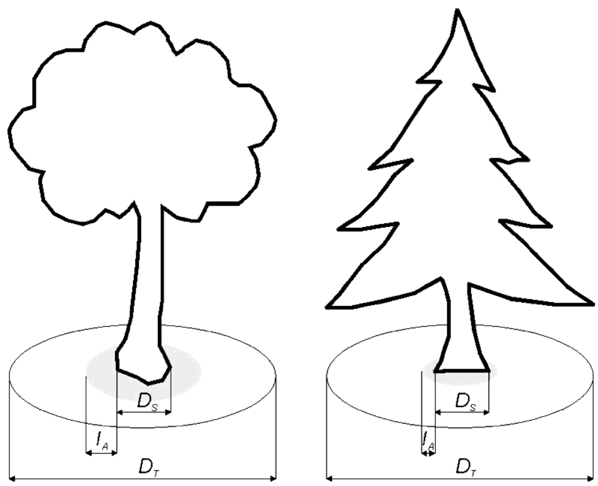

Fig. 1. Parameters used for evaluating the stemflow potential daily infiltration flux in beech (left) and spruce (right) stands: D_T – treetop diameter, D_S – stem diameter, I_A – width of area around the tree of stemflow infiltration into the soil.

RESULTS AND DISCUSSION

Resulting cumulative water and Al fluxes cross the top and bottom boundaries in time, cumulative root water uptake in time, and soil water content, pressure head and Al concentration distribution within the soil profile were for various scenarios in greater detail discussed for one of the soil profiles, Haplic Podzol (Smedava 4) by Nikodem et al. (2010). Here we show only the resulting cumulative water (Table 8) and Al (Table 9) and SO_4^{2-} (Table 10) fluxes at the end of the simulated period but for all studied soil profiles and vegetations.

The simulated values of cumulative water flow (Table 8) indicated that while the effect of the precipitation redistribution is not significant in the spruce forest, the influence of precipitation redistribution in a beech forest is considerable. Generally, in all cases the simulated fluxes for the throughfall (precipitation type 2) scenarios (PT2) were lower than for the uniform precipitation distribution (precipitation type 1) scenarios (PT1). On the contrary, the simulated fluxes for the stemflow (precipitation type 3) scenarios (PT3) were higher than for the uniform precipitation distribution (precipitation type 1) scenarios (PT1).

Table 4. Initial concentration of Al and SO_4^{2-} in the soil profiles expressed in µg of substance per cm^3 of soil.

Site name	Horizon	Al (µg cm^{-3})	SO_4^{2-} (µg cm^{-3})
Smedava 1	F	43.02	96.02
	H	16.17	55.26
	Ep	39.50	16.79
	Bhs	204.01	18.11
	Gor	287.68	12.43
Smedava 4	F	57.32	53.89
	H	72.45	46.76
	Ep	271.91	35.16
	Bhs	69.05	23.71
	Bs	71.34	24.04
Smedava 5	F	134.54	81.49
	H	69.74	62.89
	Ae	73.05	28.12
	Bvs	31.09	22.91
	Bv	4.95	41.86
Palicnik1	F	49.75	92.32
	H	9.89	70.02
	Ae	57.45	37.29
	Bhs	66.34	45.50
	Bs	74.19	50.88
Palicnik 2	F	37.67	82.24
	H	51.35	52.69
	Ae	67.23	34.58
	Bv	19.22	42.84
Palicnik 4	F	134.33	239.66
	H	114.09	125.44
	Ae	94.73	74.57
	Bvs	31.57	57.11
	Bv	36.83	66.64
Palicnik 5	F	73.35	128.76
	H	61.30	79.14
	Ah	41.59	31.79
	Bv1	18.87	31.50
	Bv2	26.92	44.95

The runoff was generated in one case of the stemflow scenarios. In other cases no runoff occurred. Furthermore, the weighted average values of the simulated cumulative water (Al and SO_4^{2-}) fluxes from scenarios PT2 and PT3 were calculated to evaluate the impact of the spatially distributed precipitation under beech and spruce trees on the average water and solute fluxes under the tree (e.g. precipitation type 4 – PT4). The weighted average values were calculated as sums of the cumulative fluxes PT2 multiplied by the throughfall infiltration area (circle area with diameter of 390 or 440 cm minus the circle area with diameter of 75 or 57 cm) plus the cumulative fluxes PT3 multiplied by the stemflow infiltration area (circle area with diameter of 75 or 57 cm minus circle area with diameter of 35 or 37 cm), and then both were divided by total infiltration area (circle area with diameter of 390 or 440 cm minus circle area with diameter of 35 or 37 cm). Comparison of values for PT1 and PT4 (Table 8) showed that the concentrated fluxes along the tree stems increased water discharge through soil profile bottom, reduced water storage in the soil, and consequently, reduced the root water uptake (e.g. tree transpiration). In the case of the grass cover (Smedava 1), not reduced precipitation due to the interception resulted in larger cumulative infiltration at the top, root water uptake and water discharge from the soil profile bottom in comparison to those obtain under the trees. Larger cumulative water fluxes accordingly impacted Al and SO_4^{2-} fluxes.

The resulting cumulative Al fluxes through the soil profiles tops and bottoms at the end of the simulated period are presented in Table 9. The results showed that the precipitation redistribution decreased (increased) recharge of Al at the soil profile top when the PT2 (PT3) was used (in comparison to PT1 scenarios). As result lower Al fluxes were obtained from PT4 than for PT1 scenarios. However, Al discharges at the soil profile bottom (leaching from the soil) were controlled mainly by the initial Al content in the subsurface soil horizons. In one case (Smedava 4) the initial Al content in the lower horizon was very high and therefore stemflow caused a significant increase of Al leaching from the soil profile when comparing PT1 and PT2 scenarios. In all other cases, the Al contents in the lower horizon were lower and due to the rapid leaching of Al from this horizons the lower Al discharge from the soil profile bottom was obtained (comparing PT1 and PT2 scenarios). The results also showed that the increase of Al concentrations (recalculated concentrations using Table 7) in precipitated water (PT1, 3 and 4) increased the cumulative fluxes of Al through the soil surface, but had a negligible effect on the value of the cumulative Al discharge from the bottom of the soil profile.

Table 5. The monthly percentages applied to calculate the rainfall without the forest interception, throughfall, and stemflow for beech and spruce forest (1977–1981) (Kantor, 1985).

Month	Rainfall minus interception (%)	Throughfall (%)	Stemflow (%)
Beech			
May	85.4	69.6	15.8
June	88.2	73.0	15.2
July	95.5	76.9	18.6
August	91.3	72.5	18.8
September	97.1	75.9	21.2
October	90.5	67.7	22.8
Spruce			
May	68.0	67.6	0.4
June	71.2	70.5	0.7
July	82.8	81.3	1.5
August	79.0	77.9	1.1
September	87.0	85.2	1.8
October	82.0	79.6	2.4

Table 6. The monthly wet deposition of Al and SO_4^{2-}.

Month	Wet deposition Al ($\mu g\ cm^{-3}$)	Wet deposition SO_4^{2-} ($\mu g\ cm^{-3}$)
May	0.13	5.50
June	0.17	5.60
July	0.27	13.90
August	0.19	7.57
September	0.02	4.80
October	0.09	4.57

Table 7. The monthly wet depositions measured in rainfall, total precipitation under trees, throughfall precipitation and stemflow for beech and spruce forest (1977–1981) by Kantor (1985) and applied to calculate concentrations in the uniformly distributed precipitations, throughfall, and stemflow.

		Rainfall	Throughfall	Stemflow
Wet deposition Al ($\mu g\ cm^{-3}$)	Beech	0.20	0.20	0.27
	Spruce	0.20	0.27	2.01
Wet deposition SO_4^{2-} ($\mu g\ cm^{-3}$)	Beech	7.0	16.7	18.7
	Spruce	7.0	36.2	138.9

In the case of the SO_4^{2-} transport, the results indicated (no shown here) that the increase of SO_4^{2-} concentrations (recalculated concentrations using Table 7) in precipitated water (PT1, 2, 3 and 4) increased the cumulative fluxes of SO_4^{2-} through the soil surface (in comparison to those obtained for the same concentration in all precipitations Table 6), but had a negligible effect on the value of the cumulative SO_4^{2-} discharge from the bottom of the soil profile for PT1 and PT2 scenarios. Considerable larger cumulative SO_4^{2-} discharge from the bottom of the soil profile was obtained for PT3 scenarios and consequently for PT4. Cumulative outflows were in both cases approximately twice higher than those obtained for the same concentration in all precipitations.

The resulting cumulative SO_4^{2-} fluxes through the soil profiles bottoms at the end of the simulated period are shown in Table 10. The results for variable concentration in precipitations in stemflow and throughfall are shown only. The results showed that the precipitation redistribution (except of one case) caused an increased SO_4^{2-} discharge from the soil profile bottom. This increase was due to increase of SO_4^{2-}concentrations in precipitated water and due to initially high contents of SO_4^{2-} in the soils. Comparison of results of simulations with different values of K_F showed that the effect of K_F was negligible when uniform precipitation distribution was assumed (there was only a difference in the redistribution of the SO_4^{2-} content in the soil profile, which is not shown here). On the other hand, increasing value of K_F caused reduction of SO_4^{2-} discharge from the soil profile bottom for stemflow scenarios (and also when stemflow with throughfall was combined).

Table 8. Cumulative water fluxes at the end of the simulated period.

Site name	Type of precipitation	Cumulative water fluxes at the soil profile top (water infiltration) (cm)	Cumulative root water uptake (cm)	Cumulative water fluxes at the soil profile bottom (water discharge) (cm)	Cumulative water runoff (cm)
Smedava 1	1	105.33	75.39	31.18	0.00
Smedava 4	1	76.47	71.49	6.11	0.00
	2	58.85	62.78	0.00	0.00
	3	445.92	150.57	285.80	177.26
	4	70.14	65.34	8.33	5.17
Smedava 5	1	76.05	68.94	7.04	0.00
	2	58.59	60.15	1.15	0.00
	3	614.07	149.90	455.03	0.00
	4	74.79	62.76	14.39	0.00
Palicnik 1	1	71.89	26.02	38.49	0.00
	2	55.07	22.80	25.10	0.00
	3	614.21	15.53	584.95	0.00
	4	74.97	22.59	41.43	0.00
Palicnik 2	1	75.37	76.96	4.18	0.00
	2	58.72	67.33	0.00	0.00
	3	616.21	136.12	470.99	0.00
	4	74.97	69.34	13.74	0.00
Palicnik 4	1	64.73	66.40	1.30	0.00
	2	63.42	65.73	0.94	0.00
	3	127.87	77.12	42.17	0.00
	4	64.05	65.84	1.34	0.00
Palicnik 5	1	75.82	74.30	3.29	0.00
	2	58.67	63.01	0.00	0.00
	3	613.93	144.07	458.77	0.00
	4	74.86	65.38	13.38	0.00

1 – rainfall without the interception, 2 – throughfall, 3 – stemflow, 4 – throughfall + stemflow.

Table 9. Cumulative Al fluxes at the end of the simulated period.

Site name	Type of precipitation	Cumulative Al fluxes at the soil profile top (Al recharge) (μg cm^{-2})	Cumulative Al fluxes at the soil profile bottom (Al discharge) (μg cm^{-2})	Cumulative Al fluxes at the soil profile top (Al recharge) (μg cm^{-2})	Cumulative Al fluxes at the soil profile bottom (Al discharge) (μg cm^{-2})
		same concentration		recalculated concentration	
Smedava 1	1	21.40	1333.20	–	–
Smedava 4	1	17.22	56.96	18.49	56.96
	2	13.58	0.0016	13.58	0.0016
	3	82.40	3070.00	110.76	3070.10
	4	15.59	89.53	16.42	89.54
Smedava 5	1	17.07	359.53	18.33	359.53
	2	13.48	57.65	13.48	57.65
	3	125.35	3203.70	168.12	3209.90
	4	16.74	149.40	17.98	149.58
Palicnik 1	1	17.23	2599.70	17.23	2599.70
	2	13.61	1699.50	14.61	1700.20
	3	125.51	7313.20	168.34	7315.40
	4	16.87	1863.21	19.09	1863.96
Palicnik 2	1	16.83	109.10	18.07	109.10
	2	13.47	0.0004	13.47	0.0004
	3	125.33	121.97	168.22	121.96
	4	16.73	3.56	17.98	3.56
Palicnik 4	1	14.58	395.25	22.20	394.99
	2	14.31	301.67	19.18	302.80
	3	26.90	2308.20	269.96	2308.20
	4	14.43	321.29	21.63	322.41
Palicnik 5	1	17.08	979.77	18.34	979.77
	2	13.48	0.005	13.48	0.01
	3	125.34	2103.30	168.11	2134.60
	4	16.75	61.33	17.99	62.25

1 – rainfall without the interception, 2 – throughfall, 3 – stemflow, 4 – throughfall + stemflow.

Table 10. Cumulative SO_4^{2-} fluxes at the soil profile bottom (μg cm^{-2}) for different coefficients K_F (cm$^{3\beta}$ μg $^{1-\beta}$ g $^{-1}$) applied in the surface horizons.

Site name	Type of precipitation	$K_F = 5$	$K_F = 10$	$K_F = 20$	$K_F = 30$	$K_F = 40$	$K_F = 50$
Smedava 1	1	571.09	537.66	476.11	427.70	393.72	372.28
Smedava 4	1	60.24	60.42	60.70	60.96	61.15	61.16
	2	0.00	2.50	0.00	2.44	0.00	8.00
	3	10633.0	10551.0	10446.0	10403.0	10775.0	10188.0
	4	310.09	310.12	304.64	305.75	314.24	304.88
Smedava 5	1	39.12	39.21	39.29	39.29	39.25	39.25
	2	6.37	6.37	6.37	6.25	6.23	6.24
	3	13946.0	13893.0	13786.0	13674.0	13568.0	13452.0
	4	412.89	411.35	408.23	404.84	401.74	398.37
Palicnik 1	1	2169.40	2173.80	2181.50	2188.0	2193.50	2198.30
	2	1325.60	1326.20	1327.00	1326.80	1327.10	1327.40
	3	20036.0	20038.0	20042.0	20046.0	20050.0	20054.0
	4	1871.26	1871.90	1872.79	1872.71	1873.12	1873.53
Palicnik 2	1	221.06	221.22	221.54	221.82	221.89	221.92
	2	0.00	0.00	0.00	0.00	0.00	0.00
	3	17619.0	17567.0	17462.0	17356.0	17249.0	17249.0
	4	513.83	512.31	509.25	506.16	503.04	503.04
Palicnik 4	1	27.21	27.13	27.13	27.13	27.08	27.06
	2	19.74	19.79	19.77	19.76	19.75	19.75
	3	8534.30	7876.40	6581.30	5367.0	4275.60	3322.50
	4	103.01	96.63	83.94	72.06	61.37	52.05
Palicnik 5	1	68.79	68.83	68.71	68.75	68.75	68.75
	2	0.00	0.00	0.00	0.00	0.00	0.00
	3	19532.0	19450.0	19283.0	19113.0	18939.0	18939.0
	4	569.62	567.23	562.36	557.40	552.33	552.33

1 – rainfall without the forest interception, 2 – throughfall, 3 – stemflow, 4 – throughfall + stemflow.

It should be noted that Al and SO_4^{2-} root uptake, which occurs by different intensities in beech and spruce forests, and may reduce contaminant's leaching from the soils, was neglected in this study. On the other hand, Al and SO_4^{2-} formation due to organic matter decomposition (Pedersen and Hansen, 1999; Vannier et al., 1993; van Scholl et al., 2005; de Wit et al., 2010) or mineral particle weathering, which may increase Al and SO_4^{2-} leaching from the soils, was not assumed as well. These phenomena should be included when simulating long-term processes in forest soils and it is likely that the model HP1 (Šimůnek at al., 2008) might help to solve such scenarios. However, this study was focused on the short-term leaching. The main goal of this study was to document great impact of precipitation redistribution, which mainly controls water and solutes leaching from the forests soils.

CONCLUSIONS

Water flow and transport of Al and SO_4^{2-} in forest soils were simulated using the program HYDRUS-1D. The influence of redistribution of rainwater at the soil surface (throughfall and stemflow) on the water flow in soils, runoff generation, groundwater recharge and leaching of Al and SO_4^{2-} from the soils was evaluated. Simulations (e.g data simulated for either throughfall or stemflow and their weighted averages) showed that the precipitation redistribution considerably impacted water and both contaminants transport in the beech forest. Redistribution of precipitation under beech trees caused runoff (in one case), increased water discharge from the soil profile, reduced water storage in the soil, and reduced water uptake by roots. Leaching of Al was controlled primarily by its initial content in the soil. Leaching of SO_4^{2-} was also controlled by the initial SO_4^{2-} content in the soil and to a lesser extent by redistributed precipitation and SO_4^{2-} deposition. In the spruce forest the impact of precipitation redistribution on water and both contaminants transport was almost negligible due to the fact that a very low stemflow was generated in this case.

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