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Hillslope hydrology – runoff dynamics and transport processes

Hydrologie svahu – dynamika odtoku a transportní procesy

Summary

Model description of runoff mechanisms in a small headwater catchment under the conditions of a humid temperate climate remains a difficult task. Headwater catchments and their smaller spatial units, individual hillslopes, provide the basic framework for studying rainfall–runoff transformations and associated transport processes of solutes dissolved in soil water. This is because they are characterized by small sizes, negligible anthropogenic disturbance, and feasible separation of above- and below-ground energy fluxes.

The aim of mathematical modeling is to improve the understanding of the mechanisms that influence runoff and transport processes and also to provide a reliable tool for predictions. Several modeling approaches, after calibration and validation against field observations from the experimental hillslope and subsurface trench, were used to analyze the hydrological response of the hillslope segment to rainfall. The modeling approaches varied in dimensionality and therefore in the complexity of geometric, material, and boundary conditions. The approaches were based on the dual-continuum concept with water flow and solute transport through the soil matrix and preferential pathways. The intensity of shallow subsurface runoff from the hillslope predicted by these modeling approaches was compared with the observed stormflow. Inclusion of water flow and solute transport through preferential pathways proved necessary to adequately describe the internal hillslope storage and dynamics of stormflow and solutes. The threshold hydrological response of the hillslope to rainfall was evaluated using one of the modeling approaches.

Stable water isotopes that naturally occur in rainfall have the potential to quantify the main transport mechanisms at scales ranging from soil profile to hillslope and catchment. Numerical modeling was used to describe the transformation of the input isotope signal in rainfall to the output signal in hillslope stormflow. Incorporating isotope tracer transport information into the modeling resulted in a more robust description of flowpaths in the hillslope. Furthermore, model analysis of long-term isotope data in different discharge components and in soil water helped to reveal the existence of isotopically distinct water pools in the headwater catchment.

Stable water isotopes can also be used to partition runoff into pre-event and event water contributions. The separation of the hillslope hydrograph was

performed using synthetic isotopic signatures. The results suggest that despite the significant role of preferential flow in the generation of subsurface stormflow, the pre-event water contribution formed a dominant part of the total hillslope runoff. Travel times associated with different hillslope discharge processes were further analyzed using one of the modeling approaches.

Additionally, numerical model was used to describe the transport of dissolved organic carbon through a hillslope soil. In contrast to the conservative behavior of stable water isotopes, dissolved organic carbon in soil undergoes numerous biogeochemical transformations. Sorption interactions of dissolved organic carbon with the solid phases of the bulk soil were found to significantly affect the leaching regime at the hillslope scale. As a result of preferential flow, the export of dissolved organic carbon from the hillslope was higher than the amount usually reported in the literature.

Souhrn

Modelový popis mechanismů tvorby odtoku v měřítku malého povodí v podmínkách mírného vlhkého podnebí stále představuje nelehkou úlohu. Zdrojová povodí a jejich menší prostorové jednotky, jednotlivé svahy a svahové segmenty, představují základní rámec pro studium srážko-odtokových vztahů a souvisejících transportních procesů chemických látek rozpuštěných v půdní vodě. Je tomu tak proto, že se vyznačují relativně malými rozměry, zanedbatelným antropogenním ovlivněním a proveditelnou separací nadzemních a podzemních energetických toků.

Cílem matematického modelování je přispět k porozumění mechanismů ovlivňujících tvorbu odtoku a transportní procesy a také poskytnout spolehlivý nástroj pro predikce. Různé modelové přístupy byly, po kalibraci a validaci na základě terénního pozorování z experimentálního svahu a podpovrchového příkopu, použity k analýze hydrologické odezvy svahového segmentu na příčinnou srážku. Jednotlivé modelové přístupy se lišily uváženou dimenzionalitou a tedy složitostí geometrických, materiálových a okrajových podmínek. Modelové přístupy byly založeny na konceptu duálního kontinua pro pohyb vody a transport rozpuštěných látek půdní matricí a sítí preferenčních cest. Simulované intenzity hypodermického odtoku ze svahu byly porovnány s měřením z podpovrchového příkopu. Zahrnutí pohybu vody preferenčními cestami se ukázalo jako nezbytné pro popsání zásoby půdní vody a dynamiky odtoku a rozpuštěných látek ze svahového segmentu. Pomocí jednoho modelového přístupu byla vyhodnocována prahová hydrologická odezva svahu na srážku.

Stabilní izotopy vody, které se přirozeně vyskytují ve srážkách, mají potenciál objasnit hlavní transportní mechanismy na různých úrovních prostorového měřítka (od půdního profilu a svahu až po malé povodí). Numerické modelování bylo použito k popisu transformace vstupního izotopového signálu ve srážce na výstupní signál v hypodermickém odtoku. Zahrnutím údajů o transportu izotopu do modelu se zlepšila jeho schopnost detailněji popsat cesty proudění vody svahovým segmentem. Modelová analýza dlouhodobých izotopových dat v různých složkách odtoku a v půdní vodě pomohla odhalit existenci izotopově odlišné vody ve zdrojovém povodí.

Stabilní izotopy vody lze rovněž použít k separaci odtoku na příspěvky tzv. staré a nové vody. Tato separace hydrogramu odtoku ze svahu byla provedena pomocí syntetických izotopových řad. Výsledky naznačují, že i

navzdory významné roli preferenčního proudění ve formování hypodermického odtoku tvořil příspěvek staré vody dominantní část celkového odtoku ze svahu. Jedním modelovým přístupem byly dále analyzovány doby zdržení spojené s různými procesy odtoku ze svahu.

Numerický model také sloužil k popisu transportu rozpuštěného organického uhlíku svahovou půdou. Na rozdíl od konzervativního chování stabilních izotopů vody podléhá rozpuštěný organický uhlík v půdě četným biogeochemickým transformacím. Bylo zjištěno, že sorpční interakce rozpuštěného organického uhlíku s pevnou fází půdy výrazně ovlivňují režim transportu uhlíku v měřítku svahu. V důsledku preferenčního proudění byl export rozpuštěného organického uhlíku ze svahu vyšší než množství obvykle uváděné v literatuře.

Keywords:

headwater catchment, hillslope, shallow subsurface runoff, solute transport in soils, stable water isotopes, hydrograph separation, hydrological response, rainfall–runoff relationship, travel times, numerical model, dual-continuum concept

Klíčová slova:

malá zdrojová povodí, svahový segment, hypodermický odtok, transport rozpuštěných látek v půdě, stabilní izotopy vody, separace hydrogramu, hydrologická odezva, srážko-odtokový vztah, doba zdržení, numerický model, koncept duálního kontinua

Contents

1. Introduction

Runoff in streams and rivers begins in headwater catchments. An important feature of headwater catchments is that they are generally in remote and pristine environments where the anthropogenic influences of urban, industrial, and agricultural activities are low and often negligible. These conditions allow us to study runoff generation processes influenced exclusively by natural controls. The intensity of runoff (discharge) has direct environmental impacts on lower-situated ecosystems with associated socioeconomic effects on human activities.

It is accepted that several runoff processes contribute to the discharge hydrograph observed at the outlet of a headwater catchment. The generation of streamflow that reveals the main mechanisms on the scale of the small headwater catchment is of great importance with respect to both the quantity and quality of water. Current knowledge of runoff mechanisms and processes is based on data obtained from a few experimental hillslopes and catchments around the world, where runoff conceptualizations were validated against field observations. Conceptual models of runoff mechanisms and transport processes are being further refined under various combinations of natural conditions in experimental headwater catchments. Therefore, the role of meteorological and hydrological monitoring in producing long-term reliable data time series is undisputable.

A stream hydrograph is commonly composed of two principal contributions: i) the baseflow and ii) the direct runoff component. The baseflow component represents a relatively steady contribution to the stream discharge from groundwater storage, while the direct runoff component represents an immediate hydrological response of the catchment to rainfall. Direct runoff is made up of surface and subsurface flow contributions. From the point of direct runoff generation, hillslopes are recognized as the most important spatial structural units within headwater catchments.

For the catchment scale, Hewlett and Hibbert (1967) proposed a conceptual model of variable source areas, in which the main feature was associated with the expansion of saturated zones along the valley floor near the stream and the lower portions of hillslopes. These zones were responsible for an increased contribution to streamflow. The source areas were found to be highly dynamic as they expanded and contracted during a single rainfall event and during a season. In fact, variable source areas are triggered by two runoff mechanisms operating on hillslopes; these include Hortonian (infiltration excess) overland flow and saturation excess overland flow.

Hortonian overland flow refers to lateral surface flow when the intensity of rainfall exceeds the infiltration capacity of the soil (Horton, 1933). Because the topsoils on hillslopes of forested catchments are typically highly permeable, there has been a shift in the recent literature away from the dominant role of this runoff mechanism in generation of catchment streamflow. The saturation excess overland flow is associated with the excess storage capacity of the soil and the lateral surface runoff initiated by the rainfall that falls on the surface of the saturated soil. On hillslopes, overland flow is usually assumed to result from return flow due to exfiltration of subsurface water (Dunne and Black, 1970). For the Hortonian overland flow, the most important factors are the intensity of rainfall and the infiltration capacity of the topsoil. The total amount of rainfall and the available water storage capacity of the soil profile receive relevant attention in case of saturation excess overland flow.

Shallow saturated subsurface flow (also known as stormflow, interflow, or throughflow) is recognized as a dominant runoff mechanism on hillslopes of vegetated headwater catchments under a humid temperate climate. Shallow subsurface flow usually develops above the sloping interface of the permeable soil and the less permeable underlying soil layer or bedrock. It occurs only for a short period of time as an immediate response to intense or long-lasting rainfall events (Weiler et al., 2006). The flow is often saturated in the downward (lateral) direction. Stormflow also contributes to the development of variable source areas in the stream vicinity. Woods and Rowe (1996) provided the following conditions for the significant contribution of stormflow to catchment runoff: i) permeable topsoil, ii) decrease in hydraulic conductivity with depth that causes lateral flow, iii) relatively high soil profile retention capacity and steep impending soil horizon, and iv) low evapotranspiration during rainfall–runoff events.

The transformation of rainfall into stormflow within a soil profile above the soil–bedrock interface is complex, as several factors affect the runoff process and related changes in the soil water storage of the hillslope. These factors can be grouped into static (e.g., hillslope spatial configuration, soil characteristics, and bedrock topography) and dynamic (e.g., storm characteristics, soil water distribution within a hillslope, and vegetation)

(Bachmair and Weiler, 2011). These are known to operate simultaneously; therefore, it remains difficult to identify the effects of the individual factor on the nonlinear hydrological response of the hillslope to rainfall. Knowledge of the temporal and spatial distribution of subsurface flow has important implications for emerging issues such as carbon dynamics and climate change (Chaplot and Ribolzi, 2014; Li and Sivapalan, 2014).

Experimental evidence demonstrated the complexity of stormflow generation on several hillslopes. The intensity of stormflow is frequently determined through experimental artificial subsurface trenches. Woods and Rowe (1996) and Freer et al. (2002) reported significant spatial variability of subsurface fluxes. The temporal development of the extent of the saturated zone above the impeding soil/bedrock layers can be monitored by piezometers and tensiometers (Montgomery et al., 2002; Masaoka et al., 2016). Dye tracer experiments provide evidence for the activation of macropore flow to runoff processes operating at the hillslope scale (e.g., Weiler and Naef, 2003). The chemical composition of soil water (isotope composition and major concentrations of ions) was also used to evaluate transport processes in the subsurface (Burns et al., 1998).

Hillslope topography represents a fundamental hydrological control that affects soil properties, vegetation and biogeochemical patterns, microclimate, soil water regime, and thus, in turn, stormflow formation. Several studies quantitatively evaluated the role of different terrain factors in runoff generation; these included slope gradient and length, hillslope geometry and aspect, and land use (Peters et al., 1995; Tani, 1997; Kirkby et al., 2002). The hillslope configuration was extensively analyzed with respect to topographic curvature (convex, planar, and concave) and contour curvature (divergent, parallel, and convergent), as these characteristics are known to influence subsurface flow and saturation/storage along hillslopes (Troch et al., 2003). In addition to large-scale hillslope geometry, the role of microtopography of the soil surface and soil–bedrock interface on the threshold behavior of runoff formation was studied by Freer et al. (2002), Tromp-van Meerveld and McDonnell (2006a), and Graham et al. (2010). Tromp-van Meerveld and McDonnell (2006b) proposed a “fill and spill” hypothesis to explain stormflow patterns on the Panola hillslope, where variable soil depths formed ridges and depressions along the soil–bedrock interface.

Mathematical modeling of runoff processes can be very helpful in analyzing the hydrological response of the hillslope to rainfall. This is because the field data is inherently loaded with uncertainty and is usually underrepresented in time and space. Another reason is related to the simultaneous effects of various factors on stormflow. Under such circumstances, modeling can be used to isolate individual factors and to make further generalizations. Evaluation of field data alone may lead to biased perceptions and conclusions under specific conditions. Therefore, numerical modeling has the potential to improve our understanding of runoff mechanisms and transport processes. A combined approach based on field observations and modeling can be used to allow a detailed analysis of the mechanisms contributing to runoff and changes in soil water storage (see e.g., Bronstert and Plate, 1997; VanderKwaak and Loague, 2001; Hopp et al., 2009).

It is known that the stormflow response to a rainstorm is significantly affected by the presence of preferential pathways (see e.g., Sidle et al., 2001; Anderson et al., 2010; Wienhöfer and Zehe, 2014). The description of preferential flow has recently received increasing attention in model applications (Beckers and Alila, 2004; Weiler and McDonnell, 2007; Klaus and Zehe, 2010). In this context, two-and three-dimensional dual-continuum models of soil water flow have been successfully applied to study hillslope responses to rainfall in some studies (Faeh et al., 1997; Stadler et al., 2012; Laine-Kaulio et al., 2014). However, the potential of these models to study the combined effects of various factors on hillslope responses has not been fully exploited.

2. Experimental hillslope

The experimental hillslope site Tomšovka is located in the headwater catchment Uhlířská, Jizera Mountains, North Bohemia, Czech Republic. The total area of the catchment is 1.78 km^2, the average altitude is 820 m above sea level, the mean annual precipitation is 1380 mm, and the mean annual temperature is 4.7°C. The studied hillslope is covered with grass (*Calamagrostis villosa*) and spruce (*Picea abies*).

The surface of the soil and the soil–bedrock interface at the Tomšovka hillslope are approximately planar and parallel. The average slope at Tomšovka is about 14%. The soil in Tomšovka is a sandy loam classified as Cryptopodzol. The soil profile is relatively shallow, about 70 cm deep.

Significant preferential flow effects at Tomšovka, affecting the hydrological response of the hillslope to rainfall, were reported by Šanda and Císlerová (2009). Preferential flow was attributed to highly conductive pathways along the roots, cracks, and biopores as well as to the spatial variability of local soil hydraulic properties.

At the Tomšovka site, the subsurface trench is used to collect hillslope discharge (stormflow) by tipping bucket gauges (Figure 1). The trench, built at a depth of 75 cm, consists of two sections, A and B, each 4 m long. The discharge is analyzed for stable water isotopes ($\delta^{18}O$ and $\delta^{2}H$) and dissolved organic carbon (DOC).

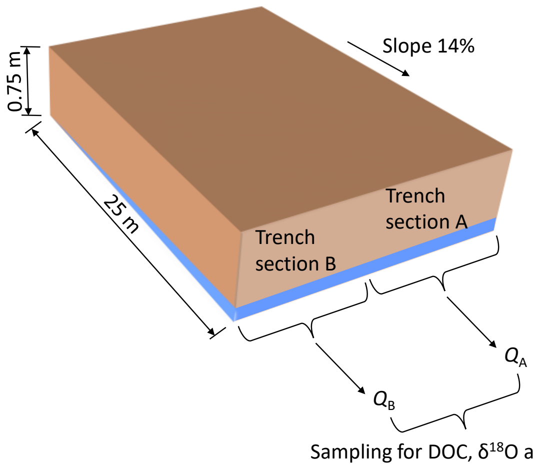

Figure 1. Schematic of the experimental trench to collect hillslope discharge at the Tomšovka site. The discharge is collected separately for the two trench sections (Q_A and Q_B). Stormflow samples for the stable water isotopes ($\delta^{18}O$ and $\delta^{2}H$) and dissolved organic carbon (DOC) analyses were combined from both sections of the trench.

3. Modeling approaches to describe stormflow

Reliable prediction of runoff from hillslopes under conditions of humid temperate climates with preferential flow-type hydrological response to rainstorms remains a challenge. With the enormous increase in computational efficiency in recent years, three-dimensional modeling representations of flow and transport processes at the hillslope and catchment scales have become possible (Rigon et al., 2006; Hopp et al., 2009; Mirus and Loague, 2013). However, from a large-scale perspective, the three-dimensional (3D) impact of local-scale features and processes (e.g., spatial heterogeneity of soil properties and preferential flow) tends to be spatially averaged since the thickness of the permeable soil is usually relatively small compared to the length of the simulated hillslope. Therefore, one- and two-dimensional approaches can often be successfully applied to predict runoff from a sloped soil profile.

One-dimensional variably saturated vertical flow was previously combined with one-dimensional saturated subsurface lateral flow by, for example, Fan and Bras (1998) and Troch et al. (2002). Subsurface lateral flow along the soil–bedrock interface is often described by a 1D Boussinesq-type diffusion wave equation, whereas models based on a solution of Richards' equation are used to predict 1D vertical water flow (Figure 2). The 1D approaches are very efficient in terms of computational speed. This becomes important when hillslope models are coupled with models used for large-scale predictions.

The diffusion wave equation for the saturated lateral flow (LatFlow model) is obtained by substituting the local hillslope discharge into the continuity equation (Vogel et al., 2003):

$$\Theta \frac{\partial h_D}{\partial t} - \frac{\partial}{\partial x}\left(K_D h_D \left(\frac{\partial h_D}{\partial x} + \frac{dz}{dx} \right) \right) = R \tag{1}$$

where Θ is the effective porosity ($m^3\ m^{-3}$), h_D is the depth of lateral flow (m), i.e. the vertical extent of the saturated stream, K_D is the effective saturated hydraulic conductivity ($m\ s^{-1}$), x is the coordinate (m) running along the bedrock slope (positive in the upslope direction), z is the vertical coordinate (positive upward), dz/dx is the local hillslope gradient (-), R is the local intensity of vertical recharge ($m\ s^{-1}$), and t is time (s).

To evaluate a shallow saturated subsurface flow, the following equation is used (Boussinesq, 1877):

$$\frac{Q}{W} = -K_D h_D \left(\frac{\partial h_D}{\partial x} + \frac{dz}{dx} \right) \tag{2}$$

where Q is the local hillslope discharge ($m^3\ s^{-1}$) and W is the hillslope width (m).

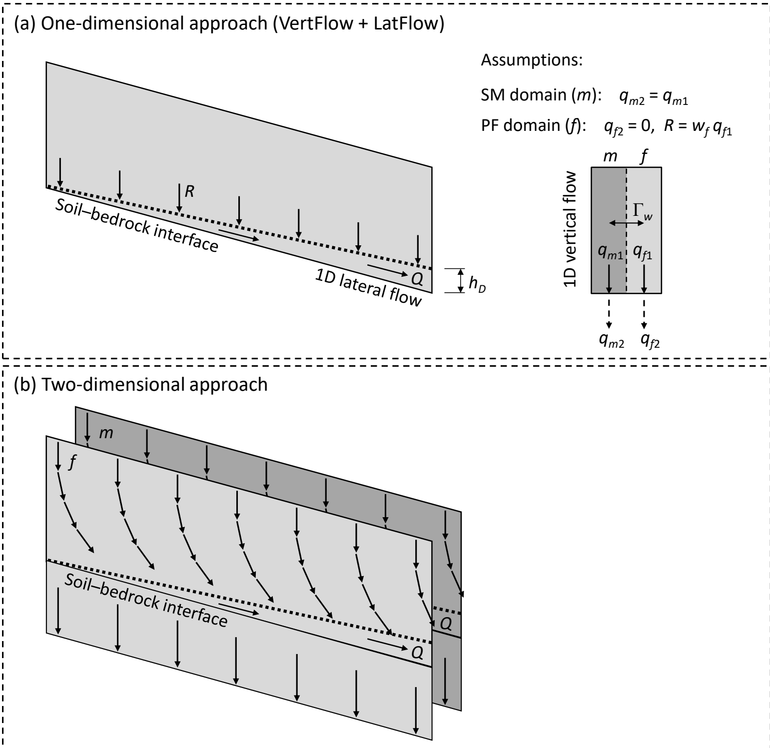

Figure 2. Schematic of flow in a hillslope segment representing two modeling approaches: (a) One-dimensional approach, in which R is the intensity of recharge feeding the saturated lateral flow (LatFlow model), h_D is the depth of lateral flow, Q is the hillslope discharge, q_{m1}, q_{m2}, q_{f1}, and q_{f2} are the soil water fluxes generated by the 1D vertical dual-continuum soil water flow model (VertFlow), and Γ_w is the inter-domain soil water transfer rate, SM and PF refer to the soil matrix and preferential flow, respectively, w_f is the volume fraction of the PF domain, (b) two-dimensional approach with two planar flow domains (SM and PF domains).

The dual-continuum concept (Gerke and van Genuchten, 1993) is used to solve the vertical water flow through a dual-continuum porous medium (VertFlow model), which means that water flow takes place in both the soil matrix (SM) and preferential flow (PF) domains, and Richards' equation describes water flow in each of the two domains. Both equations are coupled using a transfer term, which allows for dynamic water exchange between the two pore domains. The following pair of governing equations is applied to describe the 1D vertical movement of water (Vogel et al., 2010):

$$\frac{\partial w_f \theta_f}{\partial t} = \frac{\partial}{\partial z}\left(w_f K_f \left(\frac{\partial h_f}{\partial z} + 1 \right) \right) - w_f S_f - \Gamma_w \qquad (3)$$

$$\frac{\partial w_m \theta_m}{\partial t} = \frac{\partial}{\partial z}\left(w_m K_m \left(\frac{\partial h_m}{\partial z} + 1 \right) \right) - w_m S_m + \Gamma_w \qquad (4)$$

where f denotes the PF domain, m denotes the SM domain, θ is the volumetric soil water content (m^3 m^{-3}), h is the pressure head (m), K is the unsaturated hydraulic conductivity (m s^{-1}), S is the local root water extraction intensity (s^{-1}), Γ_w is the soil water transfer term (s^{-1}) controlling the water exchange between the domains, w_m and w_f are volume fractions of the respective domains ($w_m + w_f = 1$), z is the vertical coordinate (m) directed positive upward. The transfer term Γ_w is evaluated from the pressure head difference between the two pore systems and the relative conductivity of the SM-/PF-domain interface.

Two approaches to modeling hillslope responses to rainstorms, which differ in dimensionality and thus in complexity of geometric, material, and boundary conditions, were tested and confronted with soil water pressure and hillslope discharge data observed in an experimental trench (Dusek and Vogel, 2014). The one-dimensional approach combines 1D variably saturated vertical soil water flow with 1D saturated lateral flow above the soil–bedrock interface (VertFlow + LatFlow model) (Figure 2). In this approach, the vertical flow is modeled using a dual-continuum concept, while the lateral flow is described using the diffusion wave equation. In the two-dimensional approach, the movement of water in a hillslope segment is modeled as a vertical planar flow and therefore the vertical and lateral flow components are fully integrated into a single flow system (Figure 2). Similar to the 1D approach, the preferential flow effects are implemented in the 2D model (Vogel et al., 2000) by means of the dual-continuum concept.

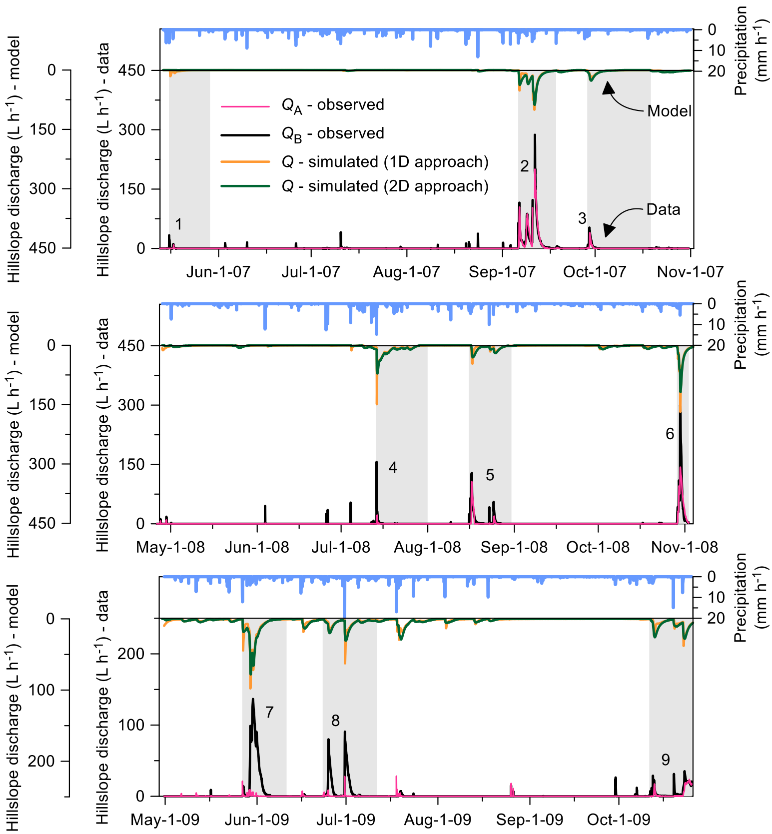

Figure 3. Observed (trench sections A and B) and simulated (using the 1D and 2D approaches) hillslope discharge during three growing seasons. The 1D approach combines VertFlow and LatFlow model. The selected major rainfall–runoff episodes are labeled with numbers and shown in shaded bars. The scales for the observed and simulated hillslope discharges are reversed.

Both model approaches (1D and 2D) resulted in similar hillslope discharge hydrographs (Figure 3), characterized by short-term runoff peaks followed by periods of zero discharge, but the 2D model showed greater agreement between observed and simulated soil water pressure heads near the trench (not shown here).

The lateral flow component becomes dominant with increasing depth towards the soil–bedrock interface (Figure 4). In the underlying bedrock, the dominant movement was vertical. Lateral intensities in the PF domain were approximately 200 times higher than in the SM domain. Significant lateral flow was also predicted in the SM domain near the soil surface. This was due to a sharp decrease in saturated conductivities between the first and second soil layers.

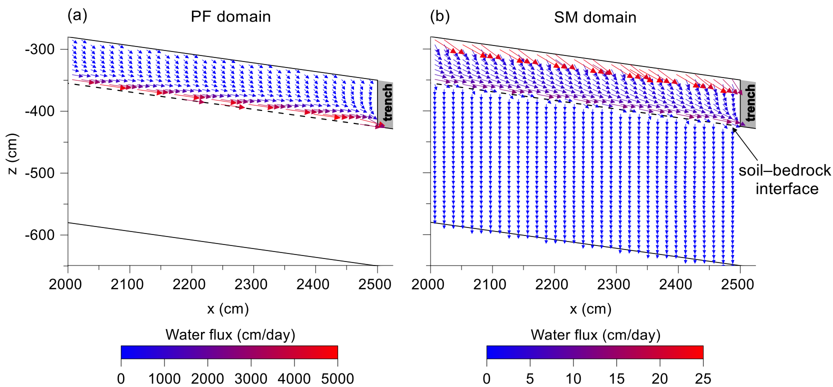

Figure 4. Vertical distribution of the water flux vectors in (a) the PF domain and (b) the SM domain obtained using a 2D dual-continuum model. The 5 m hillslope segment above the trench during the rainfall–runoff episode in September 2007 is shown. The magnitude of Darcian flux is indicated by color coding.

The simpler 1D approach based on a combination of 1D vertical flow and 1D lateral flow was found to provide a useful approximation of a more complex and flexible 2D system and is much more efficient in terms of computational time.

4. Thresholds of stormflow response

In recent literature, a threshold behavior of hillslopes with respect to the amount of rainfall that induces significant stormflow was proposed (Tromp-van Meerveld and McDonnell, 2006b; Graham and McDonnell, 2010; Steenhuis et al., 2013). As a result, a threshold relationship between rainfall and stormflow was adopted as an emergent hillslope property. To analyze threshold behavior at the Tomšovka site, a quantitative relationship between rainfall, stormflow, and bedrock leakage was sought for a hillslope where lateral preferential runoff is a dominant part of the overall hydrological response (Dusek and Vogel, 2016).

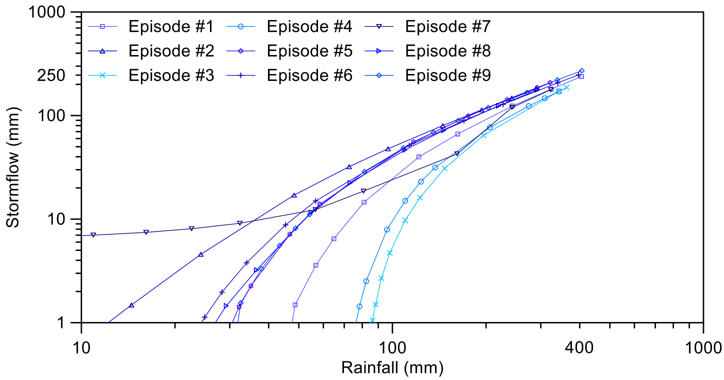

Figure 5. Relationship between rainfall and stormflow for synthetic rainfall episodes derived from the selected observed episodes. Symbols representing responses to synthetic episodes derived from the same observed episode are shown as interconnected.

The combined effects of the temporal rainfall distribution and initial hillslope saturation (antecedent moisture conditions) on stormflow, leakage to bedrock, and overall water balance were evaluated by conducting simulations with synthetic rainfall episodes. This allowed the analysis of causal relationships between initial hillslope storage, rainfall, stormflow, and bedrock leakage. A two-dimensional dual-continuum model (Vogel et al., 2000) was used in this analysis.

Figure 5 shows the effect of varying episodic rainfall on stormflow for synthetic rainfall episodes derived from individual observed episodes. The stormflow response became highly nonlinear (Episodes #3 and #4) for smaller initial hillslope storage. For large rainfall inputs (approximately 400 mm), the simulations converged to a narrow range of stormflow (240–270 mm), regardless of the initial degree of saturation.

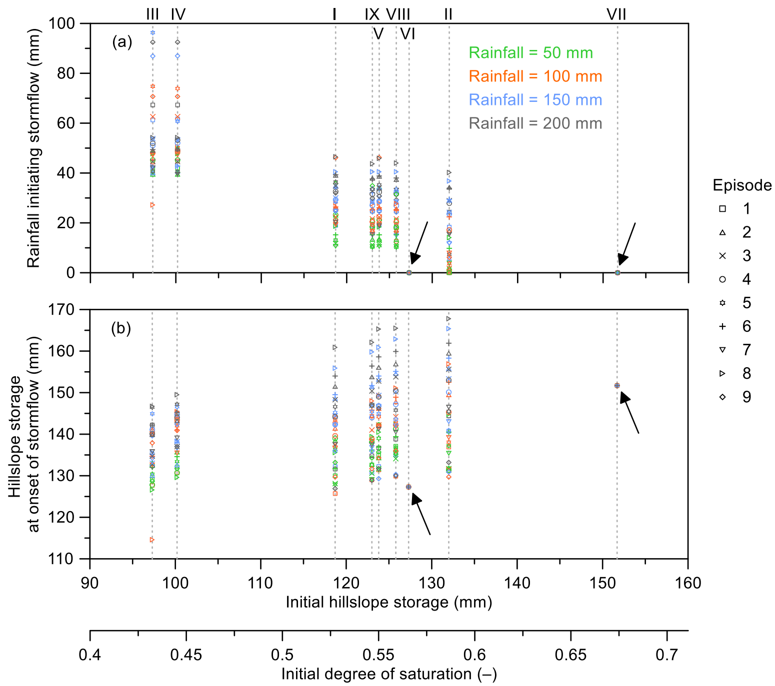

Figure 6. The volume of rainfall that initiates stormflow (*RIS*) for different synthetic rainfall episodes (distinguished by episode number and total rainfall) as a function of initial saturation (a). Hillslope storage at the onset of stormflow (*HSOS*) as a function of initial saturation (b). Arrows indicate the convergence of the *RIS* and *HSOS* values related to different rainfall episodes. Initial saturation is indicated by Roman numerals.

The threshold relationship between rainfall and stormflow is illustrated in Figure 6a. The amount of rain needed to initiate stormflow (*RIS*) appears to be a dynamic hillslope property that depends on the temporal distribution of rainfall, the initial water storage of the hillslope, and the spatial distribution of soil water within the hillslope. As expected, *RIS* was predicted to decrease with increasing initial saturation. No single rainfall threshold was found to be responsible for triggering of stormflow. The *RIS* volume is a function of both rainfall amount and initial hillslope water storage.

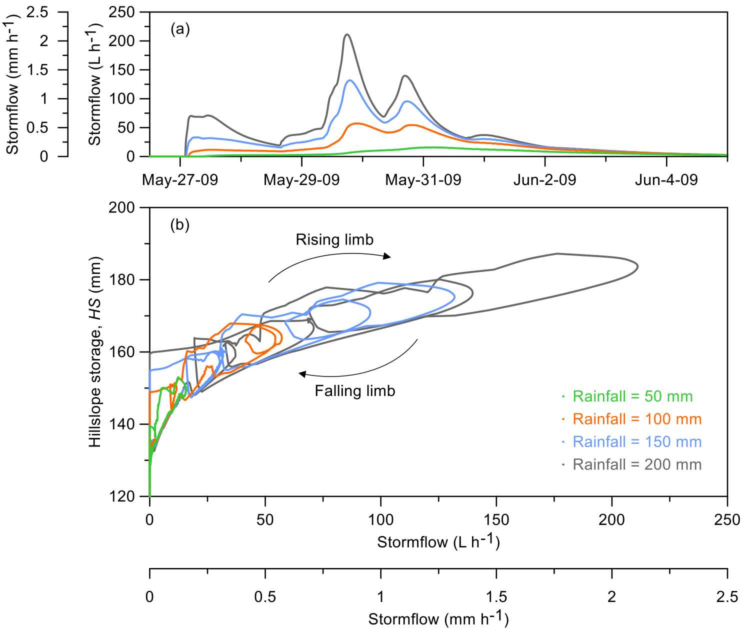

Figure 7. Simulated stormflow hydrograph (a) and hysteretic relationship between stormflow and hillslope water storage (b) for four synthetic rainfall episodes derived from the observed episode.

Similar to the *RIS* volume, the hillslope storage at the onset of stormflow can also be used to characterize conditions at the beginning of stormflow (Figure 6b). It can be seen that the onset of stormflow was controlled by a combination of the initial hillslope water storage and temporal distribution of rainfall.

The hysteretic behavior in the hillslope stormflow–storage relationship was analyzed in Figure 7. The hysteretic loop of stormflow–storage relationship was consistently oriented in a clockwise direction, indicating higher storage for the rising limbs of stormflow hydrograph than storage associated with the falling limbs. The hysteretic behavior was obtained without any additional provisions for hysteresis of soil hydraulic characteristics, variable soil depth, and variable soil–bedrock topography. The hysteretic pattern can be explained by the difference in the timing of responses between the hillslope storage and stormflow. Hillslope storage responded faster than stormflow; such response is expected for water flow in the subsurface, where a saturated zone must develop before stormflow can begin. The nonlinear dynamics of hillslope runoff processes, manifested by the hysteresis in the stormflow–storage relationship, is due to the nonlinear character of the governing equations.

5. Signatures of natural and synthetic isotopes in hillslope hydrograph

Stable isotopes of water (^{18}O and ^{2}H) that occur naturally in rainwater can reveal major transport mechanisms at a variety of scales, from soil profile to hillslope and catchment (e.g., McGuire and McDonnell, 2010). Specifically, isotope data are often used to separate runoff in pre-event (''old'') and event (''new'') water by applying a mass balance approach. Thus, isotopes can help explain the mixing mechanisms of new and old water at relevant spatial scales. Several experimental case studies showed that event water in runoff from hillslopes and catchments is a small fraction of the total runoff, even in cases where discharge is expected to be dominated by preferential flow (see e.g., McDonnell, 1990; Burns et al., 2001; Kelln et al., 2007). Based on a compilation of studies performed in small and medium-sized catchments, Buttle (1994) concluded that at least 50% of the streamflow is supplied by pre-event water. Such a finding is based on hydrograph separation techniques using experimental stable water isotope data (or other conservative tracers) in conjunction with a mass balance approach (Klaus and McDonnell, 2013).

To study the rainfall–runoff relationships at the Tomšovka hillslope, a one-dimensional approach was used that combined models of 1D dual-continuum vertical flow in a variably saturated soil profile and 1D saturated lateral flow along the soil–bedrock interface (VertFlow + LatFlow model) (Dusek et al., 2012a, 2012b). The transport of the natural stable isotope ^{18}O and a synthetic isotope tracer in the hillslope soil was considered (Dusek et al., 2012b). Using numerical experiments with synthetic ^{18}O signatures, the contributions of pre-event and event water to hillslope runoff during major rainfall–runoff episodes were evaluated. The 1D transport of the natural isotope and synthetic tracer in the saturated zone above the soil–bedrock interface is described by the advection–dispersion equation.

Similar to soil water flow (Eqs. (3) and (4)), the one-dimensional vertical transport of solute in a dual-continuum porous medium is described by a pair of advection–dispersion equations:

$$\frac{\partial w_f \theta_f c_f}{\partial t} + \frac{\partial w_f q_f c_f}{\partial z} - \frac{\partial}{\partial z}\left(w_f \theta_f D_f \frac{\partial c_f}{\partial z} \right) = -w_f S_f c_f - \Gamma_s \qquad (5)$$

$$\frac{\partial w_m \theta_m c_m}{\partial t} + \frac{\partial w_m q_m c_m}{\partial z} - \frac{\partial}{\partial z}\left(w_m \theta_m D_m \frac{\partial c_m}{\partial z} \right) = -w_m S_m c_m + \Gamma_s \qquad (6)$$

where c is the solute concentration (kg m^{-3}), q is the soil water flux (m s^{-1}), D is the hydrodynamic dispersion coefficient (m^2 s^{-1}), and Γ_s is the solute transfer term (kg m^{-3} s^{-1}). The coefficient of hydrodynamic dispersion D depends on the respective values of the local soil water flux and soil water content as well as the dispersivity and the molecular diffusion coefficient. The solute transfer term Γ_s takes into account the advective component due to water transfer and the diffusive component due to the difference in local solute concentrations.

The isotope composition observed in hillslope discharge is compared with the model prediction in Figure 8. The simulation results, based on natural isotopic signatures, supported the hypothesis of significant mixing of infiltrating rainwater and water stored in the soil profile of the hillslope. The modeling approach successfully described both the vertical and lateral mixing of water. The contribution of pre-event water accounted for 47–74% of the total hillslope discharge for the selected rainfall–runoff episodes. The simulation results based on synthetic isotopic signatures indicated that pre-event water is a significant component of runoff, although preferential flow plays an important role in the generation of hillslope runoff. These findings can be explained by the fact that pre-event water in the soil matrix domain is transferred to rapidly draining preferential pathways during rainfall–runoff episodes. As a result, a mixture of pre-event and event water is predicted in hillslope stormflow.

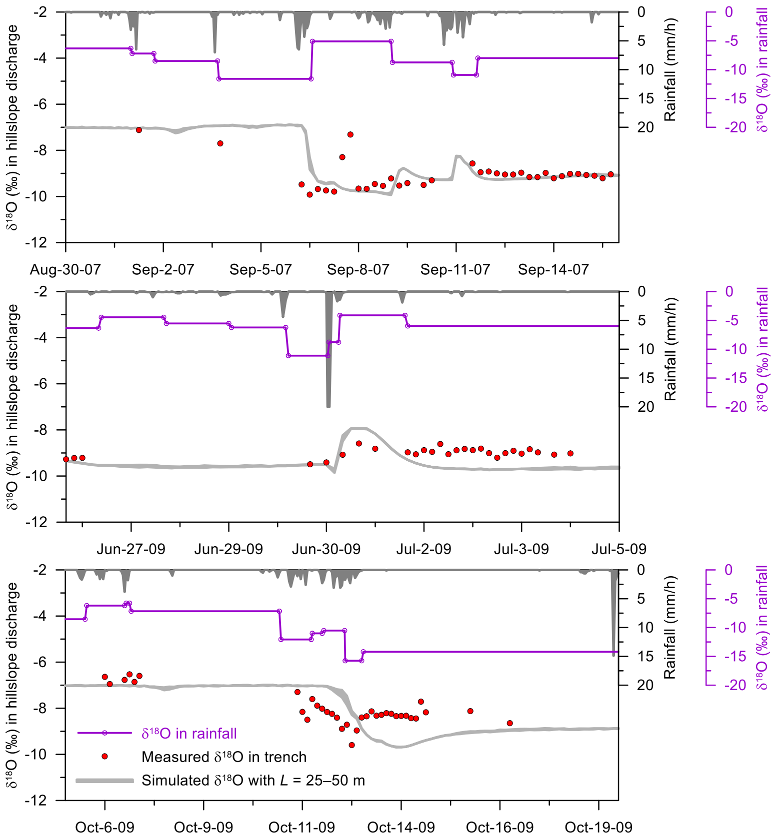

Figure 8. Observed and simulated (VertFlow + LatFlow model) ^{18}O content in hillslope discharge during the three selected episodes. The shaded area of the simulated $\delta^{18}O$ represents the uncertainty in determining the contributing hillslope length (L = 25–50 m).

In a subsequent study (Dusek and Vogel, 2018), a two-dimensional dual-continuum model was used to study the preferential flow of water and the transport of $\delta^{18}O$ in a vertical cross-section of the Tomšovka hillslope segment. The effects of hydrodynamic mixing and spatiotemporal variability of isotopic signatures on the estimated pre-event/event water fractions in hillslope discharge were studied using numerical experiments.

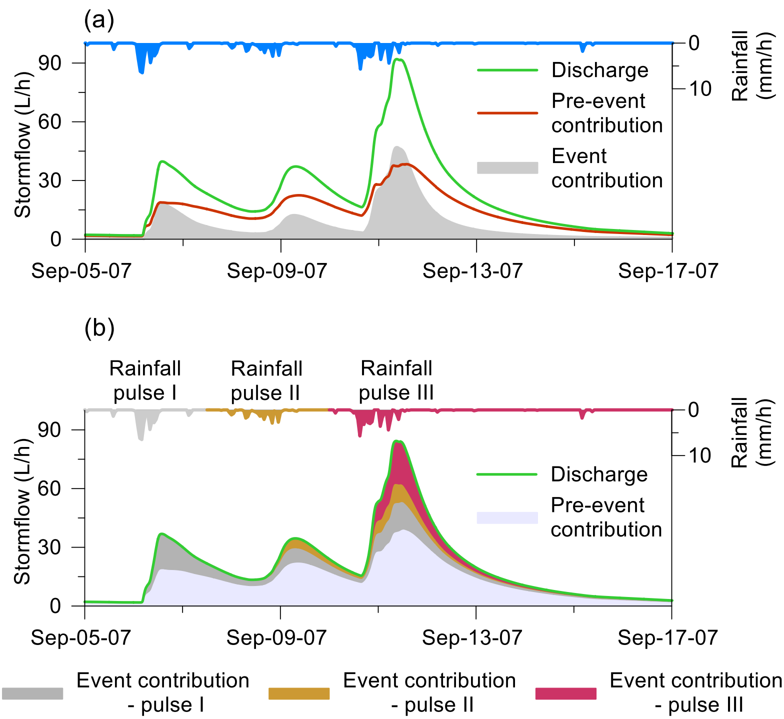

Figure 9. Separation of hillslope discharge during a single rainfall–runoff episode into pre-event and event water contributions (a) and three event water contributions induced by three rainfall pulses (b).

The mass balance approach failed to separate the hillslope discharge into pre-event/event water components for two-thirds of the selected rainfall–runoff episodes due to similar natural isotopic signatures of pre-event and event water. The analysis showed that spatially and temporally variable isotope exchange between the soil matrix and preferential pathways primarily affects estimates of the temporal origin of water in hillslope runoff. The degree of hydrodynamic mixing in the flow domain was shown to play an important role in interpreting the isotope-based separation of hydrographs.

In Figure 9, the hydrograph separation performed for a single rainfall–runoff episode is shown. For this multiple-peak episode, the pre-event water contribution was equal to 65% of the total stormflow, sustaining a large volume of the hillslope discharge during both the rising and falling limbs of the hydrograph. Figure 9b shows the individual event water contributions associated with the three rainfall pulses of this episode.

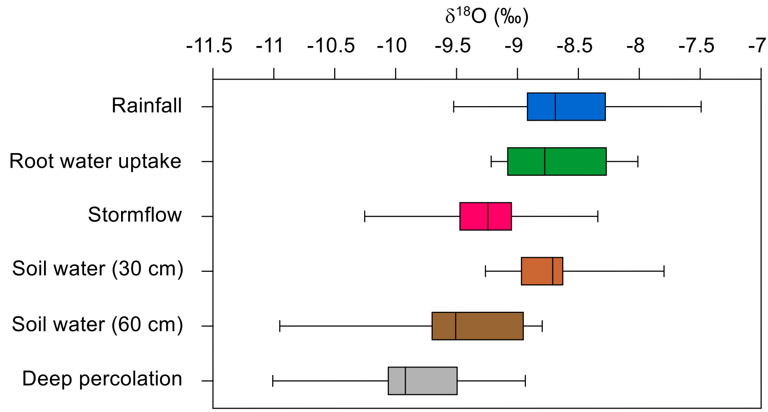

Figure 10. Simulated $\delta^{18}O$ in root water uptake, stormflow, soil water (30 cm and 60 cm depths), and deep percolation are shown for the period 2007–2016. The simulated isotope content in stormflow refers to the ^{18}O discharge from the preferential flow domain at the lower boundary of the soil profile. Deep percolation is represented by the discharge from the soil matrix domain at the lower boundary of the soil profile. The box plot represents the minimum and maximum, the 25% and 75% quartiles, and the median.

A follow-up study (Dusek and Vogel, 2024) examined the long-term isotopic composition observed in the Uhlířská catchment during the growing seasons

(2007–2016) and the temporal distribution of stable water isotopes in rainfall, soil water, stormflow, groundwater, and streamflow. Furthermore, the transport of isotopes in the hillslope soil profile at Tomšovka during ten growing seasons was studied using a one-dimensional vertical model (VertFlow) based on a dual-continuum approach. Transformation of the vertical soil water discharge by the lateral flow was neglected due to the relatively short contributing hillslope length and the enhanced soil hydraulic conductivity of preferential pathways in the direction along the hillslope. Synthetic tracer simulations were used to describe the partitioning of hillslope discharge into pre-event/event water components for selected rainfall−runoff events. The 35 selected rainfall−runoff events covered a wide range of different hydrological conditions.

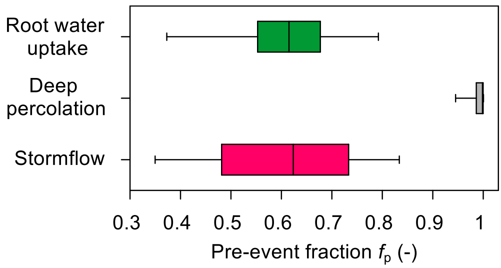

Figure 11. The simulated pre-event water fractions f_p in root water uptake, deep percolation, and stormflow evaluated for the 35 selected rainfall−runoff episodes using the flux-type weighting procedure. The box plots show the median value, the 25% and 75% quartiles. The whiskers show the minimum and maximum.

In Figure 10, the simulated flux-weighted $\delta^{18}O$ values in soil water, stormflow, root water uptake, and deep percolation are shown. The median flux-weighted $\delta^{18}O$ values in root water uptake, deep percolation, and stormflow indicate isotopically distinct water. The isotopic compositions observed in individual discharge components and soil water did not show significant differences (not shown here). However, isotopic differences in these components and soil water became apparent when flux-type weighting was considered.

The pre-event fractions in the discharge components evaluated for 35 rainfall–runoff episodes observed during the 2007–2016 growing seasons are weighted by the corresponding flux in Figure 11. For root water uptake and stormflow, a mixture of pre-event and event water is predicted, with median values equal to approximately 0.62. The median value of the pre-event deep percolation fraction is close to 1, indicating that event water from the soil matrix domain does not contribute much to discharge. It can be seen that the pre-event water fractions in the soil matrix and preferential pathways are significantly different.

6. Transport of dissolved organic carbon

Reliable quantitative predictions of water movement and solute fluxes, particularly organic carbon, at hillslope and catchment scales remain a challenge due to complex boundary conditions and soil spatial heterogeneity. Within the aqueous carbon cycle, the major forms of carbon include dissolved organic carbon, particulate organic carbon, and dissolved inorganic carbon. Recently, numerous studies reported increasing concentrations of DOC in surface waters (see e.g., Worrall et al., 2004; Weyhenmeyer, 2008; Zhang et al., 2010), which raised concerns about drinking water treatment (Oulehle and Hruška, 2009). The need for a better understanding of DOC transport in the soil compartment was highlighted by Hagedorn et al. (2000), who emphasized the role of changing hydrological pathways for DOC transport even during a single rainfall–runoff event.

A one-dimensional dual-continuum vertical flow and transport model (VertFlow) was used to simulate subsurface transport processes in the macroporous forest hillslope soil at Tomšovka for a period of 2.5-years (Dusek et al., 2017). Zero-order production and first-order decomposition processes (in the liquid and solid phase) were considered to account for microbially mediated DOC transformations. In addition, DOC transformations were assumed to depend on soil moisture and soil temperature.

The model was used to describe biogeochemical transformations of dissolved organic carbon in soil and to predict DOC concentrations in hillslope stormflow (Figure 12). Despite the complex nature of the transformations that caused uncertainty in the model parameters and subsequent prediction of DOC transport, the simulated temporal patterns of DOC concentration in stormflow exhibited similar behavior to that reflected in the observed DOC fluxes. Due to preferential flow, the contribution of DOC export from the hillslope was higher than the amounts typically reported in the literature. The model can be used to establish mass fluxes at the hillslope scale and may serve as a basis for upscaling this information to the catchment scale.

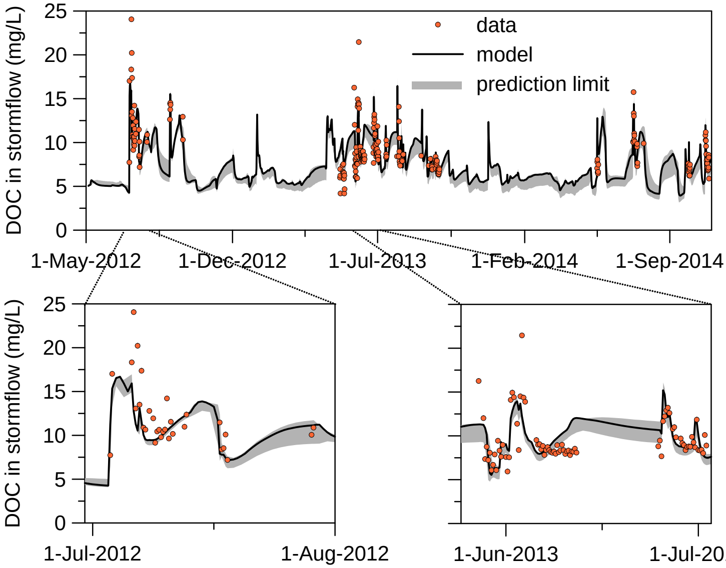

Figure 12. Observed DOC concentrations compared to simulated concentrations in hillslope discharge. Observed concentrations in the effluent are shown by symbols, the shaded area represents the prediction limit, and the solid line represents the predicted concentration based on the best behavioral simulation.

The same modeling approach model was used to simulate subsurface transport processes at the Tomšovka hillslope over an extended period of 4.5 years (Dusek et al., 2019). The main objective of this study was to test the model under different hydrological conditions that vary between seasons and years. These include contrasting weather conditions (cool and wet summers versus warm and dry summers) and extreme hydrological events, such as the extremely dry period in 2015. Particular attention was given to an alternative description of DOC sorption in the soil matrix using a kinetic sorption model and its comparison with an equilibrium sorption model.

In general, DOC transport could be adequately described assuming equilibrium sorption. The analyses performed showed that the inclusion of the kinetic description of DOC sorption only slightly improved predictions of DOC export from the hillslope. Furthermore, it was possible to observe the influence of seasonal hydroclimatological conditions on DOC hillslope export. Reduced DOC transport during extremely warm and dry summers was predicted with lower accuracy, indicating the difficulties in describing DOC transformations under dry conditions.

7. Travel times of hillslope discharge processes

The residence and travel times of water in the headwater catchments or in individual hillslopes are important descriptors of the hydrological regime of the catchments. Travel times of soil water contain useful information about flowpaths, sources and sinks of water, as well as the mixing between pre-event and event water in the catchment storage system (Danesh-Yazdi et al., 2018).

Furthermore, the residence and travel times of water in soils are of key importance for a reliable description of biogeochemical transformations of dissolved substances (such as dissolved organic carbon, nutrients, and contaminants). In addition to the mean travel or residence times, the travel time distribution is also of interest. If an environmental tracer (e.g., stable water isotope ^{18}O) is applied uniformly as an instantaneous unit pulse (the Dirac impulse) to the surface of the catchment or the hillslope, the breakthrough curve of the tracer at the outlet of the catchment or the hillslope would represent the travel time distribution, that is, the travel time probability density function (McGuire and McDonnell, 2006). This distribution is affected by the variability of the flow velocity field in soils, the variable length of the flow path, and hydrodynamic dispersion (Hrachowitz et al., 2016).

Dusek and Vogel (2019) evaluated travel time distributions and median travel times for the Tomšovka hillslope site. A two-dimensional dual-continuum model was used to simulate the seasonal soil water regime and selected major rainfall–runoff events observed at the hillslope site. The model was subsequently used to generate hillslope breakthrough curves of a fictitious conservative tracer applied to the hillslope surface in the form of the Dirac impulse.

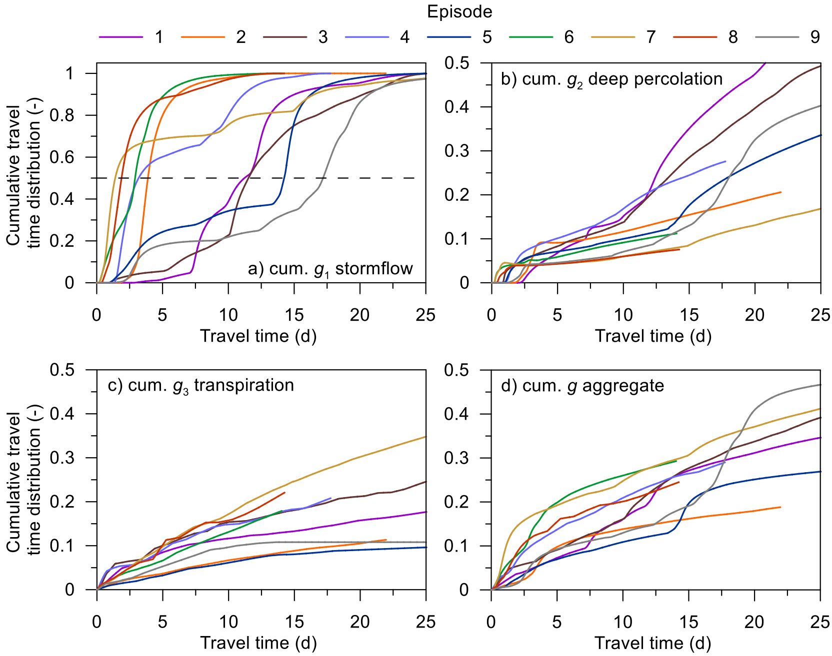

Figure 13. Cumulative travel time distributions of stormflow (a), deep percolation (b), transpiration (c), and aggregate distributions combing all discharge processes (d) for the selected rainfall–runoff episodes. The median travel time for stormflow corresponds to a value of the cumulative travel time distribution equal to 0.5.

The simulated tracer breakthroughs allowed us to estimate the travel time distributions of soil water associated with episodic subsurface stormflow, deep percolation, and transpiration, thus producing partial travel time distributions for individual discharge processes (Figure 13). The travel time distributions determined for stormflow were dominated by the lateral component of preferential flow. The stormflow median travel times calculated for the nine selected rainfall–runoff events varied considerably and ranged from 1 to 17 days. The estimated travel times were significantly affected by the temporal rainfall pattern and the distribution of antecedent soil moisture. The aggregate cumulative travel time distributions combining the individual discharge processes are shown in Figure 13d. The shape of the aggregate travel time distributions suggests that the effect of episodal stormflow is less pronounced than the combined effects of the more continuous processes (deep percolation and transpiration).

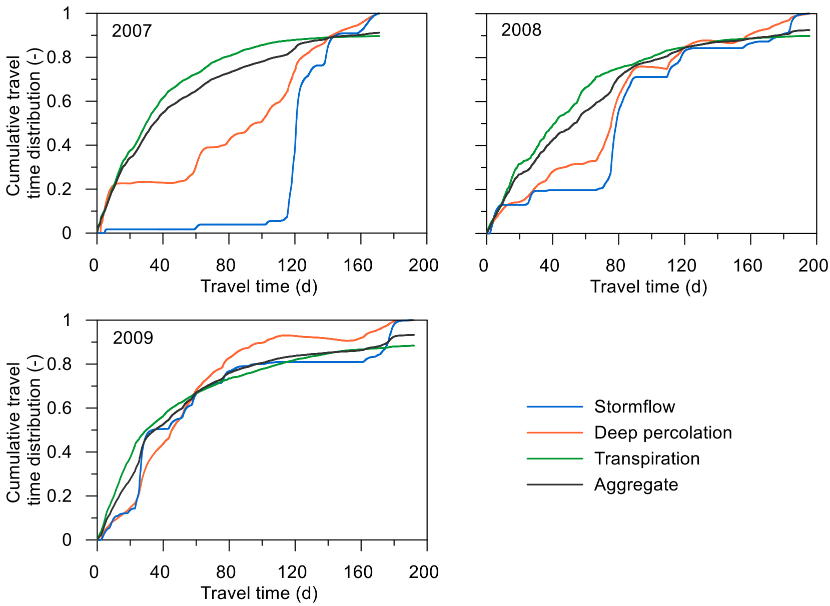

Figure 14. Cumulative travel time distributions of stormflow, deep percolation, and transpiration, together with the aggregate travel time distributions for growing seasons 2007, 2008, and 2009.

The cumulative partial travel time distributions for stormflow, transpiration, and deep percolation for the three growing seasons are shown in Figure 14. The steep increase in the cumulative travel time distribution of transpiration at the beginning of each season is related to the higher transpiration demand in the summer months and the high availability of the tracer (entering the soil profile at the beginning of each season). Later, the uptake of tracer by the roots became less intense and the tracer concentration became more diluted.

Cumulative travel time distributions for deep percolation and stormflow are more variable between seasons (Figure 14), reflecting the different number and timing of major rainfall–runoff episodes. Figure 14 also shows the aggregate travel time distributions, which combine the effects of all hillslope discharge processes. Due to the higher relative weight of transpiration compared to stormflow and deep percolation, the shape of the aggregate travel time distributions is close to the shape determined for transpiration. The seasonal median travel time (for all discharge processes combined) was estimated to range from 30 to 46 days.

8. Conclusions and outlook

The hydrological response of the hillslope to rainfall was analyzed using several modeling approaches. In addition to stormflow dynamics and associated changes in hillslope soil water storage, conservative tracer (stable isotope of water) and reactive solute (dissolved organic carbon) transport were considered in the model analyses. The conservative tracer helped to assess the residence time of water in the hillslope, which is known to significantly affect the biogeochemical transformations of reactive solutes.

Numerical models described the volumetric and mass fluxes through the mountain soil profile in reasonable agreement with experimental data. Moreover, the observations suggest that water mixing in the subsurface was well explained. The rainfall–runoff modeling showed rapid delivery of pre-event water through the system of preferential pathways. The results also indicated the interplay between the components of the hillslope water balance, revealing the nonlinear character of the hydrological hillslope response. The analyses provided quantitative information on the hydraulic functioning of hillslopes where the contribution of preferential flow forms the dominant part of stormflow.

The results of stable isotope transport simulations suggested that there is significant mixing between the infiltrating rainwater and water stored in the hillslope soil profile. It was confirmed that the inclusion of preferential flow in the conceptual model is necessary to adequately describe the flow and transport processes at the hillslope scale. The dominant part of subsurface runoff was formed by pre-event water. The spatially and temporally variable exchange of water between the preferential pathways and soil matrix was found to be a critical process in the generation of hillslope runoff. During rainfall–runoff events, water from the soil matrix was directed to preferential pathways near the soil–bedrock interface, indicating the soil matrix origin of pre-event water.

The isotopic composition observed in the individual discharge components and soil water did not show significant differences. However, when the flux-type weighting of isotopic signatures was applied in hillslope stormflow, deep percolation, and root water uptake, isotopically distinct waters became evident. Using numerical modeling, the mechanism by which different waters used for plant root uptake, stormflow, and groundwater recharge coexist at the hillslope scale was demonstrated.

In studies dealing with modeling of the transport of dissolved organic carbon, microbially mediated transformations were considered. Variations in the concentrations and mass fluxes of dissolved organic carbon in stormflow were reasonably well described by both the equilibrium model and the kinetic sorption model. However, the results indicated that the uncertainties associated with the parameterization of the dissolved organic carbon transformations in soils remain high.

The analysis aimed at evaluating travel times reveals the interplay between soil water storage and discharge processes at the hillslope site of interest. The methodology can be used to assess runoff dynamics at larger scales and also to quantify the biogeochemical transformations of dissolved chemicals. The travel time distributions associated with different discharge mechanisms provided meaningful information for the catchment runoff modeling.

The mathematical models provide effective tools for assessing water regime and transport processes in porous systems. The use of modeling tools will continue to expand in the near future as detailed monitoring campaigns are expensive and labor intensive. In addition, analysis quantifying “what-if-scenarios” can only be performed using mathematical models. Reliable parameterization of deterministic physically-based models, as well as adequate conceptualization and description of relevant runoff processes, remain key issues in hillslope hydrology.

Highly temporally resolved isotope sampling in runoff and spatially resolved isotope sampling in the soil profile seem promising for a robust model description of the transport processes. The sampling of hillslope stormflow can be complemented by sampling the fluxes from the soil lysimeter. Novel measurement techniques at the soil surface and at the soil–bedrock interface can improve the parameterization of the hydraulic characteristics of the topsoil and bedrock. This can lead to a reliable approximation of the flux separation at these interfaces, which is so important for assessing the overall hydrological response to precipitation.

Non-invasive geophysical measurements (e.g., ground penetrating radar and electrical resistance tomography) can be used to identify subsurface structures, including microtopography of the soil–bedrock interface. Techniques for visualizing soil structure, water flow, and tracer transport in undisturbed soil samples (e.g., X-ray computed tomography and neutron imaging) may also be useful, although the transferability of soil hydraulic and transport parameters between laboratory and field scales remains a challenge. Routine experimental evaluation of the temporal variability of soil hydraulic properties affected by extreme changes in weather conditions has the potential to improve the model descriptions of the water regime in hillslope soils.

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Education

2019	Associate Professor (doc.) in Water Management and Water Structures, Faculty of Civil Engineering (FCE), Czech Technical University in Prague (CTU Prague)
2008	Ph.D., Dept. of Hydraulics and Hydrology, FCE, CTU Prague
2001	Ing., Dept. of Hydraulics and Hydrology, FCE, CTU Prague.

Employment and professional experience

2019–	Dept. of Hydraulics and Hydrology, FCE, CTU Prague, associate professor
2010–19	Dept. of Hydraulics and Hydrology, FCE, CTU Prague, researcher and assistant professor
2009	Dept. of Civil & Environmental Engineering, University of Hawaii at Manoa, Honolulu, HI, USA, postdoctoral research trainee (12 months)
2005–08	Dept. of Hydraulics and Hydrology, FCE, CTU Prague, researcher and teaching assistant
2003	Dept. of Civil & Environmental Engineering, Water Resources Research Center, University of Hawaii at Manoa, Honolulu, HI, USA, research trainee (12 months).

Recent research activities

2022–24	The Czech Science Foundation project “Hydrological performance of multi-layered constructed soils” (22-25673S).

2020–22 The Czech Science Foundation project “Underrepresented processes affecting the water balance of forest catchments in headwater areas of temperate zone” (20-00788S).

2017–19 The Czech Science Foundation project “Preferential transport in structured soils - multiscale approach” (17-00630J).

2016–18 The National Science Foundation, International Research Experiences for Students (IRES, USA) “U.S.-Czech Republic collaborative research on understanding water and chemical transport in the vadose zone” (1460129).

2016–20 The Ministry of Culture (NAKI-II) “Evaluation of stability and technical conditions of the Broumov group of churches and proposal of remediation of this unique Europe culture heritage” (DG16P02R049).

2016–18 The Czech Science Foundation project “Soil water regime in headwater catchments under climatic stress” (16-05665S).

2014–16 The Czech Science Foundation project “Subsurface transport of water, carbon and heat - combined hydrological, geochemical and isotopic approach” (14-15201J).

2014–16 The Czech Science Foundation project “Isothermal and non-isothermal water flow and solute transport in near-saturated porous media” (14-03691S).

Recent selected publications

Dusek, J., Vogel, T., 2024. Isotopic signatures and soil water partitioning in a humid temperate forest catchment: Implications for the ‘two-water-worlds’ hypothesis. Journal of Hydrology 632, doi: 10.1016/j.jhydrol.2024.130893.

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Dusek, J., Vogel, T., Dohnal, M., Barth, J.A.C., Sanda, M., Marx, A., Jankovec, J., 2017. Dynamics of dissolved organic carbon in hillslope discharge: Modeling and challenges. Journal of Hydrology 546, 309–325.

Dusek, J., Vogel, T., 2016. Hillslope-storage and rainfall-amount thresholds as controls of preferential stormflow. Journal of Hydrology 534, 590–605.

Metrics

Number of articles in peer-reviewed journals (Web of Science): 45

H-index (Web of Science): 18

Number of citations in Web of Science without self-citations: 680