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Examining the role of throughfall patterns on subsurface stormflow generation

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SUMMARY

The effect of throughfall input patterns on the hydrological response of forested hillslopes is not well understood. While field studies have contributed to our understanding of subsurface stormflow generation at the hillslope scale, such work is still of limited value because of the small number of places and events that have been characterized to date and the uniqueness of each study hillslope. In recent years, virtual experiments have been used to investigate the role of topography, soil depth, bedrock permeability and storm size, on the generation of lateral subsurface flow. However, these studies have generally assumed spatially uniform rainfall, and the interaction between vegetation and its effect on the spatial structure of input (canopy interception, throughfall) for hillslope hydrologic response has not yet been explored. Here we present a number of virtual experiments that explore the interplay among hydrological inputs (temporal and spatial distribution of rainfall) and hillslope properties (subsurface topography, soil depth), i.e. physical phenomena that are sources of space and/or time variability. We address specifically the relative importance of fine-scale throughfall patterns for hillslope hydrologic response. Topography and hydrologic field observations from an existing study hillslope were used to calibrate and test a 3D Richards equation-based finite element model. Throughfall patterns were based on published throughfall patterns in an even age stand of young conifers in the Pacific Northwest. These patterns were then varied across the hillslope during the virtual experiments. Our results showed that, surprisingly, the effect of spatial input variability of throughfall on lateral subsurface stormflow generation was minimal. For our tested case, the bedrock topography control on flow generation was much greater than the fine-scale spatial variability of the input. Using a spatially uniform area-averaged "throughfall" (i.e. open rainfall reduced by some assumed fraction, which is the simplest and most common form of throughfall representations) yielded minimal differences in subsurface stormflow response. Nevertheless, using open rainfall as spatially uniform input strongly overestimated lateral subsurface stormflow, and thus, the average impact of throughfall is important for input estimation at the hillslope-scale. Overall, the effects of fine-scale throughfall patterns on subsurface stormflow generation appear to be of secondary importance compared to effects of temporal distribution of rainfall, subsurface topography and variable soil depths.

1. Introduction

Much of the benchmark work in hillslope hydrology has been based in forested catchments (Hewlett and Hibbert, 1967; Mosley, 1979; Noguchi et al., 1999). Despite this, input to hillslope hydrological models has often been rainfall measured in a forest opening (McDonnell, 1990) or, at best, some average interception loss applied to the temporally varying but spatially uniform rainfall input (Freer et al., 2002). In real systems, above-ground vegetation redistributes incident rainfall spatially. This results in patterns of throughfall measured below the plant canopy that can be spatially quite variable relative to open rainfall. While spatial throughfall patterns have been measured under various types of plant cover (Crockford and Richardson, 2000) and linked to surface runoff (Cattan et al., 2009), the role of fine-scale throughfall patterns on subsurface stormflow generation has not yet been addressed (here we define "fine-scale pattern" as input variability within the range of 1–10 m).

Assessing the role of throughfall on subsurface stormflow is a difficult problem. First, the hydrology of forested hillslopes is fraught with complexity because of variations in space of static hillslope attributes (e.g. soil depth) and variations in space and time of boundary conditions (e.g. precipitation input to the hillslope). Although early work in the field viewed hillslopes as simple additive, translatory flow systems (for review of early work see

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McDonnell, 2009), recent work has shown that distinct thresholds, patterns and feedbacks control their response to storm precipitation (Detty and McGuire, 2010; Spence et al., 2010; Tromp-van Meerveld and McDonnell, 2006a). Most problematic is how to understand and quantify the interactions among the many factors controlling subsurface stormflow generation, with each factor providing sources of spatial and/or temporal variability (Woods and Sivapalan, 1999).

Recent work has begun to address these interactions using virtual experiments (Hopp and McDonnell, 2009). However, studies to date have not yet examined if throughfall patterns matter for subsurface stormflow generation at the hillslope scale. The paired watershed approach (Bosch and Hewlett, 1982) does not lend itself easily to this question. Such experiments are exceptionally difficult to perform in the field with a given hillslope configuration because of the potential for confounding influences of both possible forest treatments and high variability in soil depth from slope segment to slope segment, even within a single watershed. Even more problematic is the pronounced variation in throughfall input across different time and space scales (Keim et al., 2005).

Consequently, the importance of spatially variable rainfall input has mostly been addressed in modeling studies. Most of these have focused on the small catchment- to large basin-scale where spatially variable rainfall inputs are caused by variability in the distribution of rain cells. More than 25 years ago Beven and Hornberger (1982) showed that the spatial distribution of rainfall significantly affected some hydrometrics (e.g. timing of the hydrograph, peak flows), but that by far the most important factor for accurate simulation of streamflow response was the knowledge of total input volume to the catchment. Subsequent studies have produced similar results since then suggesting that taking spatial rainfall patterns into account generally improves model performance (Andreassian et al., 2001; Chaubey et al., 1999; Mandapaka et al., 2009; Tetzlaff and Uhlenbrook, 2005). From this previous work, we would expect that throughfall patterns (like rainfall patterns) would have a large effect on subsurface stormflow response at the hillslope scale. The closest studies that underpin our work are the investigations of effects of throughfall patterns on soil moisture patterns (Bouten et al., 1992; Jost et al., 2004; Liang et al., 2007; Raat et al., 2002; Sansoulet et al., 2008; Shachnovich et al., 2008). However, these studies have yielded ambiguous relations between throughfall patterns and patterns of soil water percolation.

Here we build on our recent work on the effect of interactions of hillslope properties that affect subsurface stormflow generation (Hopp and McDonnell, 2009) and we hypothesize that throughfall patterns are a first-order control on lateral subsurface stormflow at the hillslope scale. Previous work on hillslopes with relatively shallow soils underlain by less permeable bedrock has shown the importance of the bedrock topography with its fill and spill areas for subsurface stormflow generation (Freer et al., 2002; Hopp and McDonnell, 2009; Tromp-van Meerveld and McDonnell, 2006a, 2006b). The assumption we test here is that the way throughfall patterns are arranged over the bedrock topography – e.g. high input over shallow soils and fill/spill areas – could have strong influence over where and when the perching of transient water tables at the soil–bedrock interface starts. These transient water tables have been shown to be a causal mechanism for the initiation of subsurface stormflow (Tromp-van Meerveld and McDonnell, 2006b). Certain combinations of throughfall patterns, soil depth distribution and underlying bedrock topography may lead to complex hydrologic response, analogous to the interaction between the pattern of landscape imperviousness and the pattern of rainfall found by Mejia and Moglen (2010). We use HYDRUS-3D as a model platform to test our hypothesis, following on work from Hopp and McDonnell (2009), to explore the effect of throughfall patterns on subsurface stormflow generation at the hillslope scale. We focus on the interactions between throughfall patterns and other spatio-temporally variable controlling factors, e.g. soil depth distribution or temporal structure of rainfall. We use a virtual experiment framework (following Weiler and McDonnell, 2004) and build on 2D modeling work of Keim et al. (2006) to address the following questions:

1. How is subsurface stormflow affected by a fine-scale throughfall pattern compared to spatially uniform rainfall measured in an opening?
2. Do different combinations of an irregular soil depth distribution and multiple realizations of the same fine-scale throughfall pattern lead to markedly different hillslope hydrologic response?
3. Is it sufficient to apply a spatially averaged precipitation reduced by the hillslope-scale averaged effect of throughfall or does the actual fine-scale pattern of the input significantly influence the outflow response at the base of the slope?
4. What is the role of throughfall relative to other spatio-temporally varying hillslope factors that control subsurface stormflow response?

2. Modeling approach

We developed two sets of simulations to address our research questions. First we investigated the effect of different realizations of a fine-scale throughfall pattern on the generation of subsurface stormflow, comparing results to spatially uniform input of open rainfall and spatially averaged throughfall (questions 1–3). Subsequently we explored the importance of throughfall patterns for subsurface stormflow generation relative to other spatio-temporally variable controlling factors (bedrock topography and soil depth variations; temporal distribution of precipitation input) in an attempt to "unscramble the omelet" (Brutsaert, 2005, p. 441) and isolate the effects of space–time variability of hillslope attributes and boundary conditions.

2.1. Comparing fine-scale throughfall patterns to spatially uniform rainfall input

2.1.1. Model domain and boundary conditions

We used the physics-based model HYDRUS-3D (Simunek et al., 2006) to investigate our research questions following the methodology presented by Hopp and McDonnell (2009). HYDRUS-3D is a finite element model that solves the Richards equation to simulate the movement of water in variably-saturated porous media. We used the geometry of the Panola study hillslope (Freer et al., 2002) as our model domain. The Panola study hillslope is part of the Panola Mountain Research Watershed (PMRW), situated in the Georgia Piedmont, 25 km southeast of Atlanta. Subsurface stormflow generation has been extensively studied at this trenched hillslope (e.g. Freer et al., 2002; Tromp-van Meerveld and McDonnell, 2006a, 2006b). The study hillslope has a slope angle of 13°. Surveyed surface and bedrock topography used in the model domain covers an area of 28 m by 48 m. The surface topography is relatively planar whereas the bedrock topography is highly irregular, resulting in variable soil depths ranging between 0 and 1.86 m, with a mean soil depth of 0.62 m and a coefficient of variation of 56% (Fig. 1). The soil is a sandy loam, devoid of discernible structure or layering and overlain by a 0.15 m deep organic-rich horizon. The bedrock directly underlying the soil consists of 2–3 m of porous saprolite (soft disintegrated granite derived from the Panola granite beneath). Previous work at this hillslope has demonstrated the importance of the bedrock topography for the development and large-scale connectivity of subsurface saturation ("fill and spill") as a prerequisite for the generation of subsurface

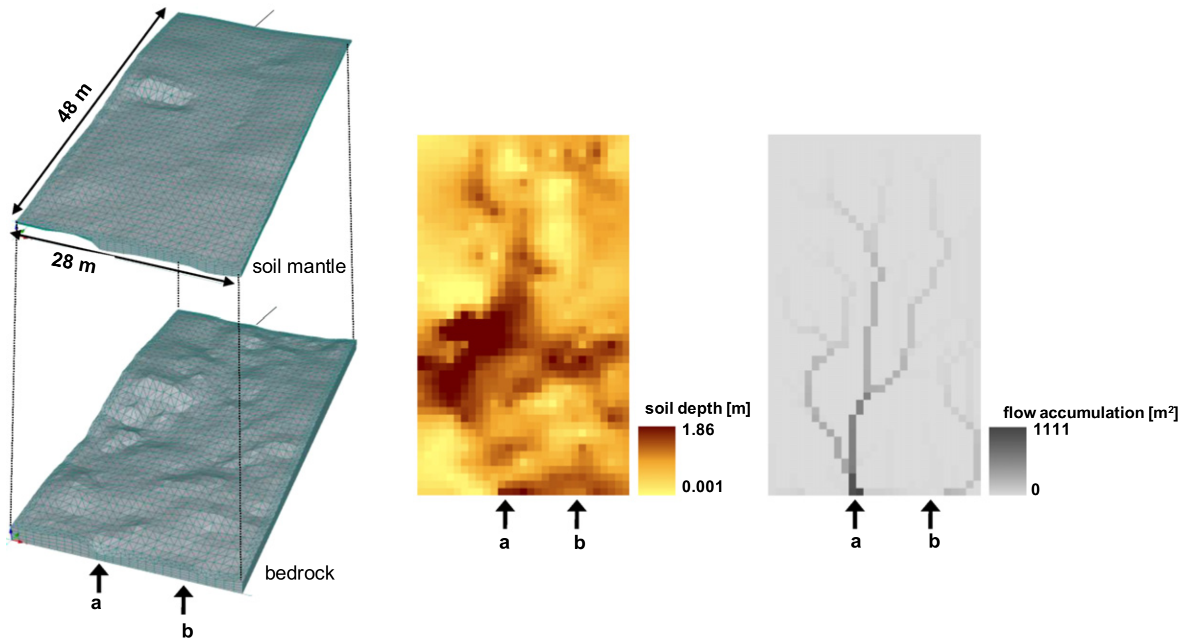


Fig. 1. Panola study hillslope: model domain showing surface and subsurface topography and finite element mesh (left), soil depth distribution (middle) and flow accumulation map of the bedrock topography (right). Flow accumulation (FA) for each cell was calculated from the 1 m DEM interpolated from the surveyed 2 m grid using the single-flow-direction D8 algorithm (Hopp and McDonnell, 2009). Arrows a and b highlight segments 10–12 m (a) and 20–22 (b) that are discussed in more detail in the analysis.

stormflow along the soil–bedrock interface (e.g. Hopp and McDonnell, 2009; Tromp-van Meerveld and McDonnell, 2006b). Digital terrain analysis showed that flow accumulation based on surface topography is different to that of bedrock topography (Fig. 1) and that bedrock topography well explains the spatial distribution of subsurface flow along the 20 m wide trench (Freer et al., 2002). As a consequence of the irregular bedrock topography with its fill and spill characteristics, a minimum storm total of approximately 55 mm is necessary to induce lateral subsurface stormflow (Tromp-van Meerveld and McDonnell, 2006a).

The details of the model setup were described in Hopp and McDonnell (2009). Here we only briefly describe how the model domain was created and how soil and bedrock parameters were determined. The model domain was generated by importing the Panola hillslope digital elevation model (*x*, *y*, *z*-coordinates of the surface and bedrock topography in 1 m resolution, interpolated from the surveyed 2 m grid), thus leading to the definition of two sublayers, one representing the soil mantle and the other one the bedrock (Fig. 1). The finite element mesh for the base case scenario contained 17,150 nodes, arranged in ten mesh layers and resulting in 29,484 3D elements in the form of triangular prisms. The thickness of the entire model domain ranged from 1.74 to 4.11 m, depending on the topography. The transition into the deeper bedrock was represented by an inclined planar base surface. The bedrock sublayer in the model domain was assumed to represent the saprolite layer described in detail in Tromp-van Meerveld et al. (2007).

The parameterization of the soil and bedrock layers used in this study was shown to reproduce subsurface stormflow response in good agreement with field observations of trench flow and spatially distributed pressure head (Hopp and McDonnell, 2009). Soil and bedrock were assumed to be homogeneous porous media. The organic layer was not represented in the model. Hydraulic parameters were described with the van Genuchten–Mualem soil hydraulic model (van Genuchten, 1980). The parameterization of the model was mostly based on field measurements of saturated hydraulic conductivity of soil and bedrock and observed ranges of soil moisture (Table 1). The parameterization of soil hydraulic properties accounted for the observed decrease in saturated hydraulic conductivities with depth, resulting in vertical anisotropy. The van Genuchten shape parameters α and n were the only hydraulic parameters that were calibrated (Hopp and McDonnell, 2009).

Table 1
Soil hydraulic parameters (van Genuchten–Mualem soil hydraulic model) used for the five materials of the model domain. Model mesh layers 1–5 represent the soil mantle, layers 6–10 the bedrock (saprolite). The organic layer is not represented in the model.

Material	Model mesh layer no.	θ_r $(m^3\ m^{-3})$	θ_s $(m^3\ m^{-3})$	α (m^{81})	n	K_s $(m\ h^{-1})$
1	1–2	0.28	0.475	4	2	3.5
2	3–4	0.28	0.46	4	2	1.5
3	5	0.325	0.45	4	2	0.65
4	6	0.3	0.45	3.25	1.75	0.006
5	7–10	0.28	0.4	3	1.5	0.0006

Initial conditions were defined in the pressure head by assuming a pressure head of −0.7 m everywhere in the domain followed by a 7 day drainage period without atmospheric input prior to the start of the actual rainstorm. The upslope boundary and the sides of the domain were treated as no flux boundaries. Two boundary conditions were defined at the downslope boundary of the hillslope (toe of the hillslope). A seepage face boundary condition was assigned to the soil sublayer across the entire width of the domain, allowing water to leave the domain through the saturated part of the boundary. The code assumes a pressure head equal to zero along the saturated part of a seepage face boundary. The bedrock sublayer was assumed to have no flux at the downslope boundary, implying that flow in the bedrock is primarily vertical and that lateral flow within the bedrock can be neglected. A free drainage boundary condition was specified for the bottom boundary (the bedrock), assuming a unit total vertical hydraulic gradient

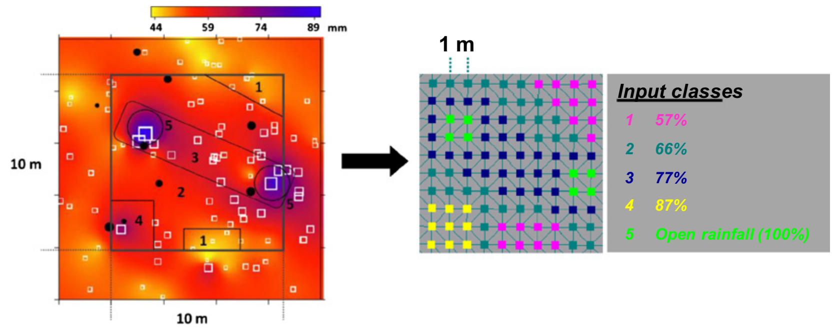
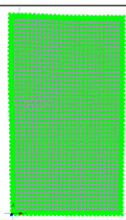
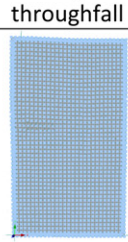
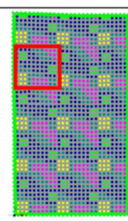
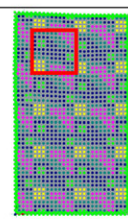
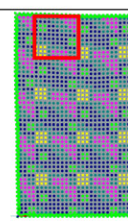
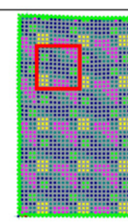
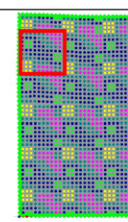
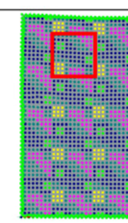


Fig. 2. Discretizing the interpolated throughfall map by Keim et al. (2005) (left; see their (c)) into five input classes that were used as surface boundary conditions in the simulations. Open white squares in Keim et al.'s figure indicate throughfall collectors, scaled to storm-total throughfall. The underlying color pattern was derived by interpolation by Kriging parameterized from variograms (see Keim et al. (2005) for more details on methods).

Table 2
Setup of the first set of simulations, investigating the effect of different realizations of throughfall on subsurface stormflow. Six realizations of a forested hillslope were generated by stitching the 10 m by 10 m throughfall map together. Red squares indicate the starting point for the stitching process. See Fig. 2 for the color legend of the throughfall pattern. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

	Open rainfall	Spatially averaged throughfall	Realization 1	Realization 2	Realization 3	Realization 4	Realization 5	Realization 6
Throughfall pattern								
Total rainfall [mm]	75	58	58	58	58	58	58	58

(i.e. a zero pressure head gradient). Boundary conditions imposed at the surface of the domain, controlling the input, are described in the following section.

2.1.2. Throughfall patterns and storm event

The throughfall pattern used in the simulations was derived based on measurements in an even age stand of young conifers in the Pacific Northwest, USA, by Keim et al. (2005). Ninety-four storage rain gauges were randomly placed within the stand to measure storm-total throughfall. Temporal dynamics of throughfall in the course of a storm event were not recorded with this setup. The throughfall pattern we selected for this study was derived from Keim et al.'s Fig. 2c that shows storm-total throughfall for a 83 mm storm (rainfall measured in an opening) with a mean throughfall of 56 mm, i.e. 67% of opening rainfall.

A 10 m × 10 m patch within the throughfall pattern measured by Keim et al. (2005) was selected (Fig. 2). Five classes of input amounts were delineated in this pattern (100%, 87%, 77%, 66% and 57% of opening rainfall) and discretized into a 1 m by 1 m grid that was used to specify five different surface boundary conditions in the model (Fig. 2, right). In HYDRUS-3D, up to five different variable flux boundary conditions can be specified, with prescribed flux rates. This means that five boundary conditions were available to describe the five input classes derived from the measured throughfall patterns.

The 100 m^2 patch was subsequently stitched together so that the entire surface of the model domain was covered with this recurring pattern, mimicking a forested hillslope. Depending on where the first 100 m^2 patch was placed, i.e. where the stitching started, different realizations of a forested hillslope could be created, resulting in six different combinations between the throughfall pattern and the underlying static bedrock topography. Six realizations of the forested hillslope were generated in this manner (Table 2) and used as surface boundary condition for the simulations.

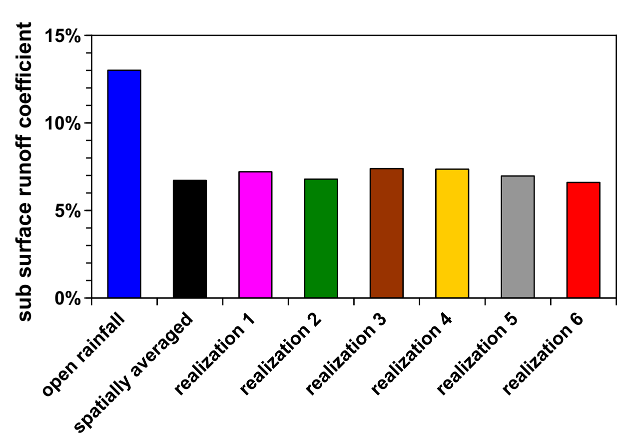


Fig. 3. Subsurface runoff coefficients for the first set of simulations: comparison of the six forest realizations (in shades of green) and the simulation with the spatially averaged (spatially uniform) throughfall (gray). All scenarios received the same total input. In addition, the subsurface runoff coefficient for the simulation using spatially uniform open rainfall is shown (in blue). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

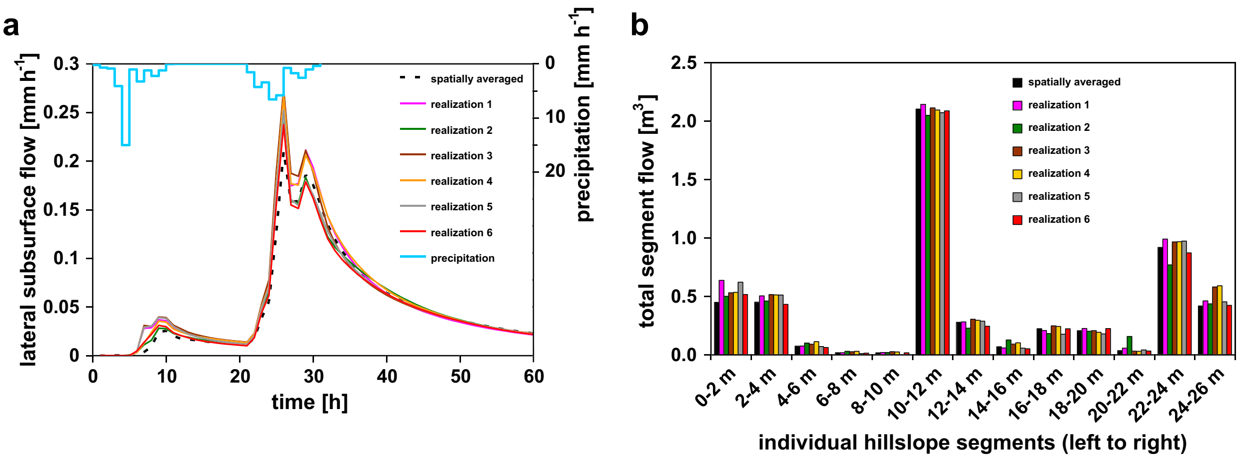


Fig. 4. Comparing subsurface stormflow response for the six forest realizations and spatially averaged throughfall. (a) Subsurface stormflow hydrographs. (b) Spatial distribution of subsurface flow along the downslope boundary of the hillslope, showing total subsurface flow per 2 m segment for the scenarios (from left to right facing upslope).

The simulations were event-based. The event used was a bimodal storm that lasted 31 h with a 10 h break in-between and is based in its temporal dynamics (but not its total rainfall depth) on a well-studied storm measured in March 1996 at the Panola study hillslope (Fig. 4). Both parts of the storm were very similar in cumulative rainfall. The total rainfall depth for the open rainfall (100%) was 75 mm, with a peak intensity of 19 mm h^{-1} in the first half and 8.5 mm h^{-1} in the second half of the storm. The hourly rainfall intensities were scaled down according to the specified input classes. With this approach we assumed that the throughfall pattern was temporally stable during the storm. The total rainfall depth for the spatially averaged throughfall scenario and the six forest realizations corresponded to 58 mm, i.e. a storm total above the precipitation threshold of 55 mm estimated for the Panola hillslope (Tromp-van Meerveld and McDonnell, 2006a). Additional effects of vegetation, such as canopy storage or intensity smoothing,

Table 3
Setup and naming of the second set of simulations, investigating the relative importance of bedrock topography, soil depth variability and spatial and temporal distribution of precipitation.

Complexity of hillslope geometry (Z)		*uniform soil depth no bedrock topography*	*uniform soil depth with bedrock topography*	*variable soil depth with bedrock topography*
Complexity of spatial variability of input (B): *spatially averaged input*	Complexity of temporal variability of input (C): *constant rate*	Z1-B1-C1	Z2-B1-C1	Z3-B1-C1
	varying rates	Z1-B1-C2	Z2-B1-C2	Z3-B1-C2
spatially variable input	*constant rate*	Z1-B2-C1	Z2-B2-C1	Z3-B2-C1
	varying rates	Z1-B2-C2	Z2-B2-C2	Z3-B2-C2

were not considered. Also evapotranspiration and root water uptake were not included in this event-based approach, assuming that these processes are only of minor importance on this short time-scale compared to the amount of input and generated subsurface runoff. In addition, the near-saturated relative humidity in the near-surface boundary layer during rainfall events effectively negates the gradient needed to drive evapotranspiration. Modeling results of the six forest realizations were compared to a simulation with spatially averaged, uniform throughfall. In all scenarios, the hillslope received the same total rainfall. Following hydrologic metrics were compared: instantaneous subsurface stormflow hydrographs (outflow from the downslope boundary of the hillslope, i.e. the seepage face boundary), subsurface runoff coefficients (total subsurface stormflow divided by total input), spatial distribution of subsurface stormflow and pressure head patterns at the soil–bedrock interface. In addition, a simulation using the open rainfall (total rain depth 75 mm), applied spatially uniform, was run for comparison (Table 2). Using rainfall measured with a rain gauge in an opening as model input represents a typical approach in hydrologic modeling.

2.2. The relative role of throughfall patterns on subsurface stormflow

Three factors that typically show variability in space and/or time were assessed in their combined influence on subsurface stormflow generation: (1) bedrock topography and variable soil depth distribution ("complexity of the hillslope geometry"), (2) the temporal structure of input (constant vs. variable input rates) and (3) spatial pattern of input (spatially uniform vs. spatially variable throughfall pattern). A systematic approach combining these factor variations was taken to isolate effects, resulting in 12 simulations (Table 3).

2.2.1. Model domain: increasing complexity of the hillslope geometry

Three hillslope geometries were used (Table 3). All were based on the Panola study hillslope described above, with the dimensions of 28 m by 48 m, and were comprised of a soil and a bedrock layer that had the same hydraulic parameters as used for the first set of simulations. The simplest geometry (Z1) consisted of a planar hillslope with a soil layer with uniform depth (0.62 m). Also the bedrock surface was planar. The next complex step was adding the real Panola bedrock topography (see Fig. 1) but keeping the soil depth spatially uniform (0.62 m) so that the surface topography was parallel to the bedrock surface (Z2). For the most complex hillslope geometry, the spatially variable soil depth distribution was added, resulting in the Panola hillslope geometry that was used for the simulations described in the previous section (Z3). All three hillslope domains had the same soil volume. The boundary conditions were set as described in the previous section (except for the surface boundary condition that is described in the following section). Also initial conditions were derived in the same manner for all scenarios.

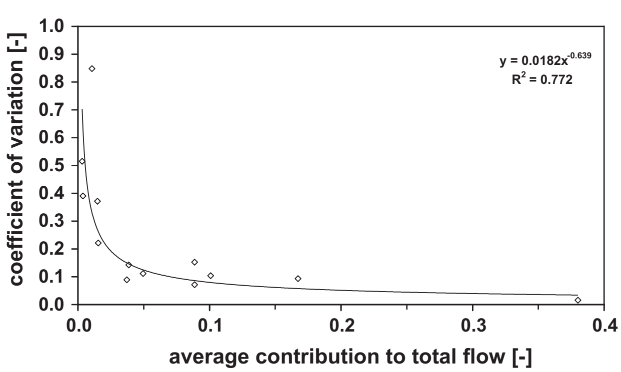


Fig. 5. Correlation between the average contribution from an individual 2 m segment to total flow and the coefficient of variation of each 2 m segment for the six forest realizations (first set of simulations).

2.2.2. Spatial pattern and temporal structure of input

For this set of simulations, a storm with a simpler structure was taken, as compared with the bimodal event used in the previous section. The total rainfall depth of the open rainfall was 81.5 mm with a peak intensity of 10 mm h^{-1} (Fig. 5), distributed over 37 h (C2). The throughfall pattern used for this set of simulations was forest realization 3 (see Table 2), and the same five input classes (100%, 87%, 77%, 66% and 57% of open rainfall) were used. The scenarios with spatially averaged input (B1) received 63 mm of rain having the same total input to the hillslope as the scenarios with the throughfall pattern (B2). For the constant rate scenarios (C1) the rain amount was distributed uniformly over the duration of the storm.

Instantaneous hydrographs as well as hydrologic response characteristics, i.e. subsurface runoff coefficients, response time (time between start of storm and start of lateral subsurface stormflow), time to peak and peak discharge, were compared for the 12 simulations. Also pressure head dynamics at the soil–bedrock interface were analyzed to derive saturation patterns.

3. Results

3.1. Uniform open rainfall vs. throughfall pattern

By using open rainfall spatially uniformly distributed over the surface of the hillslope, the total (cumulative) input to the hillslope will be higher than using the throughfall patterns we used in our study. Consequently, the scenario with open rainfall led to a markedly higher subsurface stormflow response (subsurface runoff coefficient 13%) than the scenarios using throughfall patterns (subsurface runoff coefficient 6–7%) (Fig. 3). In the following we will not elaborate on the results for the simulation using open rainfall since the study presented here focuses on the effects of throughfall patterns.

3.2. Comparing different realizations of throughfall patterns to spatially averaged throughfall

Subsurface runoff coefficients of the six forest realizations were very similar and varied between 6.6% and 7.4% (Fig. 3). The coefficient of variation among the six forest realizations for total subsurface stormflow was 4%. No significant differences between uniform and spatially variable input simulations were discernible.

Subsurface stormflow on the forest-covered hillslopes started 1–2 h earlier compared to the case with spatially uniform input (Fig. 4a), indicating that spatially variable input affected the threshold for the initiation of subsurface flow. Detailed analysis of distributed input and pressure head patterns suggested that high input locations (bright green and yellow patches) located near the downslope boundary were responsible for the slightly earlier response of the hillslopes with throughfall patterns. At these spots the input was higher than in the spatially averaged throughfall case. Six hours after the start of the event when the throughfall scenarios already produced seepage face flow but the spatially averaged throughfall case did not, the throughfall scenarios had received slightly higher cumulative input at that time. Early in the event local pressure heads along the downslope boundary were closer to zero for the forest realizations and the average pressure head at the downslope boundary was higher for the forest realizations (−0.19 m) than for the spatially averaged throughfall (−0.26 m).

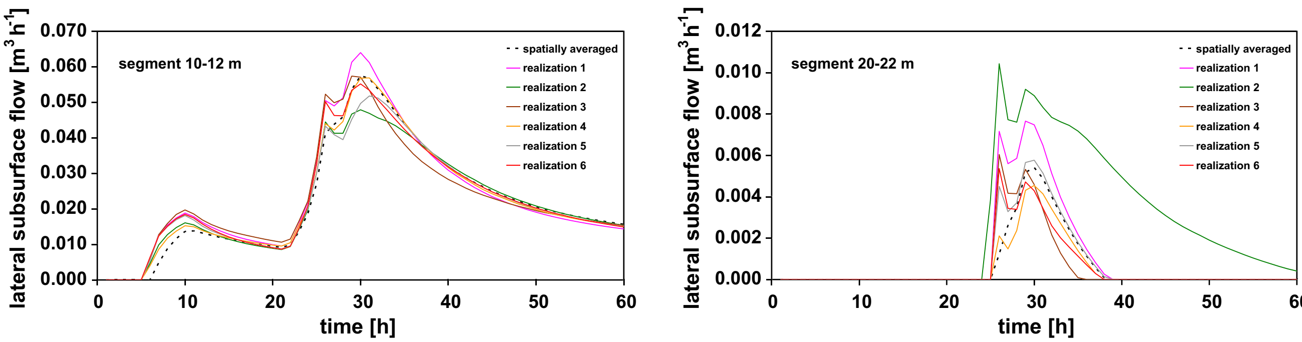


Fig. 6. Hydrographs of segment 10–12 m (average contribution to total flow 38%) and segment 20–22 m (average contribution to total flow 1.1%) for the scenarios (first set of simulations). *Note*: scale of *y*-axes differs.

The response to the first part of the event was minimal in all scenarios. Peak discharge was reached at the same time step in each scenario (26 h after the start of the storm). The scenarios with spatially variable input produced consistently higher peak discharge values than the uniform, spatially averaged throughfall case (but this was not the case for the secondary peak that occurred 3 h later at 29 h). Peak discharge values ranged between 0.32 and 0.37 $m^3\ h^{-1}$ for the six forest realizations (coefficient of variation 5.8%) whereas the subsurface stormflow of the spatially uniform reference case reached a peak value of 0.28 $m^3\ h^{-1}$. The general shape of the hydrographs was similar for all simulations, and there was no evidence for the occurrence of complex hydrologic response in certain combinations of throughfall pattern and underlying bedrock topography.

The spatial distribution of subsurface flow along the toe of the hillslope remained the same among the scenarios (Fig. 4b) and corresponded well to the flow accumulation map of the bedrock shown in Fig. 1. On average, 38% of total flow was contributed from

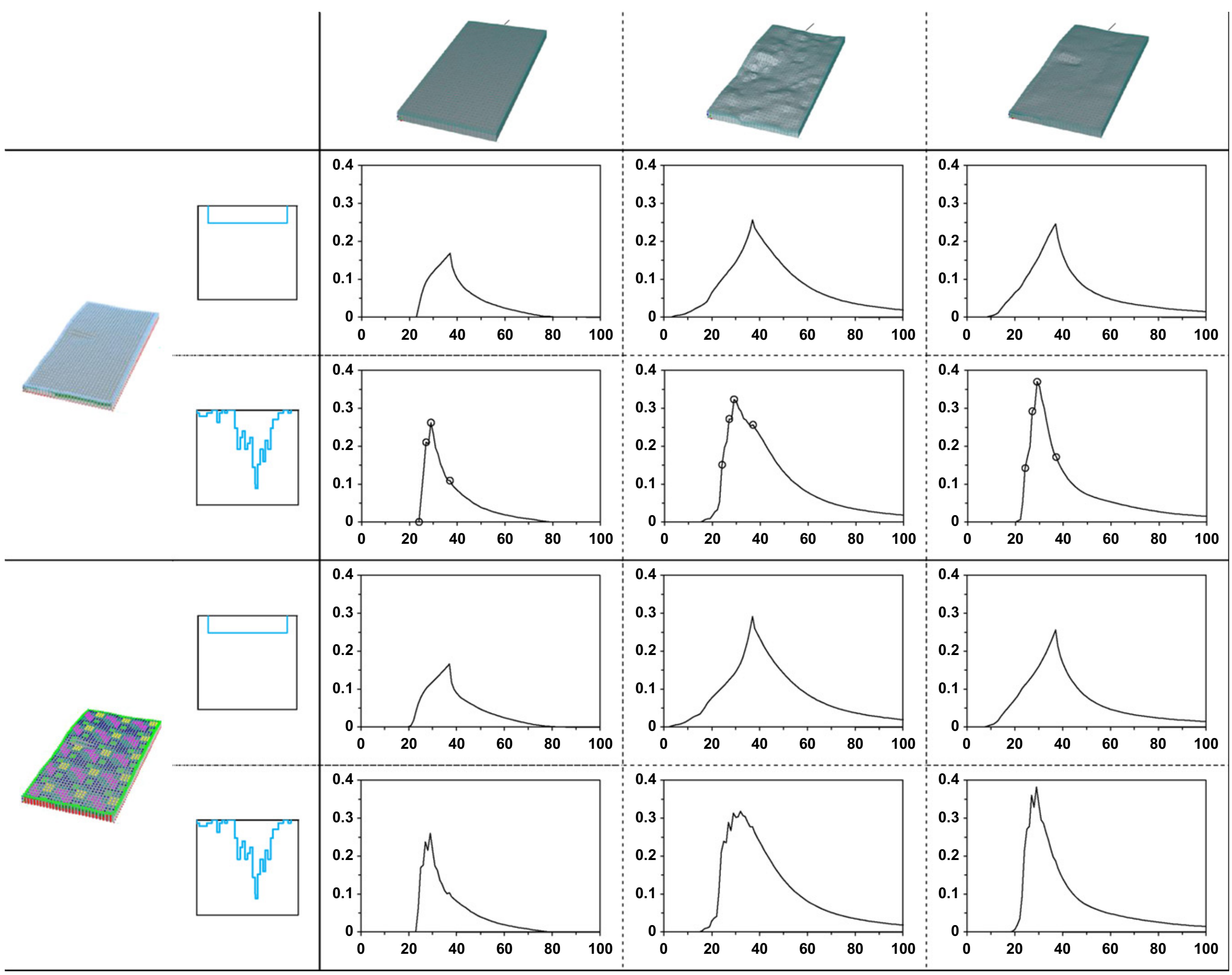


Fig. 7. Subsurface stormflow hydrographs for the second set of simulations – exploring the effects of complexity of hillslope geometry and of temporal structure and spatial pattern of input on hillslope-scale subsurface stormflow. The plots show time after beginning of rainfall input [h] on the x-axis and lateral subsurface stormflow ($m^3\ h^{-1}$) on the *y*-axis. The circles in plots Z1/Z2/Z3–B1–C2 indicate the four time snapshots for which saturation patterns are shown in Fig. 9.

the segment having the highest upslope accumulated area (segment 10–12 m, measured from the left of the domain), with flowpaths extending far upslope (see Fig. 1). Contributions from individual trench segments varied, and especially segments that contributed little to total subsurface flow showed higher variability among the realizations. Modeling results indicated a negative correlation between the average contribution from an individual 2 m segment to total flow and the variability of flow in this segment among the six forest realizations (Fig. 5).

The analysis of the hydrographs of individual segments (Fig. 6) confirmed that the spatial and temporal distribution of subsurface flow varied depending on how the throughfall patterns were located in relation to the underlying soil mantle and bedrock topography. Comparison of two segments exemplifies these differences: the segment 10–12 m that had high subsurface flow contributions and the segment 20–22 m whose contribution to total flow was small. Differences were more pronounced in the segment that had a smaller overall contribution to subsurface stormflow whereas the segment 10–12 m that had a high upslope contributing area of the bedrock topography showed relatively similar hydrographs among the forest realizations (see Fig. 1 for location of segments).

3.3. Relative role of throughfall

The shapes of the hydrographs showed marked differences between the scenarios (Fig. 7). Hillslope geometry as well as temporal structure of the input influenced substantially the shape of the hydrograph. The spatial pattern of input, on the other hand, only had a minor influence. Of the factors we explored, the geometry of the hillslope, i.e. the interplay between soil depth distribution and bedrock topography, seemed to be the primary control on the shape of the recession curve, as indicated by the very similar recession curves within one hillslope geometry. A planar subsurface geometry resulted in a quick cessation of subsurface flow whereas an irregular subsurface led to a long-lasting recession.

The subsurface runoff coefficient was primarily influenced by the hillslope geometry, i.e. the interplay between the soil depth distribution and the underlying bedrock topography (Fig. 8). A planar bedrock topography in conjunction with a uniformly deep soil mantle led to the lowest subsurface runoff coefficient. Adding irregular bedrock topography with the strong flow accumulating characteristics of the Panola bedrock layer resulted in a strong increase of total subsurface flow. This effect was damped by a soil mantle with spatially variable soil depths. Spatially variable input as well as natural storm input rates slightly increased the subsurface runoff coefficient.

The response time, i.e. the time between start of storm and start of subsurface stormflow, was influenced by all three spatio-temporally variable phenomena. Irregular subsurface topography resulted in a faster response, with a variable depth soil mantle again dampening the effect. With constant input rates, response times were generally shorter than with natural rates; this effect was particularly pronounced in combination with irregular bedrock topography. Spatially variable input patterns generally led to slightly faster response.

Time to peak was primarily controlled by the temporal structure of the input, irrespective of hillslope geometry and spatial distribution of input. With temporally varying input rates, peak discharge occurred 29 h after start of the storm whereas with constant input rates, peak discharge occurred at the end of the storm. The combination of a late response time but relatively short time

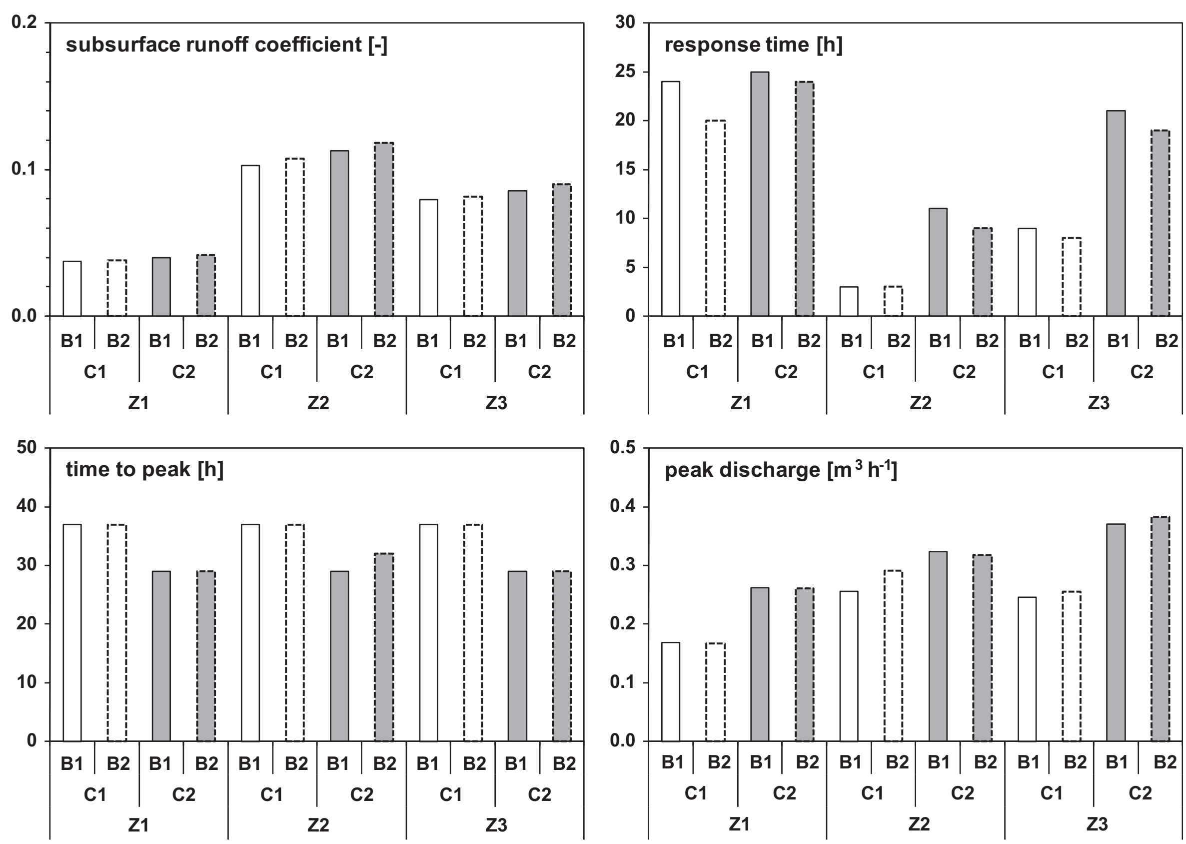


Fig. 8. Effects of complexity of hillslope geometry and of temporal structure and spatial pattern of input on characteristics of hydrologic response.

to peak as shown in the scenarios with the natural storm input resulted in a steep rising limb of the hydrograph.

The value of peak discharge was influenced by temporal structure of the input. Under natural storm input, peak discharge was higher than in the constant input rate scenarios. Also the complexity of the hillslope geometry had an effect, generally increasing peak discharge, particularly in conjunction with natural storm input rates. Spatially variable input had only a very minor and not clear effect.

Saturation patterns at the soil–bedrock interface were compared for the three hillslope geometries (uniform input, natural storm event) to demonstrate how the interplay between subsurface topography and soil depth distribution controls the hydrologic response (Fig. 9; see also Supplementary information, Figs. S1 and S2). The comparison shows that the irregular bedrock topography with its depressions and ridges (see Fig. 1) promotes the formation of transient saturation at the soil–bedrock interface. A planar subsurface (Z1) does not result in saturated patches. The spatially distributed hydrologic response is quite uniform across the hillslope. In the hillslope geometry with uniform soil depth over irregular bedrock topography (Z2) saturation builds up in depressions of the bedrock due to the accumulation ("filling") of water in zones of the bedrock that have reduced downslope drainage capability at the same time (Hopp and McDonnell, 2009). Saturated and near-saturated (i.e. ⩾95% relative saturation) patches at the soil–bedrock interface are connected to each other and the downslope boundary early because overall travel times of the infiltrating water vertically down to the soil–bedrock are relatively similar across the hillslope due to the uniform soil depth. This early connectivity and thus larger extent of very wet zones at the soil–bedrock interface lead to an earlier hydrologic response. On the most complex hillslope with irregular bedrock topography and variable soil depth distribution (Z3), reflecting the real Panola hillslope geometry, the infiltrating water reaches the soil–bedrock interface at different times across the hillslope. The ponding and subsequent accumulation of water in bedrock depressions is therefore not as temporally synchronized as in the geometry with uniform soil depth. Connectivity of near-saturation and saturated patches occurs later in the event and the overall extent of saturation at the soil–bedrock interface is smaller, yielding less subsurface flow. Specifically, the differences between Z2–B1–C2 and Z3–B1–C2 at 27 h and 29 h (Fig. 9) clearly illustrate the importance of the particularly thick patch of soil at the real Panola hillslope (see Fig. 1). At the end of the storm both scenarios with irregular bedrock topography have similarly shaped saturation patterns at the soil–bedrock interface, indicating that the pattern is controlled by the bedrock topography.

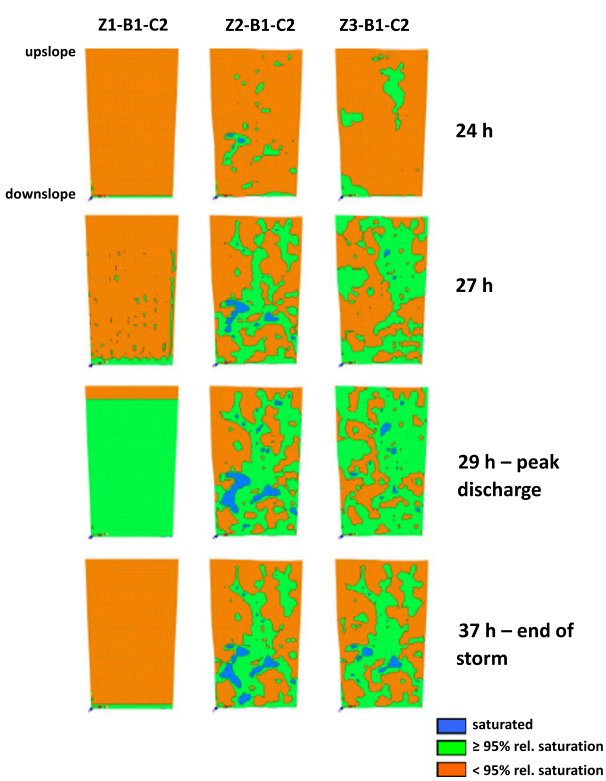


Fig. 9. Saturation patterns (as relative saturation) at the soil–bedrock interface for the three hillslope geometries (spatially averaged input, natural storm) at four time steps during the storm event (second set of simulations). See Fig. 7 for corresponding hydrographs and Fig. S2 in the Supplementary information for plots showing pressure head h along the downslope boundary for the soil–bedrock interface for time step t = 29 h.

4. Discussion

Our hypothesis going into this work was that throughfall patterns would have demonstrable effects on timing and magnitude of subsurface stormflow. This expectation was related to previously published findings at the catchment scale where rainfall patterns have been found to exert significant influence on runoff generation dynamics (Tetzlaff and Uhlenbrook, 2005). We found that throughfall patterns had only a minimal effect on the generation of subsurface stormflow at the hillslope. In all cases, throughfall pattern influences on stormflow response were trumped by hillslope geometry. Furthermore, patterns of pressure head at the soil–bedrock interface did not reflect the throughfall patterns applied at the surface of the hillslope. This finding is similar to Shachnovich et al. (2008) who also failed to observe a correlation between the spatial distribution of soil water and throughfall patterns.

So why was the importance of throughfall patterns less than expected? We found that the interplay between throughfall pattern and underlying bedrock topography had a bigger effect on subsurface flow from individual segments if those segments only had small upslope contributing areas and therefore small contributions to total subsurface flow (Figs. 5 and 6). For segments with smaller upslope contributing areas, i.e. drainage areas, the six forest realizations resulted in a marked variability in input. Nevertheless, these differences detected within individual segments did not lead to major differences in the spatially integrated hillslope hydrograph and in subsurface runoff coefficients because hydrographs were dominated by response from segments with high contributions to total subsurface flow. At larger drainage areas (e.g. segment 10–12 m; Fig. 1) the effect of the placement of the throughfall pattern on the hillslope averaged out and the total rainfall depth for that drainage area was more similar for each realization. Figs. 4–6 illustrate that for larger drainage areas, the impact of spatially variable throughfall was increasingly overpowered by the influence of bedrock topography.

The timing of when hillslope-scale connectivity of saturated (or close to saturated, i.e. within 95% of saturation as shown in Fig. 9) areas is reached is crucial for the generation of subsurface stormflow (Hopp and McDonnell, 2009; Tromp-van Meerveld and McDonnell, 2006b). Overall subsurface saturation patterns at the soil–bedrock interface for the different scenarios were the same, showing only subtle local differences in degree of saturation (Fig. 10) which were sufficient to generate the small differences in the hydrographs (see Fig. 4a). Previous work has shown that (near-)saturated areas typically maintain higher flow velocities, i.e. act as flow pathways, connecting upslope areas with downslope

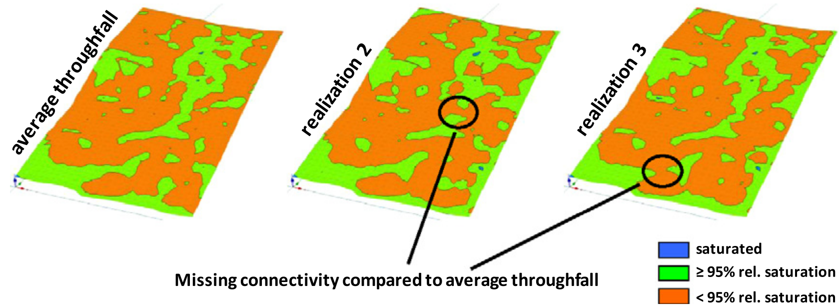


Fig. 10. Saturation patterns (as relative saturation) at the soil–bedrock interface at 4 h before the end of the storm, shown for three scenarios (first set of simulations). The general pattern reflects the bedrock topography (see Fig. 1).

boundary segments that produce substantial outflow and mimicking the pattern of bedrock depressions and channels (as described by Hopp and McDonnell (2009)). The general pattern of subsurface saturation at the soil–bedrock interface was similar for the spatially averaged throughfall case as well as the six forest realizations, again reflecting primarily the bedrock topography.

The second set of simulations revealed why the different realizations of the fine-scale throughfall pattern did not affect the general shape of the hydrographs. The slope of the rising limb determined the ratio between response time and time to peak. Since the throughfall pattern influenced the response time only slightly and did not affect time to peak, there was no noticeable effect on the rising limb. The shape of the recession limb was influenced predominantly by the hillslope geometry (i.e. subsurface topography and soil depth distribution) and not by the spatial and temporal distribution of input. This notion has been discussed in context with the hillslope Peclet (Pe) number, a similarity index developed for the use in low-dimensional hillslope storage dynamics models (Berne et al., 2005; Lyon and Troch, 2007). The hillslope Pe number is expressed in terms of hillslope geometric properties (e.g. slope length, slope angle, soil depth). The underlying assumption is that each hillslope has a characteristic way to drain, i.e. a unique recession curve. Lyon and Troch (2007) successfully applied the theoretically derived hillslope Pe number to data from real hillslopes. Our results are in line with this concept in that they show that the shape of the recession limb of the hydrograph was determined mainly by hillslope geometry and not by characteristics of the input.

One could argue that our results are an artifact of the particular Panola hillslope characteristics with its very prominent bedrock topography. However, also the simulations on a 3D planar hillslope with uniform soil depth showed the same general result. We therefore conclude that the minor effect of throughfall patterns on subsurface flow generation is a general phenomenon. Some of the reason for this lack of apparent effect of throughfall pattern on subsurface stormflow links to the discussion between Western et al. (2004) and Tromp-van Meerveld and McDonnell (2005) and the issue of whether or not mapped soil moisture patterns in the upper decimeters of the soil profile represent causally, topographically driven lateral subsurface flow. Tromp-van Meerveld and McDonnell (2005) showed that soil moisture was a passive signal between rainfall input and lateral subsurface stormflow output. More recently, Graham et al. (2010) have also found that soil moisture in the unsaturated zone is not a major control on the spatial patterns of subsurface stormflow on steep sites with poorly permeable bedrock. In these cases, lateral flow at the hillslope scale is restricted to thin zones of positive pressure head above the soil–bedrock interface and its flow pathways are not correlated with patterns of near-surface soil moisture. So, in other words, throughfall patterns are of secondary importance in the generation of lateral subsurface flow because near-surface soil moisture has a negligible effect on the development of transient saturation at the soil–bedrock interface on the hillslope. Such transient saturation is often the causal mechanism for subsurface lateral flow to the channel (Tromp-van Meerveld and McDonnell, 2005).

A few studies that have examined the effect of spatial rainfall patterns on catchment response as a function of catchment size have found a scale-dependency of this effect with small catchments responding differently to spatially variable input than larger catchments (Mandapaka et al., 2009; Nicotina et al., 2008). Nicotina et al. (2008) suggested that it is the relation between typical hillslope size in a catchment, catchment size and characteristic size of rainfall structures that determine if spatial variability of rainfall affects catchment response. At the Panola hillslope, the generation of lateral subsurface stormflow has been shown to be controlled by the size and spatial arrangement of bedrock depressions that result in a distinct fill and spill behavior (Tromp-van Meerveld and McDonnell, 2006b). We hypothesize that in the case of the Panola hillslope, the characteristic size of the bedrock features (fill and spill areas, i.e. depressions and connection between depressions) is larger than the characteristic size of the throughfall pattern and therefore the explicit spatial distribution of throughfall is not relevant for the hydrologic response of the hillslope. We would expect that if the characteristic size of the throughfall pattern was larger we would start to see the effect of how throughfall is spatially distributed on the hillslope. These aspects are currently being addressed in ongoing work that analyzes the links between patterns of throughfall, soil moisture and bedrock topography in a geostatistical approach.

So which role does throughfall play in the hierarchy of controls on subsurface stormflow? In an earlier modeling study we explored the effects of various hillslope variables on timing and magnitude of subsurface stormflow and found that storm size, slope angle, mean soil depth and soil hydraulic properties were all first-order controls on subsurface stormflow generation (Hopp and McDonnell, 2009). On one hand, the overall throughfall amount would also be a first-order control – analogous to storm size – given the highly threshold-like relation between storm size and resulting hillslope hydrologic response, as observed by Tromp-van Meerveld and McDonnell (2006a) and investigated by Hopp and McDonnell (2009). The hypothesis tested in this study was that also spatial patterns of throughfall as induced by interception by the vegetation canopy would be a first-order control through the interplay between throughfall pattern and the underlying bedrock topography with its fill and spill areas. Our results demonstrate that as expected the overall reduction of open rainfall that is caused by the vegetation canopy is a first-order control. Using open rainfall as spatially uniform model input will most likely overestimate the hydrologic response. It is therefore crucial to estimate the spatially averaged throughfall for a given hillslope in order to accurately characterize the total volume of input to the hillslope. Here our results are in line with the conclusions by Beven and Hornberger (1982). However, the actual throughfall pattern, i.e. the spatial distribution of throughfall, was shown to be only a secondary control, and we therefore reject the tested hypothesis.

Our findings are but a first step in determining the role of throughfall in subsurface stormflow generation. Obvious next step experiments should include, e.g., increasing the magnitude of throughfall variability to examine the degree of variability necessary to induce quantifiable changes in subsurface stormflow or to address the influence of antecedent moisture conditions on the sensitivity of lateral subsurface stormflow to spatially variable throughfall. Another issue that warrants further exploration is the model boundary conditions. Our model hillslope was "closed" on the sides, i.e. we defined a no-flux boundary on the sides of our domain. Therefore, in our simulations, if water was not lost to the bedrock below, it could leave only via the downslope boundary. It is possible that this setup had a homogenizing effect. We tested the effect of these boundary conditions by examining outflow not from the entire width of the hillslope but from a 12 m wide section only nested within the middle of the downslope boundary of the hillslope that would presumably be uninfluenced by the side boundary conditions. The results were the same as for our larger-scale simulations: spatially variable throughfall input had a very minor effect on subsurface stormflow hydrographs.

Our study only examined event-based hillslope hydrologic response. Yet, throughfall patterns are likely to persist over extended periods of time. This would lead to consistently higher or lower input of water on certain parts of the hillslope, potentially affecting subsurface stormflow on the longer term. First exploratory simulations suggest that also after multiple storms applied over 4 weeks the effect of throughfall patterns remains minor for the hillslope hydrologic response (see Supplementary information, Fig. S3). Further detailed analysis, using continuous hydrologic simulations over meaningful timescales and including evapotranspiration and root water uptake, would be worthwhile.

5. Conclusions

The role of throughfall on the time and space patterns of subsurface stormflow is poorly studied. Much of the reason for this to date is the problem of how to quantify the interactions among the many controlling factors for flow generation and how to begin to understand the hierarchy of controls in different field settings. Our virtual experiments with HYDRUS-3D applying measured fine-scale throughfall data on a well studied hillslope with irregular bedrock topography had the following results:

- The effect of spatial input variability on lateral subsurface stormflow generation was minor. We did not find significant differences in flow response to our different realizations of fine-scale throughfall patterns.
- Bedrock topography was dominant over fine-scale spatial variability of input for our test cases.
- Using spatially uniform "throughfall" (i.e. open rainfall reduced by some assumed fraction) yielded a general response similar to scenarios using throughfall patterns with respect to total subsurface stormflow, peak discharge and saturation patterns.
- Using open rainfall as spatially uniform input strongly overestimated lateral subsurface stormflow.
- Effects of fine-scale throughfall patterns on subsurface stormflow generation are much smaller compared to effects of temporal distribution of rainfall, subsurface topography and variable soil depths.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.jhydrol.2011.08.044.

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