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The effect of spatial throughfall patterns on soil moisture patterns at the hillslope scale

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Abstract

A better understanding of the controls on subsurface stormflow generation has been the focus of numerous experimental and modelling studies. However, the effect of the spatial variability of throughfall on soil moisture patterns and subsurface stormflow (SSF) generation has not yet been studied in detail. The objectives of this study are three-fold: (1) to investigate the influence of spatially variable throughfall on soil moisture; (2) to investigate if soil moisture patterns reflect a balance between throughfall and bedrock topography patterns; and (3) to investigate how this balance changes when soil depth, storm size and slope angle are varied. Virtual experiments are used to address these questions. A virtual experiment is a numerical experiment driven by collective field intelligence. It provides a learning tool to investigate the effect of separated processes in a complex system. In our virtual experiment we combined spatial throughfall data from the Huewelerbach catchment in Luxembourg with the topogra-

¹⁵ Watershed, Georgia, USA. We used HYDRUS-3D as a modeling platform. The virtual experiment shows that throughfall patterns influence soil moisture patterns, but only during and shortly after a storm. With a semi-variogram analysis we showed how the effective range of the soil moisture pattern (i.e. the main descriptor of a spatial pattern in case of a small nugget to sill ratio), has a similar effective range as the throughfall

phy characteristics of a well-studied hillslope within the Panola Mountain Research

²⁰ pattern during the storm and gradually returns to the effective range of the bedrock topography pattern after throughfall has ceased. The same analysis was carried out to investigate how this balance changes due to changes in storm size and hillslope controls. The analysis showed that the throughfall pattern is more important during large storms on gentle slopes. For steeper slopes the bedrock topography becomes more important.





1 Introduction

The question of how rainfall makes its way through the canopy to the forest floor has been studied for over a century (DeWalle, 2011). Following the description of interception characteristics of several tree species by Horton (1919), many papers documented

interception characteristics for many sites and tree species around the world (Navar et al., 1999; Bruijnzeel and Wiersum, 1987; Calder, 1990; Toba and Ohta, 2005). Whilst interception studies were most commonly done in mid latitude and tropical regions (Bruijnzeel, 2005; Cuartas et al., 2007; Ziegler et al., 2009) interception is also largely determined by climatic parameters. Some studies extended this work into semi-arid
 regions and snow dominated regions (Storck et al., 2002).

Although the process of forest interception, throughfall initiation, and their influence on point scale infiltration are well documented in the forest hydrology literature, the effect of spatial throughfall patterns on soil moisture patterns is poorly understood (Zehe et al., 2010; Ivanov et al., 2010). This is because the measurement of soil moisture

- patterns within a forest is much more difficult than the measurement of throughfall. Measuring such patterns jointly is a difficult experimental challenge. Those studies that attempted to explore the effect of throughfall patterns on soil moisture dynamics have been highly equivocal in their findings. For instance, Bouten et al. (1992) found that soil moisture patterns are primarily dependent on soil physical properties, and less on
- throughfall; on the other hand, Liang et al. (2007) found that topography and stemflow influence soil moisture patterns; Jost et al. (2004) found that mainly the antecedent soil moisture content is important; Raat et al. (2002) concluded that throughfall patterns and forest floor thickness determine soil moisture patterns; Sansoulet et al. (2008) related soil moisture patterns to stemflow and throughfall; and Shachnovich et al. (2008) found that throughfall is not correlated with soil moisture at point scale.

Paired catchments studies (Bosch and Hewlett, 1982) can be used to understand throughfall influences on soil moisture patterns, but the outcome of paired catchment studies requires enormous data collection and the results would always remain site and





case specific. Virtual experiments, however, could overcome these issues. Weiler and McDonnell (2004) defined virtual experiment as "numerical experiment with a model driven by collective field intelligence". A virtual experiment enables us to investigate the response of spatially variable input on hillslope behaviour.

- Recently, Hopp and McDonnell (2011) investigated the effect of throughfall patterns on subsurface stormflow (SSF) generation. Their work built upon previous examination of the interactions between slope angle, bedrock permeability, soil depth, and storm size on subsurface stormflow production (Hopp and McDonnell, 2009). Their work used multiple realizations of a fine-scale throughfall pattern and concluded that SSF was controlled by bedrock topography and that throughfall had a limited influence
- SSF was controlled by bedrock topography and that throughfall had a limited influence on amount and timing of SSF generation. The latter might be caused by the fact that throughfall often only influence the near-surface soil moisture patterns (as shown by Liang et al., 2011) and therefore has a limited influence on SSF generation. On the other hand, (Liang et al., 2011) also found that high stemflow concentrations do in-
- fluence soil moisture patterns at deeper depths. Since high stemflow concentrations might behave similar as high concentrations of throughfall we do not explore a finescale throughfall pattern as Hopp and McDonnell (2011) did, but we explore an observed throughfall pattern with a distinct "hotspot" (as shown in many process studies of throughfall in the field – Germer et al., 2006; Ziegler et al., 2009; Gerrits et al., 2010).
- ²⁰ Using a larger scale throughfall pattern can also influence the drainage behaviour as hypothesized in Hopp and McDonnell (2011). Furthermore, we only focus on soil moisture patterns and less on SSF. We use a geostatistical and visualization approach to quantify relative correlation length scales.

The questions addressed in this paper are:

- What is the influence of spatially variable throughfall on soil moisture?
 - Do soil moisture patterns reflect a balance between throughfall and bedrock patterns?





- How does this balance change when soil depth, storm size and slope angle are varied?

2 Study sites

We used field data from two sites: the Panola hillslope in Georgia, USA and the
 Huewelerbach catchment in Luxembourg. The hillslope geometry and soil hydraulic properties were derived from the well-studied Panola hillslope. Storm characteristics were also obtained from Panola; however, the spatial pattern of throughfall to the soil surface was derived from the experimental interception plot in the Huewelerbach catchment in Luxembourg (since this information was not available for the Panola hillslope at the desired temporal scale).

2.1 Panola hillslope

The Panola hillslope is located in the Panola Mountain Research Watershed (PMRW) in Georgia Piedmont, 25 km southeast of Atlanta. The site has been described in detail by Freer et al. (2002) and others and here only a brief description is made. The climate
¹⁵ is humid and subtropical with an average temperature of 16.3 °C and average rainfall of 1240 mm a⁻¹. The hillslope faces southeast and has a slope of 13°. The surface topography is relatively planar, but the permeable saprolite bedrock (soft disintegrated granite) is highly irregular (Fig. 1a). This results in highly variable soil depths ranging from 0 to 1.86 m, and an average soil depth of 0.63 m. The soil consists of loamy sand with a 0.15 m deep organic-rich horizon. At the lower hillslope boundary a 20 m wide trench has been excavated, where subsurface flow is measured by ten two meter wide sections. Further details on the Panola hillslope were described by Tromp-van Meerveld and McDonnell (2006a,b).

On 85 occasions from January 26 until August 26, 2002 soil moisture measurements ²⁵ were carried out on the Panola hillslope (Tromp-van Meerveld and McDonnell, 2006c).





On 64 locations soil moisture profiles were measured with an Aqua-pro sensor (Aquapro Sensors, Reno, NV) in polycarbonate access tubes. The tubes were installed to the soil-bedrock interface in a 4 by 4 m grid across the hillslope and on a 4 by 2 m grid on the lower 6 m of the hillslope. Measurements were carried out at 0.05 m increments

to 0.3 m below the soil surface and below at 0.1 m increments. The Aqua-pro sensor is a capacitance (radio-frequency) sensor that scales the soil moisture between 0% (in air or dried soil) and 100% (in water or saturated soil). The results of this measuring campaign can be found in Tromp-van Meerveld and McDonnell (2006c).

Tromp-van Meerveld and McDonnell (2006a) presented an analysis of 147 storms at the Panola hillslope and showed that subsurface stormflow only occurred for storm events larger than 55 mm. For this study we selected the best studied rainstorm of the Panola dataset of 6–7 March 1996 (Burns et al., 2001; Freer et al., 2002). This storm had a return period of 3 yr and a total storm depth of 87 mm in 31 h divided over two peaks (see Fig. 1b). It can be seen from Fig. 1b that the first rainfall peak almost entirely went into storage, while the second peak generated the runoff peak. This clearly shows the threshold behaviour of the Panola hillslope.

2.2 Interception plot Huewelerbach

plot can be found in (Gerrits et al., 2007, 2010).

The interception plot is located in the Huewelerbach catchment in Luxembourg, 20 km northwest of Luxembourg city. The site has been described in detail previously by Gerrits et al. (2010) and only the key details are repeated here. The experimental plot has a total area of 596 m² and consist of beech trees (*Fagus sylvatica* L.) with an average stand density of 168 trees ha⁻¹. The climate is modified oceanic with mild winters and temperate summers. The average rainfall is 845 mma⁻¹ and the average temperature is 8 °C (Pfister et al., 2005). In the plot throughfall is measured with 81 manual rainfall collectors, installed in a grid with an average distance of about 3 m (Fig. 2a). The collectors are read out at a bi-weekly interval. In an open valley close to the plot gross rainfall is measured by a tipping bucket raingauge. Further details on the interception





From the throughfall data set we selected a random period with full canopy development, because we learned from a time stability analysis that the spatial pattern does not vary much in time (Gerrits et al., 2010). We selected the period starting from the 10 May 2007 until the 25 May 2007 (see Fig. 2b). Total rainfall in this period was 33 mm.

An important funneling mechanism can be seen in Fig. 2b at coordinates (15 m, 15 m) where throughfall exceeds precipitation. This location is around a tree that creates hotspots of high throughfall with lower throughfall values in a ring around the tree. This phenomenon is also observed in field experiments of for example Germer et al. (2006) and Ziegler et al. (2009).

For the analysis we use five classes of throughfall and defined them based on the percentage of maximum throughfall (i.e. 75 mm) (Table 1). The main difference with respect to the classes as defined by Hopp and McDonnell (2011) is the variance in the throughfall data. The standard deviation of the percentage throughfall of precipitation in Hopp and McDonnell (2011) is 12% ($c_v = 0.17$), while in this case the standard deviation is 23% ($c_v = 0.31$). The higher standard deviation in the large scale pattern is caused by the hotspot. The coefficient of variation, c_v of the large scale throughfall pattern is now in the same order as the c_v of the bedrock topography of Panola ($c_v = 0.27$).

Subsequently, the Panola storm of 6–7 March 1996 ($P_{\text{panola}}(t)$) is scaled for each class *i* to represent the Huewelerbach spatial pattern:

$$P_{i}(t) = P_{\text{panola}}(t) \times \left(\Sigma \overline{T}_{f} / \Sigma P\right)_{i}$$

3 Methods and materials

3.1 Approach

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0.34).

²⁵ To investigate the effect of spatially variable throughfall on soil moisture, we selected the throughfall pattern from the Huewelerbach catchment and used this as input to



(1)



a numerical model of the hillslope. Hopp and McDonnell (2009) already developed a finite element model of the Panola hillslope. We used the same model domain and identical parameters and combined it with the large scale Huewelerbach throughfall pattern for our virtual experiment. Since the model domain of Panola is larger than

- the spatial throughfall pattern we needed to expand the throughfall pattern in a way that the spatial characterisation remained the same. Since we did not want to enlarge the pattern, we mapped the pattern in eight different ways onto the Panola hillslope. The eight patterns were derived by rotating and mirroring the original pattern of the Huewelerbach. All eight patterns had a total storm size of 63 mm. These patterns were
- ¹⁰ compared with a uniform pattern with also a total storm size of 63 mm. Finally, the pattern with the highest influence on SSF was used for this study. In Fig. 3 the selected pattern is shown. The selected pattern configuration ("Upper Right-2.1") has similar geostatistically properties as the initial pattern. See Supplement for details on the creation and selection of the eight throughfall patterns.
- Mean soil moisture patterns are analysed with semi-variograms (Cressie, 1993; Chilès and Delfiner, 1999) to investigate if the soil moisture pattern reflects a balance between throughfall and bedrock patterns, since spatial scale is an important controlling factor (Nicótina et al., 2008; Mandapaka et al., 2009). A semi-variogram represents the variance of two points separated by a certain distance in a spatial field and explains
 to which distance observations are still correlated (Keim et al., 2005):

$$\gamma(h) = \frac{\sum_{n(h)} \left(\widetilde{N}_{x,y} - \widetilde{N}_{x,y+h}\right)^2}{2n(h)}$$

Where *h* is the lag distance, n(h) is the number of measurement pairs in the data set that are a distance *h* apart, and $\tilde{N}_{x,y}$ are the normalized spatial data at measuring point (x, y):

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$$\widetilde{N}_{x,y} = \frac{N_{x,y} - \overline{N}}{\sigma(N)}$$

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(2)

(3)

with σ being the standard deviation. We used normalized data to be able to compare spatial patterns.

Important features of a semi-variogram are the nugget, sill, and range. The nugget is a measure for the randomness of observations at one and the same location. The sill

⁵ is the limit of the semi-variogram, where no autocorrelation exists anymore. The range is a measure of the distance over which there is significant spatial correlation. In case of a small nugget to sill ratio, the range is a good descriptor of a spatial pattern.

We calculated the semi-variograms of the irregularity of the bedrock topography (i.e. deviation of DEM from a plane with slope A), the throughfall, and the soil moisture pattern (average of nodal values of mesh layers 5-10, simulated by HYDRUS). 10 We fitted an exponential model (Chilès and Delfiner, 1999) to find the effective range, r, of the semi-variogram, which is the correlation length:

$$\gamma(h) = c(1 - \exp(\frac{-3|h|}{r})) + n$$
(4)

The effective range r is defined as the lag h, where the variance (γ) is 95% of the sill c, and is a measure for the correlation between the points. High spatial correlation 15 between the throughfall collectors causes the effective range to be large and vice versa. In other words, it is the length over which the data points are still spatially correlated with each other. We did not consider anisotropy, hence the effective range is equal to the modulus of the lag. Because we found that the nugget, n was small and to save computation time, we assumed a nugget of zero. 20

Furthermore, we investigate if the balance between throughfall and bedrock patterns changes if storm size (R), slope angle (A) and soil depth (S) are changed according to Table 2. We selected these three characteristics, because Hopp and McDonnell (2009) found that these are important controls for subsurface stormflow generation. By

changing the slope angle we disregard the fact that in reality throughfall patterns also 25 change due to the fact that trees grow vertically and not perpendicular to the hillslope.





3.2 Model description of base case scenario

To simulate SSF on the Panola hillslope, we used the finite element model HYDRUS-3D, version 1.10 (Simunek et al., 2006). HYDRUS-3D solves the Richards equation for water flow in variably saturated porous media. We used the model as described in detail

 ⁵ by Hopp and McDonnell (2009). Here we only briefly describe the crucial information. The model domain covers an area of 28 m by 48 m. The surface and bedrock topography have been derived from a survey with a spatial resolution of 2 m. From this survey a Digital Elevation Model (DEM) has been generated with a spacing of one m by linear interpolation; subsequently a mesh of triangular prisms was generated based
 on this DEM. The mesh consists of 10 layers, with each 1715 nodes. Layers 1 to 5 represent the bedrock sublayer, layers 6 to 10 the soil sublayer.

The model has only been parameterized to the trench outflow on an event basis, and performed in a realistic way consistent with field observations of spatially distributed state variables (Fig. 1 in Hopp and McDonnell, 2009). The model is parameterized with

- a uniform rainfall pattern. A spatially distributed pattern would possibly have resulted in a different parameter set, as shown by e.g. Arnaud et al. (2002) and Zehe et al. (2005). However, the model is not meant to represent the exact behaviour of Panola, the model is used as a benchmark model for comparison. Complex processes of Panola like preferential flow are also not included. We chose not to use the dual-porosity soil hydraulic model, because of the lack of data (Hopp and McDonnell, 2009). The model has also
- not been tested for long-term hydrological modelling.

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Soil hydraulic properties are described by the van Genuchten-Mualem model (Van Genuchten, 1980). α and *n* are calibration parameters, θ_r (residual water content), θ_s (saturated water content), and K_s (saturated hydraulic conductivity) are determined based on long-term field observations (McIntosh et al., 1999; Tromp-van Meerveld and McDonnell, 2006c; Tromp-van Meerveld et al., 2007). The values for the residual and saturated water content are determined by the minimum and maximum observed soil moisture, since the lack of retention data. In Table 3 the soil hydraulic properties are





given. For a more detailed explanation how soil parameters were specified see Hopp and McDonnell (2009).

The boundary conditions of the model domain for the upper and side boundaries are defined as "no flux". The downslope boundary is different for the bedrock and for the

- ⁵ soil layers. The downslope bedrock boundary is defined as "no flux", thereby assuming negligible lateral flow in the bedrock. The downslope boundary of the soil layers is treated as a "seepage flux", allowing water to leave the domain through saturated parts of the boundary. The bottom boundary is assigned as "free drainage", meaning a unit total vertical gradient. For the surface boundary we used the generated throughfall
- patterns as described above (Fig. 3). As the initial conditions for the entire domain a pressure head of -0.7m is used, followed by a 7 days drainage period where no rainwater enters the domain. This corresponds to the actual weather conditions that preceded the storm event of 6–7 March 1996.

In this paper we consider the outflow over the entire hillslope width (28 m) and not only the outflow from the excavated trench (20 m) as described by Freer et al. (2002). However we refer to "trench" if we mean the entire downslope boundary for simplicity in writing. The trench is divided in 13 segments, where segment 1 equals the outflow from 1–3 m, segment 2 outflow from 3–5 m, segment 3: 5–7, etc.

4 Results

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20 4.1 Throughfall effects on SSF

In Fig. 4a subsurface stormflow along the downslope trench of the base case scenario $(R = 63 \text{ mm}, A = 13^{\circ}, S = 0.62 \text{ m})$ with uniform input is shown. The upper graphs show the subsurface flow per segment (Q_s) , the lower left the total subsurface flow (Q_t) , and the lower right the variation of subsurface flow along the trench. The shape of total subsurface flow is similar to the observed hydrograph at Panola (see Fig. 1). As can be seen, subsurface flow varies strongly along the trench (variance $\bar{Q}_s/\bar{Q}_t = 10.4 \times 10^{-2}$).





especially segment 6 drains the major part of the hillslope. This segment is on the transition of the very shallow soil to the thicker soil and discharges a relatively large upslope area.

In Fig. 4b the subsurface flow of the distributed input ("Upper Right-2.1") is shown. ⁵ The hydrograph of this pattern is significantly different from the uniform pattern mainly caused by segment 6 and 7. While the uniform pattern has a rather smooth recession curve, pattern "Upper Right-2.1" has a double peak in segment 6 and 7. All other segment hydrographs do not differ much from the uniform case.

4.2 Throughfall effects on soil moisture

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In Fig. 5 the soil moisture pattern of distributed input is shown for the five soil mesh layers. The soil moisture pattern is plotted for t = 5h (first storm peak), t = 23h (just before second storm peak), t = 25h (second storm peak), t = 56h (highest deviation in SSF between uniform and distributed case), t = 190h (end of drainage).

The patterns show that at the depressions in the bedrock (see Fig. 1a) the soil mois-

ture content is low whereas it is high in the shallow soil for the top layers. The shape of the bedrock and the main drainage channels are especially visible at t = 56 h at the bedrock interface layer (mesh layer 5).

As can be seen at t = 5 h (during the first peak of the storm) only the top layers are influenced by the throughfall pattern. The four hotspots are clearly visible. During the second peak (t = 25 h) the hotspots are again visible in the top layers, but now also at the deeper soil layers.

4.3 Soil moisture comparison of uniform and distributed input patterns

The mean soil moisture content over mesh layer 5–10 does not differ much between uniform input and distributed input (Fig. 6). Only at t = 56 h there is a significant difference between the two input patterns for about a day, similar as the SSF (Fig. 4). Also the standard deviation is higher just after the second storm peak.





The spatial differences per mesh layer are shown in Fig. 7. At the beginning of the storm the distributed input pattern only has an influence on the top layers and slowly moves down in time. During the second peak of the storm the effect of the distributed pattern is largest, because the effect of the previous storm peak has not yet vanished. ⁵ Also the size of the hotspots in the soil moisture pattern are larger than at t = 5 h.

After the storm, the difference between uniform and distributed become negligible except for the shallow soils in the lower left corner. At t = 190 h also this difference disappears.

4.4 Spatial correlation of soil moisture content

- From the model results it appears that the soil moisture content (e.g. for the soilbedrock interface: mesh layer 5) is highly correlated to the bedrock topography (Fig. 8a) when it has been dry for a long time (Fig. 8b) and that during a rainfall event, or shortly after, the soil moisture pattern represents the rainfall pattern (see Fig. 8c).
- In Fig. 9a the semi-variogram of normalized throughfall is given and as can be seen the sill is not constant. Figure 9b shows the semi-variogram of the average soil moisture pattern for each time step and appears to change between the semi-variogram of the throughfall pattern and the bedrock topography (Fig. 9c). To test this hypothesis, we choose to look at the effective range of the semi-variogram, *r*, as the main characteristic of the spatial pattern. This is valid if the nugget to sill ratio is small. For the throughfall we found an effective range of 5 m and for the bedrock irregularity 21 m. We
- hypothesize that between rainfall events the soil moisture pattern has similar spatial characteristics as the topography, but during a rainfall event the pattern becomes more similar to the throughfall pattern.

In Fig. 10 this can indeed be seen for the base case scenario. The effective range of the average soil moisture starts at 13 m and drops to 11 m during the first rainfall event. After rainfall ceases the effective range returns back in the direction of the effective range of the topography. When the second rainfall starts the effective range of the soil moisture pattern again drops towards the effective range of the throughfall pattern. And



finally, after the rain stops, it again moves back in the direction of the effective range of the bedrock irregularity. Hence the change of the effective soil moisture range (blue line in Fig. 10) acts like a hydrograph, and can be called a "geo-statistical hydrograph". The fact that the effective start and end range differ, is a consequence of the (non realistic) initial soil moisture pattern.

If this plot is generated for all combinations of storm depth, angle, and soil depth, we can investigate if the hillslope attributes change the spatial pattern of the soil moisture. First, we looked at the mean performance of the fitted semi-variogram model (Eq. 4) for mesh layers 5–10 and t > 0. In Fig. 11a the R^2 is presented. Although the overall performance is good with a mean R^2 of 0.8 ± 0.1 , it appears that the steep slopes perform relatively worse. For steep slopes, the soil moisture pattern has mostly slope-parallel, straight flow paths just after the rainfall event, which can not be described well with an exponential model, causing the relatively bad performance.

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Second, we looked at the equilibrium state. This is the final effective range of the soil moisture at t = 190 h and is shown in Fig. 11b for all cases. The interpolated cube shows that with increasing slope the final effective range becomes larger. Hence with increasing slope the topography becomes more important. Furthermore, there is a slight increase in final effective range with increasing storm size. This was also observed by Western et al. (2004) and Zehe et al. (2010) and is likely inherent to the method.

Third, we analysed the second peak value of the "geo-statistical hydrograph" in Fig. 11c. As can be seen the effective peak range is related to storm size and slope angle. The bigger the storm the more the storm pattern influences the soil moisture pattern and the steeper the slope, the more the bedrock topography influences the soil moisture pattern. This is because the high gradient drains the rainwater so quickly that the throughfall pattern only remains for a short period. The soil depth appears not to

have any influence when the soil layer is thick enough. Only for very thin soil layers the throughfall pattern has a larger influence on the soil moisture pattern.





In Fig. 11d the interplay of the hillslope attributes and the time to peak is shown. The time to peak is defined as the time between the start of the rain and the peak of the effective range in the soil moisture pattern. For deep soil depths the peak occurs faster with increasing storm size and slope angle; however, for a mean soil depth of 1.22 m it appears that slope angle and storm size do not have an influence. For the very thin soil layer the pattern is similar to the thick soil layer. However, for gentle slopes and small storms the time to peak is short.

5 Discussion

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Our modelling results show that a non-uniform throughfall pattern in comparison to a uniform pattern has an effect on SSF. Although the spatial pattern does not have a significant effect on total SSF, it does influence the distribution along the trench and more importantly the shape of the hydrograph. Hopp and McDonnell (2011) also investigated the effect of throughfall on SSF; however, they did not find a clear impact. This is likely caused by the used pattern. Hopp and McDonnell (2011) used a fine scale throughfall pattern, while in this study a pattern with a distinct hotspot is used. Depending on the location of the hotspot the throughfall pattern influences the SSF. If the hotspot is located above a "channel" of high flow accumulation, this causes quick drainage. This is likely related to the connectivity of the saturated areas as found by Tromp-van Meerveld and McDonnell (2005) to be the main cause for SSF on many hillslopes.

Tromp-van Meerveld and McDonnell (2005) found that SSF is strongly correlated to hillslope average soil moisture; however, that there is a lack of correlation between (near surface) soil moisture pattern and subsurface saturation due to soil depth and bedrock topography. They found that the soil moisture pattern at the soil bedrock inter-

face is most important for subsurface saturation. In our study we found by means of the geostatistical hydrograph how the soil moisture pattern is influenced by the bedrock to-pography and the throughfall pattern during a storm. We showed that before the storm





the soil moisture pattern reflects the bedrock topography and that during the storm the througfall hotspots are clearly visible.

Similar to our study, other studies that considered hotspots also found that hotspots have a big influence on the soil moisture distribution during and shortly after an ⁵ event (Liang et al., 2007; Sansoulet et al., 2008; Jost et al., 2004; Raat et al., 2002). Shachnovich et al. (2008) did not find this relation. However, they compared the change in soil moisture over a week while the dynamics of throughfall patterns has a much shorter time scale.

During dry periods, the bedrock topography becomes more important as shown in the "geostatistical hydrograph" and thus soil physical properties are important as also found by Bouten et al. (1992). Also Tromp-van Meerveld and McDonnell (2006c) found that during the dry state soil moisture was correlated (although not much) to bedrock topography at Panola hillslope. The relatively low correlation between the bedrock and the observed soil moisture patterns compared to our modelled results are likely due to transpiration, which is not part of our analysis.

Western et al. (1999) and Grayson et al. (1997) also found that soil moisture patterns were influenced by topography, although they considered a seasonal timescale and not the event scale. They found that during the wet state (winter period) the soil moisture pattern was dominated by lateral flow and thus was organized according to the topography. During the dry state (summer period) vertical water flow was domi-

nant and hence the soil moisture was less organized by the topography. Our study is comparable to a "wet season".

Geostatistical hydrograph analysis may help to understand and predict soil moisture patterns based on throughfall and bedrock patterns; however, one should be careful with using the effective range as the descriptor of a spatial pattern. Two spatial patterns

can have the same effective range, but can have a completely different pattern.

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Our study neglects transpiration, but also its related feedback mechanisms which can be of importance. Bouten et al. (1992) for example stated that the short influence of throughfall on soil moisture is due to feedback mechanisms of drainage and water





uptake. Trees supposedly optimize their root system to water availability, causing higher water uptake when throughfall is high ("preferential uptake"). At Panola most trees indeed grow in the "drainage channels" where the soil depth is large (see Fig. 12 in Tromp-van Meerveld and McDonnell, 2006c). However, we think that where throughfall botspots exist, throughfall will be dominant over water uptake. This is also shown by Liang et al. (2007) and Sansoulet et al. (2008) who did not study hotspots by throughfall, but focused on hotspots caused by stemflow, which is in principle the same. The only difference between stemflow and throughfall hotspots is the influence of roots. As shown by Liang et al. (2007) bypass flow occurs especially close to the stem of the
trees. For throughfall hotspots this might be less important, but then antecedent soil

- moisture conditions become more important. When it has been dry for a long time, cracks can develop which facilitate macropore flow (Jost et al., 2004). Unfortunately, the effect of macropore flow has not been considered in our modelling study, because of the lack of data to properly model this. Macropores could lead to a quicker drainage
- of the throughfall, resulting in a shorter duration of impact of the throughfall pattern on the soil moisture. However, even if macropores exist the throughfall pattern will influence the soil moisture pattern. The influence of root water uptake and macropore flow needs to be further investigated.

6 Conceptual framework

As stated in the introduction, the literature is equivocal on the importance of throughfall on soil moisture content. Although their results may be contradictory, they may not be so different if one considers the conditions under which they carried out their experiments. Throughfall conspires with other factors, such as slope angle or storm size, and it are the interactions between factors that shape hillslope hydrological responses (Hopp and McDonnell, 2009).





We extended the conceptual model presented by Hopp and McDonnell (2009) by the effect of spatially variable input to analyse soil moisture. In Fig. 12 the outline of our conceptual model is shown.

We divided the model into three parts: (1) fixed hillslope configuration; (2) time variable input; and (3) the hillslope response (or state). In part 2 we added the interception threshold, which causes spatially variable throughfall patterns. These throughfall patterns influence the soil moisture content. Depending on the slope and the storm size the influence is higher or lower. On a relatively flat hillslope the impact of throughfall on soil moisture is bigger in terms of the magnitude of the effective range (Fig. 11c)
and duration before it bounces back to the bedrock pattern (Fig. 11b), because lateral

drainage along the soil-bedrock interface is slow due to the small slope angle. Storm depth mainly influences the magnitude of the effective range: the bigger the storm, the more the soil moisture pattern reflects the throughfall pattern (Fig. 11c).

In case hotspots exist (either by throughfall or by stemflow), the spatial throughfall pattern can also influence SSF (Fig. 4). It really matters where the hotspot is located in relation to the soil depth distribution and the bedrock topography. First of all, the shape of the hydrograph can be different, but also the distribution along the trench is influenced by hotspots.

As concluded by Hopp and McDonnell (2011), throughfall is not a first order control for SSF in comparison to slope angle and storm size. Our study shows that throughfall is indeed not a first order control; however, the importance of throughfall patterns on SSF highly depends on the spatial variability of the throughfall pattern in relation to the topography of the bedrock.

In our virtual experiment, we did not include the influence of water uptake by plants. Transpiration will likely reduce the effect of throughfall patterns on soil moisture patterns, because roots optimise their root system to water availability (Bouten et al., 1992). Also antecedent soil moisture conditions and the influence of macropores have not been taken into account, while they do have an influence as shown by Jost et al. (2004), Liang et al. (2007), and Sarkar and Dutta (2011). The difficulty with including





water uptake and macropore flow, is the mutual interdependence of these processes and the possible feedback between them. Furthermore, macropores are in general difficult to implement in hydrological models and require detailed information on the macropore distribution, which was not available for Panola hillslope. Future work can focus on these feedback mechanisms.

7 Conclusions

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The virtual experiment shows that throughfall patterns influence soil moisture patterns, but only during and shortly after a storm event. By means of a geo-statistical analysis we investigated the soil moisture pattern reflects the spatial throughfall pattern or that of the bedrock. As an indicator we used the effective range of the semi-variogram. We

- ¹⁰ of the bedrock. As an indicator we used the effective range of the semi-variogram. We found that during a storm the soil moisture pattern has a similar effective range as the throughfall pattern, but gradually returns to the effective range of the bedrock pattern after throughfall has ceased.
- Furthermore, we looked at the impact of hillslope controls and storm size on the geostatistical analysis. It appeared that the throughfall pattern is more important during large storms on gentle slopes. For steeper slopes the bedrock topography becomes more important. The mean soil depth appears to have no significant impact. These findings have been included in a conceptual model, which can be used to evaluate the effect of spatially varying throughfall.
- Overall, we can conclude that interception has a large influence on SSF generation and on the soil moisture patterns that occur during and shortly after rain events. Geostatistical analysis can help to understand the relationship between soil moisture patterns, throughfall patterns and subsurface characteristics. However, more research is necessary to investigate other hillslope variables, such as antecedent wetness, macroporosity, rainfall intensity, soil evaporation, and transpiration. A next research step
- would be to confront our model results with observations in an experimental setup.





However, field data of high spatial and temporal resolution are rare, and therefore our virtual experiment remain valuable.

Supplementary material related to this article is available online at: http://www.hydrol-earth-syst-sci-discuss.net/9/8625/2012/ hessd-9-8625-2012-supplement.pdf.

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Table 1. Definition of the five classes and the main characteristics, with ΣT_f throughfall sum, ΣP gross precipitation sum (=33 mm), and $\Sigma \overline{T}_f$ the mean throughfall sum in a class. The spatial cover percentage is only calculated for the initial spatial throughfall pattern.

Class definition		ΣT_f [mm]	$\Sigma \overline{T}_{f}$ [mm]	$\Sigma \overline{T}_f / \Sigma P[\%]$	Spatial cover [%]
1	0–25.0 %	0–18.8	17.4	53	12
2	25.0–37.5 %	18.8–28.1	22.6	69	76
3	37.5–50.0 %	28.1–37.5	29.8	91	6
4	50.0–75.0 %	37.5–56.3	43.3	132	4
5	75.0–100 %	56.3–75	65.3	200	2

Input	Topography				
Storm size, <i>R</i>	Slope angle, A	Soil depth,S			
32 mm	6.5°	0.62 m*			
63 mm*	13°*	1.22 m			
82 mm	26°	1.84 m			
	40°				

* indicate the base case scenario.

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Material	Mesh layers		$\theta_{\rm r}$	$\theta_{\rm s}$	α	п	Ks	
	$S = 0.62^{*}$	<i>S</i> = 1.22	<i>S</i> = 1.84	$[m^3 m^{-3}]$	$[m^3 m^{-3}]$	[m ⁻¹]	[-]	$[m h^{-1}]$
1 (soil)	9–10	10–12	12–15	0.280	0.475	4.00	2.00	3.5
2 (soil)	7–8	7–9	9–11	0.280	0.460	4.00	2.00	1.5
3 (soil)	6	6	6–8	0.325	0.450	4.00	2.00	0.65
4 (bedrock)	5	5	5	0.300	0.450	3.25	1.75	6E-3
5 (bedrock)	1–4	1–4	1–4	0.280	0.400	3.00	1.50	6E-4

 Table 3. Soil hydraulic properties of van Genuchten-Mualem model.

 * Indicate the base-case scenario with mean soil depth S = 0.62 m.

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Fig. 2. (a) Interception plot Huewelerbach: location of the 81 rain gauges to measure throughfall. **(b)** Spatial throughfall pattern (interpolated with a triangle-based cubic interpolation technique and a 10 cm mesh) of May 2007. The black contour lines represent the five throughfall classes, and the white grid the selected area for the analysis. The hotspot is located near the tree at coordinates 15 m, 15 m.







Fig. 3. Used spatial throughfall pattern ("Upper Right-2.1") on Panola hillslope. Class 1: magenta; class 2: green; class 3: yellow; class 4: dark blue; class 5: light blue.















Fig. 5. Soil moisture patterns [–] of distributed input for soil mesh layers 10 (top) to 5 (bedrock interface) at different time steps.







Fig. 6. Mean soil moisture content over mesh layers 5–10 in time for uniform input and distributed input. The dashed lines indicate the mean standard deviation over mesh layers 5–10.







Fig. 7. Difference in soil moisture content between uniform input and distributed input.







Fig. 8. (a) Flow accumulation map and location of high intensity throughfall input; **(b)** soil moisture pattern of the soil-bedrock interface after a long dry period (t = 190 h); **(c)** shortly after a rain storm (t = 8 h) at mesh layer 5 (i.e. bedrock interface layer).





















Fig. 11. (a) Interplay of hillslope attributes on model performance (average for mesh layers 5–10 and t > 0 h); (b) Interplay of hillslope attributes on equilibrium effective range; (c) Interplay of hillslope attributes on peak value of the mean effective range of the soil layers. Blue indicates that the effective range is very similar to the effective range of the throughfall pattern, and red indicates similarity to the effective range of the bedrock pattern; (d) Interplay of hillslope attributes on the time to peak (i.e. time between start of rain and peak in effective range).







Fig. 12. Conceptual model of hillslope behaviour (extended from Hopp and McDonnell, 2009) with SBI the soil-bedrock interface.

