Threshold relations in subsurface stormflow:
2. The fill and spill hypothesis

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[1]   Analysis of subsurface stormflow from 147 storms at the 20 m long trench in the Panola Mountain Research Watershed by Tromp-van Meerveld and McDonnell (2006a) showed that there was a distinct 55 mm precipitation threshold for significant subsurface stormflow production. This second paper in the series investigates the processes responsible for this threshold response. We installed a dense spatial array of maximum rise crest stage gauges and recording wells on the hillslope and studied the temporal and spatial patterns of transient saturation at the soil-bedrock interface and its relation to subsurface stormflow measured at the trench face. Results show that while transient groundwater developed on parts of the hillslope during events smaller than 55 mm, it was not until more than 55 mm of rain fell before bedrock depressions on the hillslope were filled, water spilled over microtopographic relief in the bedrock surface, and the subsurface saturated areas became connected to the trench. When connectivity was achieved, the instantaneous subsurface stormflow rate increased more than fivefold compared to before the subsurface saturated areas were connected to the trench face. Total subsurface stormflow was more than 75 times larger when connectivity was achieved compared to when connectivity was not achieved. The fill and spill hypothesis presented in this paper is a process explanation for the observed threshold behavior of Tromp-van Meerveld and McDonnell (2006a), thereby linking patterns and processes.

1.   Introduction

[2]   Hillslopes are fundamental landscape units for understanding runoff generation processes. As a result, hillslopes are the basic building blocks for many watershed models. Recent studies have suggested, however, that complexities at the hillslope scale may prevent their appropriateness as a model building block [*Sivapalan*, 2003]. Indeed, hillslopes are complex. Numerous studies in the past decades have revealed staggering complexity of flow pathways and fate of infiltrating rainfall and snowmelt due to heterogeneity of hydraulic conductivity, vertical preferential flow, lateral soil pipes, impeding layers, etc. One might question, then, whether we should continue to focus on the dynamics of hillslope response since every hillslope appears unique [*Beven*, 2001].

[3]   While subsurface stormflow has been studied in detail for decades, only recently has the threshold nature of the process been posited as an emergent behavior at the hillslope scale [*McDonnell*, 2003]. A clear exposition of this threshold behavior as an emergent behavior was presented in the first paper of this series by *Tromp-van Meerveld and McDonnell* [2006a] who analyzed 147 storms for the Panola trenched hillslope. They were able to show that 55 mm

of precipitation was required for significant (>1 mm) subsurface stormflow to occur. For storms with more than 55 mm of precipitation, total subsurface stormflow was almost 2 orders of magnitude larger than total subsurface stormflow from storms smaller than 55 mm. While *Tromp-van Meerveld and McDonnell* [2006a] is certainly not the first discussion of nonlinear relations at the hillslope scale, their unusual record length and ability to examine different storm sizes, antecedent conditions and seasons allowed them to show this threshold response very clearly. They argue that this threshold response (both the threshold value itself and the slope of the relation between storm total subsurface stormflow and precipitation after the threshold) may define emergent behavior at the hillslope scale and be useful as a tool for intercomparison of the subsurface stormflow response of different hillslopes. This could help shift the debate in hillslope hydrology from a focus on the detailed point-based description of runoff dynamics to a representation of the whole hillslope response. The threshold detection is a way to simplify the description of a complex system and perhaps classify behaviors of different hillslopes. More importantly, a hillslope-scale subsurface stormflow threshold is a potential benchmark for models to capture. Notwithstanding, if threshold-based subsurface stormflow initiation is a potential way forward for characterizing whole hillslope response, we need a clearer understanding of the linkages between patterns and processes; in this case, the internal hillslope conditions that create the threshold behavior.

[4]   One of the most commonly observed point-scale prerequisites for subsurface stormflow initiation and gener-

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Figure 1. Surface and bedrock topography on a representative upslope transect across the hillslope.

ation is the development of saturation at the soil-bedrock interface during events [*McGlynn et al.*, 2002]. Other common prerequisites for subsurface stormflow initiation shown in published studies to date are a rise in water table from poorly transmissive till up into transmissive mineral soil [*Kendall et al.*, 1999], or a deflection of flow from vertical to lateral at impeding layers in the soil profiles, both shallow [*Brown et al.*, 1998] and deep [*Harr*, 1977]. While such initiation is relatively well described at a point, few studies have quantified the development of subsurface saturation and subsurface flow initiation spatially across the entire hillslope.

[5] In this paper, we focus not on microscale complexities, but rather on the spatial patterns associated with both the temporal subsurface stormflow response and the threshold response. This pattern-based interpretive approach is an alternative to the more traditional reductionist hillslope based approach. In this paper we use patterns for the process explanation of the hillslope threshold behavior of *Tromp-van Meerveld and McDonnell* [2006a]. We instrumented the Panola Mountain Research Watershed trenched research hillslope with a dense grid of 135 crest stage gauges and 29 recording wells to examine the spatial and temporal patterns of subsurface saturation at the soil-bedrock interface and how this relates to the observed threshold for subsurface stormflow. The aim of this paper is to develop a process explanation for threshold behavior in subsurface stormflow observed at Panola and elsewhere. Specific questions we address using these new data are the following: (1) What is the spatial pattern of subsurface saturation at the hillslope scale and how does this change with precipitation amount and antecedent wetness conditions? (2) How do soil depth and bedrock microtopography influence the spatial pattern of saturation at the base of the soil profile? (3) Does the development of subsurface saturation across the hillslope explain the observed precipitation threshold for significant subsurface stormflow generation at the trench face?

2. Study Site

[6] The location of the study site, the climate and soil at the study hillslope are described in detail by *Tromp-van Meerveld and McDonnell* [2006a]. Here we describe only the soil depth variations and bedrock topography in more detail.
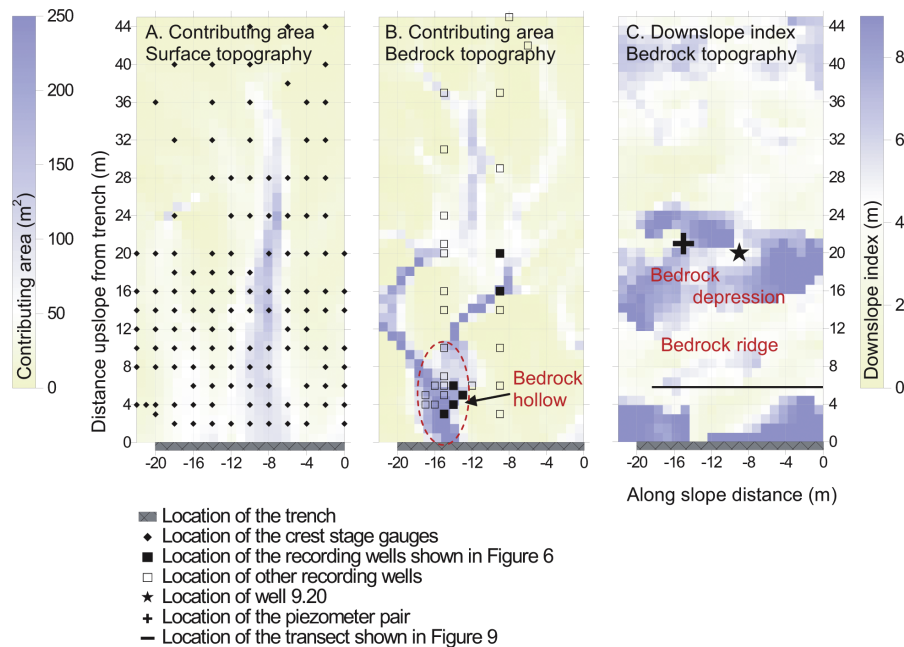
[7] The surface topography of the study hillslope is relatively planar but has a small depression near the middle

of the hillslope, while the bedrock topography is highly irregular [*Tromp-van Meerveld and McDonnell*, 2006a, Figure 1]. The average soil depth of the study hillslope is 0.63 m and ranges from 0 to 1.86 m. The omnidirectional correlation length (defined here as the distance where the normalized variance is 0.95) of soil depth is 10 m. There is an area of deep soils parallel to the contours of the hillslope between 15–22 m upslope from the trench. This is caused by a large depression in the bedrock. This area of deep soils will be called the bedrock depression in the remainder of this paper. Upslope from the bedrock depression, soils are generally shallow. The average soil depth of the area between 25 m upslope from the trench and the upper boundary of the hillslope is 0.51 m. Directly downslope of the bedrock depression is an area of shallower soils, which will be called the bedrock ridge in the remainder of this paper. This bedrock ridge results in an area of high bedrock downslope index approximately 16 m upslope from the trench (i.e., in the bedrock depression directly upslope from the bedrock ridge) (Figures 1 and 2c). The downslope index (L_d) is a topography-based index, is defined as the horizontal distance to a point with a specified elevation (d) below the elevation of the starting point, and is considered a measure of impedance to local drainage by the downslope topography [*Hjerdt et al.*, 2004]. A high downslope index indicates large impedance to local drainage. Soil depth on the lower 15 m of the hillslope is highly variable. The deepest soils are located in the area with high bedrock contributing area, which will be named the bedrock hollow in the remainder of this paper (see Figure 2b).

3. Methods

[8] We installed 135 crest stage gauges filled with cork dust on a 2 by 2 m grid across the lower 16 m of the hillslope and an irregular but approximately 4 by 4 m grid across the remainder of the hillslope (Figure 2a). These 19 mm diameter PVC piezometers were augered to refusal, screened over the lower 200 mm and installed on the soil-bedrock contact. The maximum water level rise was measured after each storm during the January–August 2002 period. The maximum and actual water levels were also measured several times during storms in the winter of 2002.

[9] In addition to the grid of crest stage gauges, 29 recording wells were installed. These recording wells were located on two transects on the hillslope and in a dense grid in the bedrock hollow (Figure 2b). These 51 mm diameter PVC wells were hand-augered to refusal and screened over

Figure 2. Map of (a) the contributing area based on the surface topography with the location of the crest stage gauges, (b) contributing area based on bedrock topography with the location of the recording wells, and (c) downslope index (L_1: horizontal distance to a point 1m below) based on the bedrock topography with the location of the piezometer pair, the location of well 9.20, and the transect shown in Figure 9. The solid squares shown in Figure 2b represent the location of recording wells shown in Figure 6. The oval in Figure 2b represents the location of the bedrock hollow and the words ''bedrock depression'' and ''bedrock ridge'' in Figure 2c show the approximate location of the bedrock depression and bedrock ridge.

the entire length. The water level was measured every 5 min from January–June 2002 using capacitance rods (Trutrack, New Zealand). The capacitance rods could not measure water levels below 75 mm of the soil-bedrock interface. Subsurface saturation was high and wide spread enough to be measured by the capacitance rods during two storms in the January–June 2002 period. These storms are the 6 February 2002 storm, a low-intensity, long-duration storm (59 mm) and the 30 March 2002 storm, a small low-intensity storm in the morning (12 mm) and in the afternoon (12 mm) followed by a very intense thunderstorm in the evening of that day (37 mm).

[10] We also installed one piezometer pair in the area of deep soils and high bedrock downslope index (Figure 2c). The deep piezometer was augered to refusal and installed in the coarser more saprolitic layer. The shallow piezometer of the piezometer pair was located 0.38 m higher in the profile, immediately above the saprolitic layer. Both piezometers were screened over the lower 0.15 m. The head in these piezometers was measured every 5 min between January and June 2002 with capacitance rods.
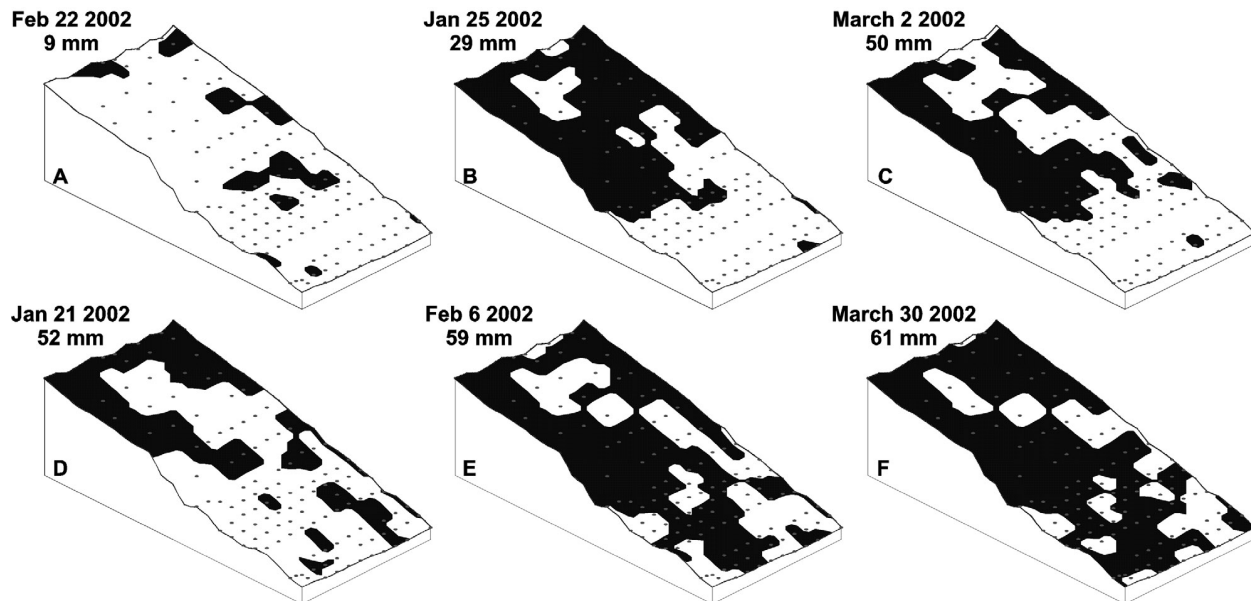
[11] The lateral subsurface stormflow measurements at the trench are described by *Tromp-van Meerveld and McDonnell* [2006a], *McDonnell et al.* [1996], *Freer et al.* [1997, 2002], and *Burns et al.* [1998]. The trench collection system and the tipping buckets were repaired prior to this study in November 2001. The precipitation measurements are described in more detail by *Tromp-van Meerveld and*

McDonnell [2006a] and *Peters et al.* [2003]. The soil depth measurements are described in more detail by *Tromp-van Meerveld and McDonnell* [2006a], and *Freer et al.* [1997, 2002].

4. Results

4.1. Spatial Extent of Subsurface Saturation

[12] During the winter period the maximum extent of the area of subsurface saturation increased with increasing storm size (Figures 3 and 4a). The spatial pattern of subsurface saturation was relatively persistent from one storm to another. During small storms (<10 mm total rainfall), subsurface saturation at the soil-bedrock interface occurred only in small (isolated) areas on the midslope. During medium-size storms (10–55 mm), the area of subsurface saturation increased in the across-slope and upslope direction compared to the area of subsurface saturation during smaller storms. In addition there were a few isolated spots of subsurface saturation closer to the trench face. For these medium-size events, the large and connected area of subsurface saturation however was located more than 16 m upslope from the trench and disconnected from the trench face. During large storms (>55 mm), subsurface saturation became more widespread across the hillslope and connected to the trench face. There was a large increase in the area of subsurface saturation that was connected to the trench between the 52 mm rainstorm

Figure 3. Observed spatial distribution of subsurface saturation at the soil-bedrock interface across the Panola hillslope with increasing precipitation overlaid on top of the bedrock topography. The shaded area represents the area where transient subsurface saturation was observed; the nonshaded area indicates the area where no subsurface saturation was observed. The diamonds represent the locations of the crest stage gauges. We used the nearest neighbor method to interpolate between the point measurements.

on 21 January and the 59 mm rainstorm on 6 February. The antecedent conditions for these low-intensity storms were similar. The 7 day antecedent precipitation index (calculated as by *McDonnell et al.* [1991] and *Woods and Rowe* [1996]) was 0.9 and 0.7 mm/day for the 21 January and 6 February storms, respectively. We found similar patterns of increasing subsurface saturated area with increasing precipitation when measurements of the maximum (and current) water level were made during a storm.

[13] Storm total precipitation and the maximum area of subsurface saturation were well correlated during the winter months (Figure 4a). The relation between the maximum area of subsurface saturation and total subsurface stormflow for this period was highly threshold-like (Figure 4b). The 52 mm 21 January storm generated only 0.04 mm subsurface stormflow while the 59 mm 6 February storm, with similar antecedent wetness conditions, generated 6.63 mm of total subsurface stormflow.

4.2. Relation Between Maximum Water Level and Total Subsurface Stormflow

[14] The relation between total subsurface stormflow at the 20 m long trench and the maximum water level above bedrock in well 9.20 (located 9 m from the right side of the trench face (when looking upslope) and 20 m upslope from the trench face; see Figure 2c) was highly threshold-like (Figure 5a). This recording well was located in the bedrock depression (i.e., in the area of deep soils and a high bedrock downslope index; see Figure 2). This location also has a high contributing area, based on both the surface and bedrock topography (Figure 2). When the maximum groundwater level above bedrock in well 9.20 was less than 300 mm, total subsurface stormflow was small (less than 0.1 mm). When the maximum water level above bedrock in well 9.20 was higher than 325 mm, subsurface stormflow
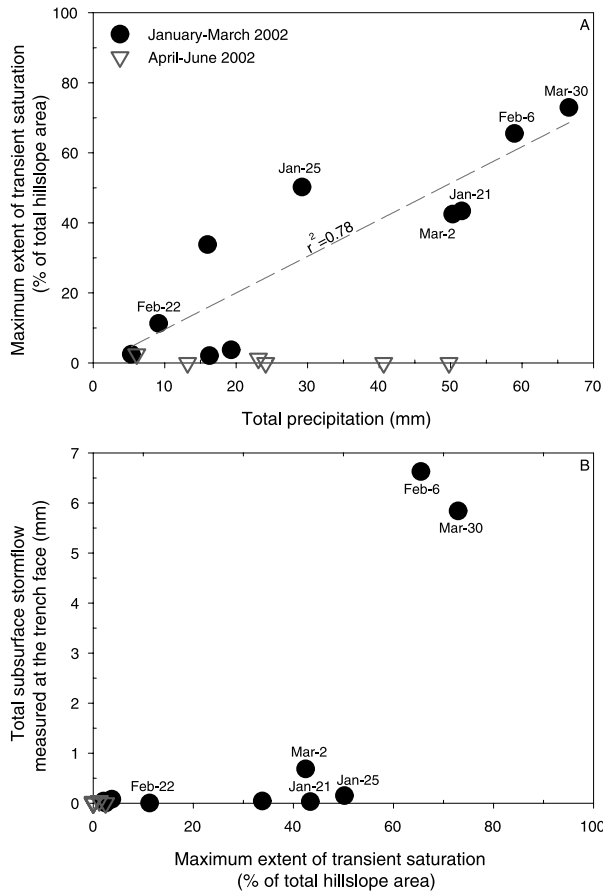
was more than 75 times larger than when the maximum water level above bedrock was less than 300 mm.

[15] The relation between the maximum water level above bedrock in well 9.20 and the maximum instantaneous subsurface stormflow rate was also threshold-like (Figure 5b). When the maximum water level in well 9.20 was less than 300 mm above bedrock, the maximum subsurface stormflow rate at the trench was less than 0.02 mm/hr. When the maximum water level was higher than 325 mm above bedrock, the maximum subsurface stormflow rate was more than 20 times higher than when the maximum water level was less than 300 mm. Although the 6 February and the 30 March storm had very different maximum rainfall intensities, the maximum subsurface flow rates were relatively similar; the 30 min maximum rainfall intensity was 5.6 mm/hr during the 6 February storm and 62.4 mm/hr during the 30 March storm while the maximum subsurface flow rate was 0.29 and 0.36 mm/hr for the 6 February and 30 March storm, respectively.

4.3. Temporal Response of Subsurface Saturation

[16] Figure 6 shows the temporal water level response in selected recording wells and the subsurface stormflow rate from the 4 m wide section of the trench below these wells. The wells shown in Figure 6 are located in the bedrock hollow; on a transect that follows the topographic lows in the bedrock topography down from well 9.20 (Figure 2b). The 4 m wide trench section located downslope from this transect is the trench section with the highest bedrock contributing area and the section that delivers, on average, 43% of all subsurface stormflow at the 20 m trench [*Tromp-van Meerveld and McDonnell*, 2006a].

[17] During the 6 February storm there was a fast (within 1 hour) eightfold increase in the subsurface stormflow rate at 2039 LT (Figure 6a). This large increase in subsurface

Figure 4. (a) Relation between storm total precipitation and the maximum area of subsurface saturation and (b) relation between the maximum area of subsurface saturation and storm total subsurface stormflow. For the maps of the spatial patterns of transient saturation for the labeled storms, see Figure 3.
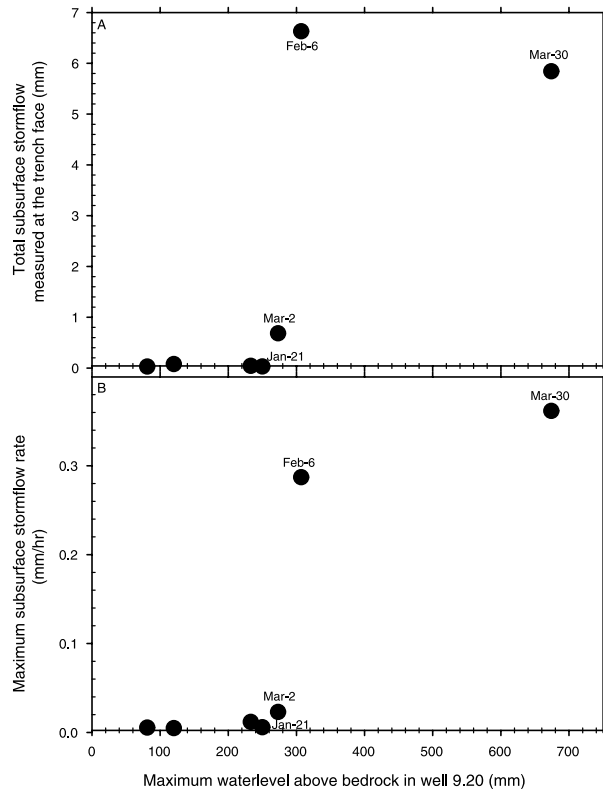
flow rate was not related to an increase in rainfall intensity. Well 9.20 was the first well to respond (at 1204 LT). After this well responded, all other wells located in the bedrock hollow downslope from this well (i.e., in the area with high bedrock contributing area, see Figure 2b) responded. The wells located closest to well 9.20 responded first and the wells located furthest downslope responded last. However, the wells located furthest downslope from well 9.20 responded before the large increase in subsurface stormflow rate. Wells located downslope from well 9.20, but outside the bedrock hollow, did not respond at all during the 6 February storm.

[18] During the high-intensity thunderstorm on 30 March, flow at the trench started during the peak of the thunderstorm. The subsurface flow rate declined 15 min after the peak rainfall intensity; having a second peak, almost 3 hours after the end of the thunderstorm (Figure 6b). Well 9.20 was the first well to respond to the small rainfall events during the morning and afternoon. The water level in well 9.20 increased rapidly in response to the thunderstorm. Similar to the 6 February storm, all wells downslope from well 9.20 responded later than well 9.20. Again, the upslope wells (closest to well 9.20) responded before the downslope wells
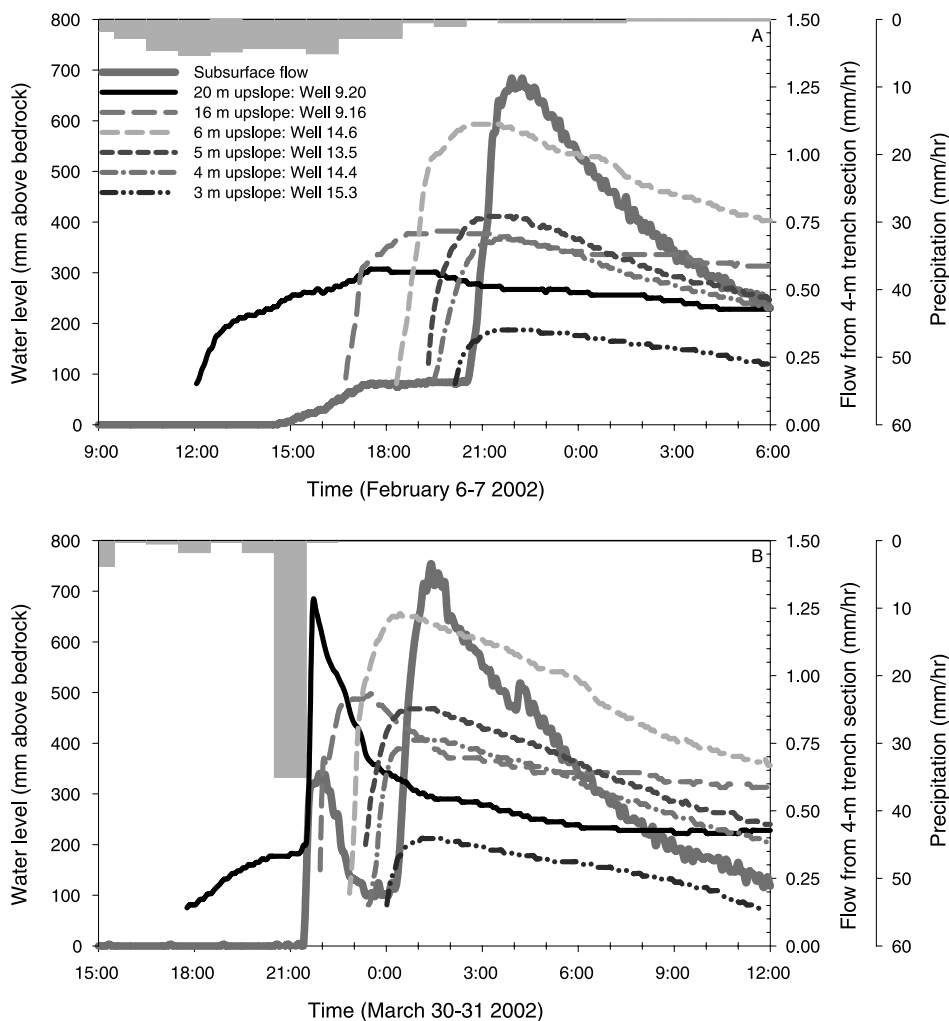
(furthest from well 9.20) responded, and the wells furthest downslope responded before the second increase in subsurface stormflow rate. Water levels in the upslope wells (but downslope from well 9.20) already started to recede before the wells furthest downslope had started to respond (Figure 6b).

[19] During the 30 March storm we observed a similar response further downslope on a similar hillslope in wells located 2 m upslope from the boundary between the riparian zone and the hillslope. Water levels in these wells showed either a double peak (e.g., well R6.8), a period of slower recession (e.g., well R6.10), or a first response (e.g., well R6.2) concurrent with or within 1.5 hours of the second peak in the subsurface stormflow rate measured at the trench (i.e., three hours after the end of the thunderstorm) (Figure 7). Other wells showed only a single peak directly after the thunderstorm (e.g., well R6.12).

[20] The relation between the time of the start of measurable subsurface saturation and the distance upslope from the trench face was linear (Figure 8). For the trench (distance 0), the time of response that was used for the 6 February storm was the time of the increase in subsurface stormflow rate (2039 LT) and for the 30 March storm the time of the second increase in subsurface stormflow rate (0021 LT). The time of response that was used for well 9.20 was the time of first measurable subsurface saturation (1204 LT) for the 6 February storm and the time of the
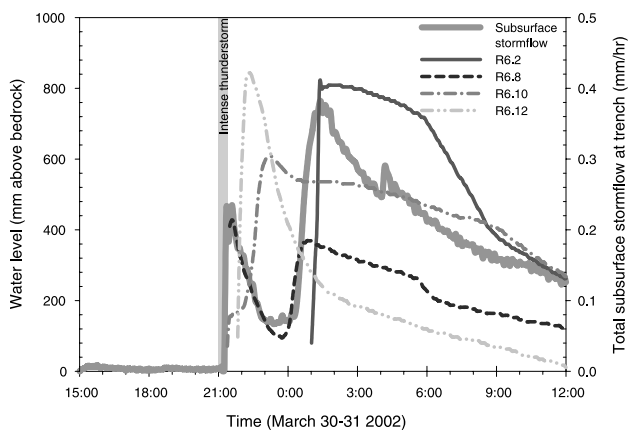

Figure 5. Relation between the maximum recorded water level in well 9.20 and (a) total subsurface stormflow and (b) the maximum subsurface stormflow rate measured at the trench face. For the maps of the spatial patterns of transient saturation for the labeled storms, see Figure 3. For the location of well 9.20, see Figure 2c.
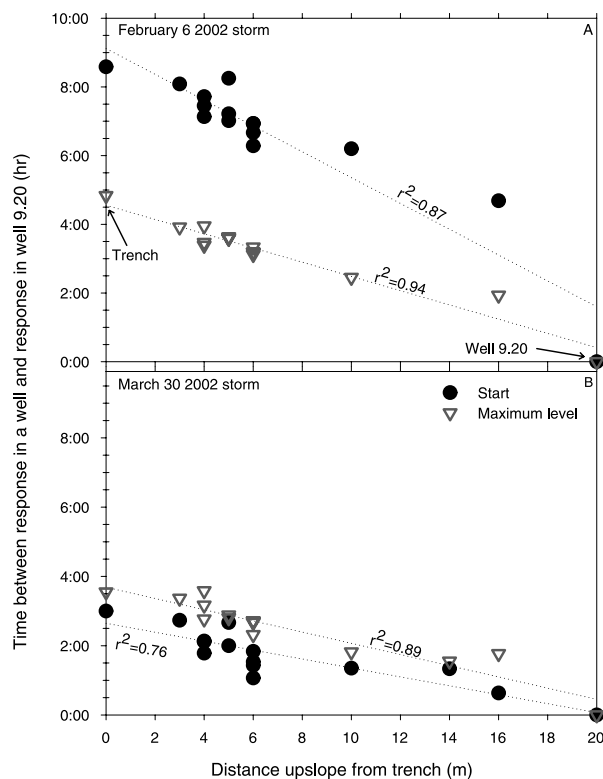
Figure 6. Precipitation intensity, water level response, and subsurface stormflow rate from the 4 m wide trench section directly downslope from the wells during (a) the 6 February 2002 storm and (b) the 30 March 2002 storm. The locations of the wells shown are represented by solid squares in Figure 2b. The capacitance rods could not measure the water level within the first 75 mm from the bedrock.

rapid increase in water level in response to the thunderstorm for the 30 March storm (2121 LT). A similar linear relation also existed between the time of the maximum water level and the upslope distance (Figure 8). From this linear relation, the velocity of the flux of water that moved downslope over the bedrock could be calculated. The calculated traveling velocity of the subsurface flow was 4 m/hr during the 6 February event and 8 m/hr during the 30 March event. The vertical matrix saturated conductivity measured in a large soil core from an adjacent hillslope was 0.64 m/hr [*McIntosh et al.*, 1999]. However, the lateral saturated conductivity of the hillslope could be larger than the vertical saturated conductivity of the soil core because of the presence of soil pipes and anisotropy. Soil pipes and mesopores, particularly at the soil-bedrock interface, were observed to deliver water to the trench face before water seeped out of the trench face matrix.

[21] The dynamics of measurable subsurface saturation for recording wells located upslope from well 9.20 were complex. Measurable saturation in these wells started after measurable saturation in well 9.20. For the high-intensity

Figure 7. Subsurface stormflow rate measured at the trench face and water level response in wells 2 m upslope from the riparian zone in a nearby hillslope during the 30 March 2002 storm. The shaded area represents the time of the intense thunderstorm.

Figure 8. Difference between the time of the first response (circles) or time of the maximum water level (triangles) in a well and the time of response in well 9.20 as a function of the distance of the well upslope from the trench face for the (a) 6 February 2002 and (b) 30 March 2002 storms. All wells located downslope from well 9.20 in the bedrock hollow (i.e., the area with high (>150 m²) bedrock contributing area) are shown. See Figure 2b for the location of these wells.

30 March storm this lag was very small (on the order of minutes). During the 30 March storm, the time of first measurable response was related to soil depth (the first response in the shallowest soil areas). This relation was not clear for the 6 February storm.

[22] Subsurface saturation was short-lived, lasting less than 1 day after the end of the storm. The wells located 20–22 m upslope from the trench were an exception to this. These wells were located in the main bedrock depression (i.e., in the section with deep soils and high bedrock downslope index; see Figure 2). Subsurface saturation at these locations was longer lived, up to maximum 5 days after the end of the storm. The lower 0.15–0.35 m of these wells was located in a coarser more saprolitic layer.

[23] Subsurface saturation started in the deepest soil section (i.e., lowest parts of the bedrock hollow) and filled more of the bedrock hollow from there (Figure 9). The bedrock topography confined the area of subsurface saturation to the main bedrock hollow. The bedrock low located 14 m from the right side of the hillslope and 6 m upslope from the trench face for example was connected to the location of well 9.20 by other lows in the bedrock and filled with water. However, the bedrock low located 4 m from the right side of the hillslope and 6 m upslope from the trench
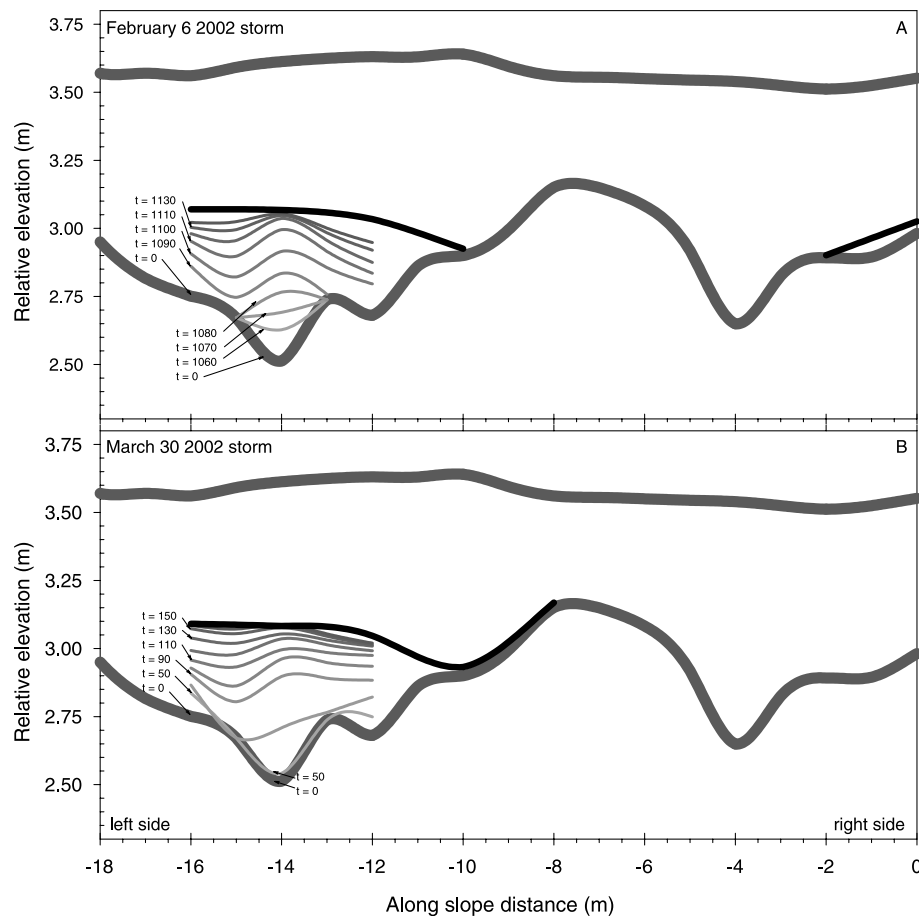
face was not connected upslope to other bedrock depressions and did not fill with water. The flow direction calculated from the interpolated water levels in the bedrock hollow (i.e., in the high bedrock contributing area with the dense grid of wells) was downslope toward the trench face (based on both the surface and bedrock topography).

5. Discussion

5.1. Patterns of Transient Saturation and the Fill and Spill Hypothesis

[24] Many of the common textbook images and descriptions of how hillslopes 'work' include a description of a saturated wedge that expands in an upslope direction with increasing precipitation and contracts as a result of drainage [e.g., *Weyman*, 1973; *Atkinson*, 1978]. While field studies have reported the development of a saturated wedge [e.g., *Whipkey*, 1965; *Weyman*, 1973; *Wilson et al.*, 1990; *Buttle and Turcotte*, 1999], many of these have been based on transect information or a limited number of wells across a hillslope. We argue that transect data is difficult to generalize to the entire hillslope because of spatially variable flow paths. Transect data could then mislead and misinform spatial patterns of saturation. Indeed, if we were to plot a single transect of wells on the Panola hillslope, we would be hard-pressed to see "connectedness" in the way that the spatial patterns of transient saturation (Figure 3) show us. We argue that our network of spatially distributed wells and crest stage gauges show clearly that subsurface saturation at the Panola study hillslope does not occur in the form of a saturated wedge that expands in the upslope direction with increasing precipitation. On the contrary, it expands downslope from the mid and upper hillslope sections toward the trench face. Transient saturation at the Panola hillslope is accomplished via a combination of subsurface saturation in shallow soil areas (located on the upslope part of the hillslope) and subsurface saturation in the bedrock depressions (located on the midslope). Measurable subsurface saturation was always observed to start on the midslope and expand outward from there (Figure 3). At the beginning of the event, positive pore pressure develops in the main depression and free water in the soil column forms at the soil-bedrock interface (i.e., it fills up with water). When the water level reaches the ridge at the edge of the depression, water "spills" downslope over the bedrock ridge toward the trench face (i.e., lateral flow in the saturated zone where elevation gradients exceed capillary potential). Finally, the trench face becomes connected with the subsurface saturated area resulting in a sudden and dramatic increase in the subsurface stormflow rate. This fill and spill process is shown schematically in Figure 10. Lateral flow appears to be restricted to the bedrock lows and thus only takes place on vary narrow ribbons of "channelized" saturated flow, even during relatively large storms. This results in highly spatially variable subsurface stormflow across the trench face, where the sections with the highest bedrock contributing area deliver most of the subsurface stormflow [*McDonnell et al.*, 1996; *Freer et al.*, 1997, 2002; *Tromp-van Meerveld and McDonnell*, 2006a].

[25] The fill and spill mechanism observed here for subsurface stormflow at the hillslope scale is similar to the fill and spill mechanism observed by *Spence and Woo*

Figure 9. Water level rise on an across-slope transect located 6 m upslope from the trench face during the (a) 6 February and (b) 30 March 2002 storms. The thick solid lines represent the surface topography and the bedrock topography, the black line represents the maximum groundwater level as measured with the crest stage gauges, and the gray lines represent the pattern of water level rise between 6 February 2002 1824 and 1954 LT (Figure 9a) and between 30 March 2002 2151 and 2321 LT (Figure 9b). The times next to the lines of water rise are in minutes after the start of the storm for the 6 February storm and after the start of the thunderstorm for the 30 March storm. The location of the transect is shown in Figure 2c.
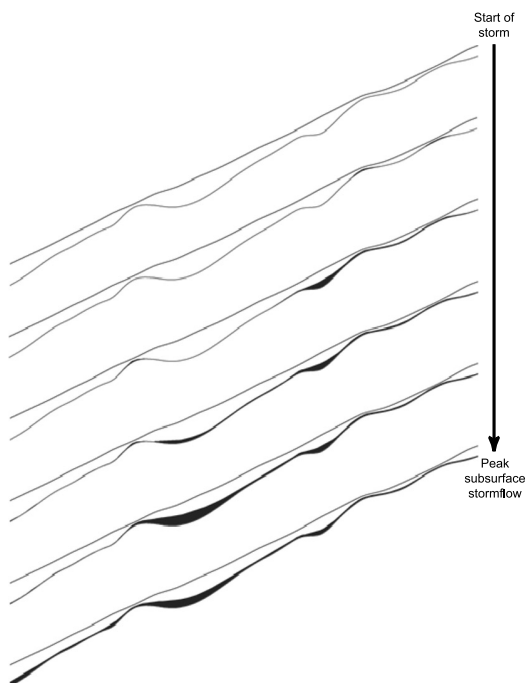
[2003] for a soil filled valley on the subarctic Canadian Shield. There, spatially variable valley storage had to be satisfied before water spilled to generate either surface or subsurface flow. The spatially variable valley storage was due to topographical diversity, soil heterogeneity and uneven thickness, and seasonal presence of ground frost. At the Panola study hillslope spatially variable soil depth (due to bedrock microtopography) results in spatially variable storage that has to be satisfied before saturation at the soil-bedrock interface can occur. The bedrock microtopography (especially the slope parallel ridges and depressions) then result in the fill and spill process that is necessary before subsurface saturated areas become connected to the trench face and significant subsurface stormflow can occur.

[26] We regard the filling of depressions at the soil-bedrock interface with water, and the spilling of water over microtopographic bedrock ridges as the subsurface analogue of depression storage in overland flow processes [e.g., *Darboux et al.*, 2001]. There, surface depressions have to be filled before saturated areas can become connected and overland flow can start. Here, depressions in the bedrock topography have to be filled before water can spill over the ridge of the bedrock depression, the subsurface saturated area can become connected to the trench face, and significant subsurface flow is measured at the trench. We view the relation between the increased subsurface flow rate and the connection of the area of subsurface saturation to the trench face also as the subsurface analogue of studies that have shown the relation between the connection of upslope and downslope saturated areas and an increase or second peak in streamflow [e.g., *Burt and Butcher*, 1985].

[27] *Tromp-van Meerveld and McDonnell* [2006b] show that there are only minor variations in soil moisture with depth or across the Panola study hillslope during the winter months. Thus preevent soil moisture variations are not the main control on the distribution of subsurface saturation during winter storms. Since soil moisture variations are small, soil depth determines the total soil moisture deficit and thus the total storage that has to be filled before saturation can occur at the soil-bedrock interface.

Figure 10. Schematic representation of the fill and spill process. The shaded areas represent the locations of subsurface saturation. The vertical exaggeration is 2 times.

We hypothesize that subsurface saturation occurs during medium-size storms in the shallow soil areas on the upslope because of the smaller total moisture deficits in these areas compared to the deeper soil areas further downslope. After saturation occurs locally at the soil-bedrock interface, water flows over the bedrock topography downslope toward the location of the main bedrock depression and well 9.20 (i.e., the area with deep soils, high contributing area and high impedance to local drainage). Water is concentrated and then retained in this region because of downslope damming, such that measurable subsurface saturation (>75 mm above the soil-bedrock interface) starts first at this well. Only when the water level rises high enough, higher than the bedrock ridge downslope of the main depression in the bedrock, which is 300 mm downslope from the location of well 9.20, does water spill downslope over the bedrock ridge and does the subsurface saturated area become connected to the trench. Because of the downslope damming of water by the bedrock ridge on the edge of the main bedrock depression, subsurface saturation lasts longer in the bedrock depression than elsewhere on the hillslope (i.e., days instead of hours after the end of the storm). Alternatively, the bedrock depression might be an area of exfiltration of water from the bedrock. We do not have piezometric data for the bedrock, but the head difference in the piezometer pair in the soil and more saprolitic layer indicates that gradients were downward during the 6 February and 30 March 2002 storms.

[28] A sequence of small storms (as observed during January 2002) did not lead to connectivity of the subsurface saturated area and thus to a very low total subsurface stormflow volume. Water levels in the wells in the bedrock depression were sustained longer than on other areas on the hillslope but still disappeared within days after the storm. We hypothesize that this is due to bedrock leakage. Sprinkling experiments and water balance calculations have shown that bedrock at Panola is not impermeable. However, there is a 2 orders of magnitude conductivity contrast between the soil and the bedrock such that water does pond at the soil-bedrock interface during events [*Tromp-van Meerveld et al.*, 2006]. Leakage to the bedrock empties the bedrock depressions that are blocked in the downslope direction by the bedrock ridge such that they have to be refilled (at least for a large part) during each storm. This increases the amount of storage that needs to be filled and results in a large threshold value for subsurface stormflow generation.

[29] We hypothesize that the small volume of subsurface stormflow before the large increase in the subsurface stormflow rate is generated from localized areas of subsurface saturation directly upslope from the trench face that are not connected to upslope areas. These subsurface saturated areas are so localized and thin that they were not observed by measurements on the 2 by 2 m grid of crest stage gauges during smaller events or in the early stages of larger events.

[30] A saturated wedge upslope from a trench face can be an artifact of the trench itself [*Atkinson*, 1978]. Although this possibility is often acknowledged, it is also often believed that the observed saturated wedge is real and would have occurred even if the trench was not there [e.g., *Buttle and Turcotte*, 1999]. In this study a saturated wedge was not observed and upslope areas responded faster than the downslope areas. Data from some other studies also suggest that upslope areas may respond faster than downslope areas. For example, data from *McDonnell* [1990, Figure 7, p. 2826] shows that in the Maimai catchment in New Zealand tensiometers upslope on the hillslope responded before tensiometers located further downslope responded and that flow increased after the downslope tensiometers had started to respond. *Sidle* [1984] reports for steep forested hillslopes in Alaska that piezometers upslope and downslope responded simultaneously and that the shallow piezometric response did not resemble a wedge building from the slope base. *Wilson et al.* [1990] note that a perched water table developed most quickly on their ridge and upper convex positions. Thus the lack of a saturated wedge expanding in an upslope direction shown here for the Panola hillslope may be a more wide spread phenomenon.

[31] *Hutchinson and Moore* [2000] show that the water table configuration follows the topography of the compacted till layer at their study site in Canada, but that with increasing flow, hydraulic gradients become more uniform in magnitude and direction across the hillslope. Here we show that at Panola only the main bedrock hollow fills up with water once the spilling over the bedrock ridge occurs. Subsurface saturation is confined to this main bedrock hollow (Figure 9) and flow is in a downslope direction. While the bedrock topography is more complex at Panola, the pattern of filling of the bedrock hollow is similar to that shown by *Torres et al.* [1998, Figure 7, p. 1874] for a site in western Oregon.

5.2. Relation Between Patterns of Saturation and Threshold Subsurface Stormflow

[32] Total subsurface flow at Panola is a threshold function of precipitation [*Tromp-van Meerveld and McDonnell*, 2006a]. In the present study, we show that subsurface saturation occurs during storms smaller than the 55 mm precipitation threshold and that the area of subsurface saturation increases with increasing precipitation but that the relation between the maximum area of subsurface saturation and total subsurface stormflow is nonlinear (Figure 4b). In addition, we show that there is a threshold-like relation between the maximum water level at an upslope location (well 9.20) and total subsurface stormflow (Figure 5a). The observed development of subsurface saturation indicates that the precipitation threshold for subsurface stormflow is related to the extension and connectivity of subsurface saturation to the trench face. When the subsurface saturated area becomes connected to the trench face, the instantaneous subsurface stormflow rate increases more than fivefold (Figure 6). Results from this study show that this occurs when storm total precipitation is larger than 55 mm and the water level in the bedrock depression rises high enough that water spills downslope over the bedrock ridge (Figures 5 and 6). This study thus shows that the small-scale bedrock topographic variations and the filling and spilling of water in depressions and over the bedrock microtopography, which are necessary before connectivity can occur, are responsible for the observed precipitation threshold for significant (>1 mm) subsurface stormflow.

[33] One could speculate that if the trench would have been constructed 20 m upslope from the current location, so that it would be located upslope from the bedrock ridge, there might not be a distinct precipitation threshold for significant subsurface stormflow at that trench because the subsurface saturated area that would be connected to that trench face would increase more linearly with increasing precipitation. In that case, the fill and spill behavior observed in this study would not necessarily occur because there are no large (slope parallel) bedrock depressions that have to be filled before water can spill and flow further downslope to that trench. Alternatively, if the trench would have been constructed further downslope, the subsurface stormflow response could be even more threshold-like if there would be more and deeper depressions in the bedrock between this point and the current trench. Comparison of the timing of water level response in wells on a similar hillslope located 2 m upslope from the riparian zone with the timing of subsurface stormflow at the trench however suggests that this difference might be small (Figure 7).

6. Conclusion

[34] We propose the fill and spill hypothesis as an explanation for observed threshold behavior in subsurface stormflow reported by *Tromp-van Meerveld and McDonnell* [2006a]. We show that bedrock microtopography influences slope-scale connectivity of subsurface saturated areas and hillslope contribution to flow at the catchment scale. The fill and spill hypothesis asserts that during small to medium-size storms, subsurface saturation occurs only (1) in areas with shallow soils because of lower total moisture deficit and (2) in areas with a combination of high bedrock

contributing area and high bedrock downslope index because water is concentrated and subsequently dammed by the bedrock topography downslope from it. Significant subsurface stormflow (>1 mm) occurs only when the subsurface saturated area becomes connected to the trench face. This occurs only when the bedrock depressions are filled and the water level in these depressions rises high enough for water to start spilling over the bedrock microtopography (Figure 10). Once spilling occurs, water flows over the bedrock, through (and mixes with soil water in) the connected lows in the bedrock topography toward the trench face. When the flux of water reaches the trench face and the subsurface saturated area becomes connected to the trench face, there is an immediate more than fivefold increase in the subsurface stormflow rate. If the storm is large enough for the water level to rise high enough that spilling and connectivity can occur (i.e., larger than the 55 mm precipitation threshold), total subsurface stormflow is more than 75 times larger than when spilling and connectivity do not occur. These results show that filling and spilling of water in the bedrock depression and over the bedrock ridge, thus the bedrock micro topography is responsible for the observed precipitation threshold for significant subsurface stormflow to occur. This fill and spill hypothesis has significant implications for how we model subsurface stormflow behavior and the transport of nutrients associated with this flux.

[35] *McDonnell* [2003] has argued that rather than characterization of "the idiosyncrasies of yet another hillslope," hydrologists might consider looking for characteristic forms of nonlinearity (thresholds, hysteresis, feedbacks) as a more fruitful way toward a general characterization of hillslopes. The work described by *Tromp-van Meerveld and McDonnell* [2006a] and the present paper are an attempt to define emergent behavior at the scale of the hillslope. This emergent behavior is connectedness to the trench, which results in the threshold response. This paper and the preceding paper by *Tromp-van Meerveld and McDonnell* [2006a] show the value of describing thresholds and patterns (i.e., patterns linked to processes). We would advocate for future studies to explore patterns (as has been pioneered by *Grayson et al.* [1997] and *Western et al.* [1999, 2004] for soil moisture research) where we use patterns to distinguish processes in the field. This may also be a way to use models to make verifiable predictions (and use the patterns themselves for predictions) and to use patterns to guide new measurements.

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