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Effect of bedrock permeability on subsurface stormflow and the water balance of a trenched hillslope at the Panola Mountain Research Watershed, Georgia, USA

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Abstract:

The effect of bedrock permeability on subsurface stormflow initiation and the hillslope water balance is poorly understood. Previous hillslope hydrological studies at the Panola Mountain Research Watershed (PMRW), Georgia, USA, have assumed that the bedrock underlying the trenched hillslope is effectively impermeable. This paper presents a series of sprinkling experiments where we test the bedrock impermeability hypothesis at the PMRW. Specifically, we quantify the bedrock permeability effects on hillslope subsurface stormflow generation and the hillslope water balance at the PMRW. Five sprinkling experiments were performed by applying 882–1676 mm of rainfall over a ~5·5 m × 12 m area on the lower hillslope during ~8 days. In addition to water input and output captured at the trench, we measured transpiration in 14 trees on the slope to close the water balance. Of the 193 mm day^{-1} applied during the later part of the sprinkling experiments when soil moisture changes were small, <14 mm day^{-1} was collected at the trench and <4 mm day^{-1} was transpired by the trees, with residual bedrock leakage of >175 mm day^{-1} (91%). Bedrock moisture was measured at three locations downslope of the water collection system in the trench. Bedrock moisture responded quickly to precipitation in early spring. Peak tracer breakthrough in response to natural precipitation in the bedrock downslope from the trench was delayed only 2 days relative to peak tracer arrival in subsurface stormflow at the trench. Leakage to bedrock influences subsurface stormflow at the storm time-scale and also the water balance of the hillslope. This has important implications for the age and geochemistry of the water and thus how one models this hillslope and watershed. Copyright © 2006 John Wiley & Sons, Ltd.

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INTRODUCTION

A common assumption in most hillslope hydrologic investigations is that the underlying bedrock is relatively impermeable. This assumption is consistent with commonly observed transient saturation at the soil–bedrock interface during rainstorms and snowmelt in steep, humid terrain (Mosley, 1979), which leads to the initiation of lateral subsurface stormflow (Weyman, 1973; Tani, 1997) often through semi-connected meso- and macropores in the lower soil profile (McDonnell, 1990; Peters *et al*., 1995; Buttle and Turcotte, 1999; McGlynn *et al*., 2002). Although other mechanisms exist for subsurface stormflow initiation, like transmissivity feedback (Bishop, 1991) and lateral flow in the (unsaturated) upper soil profile (Tsuboyama *et al*., 1994), the notion of bedrock impermeability and its control on lateral subsurface stormflow is firmly entrenched in the hillslope hydrological process literature (Weiler *et al*., 2005).

Recent studies in Oregon, USA (Anderson *et al*., 1997; Torres *et al*., 1998; Montgomery *et al*., 1997) and Japan (Terajima *et al*., 1993; Onda *et al*., 2001; Tsujimura *et al*., 2001; Uchida *et al*., 2002, 2003; Katsuyama *et al*., 2005) have begun to question the impermeable bedrock dogma by showing infiltration into, and fast lateral flow within, the underlying weathered bedrock on steep colluvial mantled slopes, substantial contributions of bedrock water to streamflow and an important role for flow through the bedrock in hillslope–riparian connectivity. For example, Terajima *et al*. (1993) found that deep percolation was at least 30% and 18% of precipitation in the Obara and Akatsu catchments (Japan) respectively, and that the percentage decreased with increasing catchment size. Anderson *et al*. (1997) injected bromide into saturated hillslope colluvium and observed rapid infiltration and flow through the underlying sandstone bedrock to the catchment outlet. Water from bedrock pathways has been observed to exfiltrate into the overlying colluvium and mix with younger unsaturated zone water in steep, humid catchments in Japan. Uchida *et al*. (2002) noted that such bedrock exfiltration created a subsurface saturated area near the stream channel head.

There is growing evidence of communication between water draining vertically in the soil mantle and continued drainage to depth into the underlying permeable bedrock between hydrologic events (Asano *et al*., 2002).

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At the Maimai catchment in New Zealand, where hydrogeological investigations of the underlying deep, firmly compacted conglomerates have been shown to be effectively impermeable (Mosley, 1979), streamwater residence times in a 3 ha watershed are on the order of 4 months (Pearce *et al.*, 1986; Stewart and McDonnell, 1991). At very similar sites with relatively permeable bedrock (e.g. the Fudoji catchment in Japan, described by Uchida *et al.* (2003)), however, streamwater residence times have been shown to be many times greater (on the order of 1·3 years). Some recent studies have reported residence times on the order of 14 years for catchments with very deep, permeable bedrock, but similar size and physiography/climate. In addition to mean age of streamwater, the bedrock permeability can alter the direction of water aging spatially in the catchment: from lateral downslope soil water age increases in catchments with effectively impermeable bedrock (Stewart and McDonnell, 1991) to down-profile soil water aging in permeable bedrock catchments (Asano *et al.*, 2002).

The Joint USA–Japan Workshop on Hydrology and Biogeochemistry of Forested Watersheds noted that examination of the infiltration process of subsurface water into bedrock and its effects on hillslope response to rainstorms is a pressing research need (McDonnell and Tanaka, 2001). Although the assumption of effective bedrock impermeability may hold for some sites, e.g. the shallow soil over Precambrian Shield bedrock catchments (Peters *et al.*, 1995; Buttle and Turcotte, 1999) and the Maimai catchments in New Zealand (Woods and Rowe, 1996), bedrock may have been incorrectly assumed to be impermeable in other watershed studies.

Such is the experience at the Panola Mountain Research Watershed (PMRW), where previous hydrologic and hydrochemical studies have implicitly assumed that the bedrock is relatively impermeable (e.g. Peters, 1989). The spatial distribution of subsurface stormflow at a trenched hillslope has been observed to be highly correlated to the accumulated area based on the bedrock topography (McDonnell *et al.*, 1996; Freer *et al.*, 1997, 2002), supporting the notion that bedrock on the hillslope is effectively impermeable. Segments of the hillslope with highest bedrock accumulated area were observed to deliver most of the water to the trench face (McDonnell *et al.*, 1996; Freer *et al.*, 1997, 2002; Tromp-van Meerveld and McDonnell, 2006a), indicating that ponding of water at the soil–bedrock interface and lateral flow over the bedrock is the dominant subsurface stormflow delivery mechanism. Consequently, the bedrock was assumed to be relatively impermeable in order to explain the spatial variability in the subsurface stormflow observations.

Notwithstanding the hydrometric data and interpretations, we began to question the bedrock impermeability assumption at the PMRW after Burns *et al.* (2003), using chlorofluorocarbon and tritium/helium-3 dating, showed that riparian groundwater midway down the valley of the 41 ha catchment was 6 to 7 years old and that the apparent age increased in both the down-valley direction and with depth below the surface. In addition, Fernandez (1989) had installed Plexiglas collectors on the bedrock outcrop above the trenched hillslope and outside the watershed to investigate the biogeochemical responses of lichens and mosses to rainstorms. The amount of water collected immediately after rainstorms varied markedly in the collectors, although they had approximately the same collection area. The relative differences in volumes were consistent among rainstorms and with respect to topographic position with the lowest volumes on ridges and the highest volumes in bedrock lows, indicating the existence of recharge and discharge areas on the bedrock outcrop.

In this paper, we return to the PMRW trenched hillslope to re-examine the importance of flow through bedrock and its effect on subsurface stormflow generation and the hillslope water balance. The existing hillslope infrastructure, including the trench, allowed us to measure lateral subsurface stormflow. Sapflow sensors in the dominant tree species across the hillslope (Tromp-van Meerveld and McDonnell, 2006c) allowed us to estimate hillslope-scale transpiration. Thus, by making measurements of all inputs (precipitation and irrigation water) and outputs (subsurface stormflow and transpiration) we could calculate the leakage from the overlying soil to the bedrock during the late part of the sprinkling experiments when soil moisture changes were small. The objective of this study is to quantify the bedrock permeability effects on hillslope subsurface stormflow generation and the hillslope water balance.

STUDY SITE

The PMRW is located within the Panola Mountain State Conservation Park in the southern Piedmont Province southeast of Atlanta, Georgia (84°10′W, 33°37′N). Historical land use included cotton cultivation, forest cutting and pasture land. Currently, the watershed is 93% forested, consisting of hickory, oak, tulip poplar, and loblolly pine (Carter, 1978). The remaining 7% of the watershed includes bedrock outcrops with small vegetation islands, including a 3·6 ha outcrop in the southwestern corner of the watershed. The 41 ha catchment can be represented by three landscape units (Peters *et al.*, 2003). Bedrock outcrops comprise a small landscape unit ($\sim$10%) that has little or no soil cover. Hillslopes comprise most of the catchment (>75%) and have shallow soils (<1 m). The riparian zone, which has the deepest soils ($\leq$5 m) is relatively narrow (<50 m) and occupies less than 15% of the total catchment area.

Bedrock at the PMRW is dominated by the Panola Granite (granodiorite composition), a biotite–oligioclase–quartz–microcline granite of Mississippian to Pennsylvanian age (Atkins and Higgins, 1980). Locally, the Panola Granite has intruded the Clairmont member of the Stonewall Gneiss, described as a tectonic mélange with a variety of clasts that float in a sheared and granitized matrix (Crawford *et al.*, 1999). A chemical

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weathering study on a ridge at the PMRW showed that bedrock permeability is primarily intragranular and is created by internal weathering networks of interconnected plagioclase phenocrysts (White *et al*., 2001). At this site, a 2 to 3 m thick porous saprolite layer (soft disintegrated granite) underlying the soil retains the original granodiorite texture and grades from friable saprock to competent bedrock over an interval of several centimetres at a depth of 4·7 m (White *et al*., 2002). In general, the thickest saprolite layers are found near broad gentle ridge tops. On steeper side slopes, the weathered zones are generally thinnest (Daniels and Hammer, 1992). During the installation of wells and soil moisture access tubes across the hillslope of the study herein, saprolite was found only in the deepest soil section of the hillslope located 20–22 m upslope from the trench face. Bedrock at the base of the trench is competent. Although a chemical weathering study was conducted on bedrock cores extracted at the PMRW (White *et al*., 2001, 2002), no study has examined the permeability of the bedrock under the trenched hillslope or the contribution of subsurface flow through the bedrock to either the hillslope or catchment water balance.

The climate at the PMRW is classified as humid, subtropical. During water years (October–September, WY) 1986 to 2001, the mean annual temperature was 15·2 °C and mean annual precipitation was 1240 mm, which on average is distributed uniformly throughout the year (Peters *et al*., 2003). Rainfall typically has a long duration and low intensity associated with the passage of fronts in the winter and has a short duration and high intensity associated with convective rainstorms in the summer. Streamflow at the PMRW has a strong seasonal pattern, with the highest flows occurring during the November–March dormant season. During WY1986 to WY2001, the annual runoff coefficient (runoff percentage of precipitation) ranged from 18 to 50% (Peters *et al*., 2003). The average stormflow water yield during this period was 5% and varied between 10% in winter and 3% in summer (Peters *et al*., 2003). Streamflow response to rainfall is strongly affected by the 3·6 ha bedrock outcrop in the headwater that provides rapid runoff during rainstorms (Shanley and Peters, 1988; Peters *et al*., 2003).

The lower boundary of the study hillslope is located approximately 30 m upslope from an ephemeral stream in the southwest part of the watershed opposite the 3·6 ha bedrock outcrop and is formed by a 20 m long trench. The top of the hillslope is bounded by a small bedrock outcrop, which extends ~15 m to the basin boundary. Soils on the study hillslope consist of a light-coloured sandy loam with an ~0·15 m thick layer of humus-rich material. The soils on hillslope positions like the study hillslope are of the Ashlar–Wake mapping unit, i.e. a multitaxonomic complex composed of mixed, thermic Lithic Udipsamments from the Wake series and coarse, loamy, mixed thermic Typic Dystrochrepts from the Ashlar series (Zumbuhl, 1998). These soils are hillslope sediments or colluvium from upslope erosional processes. Our specific study hillslope is composed exclusively of the coarse, loamy, mixed thermic Typic Dystrochrepts from the Ashlar series. The average soil depth is 0·63 m and ranges from 0 to 1·8 m. Average runoff coefficients from the study hillslope for the February 1996–May 1998 period were 6%, 10%, 1%, and <1% for the fall, winter, spring and summer respectively, and 5% for the whole period (Tromp-van Meerveld and McDonnell, 2006a). The runoff coefficient from the study hillslope was greater than 10% for only 8 of 147 rainstorms during the February 1996–May 1998 period (Tromp-van Meerveld and McDonnell, 2006a). The maximum runoff ratio was 26·5% for an 80 mm rainstorm with wet antecedent conditions and a maximum rainfall intensity of 21 mm h^{-1}.

METHODS

Air temperature, relative humidity, and precipitation measurements

Air temperature and relative humidity were measured at 3 m above the ground surface on a tripod in a clearing approximately 200 m from the study hillslope using a Campbell Scientific Model CS500 probe (Campbell Scientific, Logan, Utah). Precipitation was recorded each minute at three locations using tipping-bucket rain gauges, continuously using a weighing-bucket gauge in the clearing, and each week using several Tenite gauges. The tipping-bucket rainfall data series were combined to yield one rainfall time-series for the watershed. Throughfall was estimated from the combined rainfall measurements using a linear fit ($r^2 = 0{\cdot}99$) to the measured precipitation and throughfall from four 0·04 ha deciduous forest plots at the PMRW for 26 rainstorms (Cappellato and Peters, 1995):

$$T = 0{\cdot}95P - 0{\cdot}89 \qquad (1)$$

where T (mm) is total throughfall and P (mm) is total rainfall.

Water applications

Potable water from a local residential water supply was applied to sections of the lower 14 m of the hillslope using a commercially available oscillating garden sprinkler. Five sprinkling experiments were conducted on four hillslope sections, ultimately covering the entire width of the trenched hillslope (Figure 1). The area to which water was applied ranged from 69 to 79 m^2 (see Table I). During each experiment, water was applied to an approximate 5·5 m wide (across slope) and 12 m long (upslope) area with the lower edge of the area beginning 3–4 m upslope from the trench face to avoid direct application on the trench (Figure 1). During each experiment, water was applied continuously for 8–9 days, except for sprinkling experiment 1 when water was applied for only 4·5 days (Table I). The water application rate was ~8 mm h^{-1} for each experiment (Table II). The application rate was higher than the average natural rainfall intensity during

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Table I. Specifications of the sprinkling experiments. All volumes are normalized by the area of the sprinkling application. The average yearly precipitation for the PMRW is 1240 mm

Expt no.	Start time	End time	Duration (days)	Sprinkling area (m^2)	Total water applied (mm)	Uniformity coefficient[a]
1	18 June 2002, 05:18	22 June 2002, 18:16	4·5	71	882	0·79
2	25 June 2002, 06:02	3 July 2002, 15:56	8·4	69	1675	0·80
3	3 July 2002, 17:19	12 July 2002, 10:04	8·7	72	1676	0·74
4	30 July 2002, 10:00	7 August 2002, 13:46	8·2	73	1545	0·70
5	10 August 2002, 08:04	16 August 2002, 10:33	6·1	79	1065	0·80
5	16 August 2002, 10:33	20 August 2002, 11:25	4·0	38	1476	0·84

[a] Christiansen's uniformity coefficient (Christiansen, 1942).

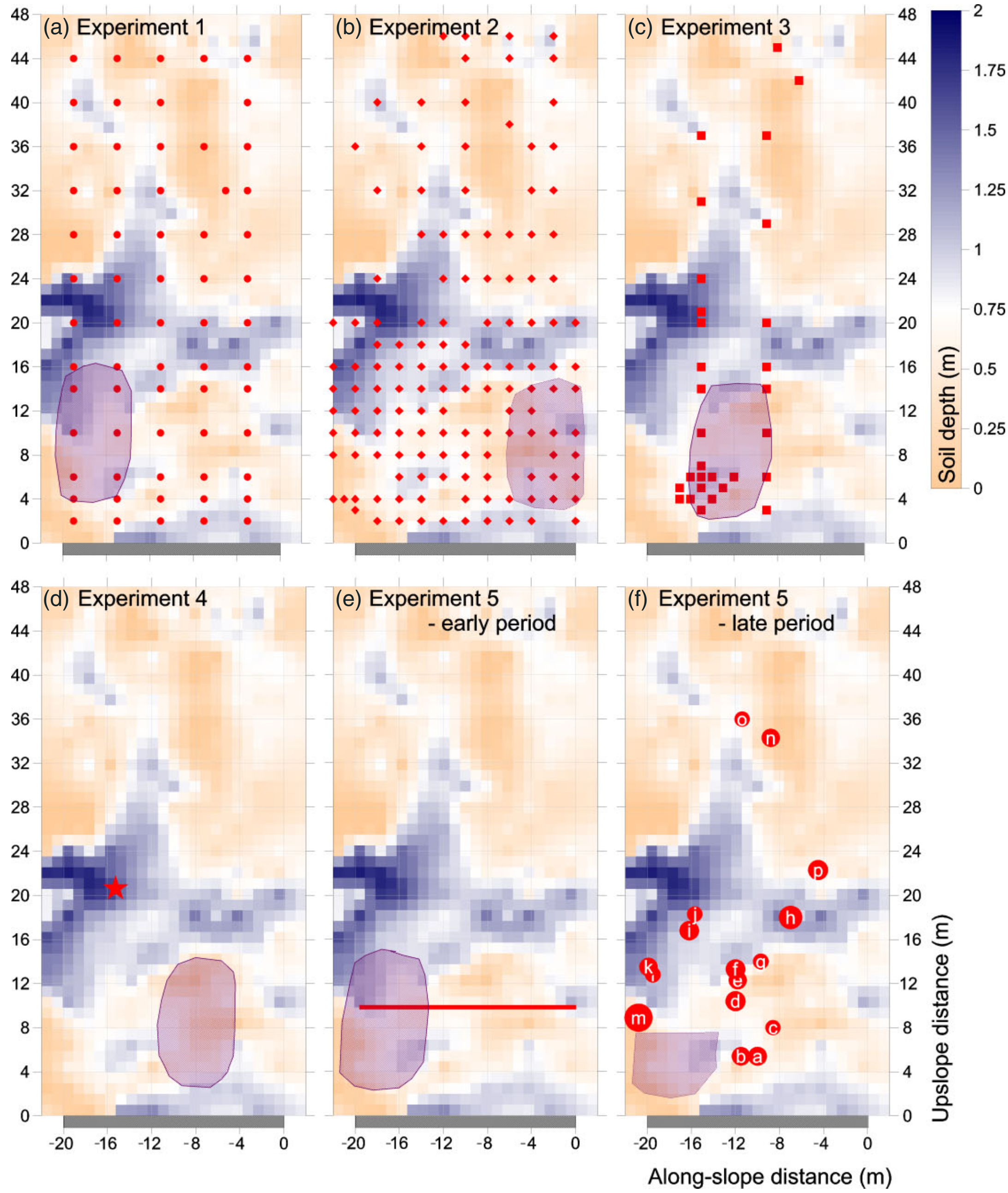

Figure 1. Location of the sprinkled areas during sprinkling experiments 1–5 (shaded areas), and the location of the soil moisture measurements (a), the location of the crest-stage gauges (b), the location of the recording wells (c), the location of the piezometer pair (d), the location of the line source tracer application (e), and the location of the trees with the sapflow sensors (f). During the later part of sprinkling experiment 5, the sprinkler was moved 1 m downslope and water was applied only to the lower part of the hillslope (see text). Coordinates of measurement locations are given in this paper as (along-slope distance (m). upslope distance (m))

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Table II. Calculated components of the water budget during the late period of the sprinkling experiments. Total subsurface flow in response to the rainstorms was calculated as the difference between measured subsurface flow and an interpolated sinusoidal line that represented the estimated subsurface flow if the rainstorm had not occurred. Values for the storms during experiment 3 are the additional precipitation input and additional subsurface flow in response to the rainstorm and are converted to daily values for ease of comparison. All values are normalized by the area of the water application (see Table I)

Expt no.	Total water applied (mm day^{-1})	Total subsurface flow (mm day^{-1})	Evaporative loss (mm day^{-1})	Non-evaporative loss (mm day^{-1})	Runoff ratio (%)
1	194	0	194		0
2[a]	200	4	1·8	194	2
3	193	14	3·7	176	7
3, rainstorm 1	15	4	0[b]	11	26
3, rainstorm 2	7	2	0[b]	6	26
4	189	12	4·5	173	6
5, early part	175	0	175		0
5, late part	369	0·4	368		0·1

[a] Subsurface flow could have bypassed the trench during this experiment. The values reported here are for the case where we assume that subsurface flow around the trench did not occur (see text).
[b] Assumed negligible because the canopy was wet.

long-duration low-intensity winter rainstorms, but it was lower than the rainfall intensity of short-duration high-intensity summer thunderstorms.

An exception to this was the later part of sprinkling experiment 5. Sprinkling experiment 5 was a repetition of sprinkling experiment 1 during the first 6 days of the experiment. After 6 days of sprinkling, we reduced the area over which water was applied by half, by making the sprinkler oscillate only half of its potential arc, thus doubling the water application rate for this area. Also, the sprinkler was moved 1 m downslope (see Figure 1e and Tables I and II).

To estimate the spatial distribution and depth of water applied to the sprinkled area, 20 polyethylene precipitation gauges, 55 mm diameter 100 mm high, were placed across the sprinkled area at ~0·15 m above the soil surface. The gauges were read and emptied about five times per day during the sprinkling experiments. Water was applied relatively uniformly across the sprinkled area, except near the edges (~1 m) where the sprinkling rate was decreased (Table I).

Two rainstorms occurred during sprinkling experiment 3: a 14·5 mm (open precipitation) rainstorm on 6 July 2002, at 20 : 00, and a 7·4 mm rainstorm on 11 July 2002, at 13 : 00. Other small thunderstorms occurred during the sprinkling experiments, but they were not large enough to have a noticeable effect on measured groundwater levels and the subsurface flow rate.

Lateral subsurface flow measurements

Lateral subsurface flow was measured in a 20 m long trench, excavated normal to the fall line of the slope down to bedrock. The trench was divided into 10 sections, each 2 m wide, along the bedrock surface using PVC sheets that funnelled flow through PVC-lined hoses to tipping buckets. The number of tips was recorded every minute. Additional details of the trench and the flow-collection system are described in McDonnell *et al.* (1996), Freer *et al.* (1997, 2002) and Burns *et al.* (1998).

For the sprinkling experiments, the depth of subsurface flow was calculated by dividing the total measured subsurface flow volume by the area of the sprinkled region. *Total water loss* was calculated as the difference between the depth of water applied and observed subsurface flow during the later part of the sprinkling experiments. *Total water loss* was divided into *evaporative loss* and *non-evaporative loss*. The *evaporative loss* was calculated as the difference between the maximum daily subsurface flow rate and the actual measured subsurface flow rate. Transpiration was negligible during the period of maximum subsurface flow (i.e. late night/early morning). We assumed that evaporation from the wet soil was also negligible during this late-night period because of the high relative humidity during the night and low wind speed under the canopy. We thus assumed that transpiration and evaporation were negligible during the period of maximum subsurface flow. *Non-evaporative loss* was calculated as the difference between the calculated total water loss and the calculated evaporative loss. For the two rainstorms during experiment 3, we assumed that the evaporative water loss immediately after the rainstorm was negligible and thus that the non-evaporative water loss after the rainstorm was equal to the total water loss.

Soil moisture measurements

Soil moisture was measured using the AquaPro sensor (AquaPro Sensors, Reno Nevada) in polycarbonate access tubes that were installed on the soil–bedrock interface (i.e. the point of refusal). The access tubes were distributed on a 4 m × 4 m grid across the hillslope and on a 4 m × 2 m grid across the lower 6 m of the hillslope (Figure 1a). The AquaPro sensor is a capacitance sensor (radio frequency) that measures soil moisture, ranging from 0% (in air or air-dried soil) to 100% (in saturated soil or water). Soil moisture was measured approximately four times per day during the sprinkling experiments at 0·05 m increments from the soil surface to 0·3 m below the soil surface and at 0·1 m increments between 0·3 m

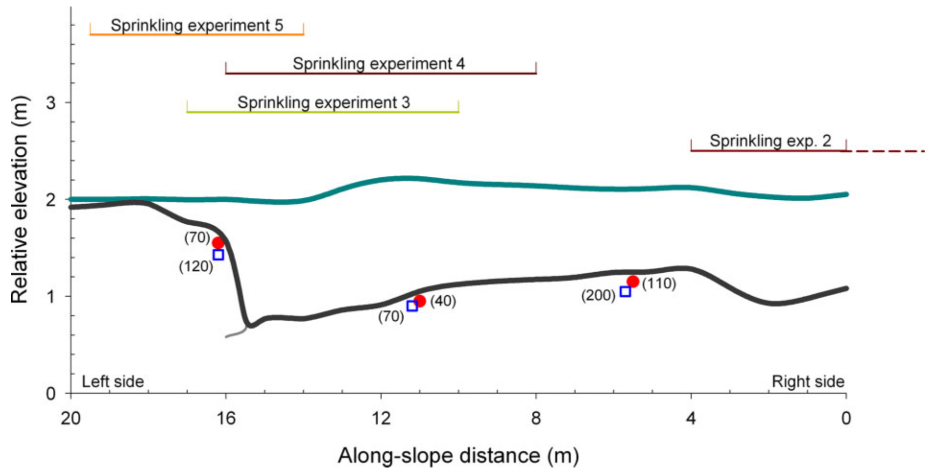

Figure 2. Schematic front view of the trench face and the along-slope locations of the bedrock moisture measurements (closed circles) and the suction lysimeters in the bedrock (open squares) downslope from the trench face and the subsurface flow collection system. The values in parentheses represent the depth (mm) below competent bedrock of the bedrock moisture measurements and the suction lysimeters. The horizontal lines represent the sections that produced subsurface flow during the sprinkling experiments. The light grey line between along-slope distance 15–16 m represents the excavation under the bedrock block (see text). Coordinates of measurement locations are given in this paper as (along-slope distance (m). upslope distance (m)). The vertical exaggeration is 2·5×

and the soil–bedrock interface. For more information about the soil moisture measurements, see Tromp-van Meerveld and McDonnell (2006c).

Three soil moisture access tubes were installed in the bedrock downslope of the water-collection system in the trench (Figure 2) to estimate temporal changes in bedrock wetness. These access tubes were inserted into the competent bedrock by drilling a tight-fit hole into the bedrock. One access tube was installed on the left side of the trench (along-slope location 16 m; see Figure 2) at a depth of 70 mm below the bedrock surface in March 2002. Another access tube was installed on the right side of the trench (along-slope location 6 m; see Figure 2) at 110 mm below the bedrock surface in April 2002. Bedrock moisture was measured on a regular basis (approximately once per week) at these two locations during the spring and several times per day during two relatively small rainstorms under wet antecedent conditions in April 2002. Another access tube was installed in the middle of the trench (along-slope location 11 m; see Figure 2) at 40 mm below competent bedrock in June 2002 prior to the sprinkling experiments. During the sprinkling experiments, bedrock moisture was measured about five times per day using the AquaPro sensor.

Measurements of transient saturation

We installed 135 crest-stage gauges across the hillslope. The crest-stage gauges were located on an approximately 2 m × 2 m grid across the lower 16 m of the study hillslope and an irregular but approximately on a 4 m × 4 m grid across the remainder of the hillslope (Figure 1b). These 19 mm diameter PVC piezometers were augered to refusal, installed on the soil–bedrock contact and screened over the lower 200 mm. Water-level rise was measured manually about five times per day during the sprinkling experiments.

In addition, 29 recording wells were installed along two transects across the hillslope and in a region of deeper soils on the lower 15 m of the hillslope, i.e. the area of sprinkling experiment 3 (Figure 1c). These 51 mm diameter PVC wells were augered to refusal and screened over the entire length. The water level was measured every 5 min using capacitance rods (TruTrack, Christchurch, New Zealand). The capacitance rods could not measure water levels within 75 mm of the soil–bedrock interface.

Sapflow measurements

Transpiration was estimated from constant-heat sapflow measurements using the thermal-dissipation technique developed by Granier (1985, 1987), generally following the procedures described by Phillips *et al*. (2002). Sapflow was measured at 15 min intervals in 14 hickory trees (*Carya* sp.), the dominant species on the hillslope, using 28 sensors. Two 20 mm long sensors were inserted 20 mm into the sapwood of each tree. For each tree, the 15 min measurements from the two sapflow sensors were averaged hourly. The 14 trees were in two diameter at breast height (DBH) classes: 0·11–0·125 m (five trees) and 0·175–0·215 m (nine trees) (Figure 1f). Trees A and B were located at the edge of sprinkling experiments 3 and 4 and trees K and L were located at the edge of sprinkling experiments 1 and 5 (see Figure 1f for the location of these trees). The other trees with sapflow sensors were located upslope from the sprinkling experiments.

Line tracer test

As part of a related study, 512 g bromide was applied (as a lithium bromide solution) along a 20 m long line across the slope at 0·15 m below the soil surface and 11 m upslope of the trench on 1 March 2002, at 20:00 (Figure 1e). Subsurface flow samples were collected for chemical analysis in 100 ml polyethylene bottles from the tipping buckets draining the trench. Bedrock water was collected after 25 March 2002, from one suction lysimeter located in the competent bedrock downslope from the water collection system in the middle of the trench (along-slope distance 11 m) at 70 mm depth below the soil–bedrock interface (Figure 2). After 8 April 2002, bedrock water was also collected from two additional suction lysimeters in the bedrock at 120 and 200 mm depths below the bedrock surface (Figure 2). The suction lysimeters were pumped to ~0·7 bar prior to sample collection. The bromide concentration in each sample was determined using a Dionex Model DX500 ion chromatograph with an AS9-HC column. The samples were stored at room temperature prior to analysis.

RESULTS

Bedrock moisture response to rainstorms during the spring

Bedrock moisture responded quickly to rainstorms during the early spring (Figure 3). During the 13 mm rainstorm with very wet antecedent conditions on 12 April 2002, bedrock moisture increased $6\%_{\mathrm{AquaPro}}$ within 4 h (see inset in Figure 3). Bedrock moisture did not respond to the 50 mm rainstorm of 4–6 June 2002, during which the wetting front did not penetrate more than 0·5 m vertically through the soil profile at most locations on the hillslope (Tromp-van Meerveld and McDonnell, 2006c).

Tracer breakthrough in response to rainstorms during the spring

Although there was some tracer breakthrough in subsurface stormflow during the 50 mm rainstorm on 2–3 March 2002, directly after tracer application, the peak breakthrough occurred after peak subsurface stormflow from the 61 mm rainstorm on 30 March 2002 (Figure 4). This rainstorm consisted of 24 mm of low-intensity rainfall in the morning and afternoon followed by a 37 mm high-intensity thunderstorm during the evening. The 30 min maximum rainfall intensity of the thunderstorm was 62 mm h^{-1}. Peak tracer breakthrough in the bedrock lysimeter was delayed by 2 days compared with the peak breakthrough in subsurface stormflow from the section that had (first tracer breakthrough occurred on 2 March 2002 while the peak tracer breakthrough occurred on 30 March 2002) and delivered most of the subsurface stormflow to the trench during the 30 March 2002 rainstorm (section 11, along-slope distance 10–12 m) (Figure 4). Bromide in the bedrock was remobilized during the 20 mm rainstorm on 12–13 April 2002. During this rainstorm only 0·04 mm of subsurface flow was measured in the trench, of which 46% was delivered by the two trench sections with shallow soils on the left 4 m of the trench (Figure 2).

Sprinkling experiments

Experiment 1. No subsurface flow was observed at the trench during experiment 1 (Figure 5c). Subsurface saturation at the soil–bedrock interface began approximately 1 day after the start of the water application (Figure 5d). Piezometers outside the sprinkled area and next to the trench remained dry, indicating that it is not very likely that saturated flow occurred around the edge of the trench face. Bedrock moisture and soil moisture next to, above and downslope from the sprinkled area did not change during the experiment.

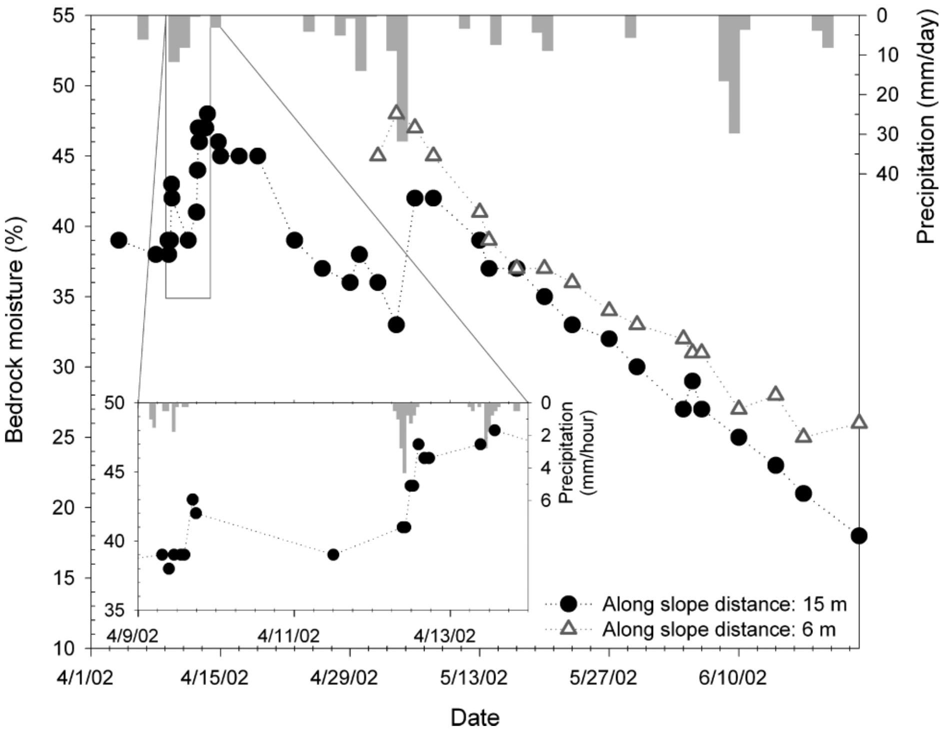

Figure 3. Measured bedrock moisture at 50 mm below the (competent) bedrock surface near the middle of the trench (along-slope distance 11 m; closed circles) and near the right side of the trench (along-slope distance 6 m; open triangles) during the spring of 2002. The inset shows the 9–14 April 2002 period in more detail, when measurements were made during two rainstorms. See Figure 2 for the location of the bedrock moisture measurements

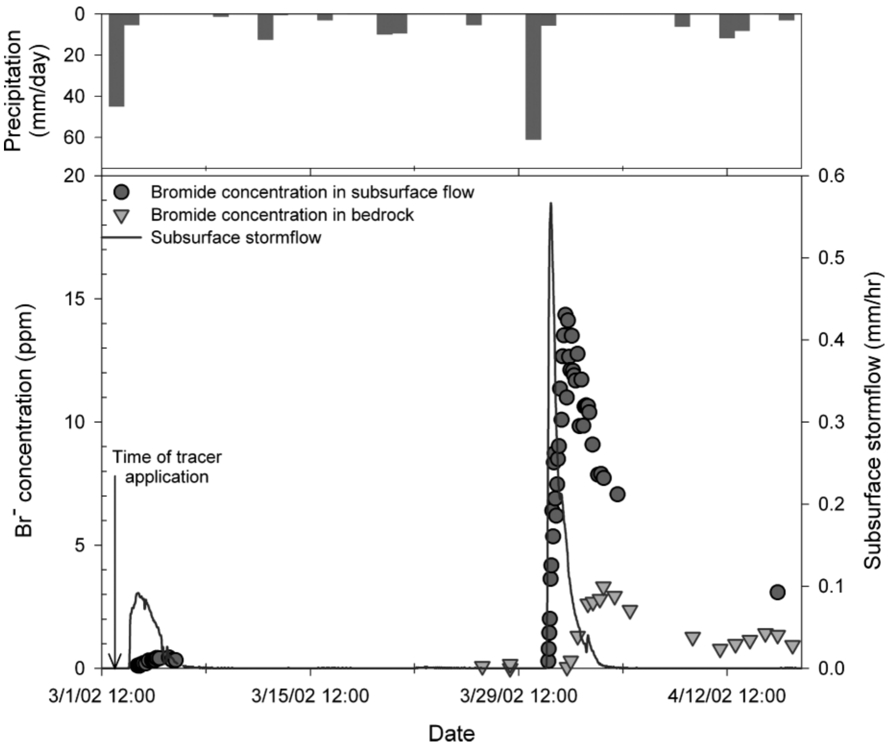

Figure 4. Measured subsurface stormflow from the 2 m wide trench section in the middle of the trench (along-slope distance 10–12 m) and the breakthrough curve of bromide in subsurface stormflow from this trench section (circles) and from the suction lysimeter installed in the bedrock at 70 mm below the bedrock downslope from this section (triangles). See Figure 2 for the location of this trench section and the bedrock lysimeter. Bromide was applied as a line source 11 m upslope from the trench on 1 March 2002, at 20:00 (see Figure 1e)

Experiment 2. Subsurface flow was only a small fraction (2%) of the volume of water applied during experiment 2 (Figure 6c and Table II) and decreased with increasing time after the onset of subsurface flow. Subsurface saturation at the soil–bedrock interface developed within 1 day of the start of the experiment at most measurement locations in the sprinkled area and decreased after the start of subsurface flow (Figure 6c–d).

Bedrock moisture measured downslope and 1 m to the left of the sprinkled area (see Figure 2) increased within 1 day after the start of subsurface flow at the trench (Figure 6e). Soil moisture inside the sprinkled area reached steady state within 6 h after the start of the experiment. Soil moisture measured 3 m or more outside (above or next to) the sprinkling area did not change during the experiment (Figure 6f). Also, sapflow in trees ($\sim$6 m) outside the sprinkling area did not change during the experiment.

Subsurface flow, groundwater level and soil moisture varied diurnally. The maximum subsurface flow routinely occurred 3–4 h after sapflow ceased. During the later part of the experiment, when soil moisture had reached steady state, the calculated non-evaporative loss was much larger than the calculated evaporative loss and also much larger than measured subsurface flow (Table II). However, the calculated evaporative loss for experiment 2 (1·8 mm day^{-1}) was smaller than for the other experiments and was also smaller than the average calculated transpiration rate during the experiment based on the sapflow data (2·6 mm day^{-1}). It is possible that there was some subsurface flow around the trench, because the sprinkled area was at the edge of the trench excavation (Figure 1b). Unfortunately, there were no piezometers adjacent to the trench, so that saturation beyond the trench could not be evaluated. If we assume that the trench captured only half of total subsurface flow, then total subsurface flow would have been 8·1 mm day^{-1} (4% of the amount of water applied), calculated non-evaporative loss would have been 188 mm day^{-1} and calculated evaporative loss would have been 3·6 mm day^{-1}. This is comparable to the calculated evaporative loss during the other experiments and the calculated transpiration rate from the sapflow measurements. We assume that the difference between the calculated evaporative loss from the diurnal variations in subsurface flow and calculated transpiration from the sapflow measurements is at least in part due to evaporation from the wet soil surface and herbaceous understory vegetation.

Experiment 3. Similar to experiment 2, subsurface flow during experiment 3 was only a small fraction (7%) of the total volume of water applied (Figure 7c and Table II). Bedrock moisture measured in the trench increased approximately 16 h after the onset of subsurface flow (Figure 7e). Transient saturation at the soil–bedrock interface developed soon (within 1 day) after the start of the experiment at most measurement locations in the sprinkled area. After the onset of subsurface flow, water levels in the wells decreased, similar to experiment 2. There was a good visual relation between the decrease in water levels in the recording wells and the decrease of subsurface flow. But for the same water level above

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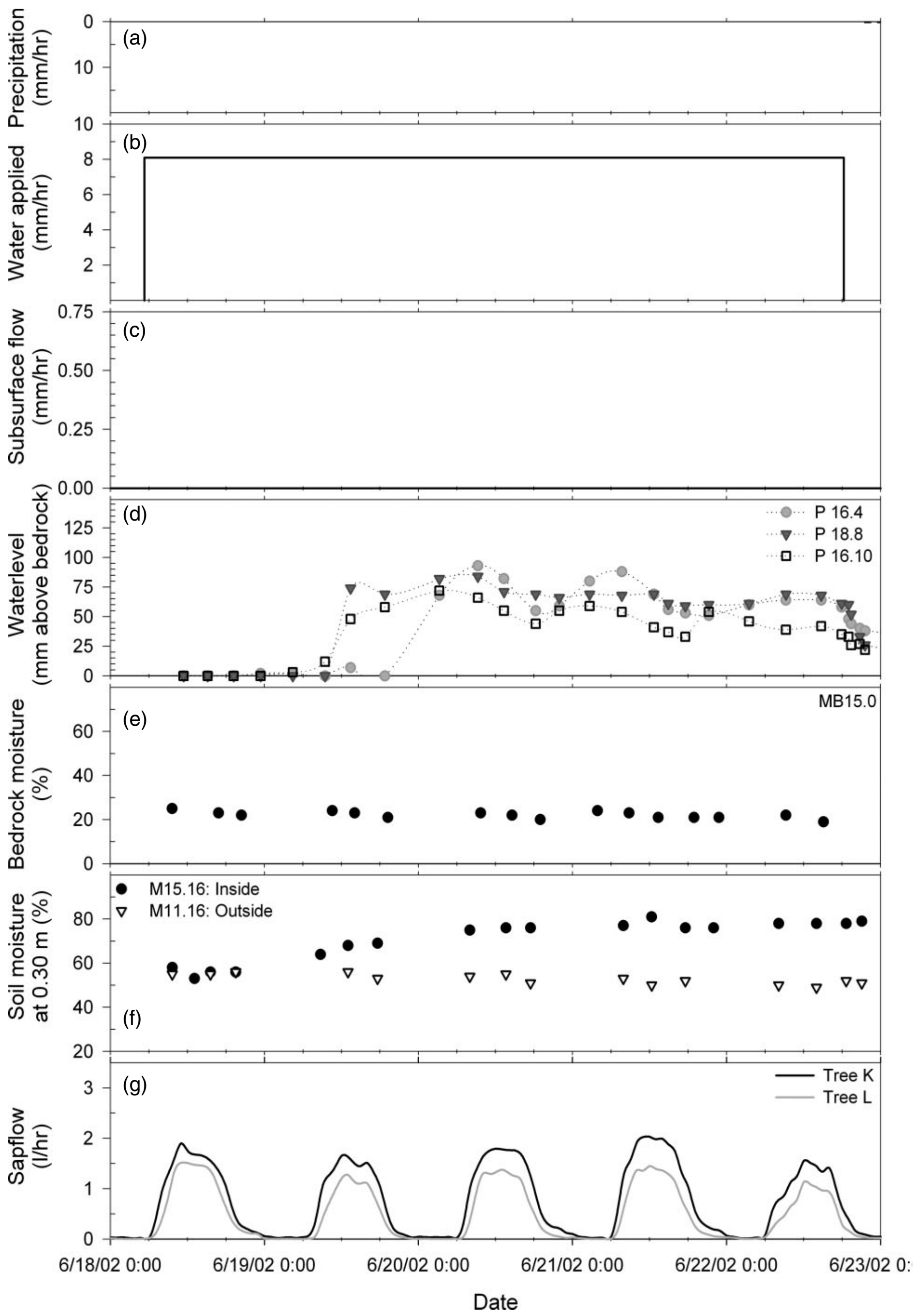

Figure 5. Sprinkling experiment 1: rainfall (a), water applied (b), measured subsurface flow in the trench (c), water level in selected piezometers (d), bedrock moisture (e), soil moisture at a selected location inside and outside the sprinkling area (f), and sapflow in two trees on the edge of the sprinkling area (g)

bedrock, the subsurface flow rate was lower during the beginning of the experiment than during the end of the experiment (Figure 8). The lag between the diurnal signal of maximum water level and maximum subsurface flow rate typically was 1 h. The lag between maximum subsurface flow and minimum air temperature or sapflow was 3–4 h, similar to experiment 2.

Similar to experiments 1 and 2, we did not detect any soil-moisture changes above and next to the sprinkled area. Soil moisture measured 2 m downslope from the sprinkling area increased during the experiments. Soil moisture at depth increased rapidly coincidence with the onset of subsurface flow. The shallower soil layers wetted up after the rapid soil-moisture increase at depth (Figure 9). Soil moisture at all depths in this region remained constant after 8 July 2002, i.e. 4·5 days after the start of the water application, until after the end of the sprinkling experiments. These results and the decreasing water levels after the onset of subsurface flow indicate that, following the hydrological connection of the sprinkled area and the trench face (i.e. through the wet soil connecting the sprinkled area to the trench), the hillslope drained, resulting in a decline in the water level above bedrock in the sprinkled area.

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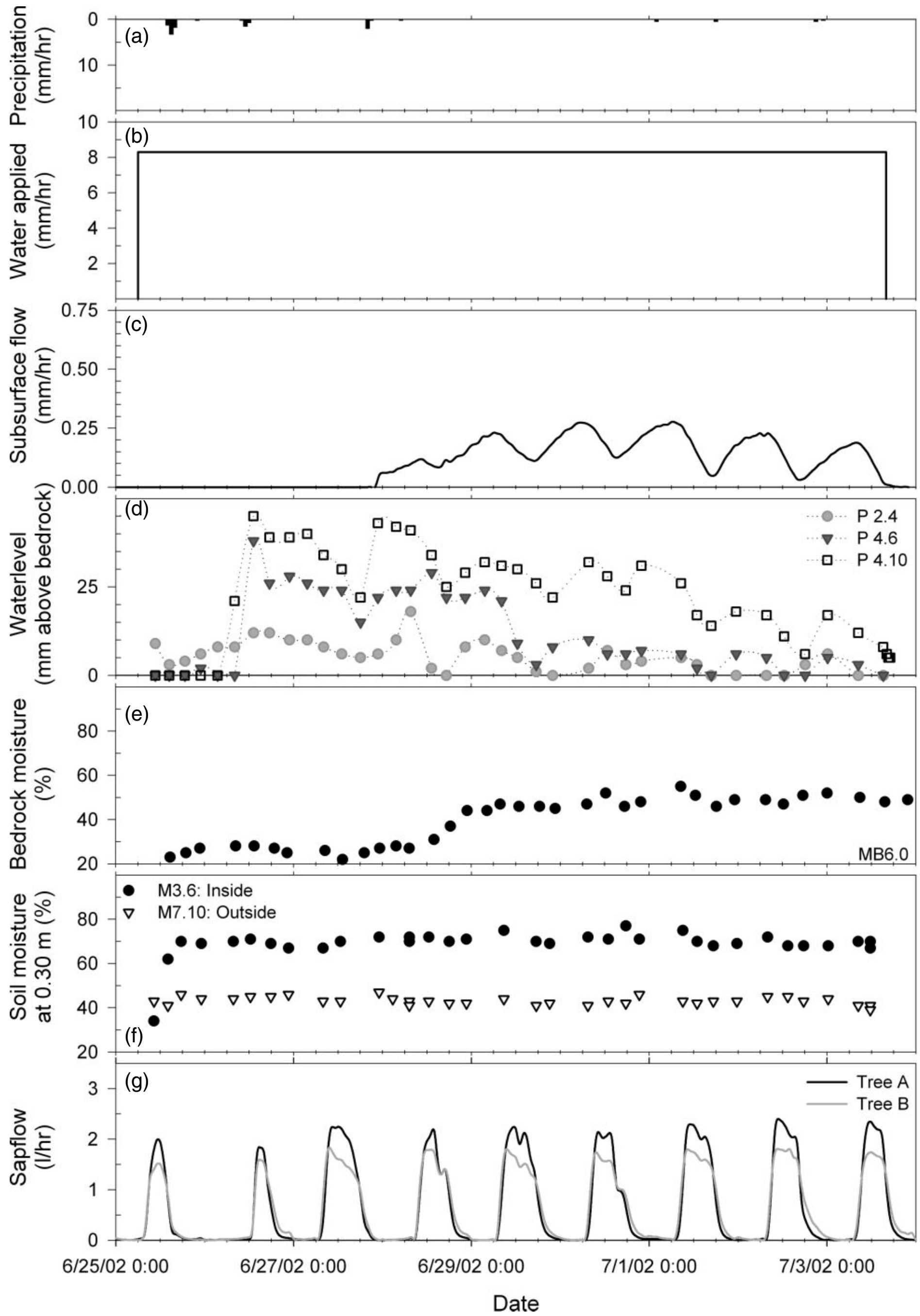

Figure 6. Sprinkling experiment 2: rainfall (a), water applied (b), measured subsurface flow in the trench (c), water level in selected piezometers (d), bedrock moisture (e), soil moisture at a selected location inside and outside the sprinkling area (f), and sapflow in two trees outside to the sprinkling area (g)

Similar to experiment 2, the calculated non-evaporative loss toward the end of the experiment, when soil moisture changes were small, was much larger than the calculated evaporative loss and also much larger than measured subsurface flow (Table II). During the experiment and the rainstorms, both the 3 h average subsurface flow rate and the calculated non-evaporative loss were linearly related to the water level above bedrock (Table III). The linear relation between water level and calculated non-evaporative loss (i.e. bedrock infiltration) is consistent with infiltration theory (Green and Ampt, 1911), when the water level above bedrock is taken as the depth of ponding and the wetting front suction is assumed to be negligible during the later part of the experiments because of the very large amount of water that had already been applied to the sprinkled area. The thunderstorms during experiment 3 temporarily increased the water level above bedrock, causing bedrock infiltration (i.e. non-evaporative loss) to increase (Table III). Consequently, only a fraction of the rainfall (additional input) resulted in additional subsurface flow (Table II). These thunderstorms did not result in subsurface stormflow from the other trench sections because of the dry antecedent moisture conditions outside the sprinkled area.

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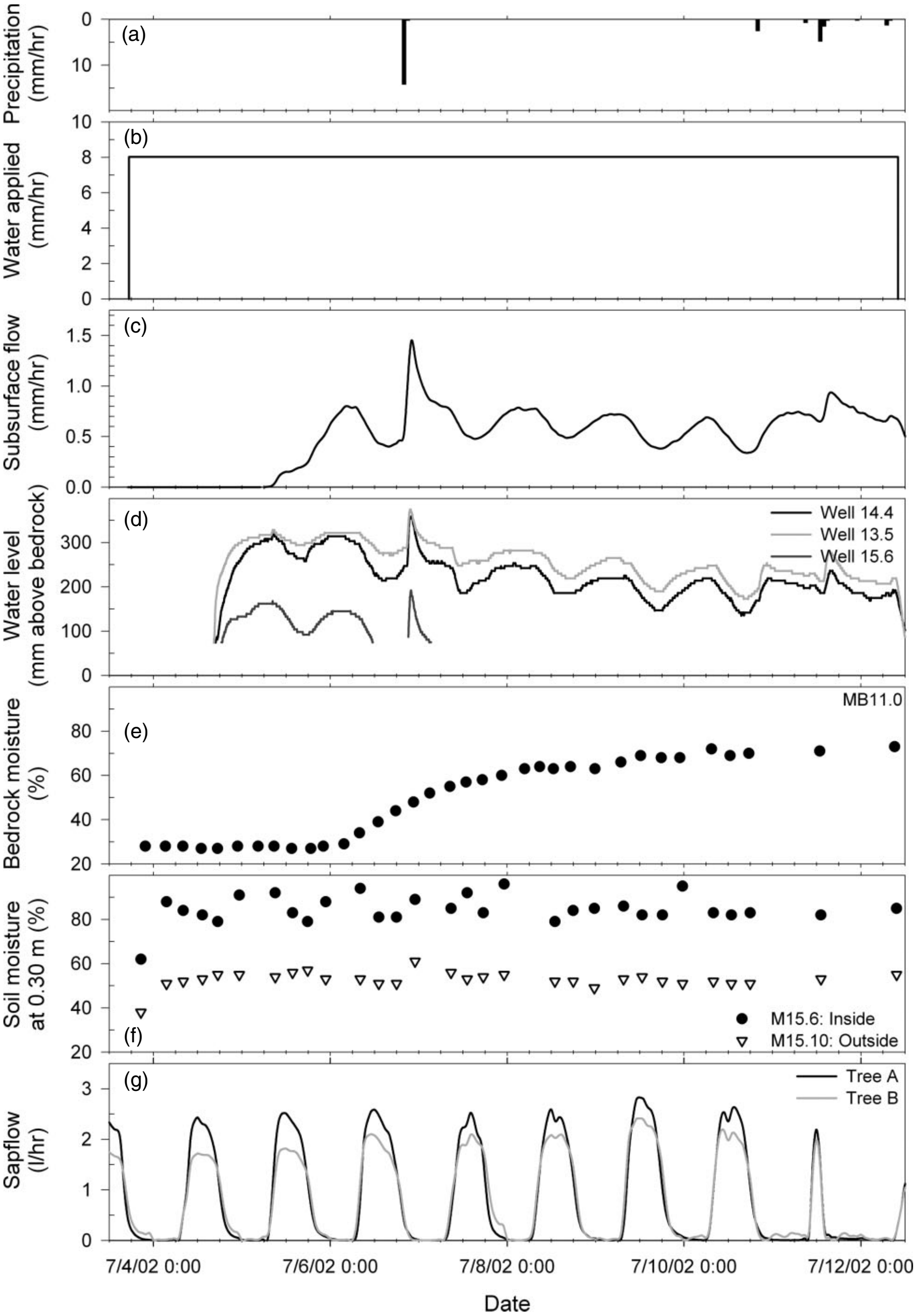

Figure 7. Sprinkling experiment 3: rainfall (a), water applied (b), measured subsurface flow in the trench (c), water level in selected recording wells (d), bedrock moisture (e), soil moisture at a selected location inside and outside the sprinkling area (f), and sapflow in two trees adjacent to the sprinkling area (g)

Table III. The 3 h average of the depth of water applied, measured subsurface flow, the runoff ratio, the calculated non-evaporative loss, and the water level in well 13.5 during sprinkling experiment 3. All values are normalized by the area of the water application (Table I). Changes in storage during the 3 h period are ignored

	Total water applied (mm h^{-1})	Total subsurface flow (mm h^{-1})	Runoff ratio (%)	Non-evaporative loss (mm h^{-1})	Water level (mm above bedrock)
Prior to rainstorm 1	8·0	0·5	6	7·5	282
Storm 1	12·9	1·3	10	11·6	368
Prior to rainstorm 2	8·0	0·7	9	7·3	230
Storm 2	10·2	0·9	9	9·3	276

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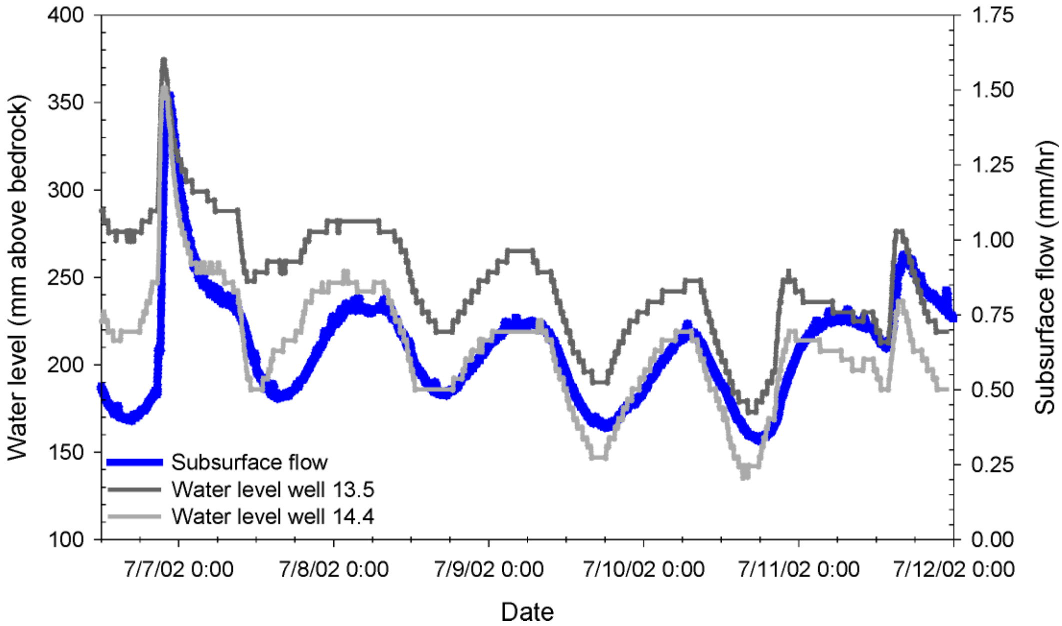

Figure 8. The relation between subsurface flow and water level above bedrock in two wells during sprinkling experiment 3

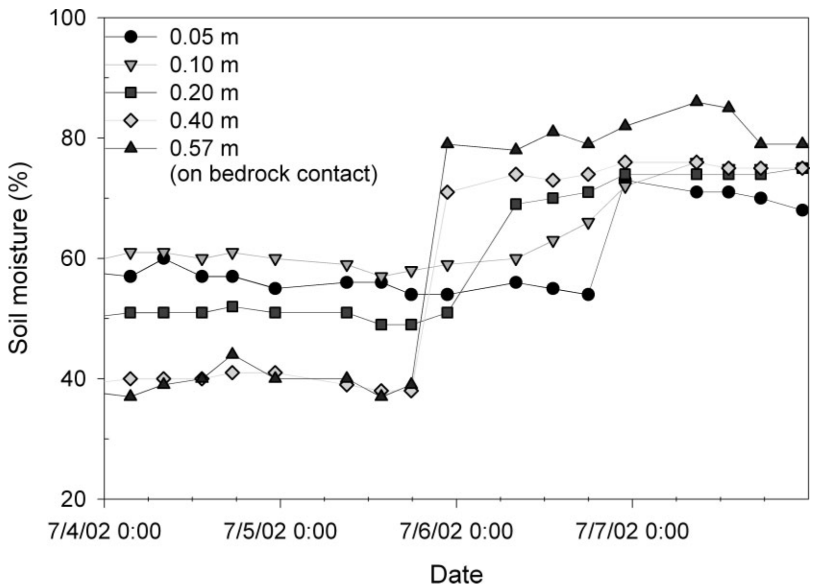

Figure 9. Soil moisture at different depths below the soil surface for measurement location 11.2, located 2 m upslope from the trench face and downslope from the sprinkling area during experiment 3. Water application during this experiment started on 3 July 2002, at 17:19

They also did not produce any overland flow on the study hillslope.

Experiment 4. During experiment 4, subsurface saturation was also observed to the left of the sprinkled area (the location of experiment 3; see Figures 1 and 2). During the other experiments, subsurface flow was observed only directly downslope of the sprinkled area. The bedrock under the sprinkled area of experiment 4 slopes towards the left side, thus towards the area of experiment 3 and the trench sections where subsurface flow was observed during the experiment. Transient saturation at the soil–bedrock interface developed within 12 h after the start of the experiment (Figure 10d). Bedrock moisture increased at the same time as the onset of subsurface flow (Figure 10e). Similar to experiments 2 and 3, the water level in each well on the hillslope decreased coincidence with a decrease in subsurface flow. During the later part of the sprinkling experiment, when soil moisture changes were small, total subsurface flow was only a small fraction of the total depth of water applied and the non-evaporative loss was the largest component of the water balance, which was also similar to experiments 2 and 3 (Table II). Finally, the temporal patterns of soil moisture, sapflow and bedrock moisture during experiment 4 were similar to those described for experiments 2 and 3.

Experiment 5. During the first 6 days of experiment 5 with the same water application intensity as experiment

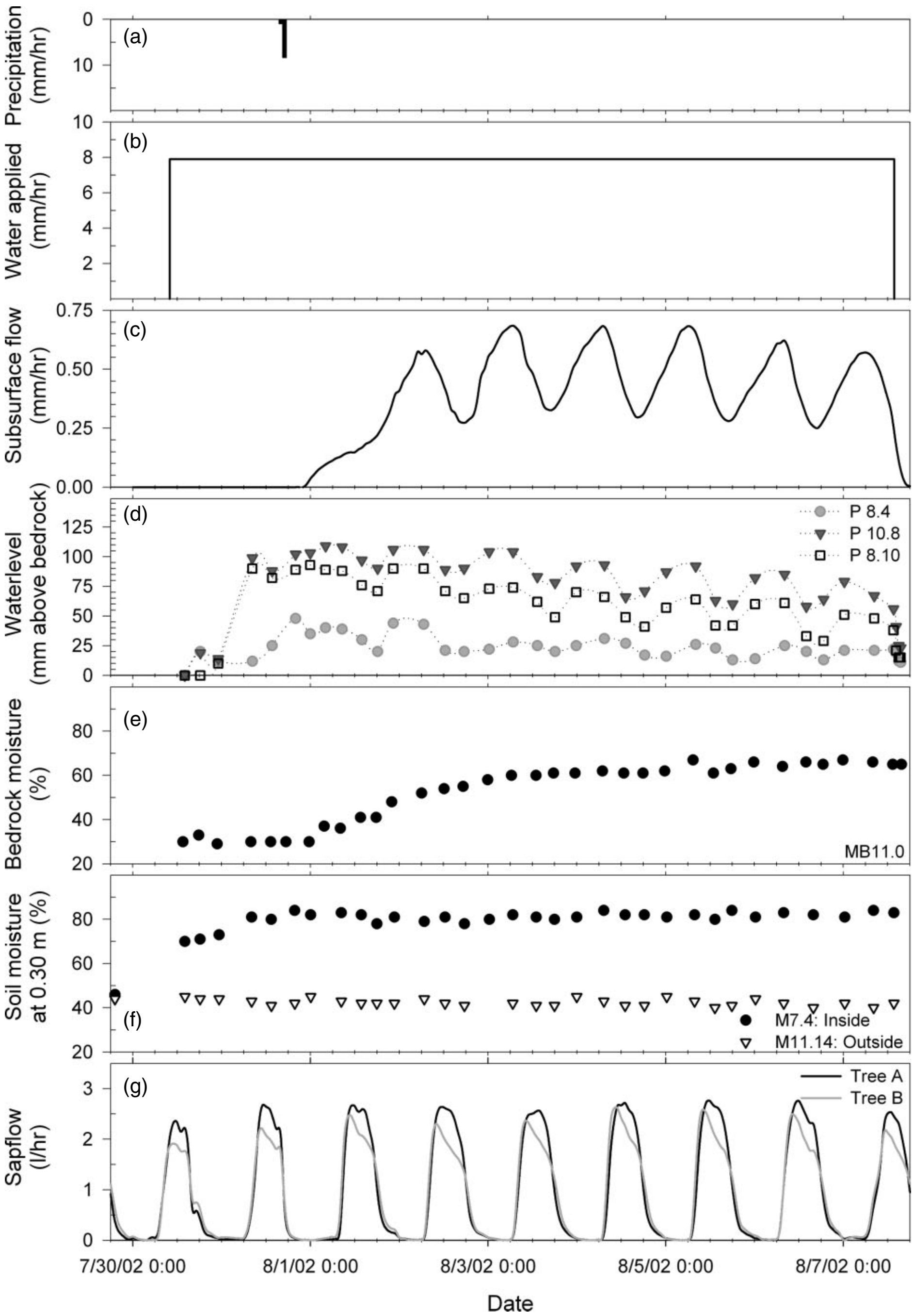

Figure 10. Sprinkling experiment 4: rainfall (a), water applied (b), measured subsurface flow in the trench (c), water level in selected piezometers (d), bedrock moisture (e), soil moisture at a selected location inside and outside the sprinkling area (f), and sapflow in two trees adjacent to the sprinkling area (g)

1 (i.e. before doubling the water application intensity), subsurface flow did not occur and bedrock moisture in the trench did not increase (Figure 11), as was observed during experiment 1. Piezometers outside the sprinkled area and next to the trench remained dry, indicating that it is not likely that saturated flow occurred around the edge of the trench face.

Subsurface flow occurred only after the sprinkler was moved 1 m downslope and the application rate was doubled and augmented by a 16·5 mm h^{-1} thunderstorm on 16 August 2002, at 18 : 00. However, subsurface flow was very small, even compared with the subsurface flow measured during the other experiments (Figure 11c and Table II). Furthermore, subsurface flow was intermittent and only occurred during the night, when transpiration and evaporative loss were negligible. Some of the subsurface flow occurring during the 18 mm thunderstorm on 16 August 2002, at 18 : 00, was caused by localized overland flow into the trench. Overland flow was not generated from the sprinkled area but from areas downslope of the sprinkled area and directly upslope (<1 m) of the trench. Overland flow appeared to be due to the seasonal hydrophobicity of the upper mineral soil and litter layer. Both the rainstorm and the increase in sprinkling

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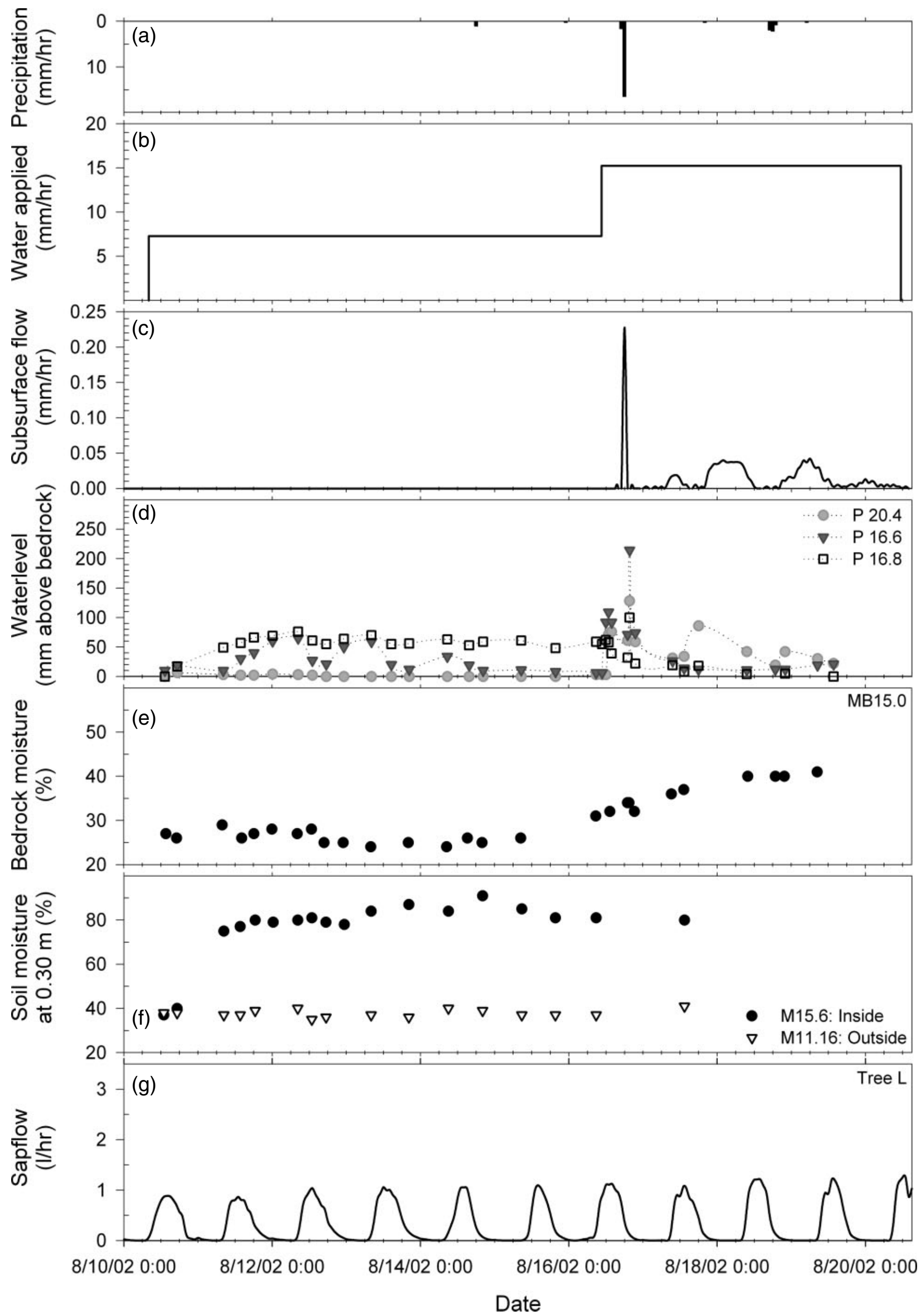

Figure 11. Sprinkling experiment 5: rainfall (a), water applied (b), measured subsurface flow in the trench (c), water level in selected piezometers (d), bedrock moisture (e), soil moisture at a selected location inside and outside the sprinkling area (f), and sapflow in a tree on the edge of to the sprinkling area (g)

intensity led to a temporary increase or first occurrence of subsurface saturation in the sprinkled area (Figure 11d). The temporal patterns of soil moisture and sapflow were similar to experiments 2–4.

DISCUSSION

Bedrock permeability at the Panola Mountain Research Watershed

Despite the implicit assumption in previous hillslope hydrological studies at the PMRW, bedrock underlying the trenched hillslope is not impermeable. Bedrock moisture increased rapidly in response to rainstorms during early spring (Figure 3). Peak tracer breakthrough in the bedrock downslope from the trench was delayed only by 2 days relative to peak tracer breakthrough in subsurface flow (Figure 4). Non-evaporative losses were a very large component of the water balance during the sprinkling experiments (Table II). In general, soil moisture changes outside the sprinkled area (upslope or to the sides) were not observed during the experiments, indicating that the extent of the radial wetting was limited. Furthermore, soil moisture downslope from the sprinkled region did not change after about 4·5 days from the

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beginning of any experiment. If we assume an area of 160 m^2 (20 m × 8 m, which is larger than the sprinkled area plus the area between the water application and the trench, and a 1·5 m boundary next to the sprinkled area), an average soil depth of 1 m, and a soil moisture deficit of 25%, which is more than the actual moisture deficit, then 40 m^3 of water is required to wet the soil. Given an application rate of ∼10 l min^{-1}, only 3 days are required to replenish this deficit. Consequently, we can assume that most of the non-evaporative loss during the later part of the experiments (days 6 to 8) is due to bedrock leakage and not due to moisture changes. If one assumes that during the later part of the experiments, when soil moisture change was small, (1) the non-evaporative loss was entirely due to infiltration of water into the bedrock; (2) the bedrock area in which water could have infiltrated was 1·25 times the sprinkled area, i.e. water could also infiltrate into the bedrock between the sprinkled area and the trench; (3) the bedrock infiltration rate approached the saturated conductivity of the bedrock, then the area-average effective conductivity of the bedrock is 5·8 mm h^{-1} for experiment 3. This corresponds to a saturated conductivity of $1{\cdot}6 \times 10^{-6}$ m s^{-1}, which is in the range (10^{-4}–10^{-9} m s^{-1}) of saturated conductivities for fractured crystalline rock given by Freeze and Cherry (1979) and comparable to the measured saturated hydraulic conductivity at Fudoji, Japan ($3{\cdot}3 \times 10^{-6}$ m s^{-1}; Uchida *et al*., 2003), at the Kiryu Experimental Watershed, Japan ($5{\cdot}8 \times 10^{-6}$ m s^{-1}; Katsuyama *et al*., 2005), the Sierra Nevada Range, California, USA ($1{\cdot}0 \times 10^{-5}$–$3{\cdot}9 \times 10^{-6}$ m s^{-1}; Graham *et al*., 1997), the weathered granite in the San Jacinto Mountains, California, USA ($1{\cdot}5 \times 10^{-5}$ m s^{-1}; Johnson-Maynard *et al*., 1994), and weathered granite in the Idaho batholiths, USA (mean of $2{\cdot}0 \times 10^{-6}$ m s^{-1}; Megahan and Clayton, 1986). The measured saturated hydraulic conductivity of the saprolite at 2·35 m below the soil surface on the ridgetop at the PMRW is 5×10^{-6} m s^{-1} (White *et al*., 2002). Although the observed infiltration rates into the bedrock and the saturated hydraulic conductivity of the bedrock are high, these rates are small compared with the vertical saturated conductivity of 644 mm h^{-1} ($= 1{\cdot}79 \times 10^{-4}$ m s^{-1}) measured in a large soil core from the PMRW (McIntosh *et al*., 1999). Thus, although the bedrock at the PMRW has a relatively high infiltration rate, the conductivity contrast between the soil and the bedrock at the PMRW hillslope is sufficient for water to pond at the soil–bedrock interface during rainstorms, as is assumed in most conceptual models with impermeable bedrock and was observed at the study hillslope by Freer *et al*. (2002) and Tromp-van Meerveld and McDonnell (2006b). Consequently, during large rainstorms, subsurface stormflow occurs laterally over the bedrock surface and through the bedrock at the PMRW study hillslope. The large saturated hydraulic conductivity of the bedrock and the two orders of magnitude larger saturated hydraulic conductivity of the overlying soil, and thus the conductivity contrast between the soil and the bedrock, were also found in granitoid watersheds elsewhere, e.g. the Idaho Batholith, USA (Megahan and Clayton, 1986) and the Kiryu Experimental Watershed, Japan (Katsuyama *et al*., 2005).

A chemical weathering study on a ridge at the PMRW showed that bedrock permeability is primarily intragranular and is created by internal weathering networks of interconnected plagioclase phenocrysts (White *et al*., 2001). Subsurface flow may occur not only through the bedrock, but also along fractures subparallel to the land surface, resulting in heterogeneous hydrologic pathways below the bedrock surface. Road cuts through similar bedrock types in the Piedmont Physiographic Province display large blocks and horizontal fractures. In addition, there are many large granite blocks (approximately 0·2–0·4 m thick), parallel to the surface, on both the 3 ha bedrock outcrop across from the study hillslope and the bedrock outcrop upslope from the study hillslope. Exfoliation produces these blocks and their related lateral fractures. If there are vertical connections of these horizontal fractures to saturated soil, then flow along these fractures is likely higher than flow through the bedrock.

The trench was excavated to competent bedrock, but this could be a block with exfoliation fractures (i.e. sheeting joints) running more or less parallel to the land surface. In fact, the bedrock topography of the trench face has the shape of three blocks sloping towards the left (when looking upslope) with one block extending from 3 to 15 m in the along-slope direction and one block to the left and the right from this main block (Figure 2). The bedrock on the left side of the trench with very shallow soils (downslope from sprinkling areas 1 and 5; along-slope distance 16–20 m in Figure 2) has the shape of a large block at the location of the sharp increase in soil depth (along-slope distance 16 m in Figure 2). Excavation in the trench showed that there was some space filled with dense clay under the bedrock (light grey line in Figure 2). If the left side of the trench is located on top of a block, it is not surprising that subsurface flow was not measured during experiment 1 and the early part of experiment 5. Bedrock moisture downslope from the sprinkled area did not increase during these two experiments, which also indicates that water did not flow through the bedrock (block), but could have flowed along a fracture and underneath the trench. Saturation was not observed next to the trench, indicating that saturated flow around the trench did not likely occur. Only after the sprinkler was moved downslope, the application rate was doubled, and rainfall occurred during a thunderstorm was there some subsurface flow in the trench. Although this trench section delivered a very large portion of total subsurface flow during small natural rainstorms and rainstorms with dry antecedent conditions, its contribution during larger natural rainstorms was minor, consistent with a small contributing area for this trench section (Freer *et al*., 2002; Tromp-van Meerveld and McDonnell, 2006a). Because the sprinkled areas were located upslope of the trench, the actual contributing areas could not be determined from the subsurface flow measurements (i.e. as was done by Parlange *et al.* (1989)).

Calculated bedrock infiltration (and non-evaporative loss) was lowest for sprinkling experiments 3 and 4, which were located on the middle of the study hillslope and trench. The trench sections downslope from sprinkling experiment 3 deliver, on average, more subsurface stormflow than the other trench sections (McDonnell *et al.*, 1996; Freer *et al.*, 1997, 2002; Tromp-van Meerveld and McDonnell, 2006a). The difference between the inner and outer sections might be attributed to flow around the trench during sprinkling experiments 1, 2 and 5. Soil-moisture and water-level data to the left of the trench during sprinkling experiments 1 and 5, however, suggest that it is not likely that saturated flow occurred around the trench. We do not have data from the area next to trench for sprinkling experiment 2, but the low calculated evaporative loss indicates that some flow may have occurred around the trench. Even if the trench had captured only 50% of the subsurface flow, bedrock losses were still larger than during experiments 3 and 4. During rainstorms, the trench sections downslope from experiment 2 deliver water to the trench only late during the rainstorm and also only during large rainstorms (Freer *et al.*, 2002; Tromp-van Meerveld and McDonnell, 2006a), indicating that infiltration into the bedrock could be larger in this area than in the other parts of the study hillslope. Visual observations of the bedrock in the trench suggest that bedrock on the right side of the trench (along-slope distance 0–4 m) is more friable than the bedrock elsewhere in the trench. Unfortunately, we do not have direct measurements of the bedrock permeability to determine the spatial variability across the hillslope.

Bedrock flow effects on the hillslope water balance at the Panola Mountain Research Watershed

Although previous studies at the PMRW have not looked specifically at the influence of subsurface flow through bedrock, a re-evaluation of some previously published results for the 96 mm rainstorm on 6–7 March 1996 at the PMRW (McDonnell *et al.*, 1996; Freer *et al.*, 1997, 2002; Burns *et al.*, 1998, 2001) also indicates that there was likely some leakage to bedrock during this winter rainstorm. Less than 0·4 mm of subsurface flow was generated at the trench in response to the 49 mm rainstorm on 6 March 1996, whereas 24 mm of subsurface flow was generated in response to the 47 mm rainstorm on 7 March 1996. Thus, the runoff ratio of the 7 March 1996 rainstorm was only 51%. Because the 6 March 1996 rainstorm replenished the soil moisture deficit and filled the available storage, the runoff ratio should have been larger (closer to 100%) for the 7 March 1996 rainstorm if the bedrock was impermeable.

A hillslope water balance calculation for the period from 22 February 2002 to 20 April 2002 shows that subsurface stormflow is only a fraction of total precipitation or throughfall during natural storms (Figure 12). Although there were changes in soil moisture during this period, hillslope average soil moisture on 22 February 2002 was similar to hillslope average soil moisture on 20 April 2002 (Figure 12a), such that the net change in soil moisture during this period was negligible. The difference between total throughfall (166 mm) and total subsurface flow (7 mm) during this period is attributed to bedrock infiltration and evapotranspiration losses. Transpiration during this 2-month period was relatively small (compared with the total precipitation flux), because full leaf out did not occur until late April. Thus, it is likely

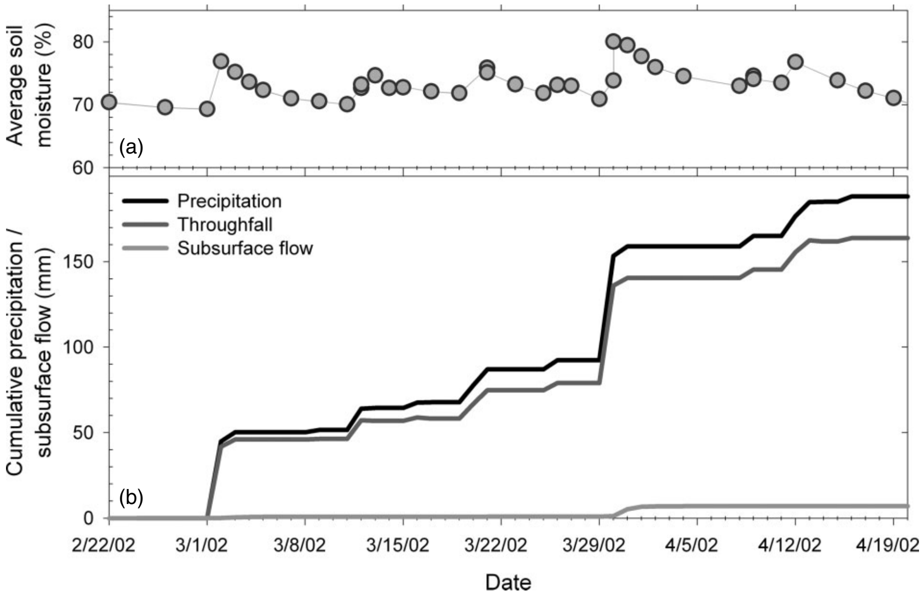

Figure 12. (a) Hillslope average soil moisture; (b) cumulative precipitation, cumulative throughfall and cumulative subsurface stormflow during late winter and early spring 2002. Hillslope average soil moisture was calculated by averaging the profile average soil moisture for all measurement locations. Profile average soil moisture was calculated for each measurement location by multiplying the measured AquaPro values at the different depths by the distance between the subsequent measurement depths and dividing this by the soil depth at the measurement location

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that at least a part of the difference between throughfall and lateral subsurface flow is due to bedrock leakage.

Total subsurface stormflow from the PMRW study hillslope is a threshold function of rainstorm total precipitation (Tromp-van Meerveld and McDonnell, 2006a). For large rainstorms between February 1996 and May 1998, subsurface stormflow increased only 0·3–0·8 times the rainfall that occurred after the threshold was reached. In contrast, Tani (1997) reports a 1 : 1 relation between rainstorm total subsurface stormflow and precipitation above a precipitation threshold. Assuming that the threshold precipitation amount is necessary to fill all storage, then the relation between subsurface stormflow and precipitation after the threshold indicates that losses during large natural rainstorms vary between 20 and 70% of total rainstorm precipitation.

Bedrock flow effects on hillslope subsurface stormflow and streamflow

Although the bedrock at the PMRW has a relatively high infiltration rate, the conductivity contrast between the soil and the bedrock at the PMRW hillslope is sufficient for water to pond at the soil–bedrock interface during rainstorms so that, during large rainstorms, subsurface stormflow occurs laterally over the bedrock surface and through the bedrock. However, during small rainstorms or the early part of larger rainstorms, the saturated areas above the bedrock are disconnected and subsurface flow at the trench face is small. Only when depressions in the bedrock are filled and the saturated areas become connected to each other and the trench face does significant subsurface flow occur (Freer *et al*., 2002; Tromp-van Meerveld and McDonnell, 2006b). Transient saturation at the soil–bedrock interface is short-lived, except in the main bedrock depression. In this bedrock depression, transient saturation is sustained up to several days after the end of the rainstorm (Tromp-van Meerveld and McDonnell, 2006b). The bedrock ridge downslope from this depression blocks lateral flow. The reduction in the water level in the main bedrock depression is attributed to infiltration into the bedrock because evapotranspiration is small during the winter and the soil above the transient saturated area is close to field capacity after a winter rainstorm. Bedrock leakage thus empties the bedrock depression such that it has to be refilled again by each rainstorm. Therefore, bedrock infiltration between rainstorms results in more available storage at the start of the next rainstorm, resulting in a larger threshold for subsurface stormflow and less subsurface stormflow.

A critical evaluation of the water balance of the three landscape units at the PMRW indicates that there must be some contribution of flow through the bedrock to streamflow at the catchment outlet, i.e. within the watershed. Consider the following simple three-component mixing model:

$$Y_{\text{stream}} = Y_{\text{riparian}}A_{\text{riparian}} + Y_{\text{hillslope}}A_{\text{hillslope}} + Y_{\text{outcrop}}A_{\text{outcrop}} \quad (2)$$

where Y is water yield, A is the contribution of a landscape unit to the entire watershed area, Y_{stream} is the average stream yield, and the subscripts 'riparian', 'hillslope' and 'outcrop' refer to the three main landscape units. The annual runoff coefficient for the 41 ha watershed at the PMRW during WY1986 to WY2001 averaged 30%, but ranged from 18 to 50% (Peters *et al*., 2003). The stream runoff coefficient for the February 1996–February 1998 period was 37%. The maximum estimated yield of the bedrock outcrops, which cover 10% of the basin area, is 90% of precipitation, which accounts for both storage in bedrock depressions and interception by vegetation on the bedrock outcrops (~2 mm per storm; Peters, 1989). The average yield of the hillslopes, which cover more than 75% of the basin, was 5% for the February 1996–February 1998 period (Tromp-van Meerveld and McDonnell, 2006a). The results of the three-component mixing model (Equation (2)) indicate that the contribution from the riparian zone is an unrealistic 162% for the February 1996–February 1998 period. To overcome this, a fourth component is added to account for saturated flow through the bedrock:

$$Y_{\text{stream}} = Y_{\text{riparian}}A_{\text{riparian}} + Y_{\text{hillslope}}A_{\text{hillslope}} + Y_{\text{outcrop}}A_{\text{outcrop}} + \text{BR} \quad (3)$$

where BR refers to the contribution of subsurface flow through bedrock to streamflow. If one assumes a water yield of 20–70% for the riparian zone, then the contribution of bedrock water to streamflow is 14–21% (Equation (3)) for the February 1996–February 1998 period and at least 7–14% for an average year. The contribution of bedrock water to streamflow is consistent with the large mean age of riparian groundwater and the increase in age of riparian groundwater in the downvalley direction and with depth below the surface found by Burns *et al*. (2003).

Thus, whereas the hillslope may be disconnected from the stream at the event time-scale, as was indicated by geochemical analysis (Hooper *et al*., 1998, Hooper, 2003), hydrochemical and hydrometric studies (Peters and Ratcliffe, 1998) and the low runoff ratios from the PMRW hillslope (Tromp-van Meerveld and McDonnell, 2006a), it appears that the hillslopes are connected to the stream at longer time-scales by flow through the bedrock. This has important implications for the geochemistry of the stream water (Burns *et al*., 2003).

The geochemical composition of groundwater in a well in bedrock near the gauging station at the basin outlet indicates that the water is very old (26–27 years; Burns *et al*., 2003). The major ion concentrations of the groundwater are relatively constant temporally at this location, indicating that 'new' water contributions to the groundwater do not vary despite large temporal variations in the wetness conditions of the watershed. Furthermore, the high and relatively invariable solute concentrations of groundwater in the bedrock well indicate that water lost below the gauging station is probably negligible relative to the magnitude of streamflow at the watershed scale.

The Panola Mountain Research Watershed hillslope in the context of other reported hillslopes

The few studies that have looked at the importance of subsurface flow through bedrock (either directly or indirectly by deducing it from other measurements) have focused mainly on the influence of exfiltrating bedrock water on subsurface flow or streamflow quantity and timing (e.g. Anderson *et al*., 1997; Onda *et al*., 2001; Uchida *et al*., 2003), streamflow chemistry (e.g. Tsujimura *et al*., 2001) and hillslope riparian linkages (Katsuyama *et al*., 2005). At the PMRW hillslope, measured heads in a piezometer pair indicate there was always a negative gradient on this hillslope (Tromp-van Meerveld and McDonnell, 2006b), indicating continuous infiltration potential from the soil into the bedrock. The absence of bedrock groundwater exfiltration at this hillslope indicates that lateral subsurface stormflow over the soil–bedrock interface 'loses' water to the bedrock along the way, much like an influent stream loses water to its streambed along the way.

In terms of bedrock permeability effects on subsurface stormflow and streamflow, the PMRW may be placed on the permeable side in a continuum from very permeable (Fudoji, Japan; Coos Bay, USA) to effectively impermeable bedrock (Maimai, New Zealand; Plastic Lake, Canada) and may be only one example of a well-studied hillslope or catchment where flow through the bedrock is a larger component of the water balance than previously assumed.

CONCLUSIONS

Although conceptual models of how the PMRW hillslope 'works' implicitly assumed that the bedrock is relatively impermeable, flow through bedrock is an important component of the hillslope water balance and cannot be ignored. Bedrock moisture increased rapidly in response to rainstorms during the early spring (Figure 3). Peak tracer breakthrough in bedrock was delayed only 2 days compared with peak tracer breakthrough in subsurface stormflow (Figure 4). During the 8-day long sprinkling experiments, when more than the average yearly precipitation was applied to a 69–79 m^2 area on the hillslope, the measured subsurface flow during the later parts of the experiments, when soil moisture changes were small, was only a small fraction ($<10\%$) of total water applied (Table II). Even though the calculated infiltration rates into the bedrock are high, there is a large permeability contrast between the saturated conductivity of the soil and the bedrock at this hillslope. Thus, although there is leakage into the bedrock, lateral subsurface flow over the bedrock also occurs.

The relation between precipitation after a threshold and total subsurface flow (Tromp-van Meerveld and McDonnell, 2006a) indicates that at least 20% of the precipitation during large rainstorms infiltrates into the bedrock. A water balance calculation for the 22 February–20 April 2002 period, during which there were no net changes in soil moisture and transpiration was assumed to be relatively small, showed that subsurface flow was only 4·3% of total throughfall. A simple four-component water balance calculation showed that subsurface flow through the bedrock contributed at least 14–21% of streamflow between February 1996 and February 1998.

These results indicate that the hillslopes, which dominate the landscape at the PMRW, are not disconnected from the stream but are likely connected to the stream at longer than the event time-scales by flow through the bedrock. Flow through the bedrock can account for the very low runoff coefficients for the hillslope (Tromp-van Meerveld and McDonnell, 2006a) and the long residence times of riparian groundwater (Burns *et al*., 2003). At the PMRW, future research and hydrological modelling efforts at the hillslope and watershed scales should incorporate the subsurface flow processes through the bedrock and attempt to quantify its behaviour better temporally and spatially in the watershed.

Finally, sprinkling experiments, tracer experiments, or other manipulative experiments on the intensively instrumented hillslope at the PMRW were invaluable in revealing bedrock infiltration. These techniques should be considered in other hilllslope or watershed studies to improve our understanding of hydrological processes and the relative contribution of the individual water balance components.

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