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Role of upslope soil pore pressure on lateral subsurface storm flow dynamics

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[1] The role of upslope soil pore water pressure on lateral subsurface storm flow dynamics is poorly understood. Further development of hillslope hydrologic models requires new understanding from field understanding. In particular, we need new, quantifiable measures that link upslope soil pore pressure and water table dynamics to the timing and volume of subsurface storm flow. Here we examine the relationship between hillslope-scale pore pressure and lateral outflow from slope base using the fine-temporal-resolution hydrometric data (10 min interval) from two steep unchanneled concave hillslopes, one hillslope (Fudoji) covered by relatively high hydraulic conductivity sandy soil and the other (Toinotani) covered by relatively low hydraulic conductivity clay soil. In both hillslopes, pore pressures in the area close to the slope base were only weakly related to subsurface storm flow dynamics. During periods of storm flow production, hillslope discharge was strongly related to the cross-sectional area of the upslope saturated layer. During slope seepage periods between events, hillslope discharge from the highly permeable hillslope was still related to the upslope cross-sectional subsurface saturated area. However, during this same period at the low-permeability site, hillslope discharge was not related to the upslope subsurface saturated area. Through intersite comparison we show that the soil matrix permeability has a large impact on the hydrological extension of preferential flow and hence the linkage between upslope pore pressure and subsurface storm flow dynamics. *INDEX TERMS:* 1860 Hydrology: Runoff and streamflow; 1866 Hydrology: Soil moisture; 1829 Hydrology: Groundwater hydrology; *KEYWORDS:* hillslope discharge, soil pore water pressure, saturated area, preferential flow

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1. Introduction

[2] Subsurface storm flow in steep unchanneled soil-mantled hillslopes is a first-order control on runoff generation in many parts of the world [*Bonell*, 1998]. While study of this process is clearly an important academic issue, knowledge of subsurface storm flow processes is important for mapping landslide occurrence [*Wu and Sidle*, 1995], managing silvicultural operations [*Jones and Grant*, 1996] and quantifying the flushing of labile nutrients into surface waters [*McHale et al.*, 2002]. The mechanism of subsurface storm runoff generation in forested headwater catchments has been debated since the 1930, but not until the 1960s was the importance of shallow subsurface flow well documented as the main control on the hydrologic response of steep hillslopes [*Tsukamoto*, 1961; *Whipkey*, 1965; *Hewlett and Hibbert*, 1967]. Since then, a number of hydrological studies have demonstrated specific triggers for subsurface storm flow occurrence, including transmissivity feedback [*Rodhe*, 1989; *Seibert et al.*, 2003], flow through the fractured bedrock [*Montgomery et al.*, 1997], pressure wave [*Torres et al.*, 1998; *Williams et al.*, 2002] and flow through soil pipes [*Jones*, 1987; *Kitahara*, 1989, 1994; *Uchida et al.*, 1999]. Perhaps the most common observation for rapid subsurface flow on steep wet hillslopes is lateral preferential flow at the soil-bedrock interface [*Mosley*, 1979; *Tsukamoto et al.*, 1982; *McDonnell*, 1990; *Peters et al.*, 1995; *Tani*, 1997; *Sidle et al.*, 2000; *Freer et al.*, 2002; *Koyama and Okumura*, 2002]. There appears to be wide consensus that in areas with steep slopes, thin soils and matrix hydraulic conductivities above maximum rainfall intensity, water moves vertically as matrix and preferential flow, and perches at the soil-bedrock or an impeding layer at depth and then moves laterally along the lowest depths of the profile [*McGlynn et al.*, 2002]. The development of transient saturation is accelerated by the often observed rapid decline in effective porosity (i.e., the total void space available for storage) with depth [*Weiler and McDonnell*, 2004], that promotes a bottom-up saturation and subsequent lateral

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flow, dictated by the slope of the underlying bedrock. In most studies reporting this mechanism, a zone of secondary porosity often exists at this interface, be it a series of well defined soil pipes [*Mosley*, 1979] or enlarged openings (formed through eluviation) at the soil-bedrock interface [*Buttle et al.*, 2001]. While extremely computationally complex in many model environments, *Seibert and McDonnell* [2002] argued recently that this type of subsurface storm flow response can be described in a simple hydrologic model, where the complex pipe flow dynamics are described as a set of simple nonlinear storage equations.

[3] Notwithstanding these developments, the ability to relate lateral pipe flow dynamics to internal conditions on the hillslope remains elusive. While some recent studies have shown relationships between precipitation amount and intensity and subsurface pipe flow [*Uchida et al.*, 1999; H. I. Tromp-van Meerveld and J. J. McDonnell, Measured nonlinearities in subsurface flow, submitted to *Water Resources Research*, 2004], no studies have yet examined the relationship between lateral pipe flow and upslope transient water table height with upslope subsurface contributing area or upslope subsurface contributing volume. Despite a lack of empirical data, some physically based models have incorporated the effects of lateral preferential flow on subsurface storm flow dynamics [*Tani and Abe*, 1996; *Fach et al.*, 1997; *Jones and Connelly*, 2002; *Kosugi et al.*, 2004]. Recent studies have also proposed a modified TOPMODEL to incorporate the effects of lateral preferential flow in the form of "lateral quick flow" [e.g., *Scanlon et al.*, 2000; *Shaman et al.*, 2002]. Most of these models have focused on the lumped prediction of the catchment storm hydrograph, and have not described the functional relationship between pore pressure dynamics on the hillslope and outflow from the slope base into the stream or into a riparian zone. *Tani and Abe* [1996] analyzed the hillslope storage-discharge relationship using a physically based model which incorporated the effects of lateral preferential flow.

[4] Despite these modeling efforts, we still need quantifiable measures from the field that link upslope soil pore pressure and water table dynamics to the timing and volume of subsurface storm flow in order to improve our hydrologic models of subsurface storm flow processes (both simple reservoir approaches and more complex finite element schemes). Here, we present new data and interpretations from two well-studied catchments in Japan and examine the relationship between hillslope-scale internal pore pressure and lateral outflow from the slope base. We contrast two mechanisms of subsurface storm flow dynamics from these sites, lateral pipe flow and matrix flow at the soil bedrock interface, and use these comparisons to address the following: what is the relationship between pore pressure dynamics, transient groundwater development and lateral subsurface storm flow and measured pipe flow from steep hillslopes and how do differences in slope material properties influence these relations? We use the fine-temporal-resolution hydrometric data (10 min interval) from two steep unchanneled concave hillslopes; one covered by relatively high hydraulic conductivity sandy soil, and the other is covered by relatively low hydraulic conductivity clay soil. Our previous work at these sites has focused on simultaneous hydrometric and natural tracer measurements [*Asano et al.*, 2002, 2003; *Uchida et al.*, 2002, 2003a, 2003b] and soil matrix-soil pipe interactions [*Uchida et al.*, 1997, 1999]. This is our first attempt to relate internal dynamics of soil pore pressure to measured outflow.

2. Study Site

2.1. Fudoji

[5] The Fudoji zero-order watershed is located in southeastern Shiga Prefecture, central Japan. The catchment is underlain by Tanakami granite and covers an area of 0.10 ha. The mean slope gradient in the catchment is 37 degrees and the vegetation consists of dense natural forest, predominately *Chamaecyparis obtusa*. The mean annual precipitation and runoff in Kiryu Experimental Forest (10 km north of Fudoji) from 1972 to 2001 was 1645 mm and 888.5 mm, respectively [*Katsuyama*, 2002]. The soil depth along the main axis of the monitored hillslope ranges from 60 to 120 cm [*Asano et al.*, 2002]. This depth was measured using a cone penetrometer with a cone diameter of 19.5 mm, a weight of 1.17 kg, and a fall distance of 20 cm. We defined N_4 as the number of blows required for a 4 cm penetration of the cone device. The soil-bedrock interface was assumed to be reached at N_4 values greater than 100 [*Uchida et al.*, 2003b]. The soils are predominantly cambisols. The average saturated hydraulic conductivities of the A and B horizons (measured using three 100 cm^3 field cores in the laboratory) were 9480 and 235 mm hr^{-1}, respectively [*Asano et al.*, 2002]. Porosities range from 55–68% [*Ohte*, 1992].

[6] Two perennial springs contribute to "hillslope discharge" at the base of the experimental hillslope: one from the soil matrix and various soil pipes embedded within it and the other from a crack in the bedrock (Figure 1). The variation in the discharge rate from the bedrock spring was small; observations from April 2000 to July 2001 were in the range from 0.9 to 1.5 m^3 d^{-1}. In addition, soil pipe outlets with diameters ranging from 3 to 10 cm were mapped at the base of the slope adjacent to the spring. In the small area near the spring (F1), a saturated area was present continuously above the bedrock except during the driest rain-free periods. In this small, perennially saturated area near the spring, our earlier work showed that water percolated through the vadose zone and mixed with water emerging from the bedrock [*Asano et al.*, 2002]. In contrast, within most of the hillslope area, the soil-bedrock interface was not commonly saturated between events. Most monitored storms produced saturation at the soil-bedrock interface. Our previous work suggests that both rainwater and preevent shallow soil water have important effects on the formation of transient saturated groundwater on the upper slope [*Uchida et al.*, 2003b].

2.2. Toinotani

[7] Toinotani is a zero-order watershed located in the northeastern part of Kyoto Prefecture in the central part of Japan. The catchment is underlain Paleozoic sedimentary rock, with an area of 0.64 ha and a mean gradient of 36 degrees. The vegetation consists of a closed secondary forest of predominately *Cryptomeria japonica*. The mean annual precipitation is 2885 mm, 30% of which falls as snow. The mean annual runoff measured in Kamitani

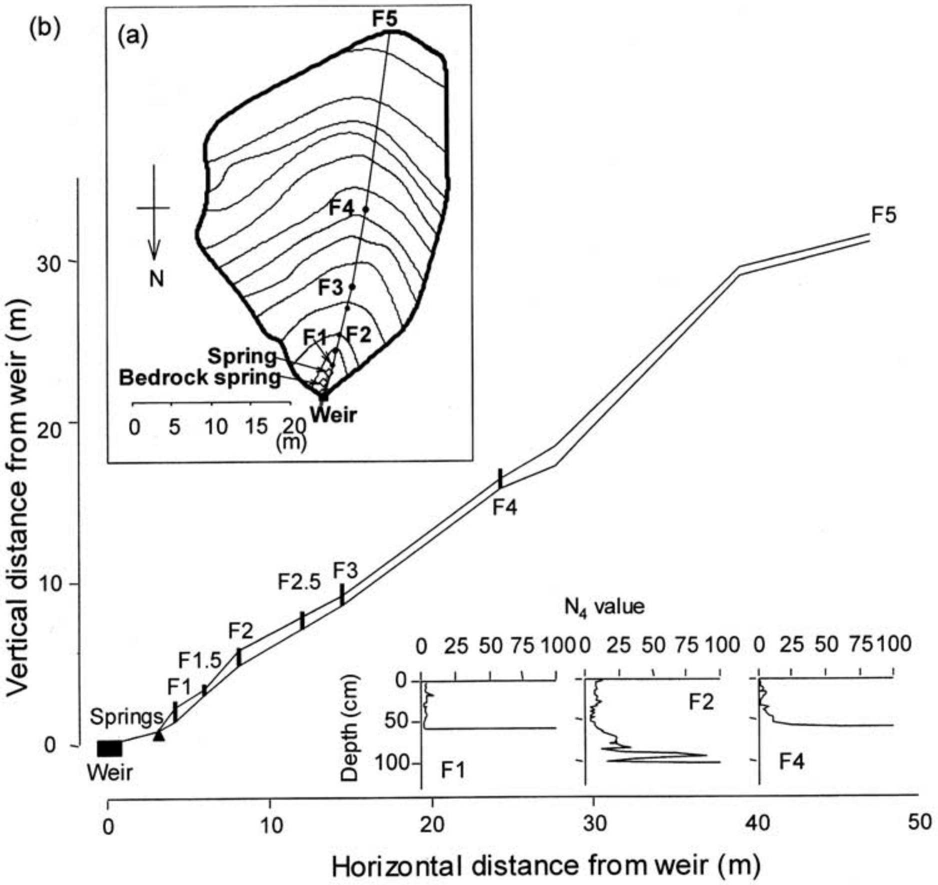

Figure 1. (a) Topographic map of the Fudoji watershed with a 2.5 m contour interval. (b) Longitudinal axis of the concave slope (line Weir–F5, as noted in Figure 1a). The profiles of the N_4 penetrometer values are shown in the inset graph.

Watershed in Kyoto University Forest in Ashiu (adjacent to Toinotani) was 2448 mm [*Nakashima and Fukushima*, 1994]. The soil depth to the bedrock along the axis of the monitored concave hillslope section ranges from 20 to 80 cm. Soils are predominantly cambisols. Average saturated hydraulic conductivity as measured from minimally disturbed 100 cm^3 cores at depth of 12–17, 18–23 and 45–50 cm were 3300, 2900 and 630 mm hr^{-1}, respectively [*Uchida et al.*, 1995]. Excavation of one soil pipe indicated that the soil pipe depth ranges from 45 to 85 cm [*Michihata et al.*, 2001]. Saturated conductivity and porosity were measured at the depth of soil pipe formation from minimally disturbed 100 cm^3 cores and showed average values of 0.23 mm hr^{-1} and 29%, respectively [*Michihata et al.*, 2001].

[8] Fresh bedrock is exposed at the lower portions of the small watershed (Figure 2). Water flows continuously from the soil layer just above the weir. One surface outlet of a natural soil pipe was observed at 6 m upslope from the weir (Pipe A) and six others were mapped at about 10 m upslope (Pipe group B). During base flow periods, pipe flow did not occur, but during a heavy rain, water flowed from the spring at Pipe A and Pipe group B [*Mizuyama*, 1994]. Pipe flow discharge resulted in surface flow in between the outlet of Pipe A and the spring [*Uchida et al.*, 2002]. A saturated area was present continuously above the bedrock, except for the driest period, in the small area near to the spring. Most of the storms produced transient groundwater at wells W1 through W7. The transient groundwater at the upper hillslope was dominated commonly by preevent soil water [*Uchida et al.*, 2002]. Only after large storms with wet antecedent conditions did water emerge from the bedrock and mix with preevent soil water in the transient saturated area at the upper hillslope between W1 and W7 [*Uchida et al.*, 2002].

3. Methods

3.1. Data

[9] The rate of hillslope discharge was measured using a V notch weir and a water level recorder installed at the zero-order watershed outlets. We use the term hillslope discharge for these waters, since they contain a mixture of subsurface storm flow and deeper bedrock groundwater exfiltrating to the surface through bedrock springs. Pore pressures immediately above the bedrock were measured with tensiometers embedded within the soil and instrumented with recording pressure transducers (COPAL PA-800 and Daiki DIK-3150). Five locations in Fudoji and at six locations in Toinotani were monitored along the longitudinal axis of the hillslope hollow (Figures 1 and 2). The outflow of pipe A at Toinotani was directed to a 500 cm^3 tipping bucket; tips were recorded using a KADEC-UP logger [*Uchida et

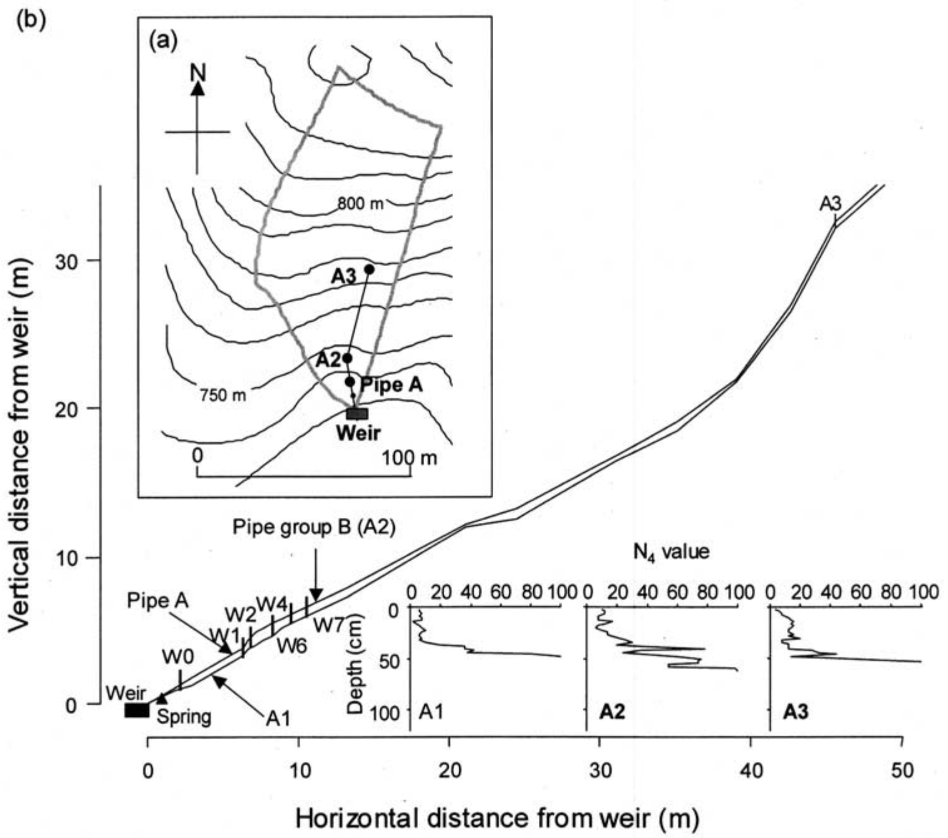

Figure 2. (a) Topographic map of the Toinotani watershed with a 10 m contour interval. (b) Longitudinal axis of the concave slope (line Weir-A3, as noted in Figure 2a). The profiles of the N_4 penetrometer values are shown in the inset graph.

al., 1999]. This study presents data for 84 days of intensive observation from Fudoji (from 1 June to 25 August 1999) and 75 days of data from Toinotani (from 14 August to 27 October 1996). Total precipitation in these analysis periods in Fudoji and Toinotani were 598 and 832 mm, respectively. The API_{10} (antecedent precipitation index defined as $\mathrm{API}_{10} = \sum_{i=1}^{10}(P_{p,i}/i)$ where $P_{p,i}$ is the total rainfall amount i days beforehand) on the first day in the analysis periods at Fudoji and Toinotani was 14.2 and 1.3 mm, respectively.

3.2. Data Analysis Preamble

[10] The observation periods were classified into three groups based upon the hillslope discharge rate. When hillslope discharge was less than half of mean hillslope discharge for the analysis period, we classified this as the "low-flow period." We define the "subsurface storm flow period" as the period when hillslope discharge was greater than 500% of mean hillslope discharge rate. The remaining period was defined as the "normal slope seepage period."

[11] Much of our quantitative analysis of internal pore pressure dynamics and subsurface storm flow rely on correlation between the hillslope discharge and the pore pressure using the Spearman rank correlation coefficient. This approach is motivated by recent findings of *Seibert et al.* [2003], where their plotting of runoff against groundwater level often revealed a strong nonlinear and hysteric response. The functional expression which describes the relationship best may vary for different locations. *Seibert et al.* [2003] showed that nonparametric statistics could be used to overcome these difficulties. We approximated the cross-sectional area of the transient saturated layer on the two-dimensional longitudinal cross section (S_a) (Figure 3) for each hollow axis. Hereafter, we refer to the value of S_a as the "subsurface saturated area." If measured pore pressure values from the tensiometers were positive, the groundwater level at that point was assumed to be equal to the measured pore water pressure head. If the measured pore pressure was negative, then the groundwater level at that point was assumed to be zero. We confirmed the appropriateness of this assumption in the Fudoji hillslope by measuring independently the groundwater level using wells and tensiometer-based pore water pressures simultaneously [*Asano et al.*, 2002; *Uchida et al.*, 2003b]. These observations support our approach.

4. Results

4.1. Correlation Between Internal Pore Pressures and Hillslope Discharge

[12] The relationship between pore pressure P and hillslope discharge Q was greatly affected by slope position at both sites (Figures 4 and 5). At Fudoji, the variations in pore pressure at the near-spring area (<2.9 m form the perennial springs) were relatively small (<60 cm H_2O) compared to the upper slope positions (>100 cm H_2O) (Figures 4a and 4b). The correlation between pore pressure at the lowest point and hillslope discharge was relatively weak through-

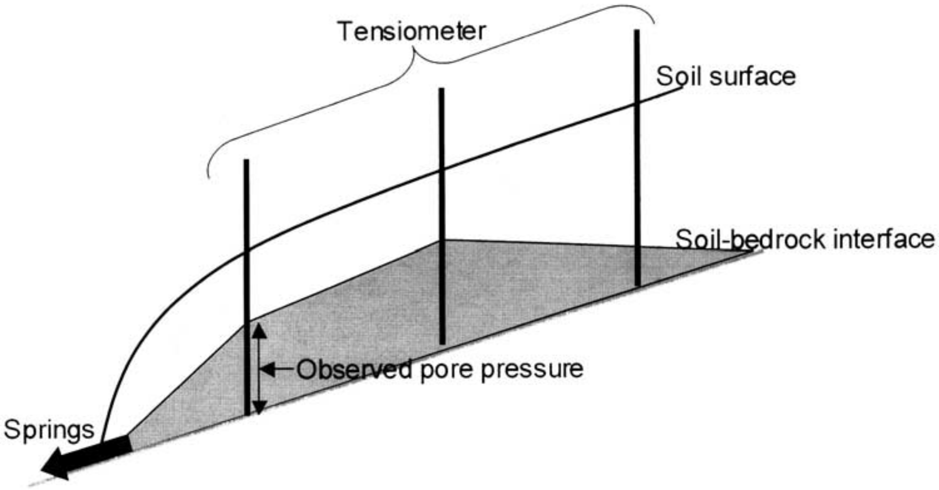

Figure 3. Schematic of subsurface saturated area.

out the period (Table 1) but the strength of the regression relationships improved for positions farther upslope from the weir. During the subsurface storm flow period, the pore pressure at the point 2.9 m upslope from the springs also remained constant (Figure 4). Here, the correlation coefficient of *P*-*Q* relationship was greater than 0.84 in both the low-flow and normal seepage flow periods, although the correlation coefficient for the subsurface storm flow period was small (r = 0.27). In contrast, the pore pressures at the points 5.0 and 8.5 m upslope from the weir were strongly associated with hillslope discharge regardless of hillslope discharge rate (Table 1 and Figures 4c and 4d), although in most of the low-flow period these pore pressures exhibited negative values (suggesting unsaturated conditions). The *P*-*Q* correlation at the point of 11.0 m upslope from the perennial spring was weak compared to the 5.0 and 8.5 m points. However, during the subsurface storm flow conditions, the pore pressure at the 11.0 m point was strongly associated with the hillslope discharge (r = 0.88).

[13] At Toinotani, the temporal variation in pore pressure at the point 1.0 m upslope from the spring was very small (<20 cm H_2O), qualitatively similar to Fudoji (Figure 5a). The *P*-*Q* correlation at the 1.0 m point was 0.62 (Table 1). While we did not excavate an artificial trench at this site, these small variations of pore pressures at the base of the hillslope might be affected by boundary condition at the soil-bedrock interface. The pore pressures at 7.0 and 7.4 m upslope, located just above the soil pipe outlet, were not related to the hillslope discharge. The correlation coefficients were smaller than 0.60, regardless of hillslope discharge amount. During the subsurface storm flow period, the correlations between pore pressures at the 8.4, 9.4 and 10 m points and hillslope discharge was strong (r > 0.70), while the correlation coefficients during the normal seepage

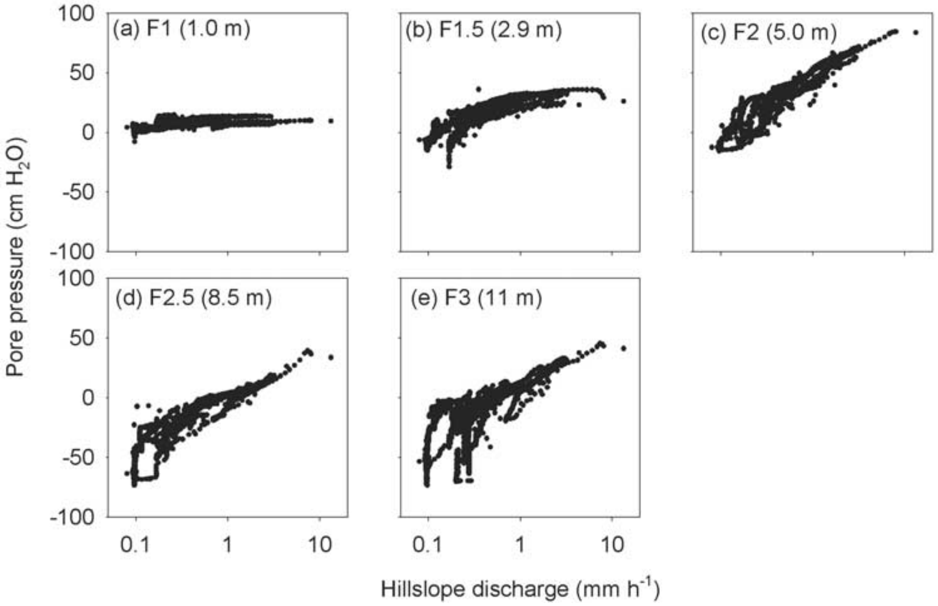

Figure 4. Relationships between Fudoji hillslope discharge and soil pore pressure at (a) F1, (b) F1.5, (c) F2, (d) F2.5, and (e) F3.

Table 1. Spearman Rank Correlation Coefficients

	All	Low Flow	Normal Slope Seepage	Subsurface Storm Flow
		Fudoji		
n	11,962	3015	8803	144
Pore pressure				
F1, 1.0 m	0.45	−0.03	−0.24	0.26
F1.5, 2.9 m	0.91	0.84	0.86	0.27
F2, 5.0 m	0.93	0.87	0.89	0.86
F2.5, 8.5 m	0.94	0.85	0.92	0.91
F3, 11.0 m	0.32	0.87	0.23	0.88
Groundwater level				
F1, 1.0 m	0.45	−0.03	−0.23	0.26
F1.5, 2.9 m	0.88	−0.04	0.86	0.27
F2, 5.0 m	0.77	−0.36	0.84	0.86
F2.5, 8.5 m	−0.87	−0.96	−0.92	0.91
F3, 11.0 m	−0.63	−0.96	−0.60	0.88
Gradient (F1–F1.5)	0.80	0.66	0.79	0.28
Subsurface saturated area	0.96	0.56	0.91	0.89
		Toinotani		
n	10,908	2718	8497	233
Pore pressure				
W0, 1.0 m	0.62	0.32	0.31	0.08
W1, 7.0 m	0.36	0.39	0.32	0.51
W2, 7.4 m	0.47	0.56	0.31	0.13
W4, 8.4 m	0.49	0.79	0.29	0.70
W6, 9.4 m	0.57	0.78	0.45	0.80
W7, 10.0 m	0.38	0.86	0.01	0.85
Groundwater level				
W0, 1.0 m	0.62	0.17	0.31	−0.08
W1, 7.0 m	−0.11	−0.47	−0.13	0.51
W2, 7.4 m	0.50	0.29	0.41	0.13
W4, 8.4 m	−0.28	−0.69	−0.30	0.70
W6, 9.4 m	−0.49	−0.77	−0.55	0.80
W7, 10.0 m	−0.62	−0.98	−0.66	0.85
Gradient (W0–W1)	0.28	0.36	0.29	0.28
Subsurface saturated area	0.59	0.62	0.30	0.81

Table 2. Percentage of Saturated Period to Total Period

	All, %	Low Flow, %	Normal Slope Seepage, %	Subsurface Storm Flow, %
		Fudoji		
F1	98	92	100	100
F1.5	71	20	88	100
F2	55	12	69	100
F2.5	2	0	1	98
F3	6	0	7	100
		Toinotani		
W0	84	21	99	100
W1	19	9	19	100
W2	58	27	63	100
W4	14	4	14	100
W6	9	3	8	100
W7	7	0	6	100

flow period were smaller than 0.45 (Figures 5d–5f). Although most of the pore pressures in the low-flow period at these sites were negative (Table 2), the correlation coefficients between pore pressures and hillslope discharge were high ($r > 0.78$). Overall, the correlation between pore pressure and hillslope discharge was relatively weak (Table 1). During the normal seepage flow period, there was no relation between pore pressure and the hillslope discharge.

[14] Major differences in the *P-Q* relationship between Fudoji and Toinotani occurred at the positions greater than 5 m from the springs. During the subsurface storm flow period, the variation in the 2.9 m location pore pressure at Fudoji was small, while the pore pressures at the 5.0, 8.5, 11.0 m locations increased linearly with increases in hillslope discharge. In contrast, the variations in pore pressures at all observed points at Toinotani were relatively small, similar to the 1.0 and 2.9 m points of Fudoji. Pore pressure and hillslope discharge relations at Toinotani and Fudoji can

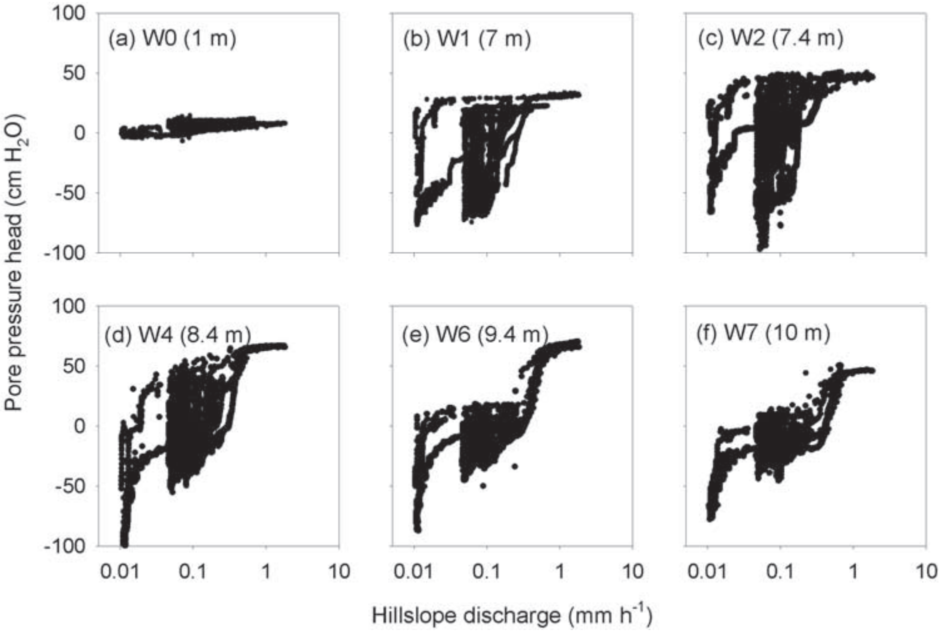

Figure 5. Relationships between Toinotani hillslope discharge and soil pore pressure at (a) W0, (b) W1, (c) W2, (d) W4, (e) W6, and (f) W7.

be summarized as: (1) pore pressure dynamics in the area close to the springs (<2.9 m) varied little and were only weakly related to measured hillslope discharge, (2) during the subsurface storm flow period, measured hillslope discharge at both sites was strongly related to pore pressure observations at points greater than 8.0 m upslope from the perennial springs.

4.2. Relationship Between Groundwater Levels and Hillslope Discharge

[15] Hillslope discharge at Fudoji was well correlated to the groundwater levels at points 1.0, 2.9 and 5.0 m upslope from the springs. Beyond 5 m upslope, we found no relation between hillslope discharge and well response at measurement locations at 8.5 and 11.0 m upslope from the springs (Table 1). During most of the low-flow period, saturation either did not develop, or extend, between 2.9 and 11 m upslope from the springs (Table 2). While most of low-flow period showed consistent groundwater at the 1.0 m upslope point, hillslope discharge was not well correlated to measured groundwater levels at this position (Table 1). Thus during the low-flow period, hillslope discharge was not related to any monitored groundwater levels on the hillslope (Table 1). During the normal slope seepage period, hillslope discharge at Fudoji was strongly related to the groundwater levels at 2.9 and 5.0 m upslope from the spring ($r > 0.84$). For most of the normal slope seepage period, the 8.5 and 11.0 m points did not develop saturation. Hence the correlation coefficients between the measured groundwater levels at these points and hillslope discharge were very weak. During the subsurface storm flow period, the saturated area extended upslope all the way to the 11.0 m location. Hillslope discharge was strongly related to the groundwater levels at 5.0, 8.5 and 11.0 m upslope from the springs ($r > 0.86$) during this subsurface storm flow period.

[16] At Toinotani, the correlation coefficient between the measured 1.0 m upslope groundwater and hillslope discharge was higher than any other measured groundwater positions on the slope (Table 1). During the low-flow period, groundwater was largely absent on the slope and even the 1.0 m well upslope from the spring was dry 79% of the time. Not surprisingly, hillslope discharge was not related to any of the measured groundwater levels ($r < 0.29$). During most of the normal slope seepage period, the point 1.0 m upslope from the spring showed consistent groundwater presence. The point 7.4 m from the spring also showed some groundwater present much of this time (Table 2). However, in this period, wells at 7.0, 8.4, 9.4 and 10.0 m upslope from the spring were often dry (Table 2). The correlation coefficient between the groundwater levels at the 1.0 and 7.4 m points and hillslope discharge for the normal slope seepage period were larger compared other sites; nevertheless correlation coefficients were still small (less than 0.41, Table 1). During the subsurface storm flow period, the hillslope discharge was more related to the groundwater levels at upper hollow positions (8.4–10.0 m upslope from the springs), compared to the lower well points.

[17] At both Fudoji and Toinotani, differences in relations between hillslope discharge and pore pressure and between groundwater level occurred during the normal slope seepage and low-flow periods, since most of the tensiometers showed positive values in the subsurface storm flow period. Although there was a relatively strong correlation between pore pressure and hillslope discharge during low flow (e.g., F2, F3, W7 etc.), the hillslope discharge was not well correlated to measured groundwater levels. During normal slope seepage conditions, the correlation between hillslope discharge and pore pressure at upper hillslopes (8.5 and 11.0 m points in Fudoji and 8.4 and 9.4 m points in Toinotani) was similar to the that in the lower hillslopes (2.9 and 5.0 m points in Fudoji and 1.0 m points in Toinotani). In contrast, during this period, the positive correlation between the hillslope discharge and the groundwater levels can be seen at lower hillslopes (2.9 and 5.0 m points for Fudoji and 1.0 and 8.4 m points for Toinotani), although the correlation coefficients for Toinotani was relatively small ($r < 0.41$).

4.3. Relationship Between Computed Hydraulic Gradients and Hillslope Discharge

[18] We computed hydraulic gradients from tensiometer positions at 1.0 and 2.9 m for Fudoji and 1.0 and 7.4 m for Toinotani. At Fudoji, the hydraulic gradient between F1 and F1.5 was strongly correlated with the hillslope discharge ($r = 0.80$). However, the variation in hydraulic gradient during the study period was small (0.52–0.75), compared to the range in measured hillslope discharge (0.1–23 mm hr^{-1}). Hydraulic gradient variations during subsurface storm flow periods were relatively small (Figure 6a). The correlation coefficient between computed hydraulic gradient and hillslope discharge during the subsurface storm flow period was very small ($r = 0.28$), although the correlation coefficients for the low and normal slope seepage periods were high (0.66 and 0.79).

[19] At Toinotani, the variation in computed hydraulic gradient was small (0.25–0.43), compared to the large range of measured hillslope discharge values (0.005–2 mm hr^{-1}) (Figure 6b). The correlation coefficients between computed hydraulic gradient and hillslope discharge were also small ($r < 0.36$), regardless of hillslope discharge rate (Table 1).

4.4. Relationship Between Upslope Subsurface Saturated Area and Hillslope Discharge

[20] The cross-sectional subsurface saturated area was computed for each hillslope. At Fudoji, the hillslope discharge and the subsurface saturated area exhibited a linear relationship on the semilogarithmic plots (Figure 7a). The subsurface saturated area was strongly correlated with the hillslope discharge for all periods ($r = 0.96$), although during low-flow periods, the correlation coefficient was somewhat weaker ($r = 0.56$). At Toinotani, the hillslope discharge and the subsurface saturated area did not show a clear linear relationship on the semilogarithmic plots (Figure 7b). Hillslope discharge was not related to the subsurface saturated area for the low-flow or the normal slope seepage period. However, during the subsurface storm flow period, the correlation coefficient improved significantly to $r = 0.81$. At both hillslopes, the subsurface saturated area was correlated with the hillslope discharge for all periods. This correlation was strongest during the subsurface storm flow period.

5. Discussion

5.1. Subsurface Saturated Area Control on Hillslope Discharge and the Role of Soil Pipes

[21] Our previous work at the Fudoji and Toinotani sites showed that during the low-flow period, hillslope discharge

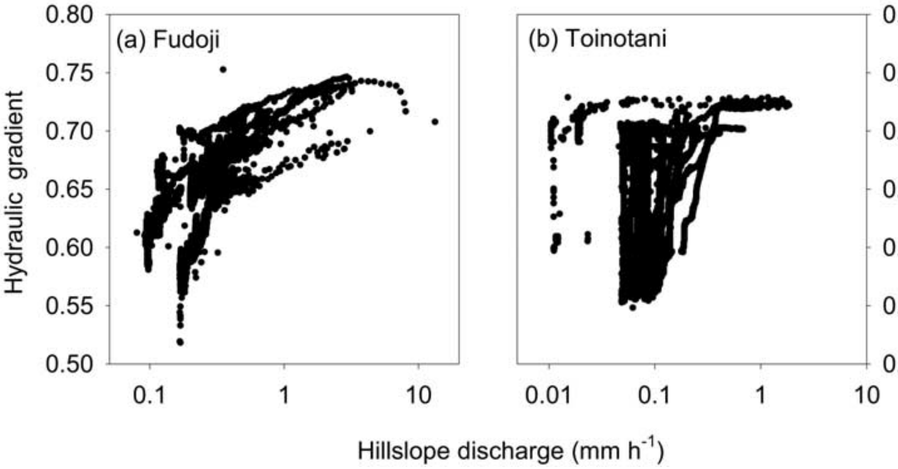

Figure 6. Relationships between hillslope discharge and lateral hydraulic gradient (a) between F1 and F1.5 at Fudoji and (b) between W0 and W7 at Toinotani.

was dominated by the water emerging from the bedrock fissure [*Uchida et al.*, 2002, 2003b]. Not surprisingly, during this low-flow period, the correlation between groundwater level, as measured by the transect of tensiometers embedded in the mineral soil, and hillslope discharge in this study was very small. Transient water tables developed at the soil-bedrock interface but rarely persisted through these low-flow periods. When matrix flow dominated flow at the two sites and pipe flow was not observed, hillslope discharge was not related to measured groundwater levels at any slope positions. In these "low-flow periods," we interpret the hillslope discharge as being controlled by groundwater levels below the soil-bedrock interface in the bedrock itself.

[22] At both hillslopes, soil pipe outlets were found along the longitudinal axis of the hollow [*Uchida et al.*, 1999, 2003a]. On the basis of the thermal response in the springs, *Uchida et al.* [2002, 2003b] showed that much of the storm runoff traveled considerable distances via subsurface lateral preferential flow paths, bypassing the saturated area around F1 or W0. These results are consistent with the measured variations in pore pressure in this study that show that hillslope discharge was more related to pore pressure dynamics at upper slope sections (F2–F3 or W2–W6), rather than downslope areas near to the spring (F1 or W0) (Table 1).

[23] At both sites, the upslope subsurface saturated area was highly correlated with the hillslope discharge during the subsurface storm flow period. This concurs with results at the Hakyuchi watershed where *Ohta* [1990] found that the outflow from an unchanneled concave hillslope was related to the upslope volume of groundwater above the bedrock interface. Similarly, at Plastic Lake-1 (PC-1), Canada, *Buttle and Turcotte* [1999] reported that hillslope discharge was strongly associated with the volume of the saturated layer above the bedrock surface. *Troch et al.* [2003] provide a conceptual framework to analyze the relationship between hillslope saturated storage and matrix flow rate. This frame-

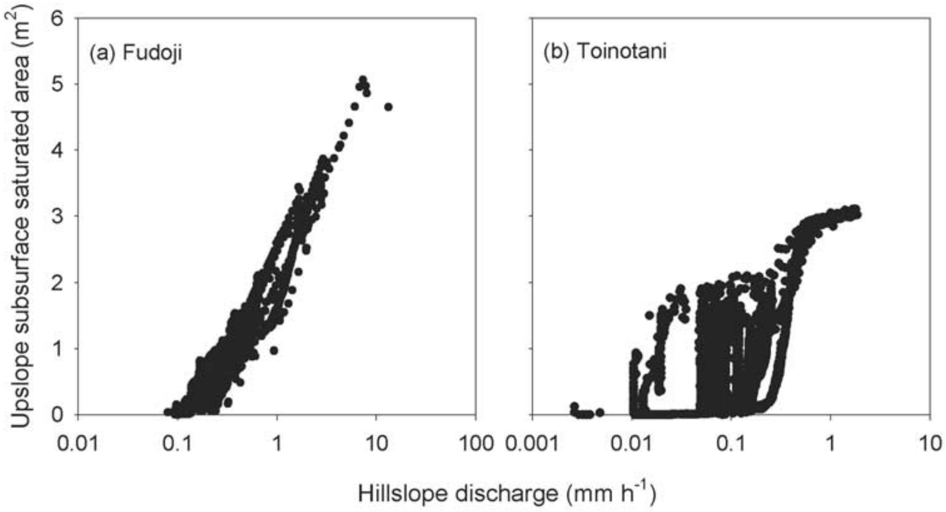

Figure 7. Relationships between hillslope discharge and subsurface saturated area at (a) Fudoji and (b) Toinotani.

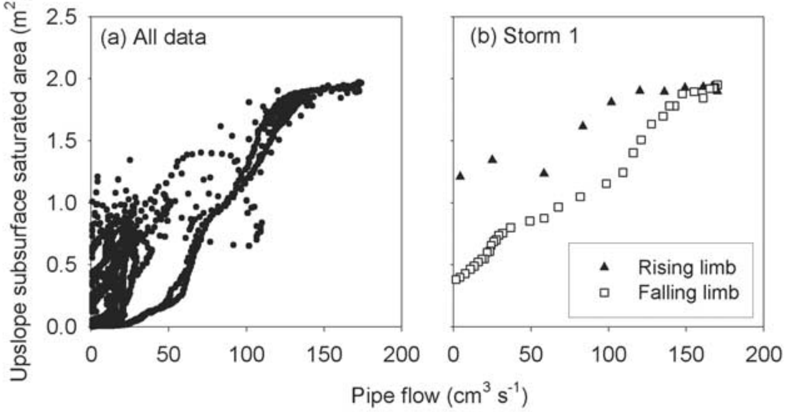

Figure 8. Measured relationships between outflow rate from pipe A at Toinotani and upslope subsurface saturated area for (a) all data and (b) storm T1.

work accounts for the effects of hillslope geometry on subsurface saturated storage and hillslope discharge. Even though their ideas may well be a new way forward for theoretical advancement of hillslope water storage and hillslope discharge dynamics, this theory does not include the relationship between hillslope water storage and the lateral preferential flow. Previous modeling work by *Barcelo and Nieber* [1981] showed that the orthogonal supply of seepage water along soil pipes is controlled by the lateral hydraulic conductivity of soil, the soil pore water pressure at surrounding soil matrix, and the area of the pipe boundary that is below the phreatic surface at the circumstance of the pipe. They also showed that the relationship between the water flux into soil pipe and the surrounding soil pore pressure was linear. These results concur with our field observations, indicating that the discharge rate of the lateral pipe flow is in fact controlled by "subsurface saturated area."

5.2. Why Was Hillslope Discharge Poorly Related to Subsurface Saturated Area at Toinotani During the Normal Slope Seepage Periods?

[24] While hillslope discharge in Fudoji was strongly associated with the subsurface saturated area during the normal slope seepage periods, hillslope discharge was not well related to subsurface saturated area during similar periods at Toinotani. We propose three possible hypotheses to explain this: (1) the lateral preferential flow was not a large contributor to hillslope runoff at this time period, (2) the lateral preferential flow path did not "hydrologically extend" to the upper hillslope, or (3) the water flux into the soil pipe could not be fully described by groundwaters level alone. To explore these relations further we focus on the relationship between pipe flow and upslope saturated area, and the effects of antecedent wetness and rainfall amounts on the relationship between the subsurface saturated area and the hillslope discharge.

[25] Figure 8a shows the relationship between the outflow from pipe A and the subsurface saturated area upslope of the pipe A outlet in Toinotani. The Spearman rank correlation coefficient between pipe flow and upslope subsurface saturated area was not high ($r = 0.66$). When measured pipe flow was less than 50 cm^3 s^{-1}, the pipe flow was even less related to the subsurface saturated area ($r = 0.37$). However, when the pipe flow was greater than 50 cm^3 s^{-1}, pipe flow rate was strongly correlated with the subsurface saturated area ($r = 0.95$). During an individual storm, the relation between the pipe flow and the subsurface saturated area showed significant hysteresis (higher subsurface saturated area for a given pipe flow on rising limb than at the same pipe flow on the falling limb) (Figure 8b). This result indicates that the pipe flow at Toinotani cannot be fully characterized by the subsurface saturated area. This finding would lend support to hypotheses 2 and 3 above.

[26] The relationship between the subsurface saturated area and hillslope discharge also showed clockwise hysteresis (Figures 9a and 9b, Table 3). When the total amounts of rainfall were greater than 60 mm, the relationship between the subsurface saturated area and the hillslope discharge on falling limb was less varied. This relation on the rising limb varied with antecedent moisture condition (lower hillslope discharge for given subsurface saturated area resulted in small initial hillslope discharge). When the total rainfall was less than 60 mm, the relation on the falling limb also showed a variety of responses (lower hillslope discharge for given subsurface saturated area in small storm than at the same subsurface saturated area in large storm). We conclude that in spite of the same subsurface saturated area, the hillslope discharge on the rising limb was related mostly to the antecedent soil moisture condition, whereas the falling limb was also related to the total rainfall (at Toinotano if total rainfall amount was less than 60 mm).

[27] *Uchida et al.* [2001] proposed a perceptual model of pipe flow where the hydrologically active area at the soil matrix-pipe interface and a hydrologically active macropore network extended as the soil wetted up and as the duration of transient saturated layer increased. These ideas were based on previously published tracer tests in Hitachi Ohta, Japan [e.g., *Tsuboyama et al.*, 1994] and hydrological observations in Japan at different sites (e.g., the Tatsunokuchi catchment by *Tani* [1997]). The relationship between hillslope discharge and subsurface saturated area in this study supports the general perceptual model of *Uchida et al.* [2001] and data presented in other Japanese studies whereby when the soil was the wettest, and the duration of the saturated layer was longest, the hydrologically active area at the soil matrix-pipe interface and the macropore network upslope was most fully extended. At this time, hillslope

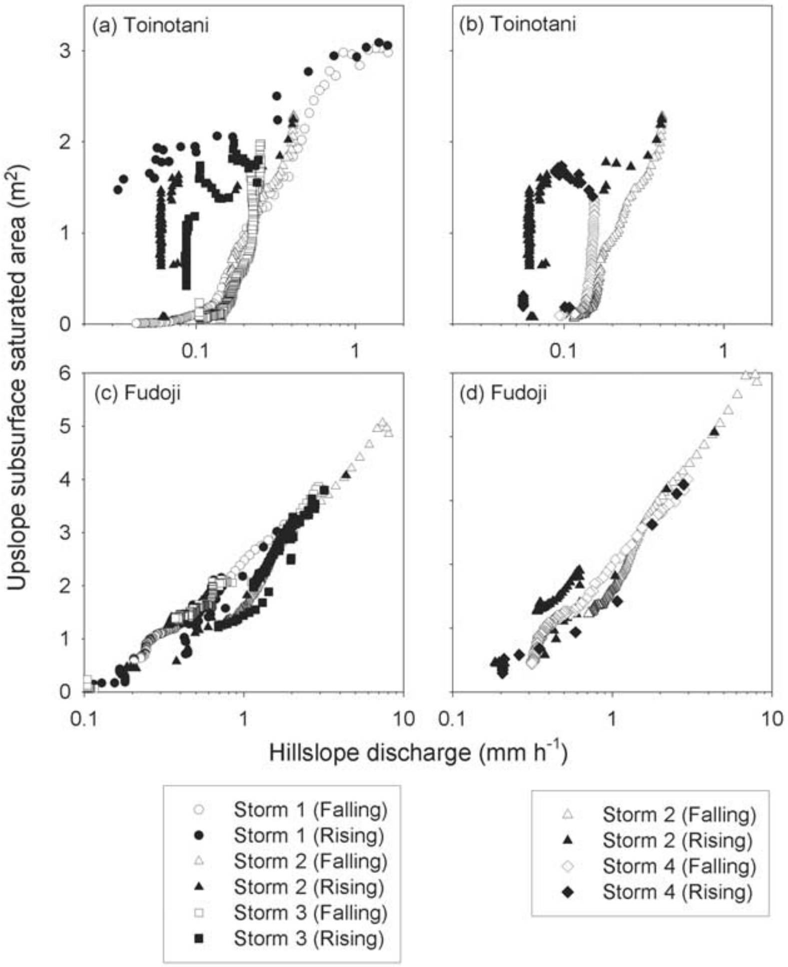

Figure 9. Measured relationships between hillslope discharge and upslope subsurface saturated area during each storm. Total rainfall amounts and prestorm hillslope discharge for each storm are listed in Table 3.

discharge was controlled mainly by the subsurface saturated area (Figure 10b, lower panel). During smaller events on relatively dry soil, the hydrologically active area at soil matrix-pipe interface and the macropore network were very limited in their upslope extent. Under these conditions, the hillslope discharge was controlled not only by a subsurface saturated area, but also by the extension of the locally hydrologically active area at soil matrix-pipe interface (Figure 10b, upper panel). Thus the correlation between the hillslope discharge and the subsurface saturated area was relatively weak at Toinotani during the normal seepage periods. This concept is also consistent with the results of recent modified TOPMODEL simulations that have shown that the extension of hydrological connectivity in hillslopes controls the stream flow rate [*Scanlon et al.*, 2000; *Stieglitz et al.*, 2003].

[28] Finally, by comparing the very different soil properties at the Fudoji and Toinotani sites, we can comment on the effect of these differences on the extension of the hydrologically active preferential flow paths (pipe flow). At Fudoji, the relationship between subsurface saturated area and the hillslope discharge was strongly linear, regardless of the antecedent soil moisture condition and the rainfall magnitude (Figures 9c and 9d). No hysteresis was apparent in this relationship (Figures 9c and 9d). These results suggest that if the hillslope is composed of highly permeable matrix material, the hydrologically active preferential flow path is easily extended (Figure 10a). If the hillslope is composed of low-permeability matrix material, as found at Toinotani, more time appears to be required for

Table 3. Characteristics of Storms

	Total Rainfall, mm	Initial Hillslope Discharge, mm hr^{-1}
	Fudoji	
Storm 1	81	0.115
Storm 2	86	0.195
Storm 3	96	0.690
Storm 4	45	0.2
	Toinotani	
Storm 1	106	0.004
Storm 2	63	0.048
Storm 3	73	0.081
Storm 4	32	0.037

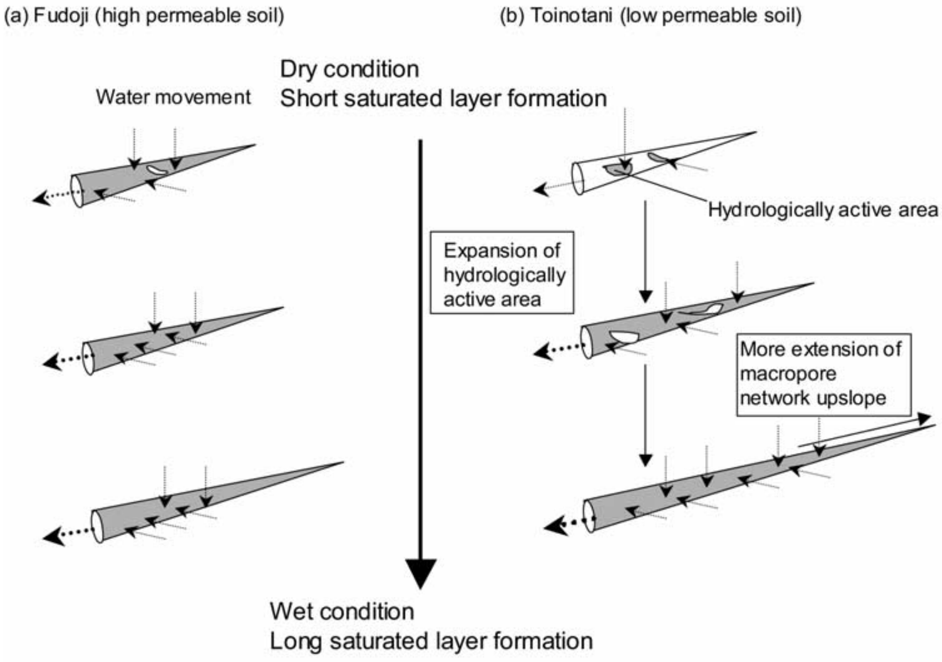

Figure 10. Schematic describing our conceptualization of the extension of the hydrologically active soil pipe at (a) Fudoji and (b) Toinotani.

the connection and upslope extension of the hydrological active preferential flow path (Figure 10b).

5.3. Pore Pressure Dynamics and Hillslope Discharge

[29] A number of studies, like ours, have reported pipe-flow dominance of hillslope subsurface flow during subsurface storm flow periods [*McDonnell*, 1990; *Montgomery and Dietrich*, 1995; *Freer et al.*, 2002]. *Montgomery and Dietrich* [1995] and *Tsuboyama et al.* [2000] showed that in low-gradient hollows, macropore flow could provide an upper limit to soil piezometric response because preferential flow would move excess water laterally downslope, preventing further rise up into the soil matrix. Our results support this concept whereby observed lateral preferential flow at Fudoji and Toinotani limited the increase in pore pressure at the lower end of each of the monitored unchanneled hollow. To the best of our knowledge, ours is the first study to present this sort of fine-time interval pore pressure data and to evaluate the correlation coefficients between different slope positions and slope base subsurface flow. We show that pore pressure and groundwater levels in areas close to hollow outlet are rather constant and poorly correlated with subsurface flow dynamics. Conversely, pore pressure and groundwater levels in areas farther upslope from the channel are rather variable and highly correlated with subsurface flow as measured at the base of each instrumented hollow.

[30] These findings are quite different to recently published findings on glacial till mantled hillslopes using recording wells and streamflow information [*Seibert et al.*, 2003]. They showed that streamflow was strongly associated with the groundwater levels in the near-stream riparian area. A number of studies conducted in nonglaciated hillslope settings, comparable to the Japanese characteristics, have also reported that there is large difference in groundwater level response between riparian and hillslope areas [e.g., *McDonnell*, 1990; *Seibert and McDonnell*, 2002]. However, in low-order streams in catchments in steep mountainous regions, the percentage of riparian area to total catchment area is often very small [*Montgomery et al.*, 1997; *Tsujimura et al.*, 1999; *McGlynn and Seibert*, 2003]. While the monitored groundwater levels in the *Seibert et al.* [2003] near-stream area varied about 1.0 m, these levels were well correlated to subsurface storm flow. Transient groundwater levels in their upslope areas (comparable to our subsurface saturated area) were not correlated with stream flow. These differences between our observations in Japan and those of *Seibert et al.* [2003] in Sweden may be controlled, first and foremost, by what lies beneath the mineral soil profile: the Swedish slopes were underlain by glacial till. Also, our analysis periods did not include the driest period where the greatest possible separation between upslope and downslope might be observed. *Seibert et al.* [2003] also included the near-stream riparian zone groundwater dynamics, while the steep hillslope study sites in this paper does not include any riparian zone positions. At both Fudoji and Toinotani, the correlation coefficients between the groundwater levels at 1.0 m point and the hillslope discharge for whole analysis period was higher (0.45 and 0.62) than for subsurface storm flow periods (0.26 and −0.08). *Seibert et al.* [2003] also showed a small variation in the groundwater level in the near-stream area, suggesting that the correlation coefficients in their subsurface storm flow periods were relatively small, if their analysis periods were stratified between different flow conditions.

6. Summary and Conclusions

[31] The relationship between the pore pressure and the hillslope discharge was examined using fine-temporal-

resolution hydrometric data (10 min interval) from two steep unchanneled concave hillslopes; one hillslope (Fudoji) covered by relatively high hydraulic conductivity sandy soil, and the other (Toinotani) covered by relatively low hydraulic conductivity clay soil. For both hillslopes, the pore pressures immediately upslope from the springs at the slope base remained almost constant and hillslope discharge was only weakly related to the pore pressure and the lateral hydraulic gradient in and around the slope base. During subsurface storm flow periods, hillslope discharge at both sites was strongly correlated with the pore pressure measured at upper hillslope positions. Hillslope discharge was strongly related to the upslope subsurface saturated area during the storm flow conditions. During the normal slope seepage periods, hillslope discharge from the highly permeable hillslope at Fudoji was related to the upslope subsurface saturated area. During this period at the low-permeability site at Toinotani, hillslope discharge was not related to the upslope subsurface saturated area. Here, the hydrologically active area at soil matrix–pipe interface and macropore network varied with soil wetness and the duration of saturated layer formation. Intersite comparison of these two sites enabled us to identify this effect soil matrix permeability has on the hydrological extension of preferential flow.

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