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The role of lateral pipe flow in hillslope runoff response: an intercomparison of non-linear hillslope response

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Abstract

The importance of lateral pipe flow on runoff generation in wet steep hillslopes has been described in many case studies from around the world. However, most hillslope studies are done in isolation and usually focus on the idiosyncrasies of individual hillslope characteristics and pipe flow response at a single site. Consequently, the first order controls on pipe flow responses remain poorly understood. We present a new intercomparison of pipe flow response to storm rainfall at four well instrumented sites: Panola (Georgia, USA), Toinotani (Kyoto, Japan), Jozankei (Hokkaido, Japan) and Hakyuchi (Tokyo, Japan). Our objective was to minimize the complexities of lateral pipe flow on hillslopes by looking for commonality across different hillslope types. Despite the large differences between the study sites in topography, climate, soil type and soil matrix hydraulic conductivity, we found several common pipe flow responses to storm rainfall: (1) the relationship between total rainfall amount and total pipe flow volume was highly non-linear at each site, (2) initiation of measurable pipe flow was threshold-dependent, controlled by the total rainfall amount and the pre-storm wetness, (3) once significant pipe flow response occurred, the maximum pipe flow rate was sensitive to the measured rainfall intensity, and (4) the ratio of total pipe flow to total hillslope discharge for each site was constant, regardless of total rainfall amount once the precipitation threshold for significant pipe flow response was reached. We used these results to develop a decision tree to determine the general conditions necessary for significant pipe flow to occur. The controls derived from our comparisons agree largely with the controls reported by the previous individual hillslope pipe flow studies in the literature. The commonality of response between our four very different forested hillslope settings indicates that site intercomparison may be effective for extracting common first order controls on

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complex hillslope processes. We argue that a decision tree may be a useful organizational framework to summarize and organize comparative analyses and may provide a structure for defining the hierarchy of process controls necessary for model development.

Keywords: Pipe flow; Non-linear hydrologic response; Decision tree; Forested hillslopes; Site intercomparison

1. Introduction

There have been many observational studies of hillslope discharge from a variety of experimental hillslopes worldwide since the pioneering work of Whipkey (1965) (e.g. Dunne and Black, 1970; Mosley, 1979; Tsukamoto and Ohta, 1988; McDonnell, 1990; Woods and Rowe, 1996; Tani, 1997; Buttle and Turcotte, 1999; Hutchinson and Moore, 2000; Uchida et al., 2003). These and other studies (reviewed in Bonell, 1993, 1998) have demonstrated specific triggers for the occurrence of subsurface stormflow, including transmissivity feedback (Rodhe, 1989; Seibert et al., 2003), flow through weathered bedrock (Montgomery et al., 1997; Onda et al., 2001), kinematic wave routing (Williams et al., 2002) and flow through discrete soil pipes (Jones, 1987; Uchida et al., 2002). This later observation of flow through discrete soil pipes is perhaps the most common observation for rapid subsurface stormflow delivery on steep wet hillslopes (Bonell, 1998). This type of flow is most prevalent at the soil–bedrock interface or at an impeding layer within the soil profile (Sidle et al., 2000; Koyama and Okumura, 2002).

Previous studies at individual field sites have revealed much about the mechanisms and role of pipe flow on hillslope discharge at specific locales (e.g. Jones and Crane, 1984; Roberge and Plamondon, 1987; Carey and Woo, 2000). However, the generalizabiliy of these findings has not been tested. For example, Kitahara and his colleagues (Kitahara and Nakai, 1992; Kitahara et al., 1994) examined the relationship between lateral pipe flow and total hillslope discharge at Jozankei, Hokkaido in Japan. They found that the ratio of pipe flow to total hillslope discharge for each storm increased with an increase in total amount of rainfall, for total rainfall amounts less than 20 mm. They observed a hysteretic relationship between pipe flow and total hillslope discharge for the rising and falling limb of the subsurface stormflow hydrograph. While these results are important and novel, no other pipe flow studies have been compared to the Jozankei hillslope findings to see if these relations are generalizable. Indeed, most hillslope studies are done in isolation and usually focus on the idiosyncrasies of individual hillslope characteristics and pipe flow response. While we acknowledge that the pipe flow studies reporting peculiarities of pipe flow at particular hillslopes have yielded important and useful information on pipe morphology (e.g. Terajima et al., 2000), hydraulics (e.g. Kitahara, 1989), biogeochemistry (Burns et al., 1998) and pipe flow in relation to general hillslope hydrology (e.g. Uchida et al., 1999), few studies have compared pipe flow responses at different study sites with the goal to seek an understanding of commonalities of pipe flow behaviors across diverse settings.

It has been difficult to derive general hydrologic principles from single research studies at intensively studied small basins (Jones and Swanson, 2001; Kirchner, 2003; Sivapalan, 2003). We believe that comparing different sites will allow us to extract commonalities or major differences between sites and help us define the first order controls on subsurface flow and lateral pipe flow. This paper builds upon the philosophical approach of Freer et al. (1997) and Uchida et al. (2004) where inter-site comparison is used to explore the first order controls on hillslope hydrology. Here we focus on the intercomparison of the phenomenological responses of pipe flow.

Intercomparison requires some sort of organizational framework to summarize and evaluate the comparative analyses. Scherrer and Neaf (2003) proposed a decision tree to define the dominant hydrological flow processes on a variety of grassland sites in Switzerland. They showed, rather convincingly, that the decision tree approach can be a powerful tool to clarify the first-order controls on dominant runoff processes. We build on ideas reported in Scherrer and Neaf (2003) and use the decision tree approach to organize our 'new knowledge' gained from the intercomparison in this paper.

The decision tree approach is not new to pipe flow hydrology. Indeed, Wilson and Smart (1984), Jones (1987) and Jones and Connelly (2002) proposed decision trees as a way to describe pipe flow response at their individual sites. While these studies showed that the decision tree approach was a useful tool for clarifying the pipe flow response, the decision tree approach has not been used for organizing 'knowledge' about pipe flow response at several different hillslopes in different climate and geological settings. The early decision tree approaches were exclusively for pipe flow response at a single site. The objective of this study is to quantify the first order controls on pipe flow generation using a decision tree that can be applied to many different hillslopes at different locations. Here we compare four well instrumented but very different sites, Panola (Georgia, USA), Toinotani (Kyoto, Japan), Jozankei (Hokkaido, Japan) and Hakyuchi (Tokyo, Japan), for which data from many storms ($n=16$–147) are available. Data from Jozankei and Hakyuchi were based largely on the data in the literature by Kitahara et al. (1994) and Ohta et al. (1983), respectively. Detailed results of subsurface flow in Panola and Toinotani are from Tromp-van Meerveld and McDonnell (in review) and Uchida et al. (1999), respectively. The slopes are remarkably different in soil type, soil matrix saturated conductivity, steepness and climate. Two hillslopes (Panola and Jozankei) are side slopes of first-order streams and two of the slopes (Toinotani and Hakyuchi) are concave headwater hollows. All slopes are very well instrumented and total hillslope discharge and lateral pipe flow are measured individually and recorded via lateral trenching (except Toinotani). These data provide us the ability to relate pipe flow at each site directly to the internal hillslope properties. Here we address the following questions:

How does rainfall amount and peak rainfall intensity influence pipe flow volume and peak pipe flow rate?

What is the relationship between total hillslope discharge and lateral pipe flow at the hillslope scale?

What parameter set determines whether or not pipe flow occurs and explains most of the observed variation in total hillslope discharge and pipe flow partitioning?

2. Study sites and methods

2.1. Panola

The Panola hillslope is located in the Panola Mountain Research Watershed, about 25 km southeast of Atlanta, GA. The climate is humid and subtropical with a mean annual air temperature of 16.3 °C and mean annual precipitation of 1240 mm (NOAA, 1991). Rainfall tends to be of long duration and low intensity in winter, associated with the passage of fronts. Summer rainfall is often of short duration but high intensity, associated with convective thunderstorms. Annual stream yield from the 41-ha catchment, in which the study hillslope is located, varies from 8 to 50% of precipitation (following analysis of Peters et al. (2000) for the period 1986–1999). Soils on the study hillslope are light colored sandy loam soils with little textural differences. The upper 0.15 m of the soil profile is humus rich. There are no observable differences in soil type across the study hillslope. Soil depths on the study hillslope range from 0 to 1.86 m and average 0.63 m. Soil saturated conductivity measured in large (0.30×0.45 m) intact soil cores extracted from an adjacent hillslope (at 0.30 m depth) is 644 mm/h (McIntosh et al., 1999). The 20 m long trench is located 30 m upslope from an ephemeral stream channel (Fig. 1(a)). The slope of the study hillslope is 13°. The trench is divided into 10, 2-m sections along the bedrock surface. Subsurface storm flow from these 10 sections emanates primarily from the soil matrix and is referred to as 'matrix flow'. However, some smaller spots of preferential flow at the soil bedrock interface have been observed during storms. Flow is also measured from five individual natural soil pipes on the trench face, referred to hereafter as 'pipe flow'. The individual natural soil pipes are located between 0.6 and 0.9 m below the soil surface (Fig. 2(a); Freer et al., 2002). The outer part of the pipes is formed by root bark, indicating that these pipes are former root channels from the oak and hickory forest stands above ground. The observed pipes have diameters that vary

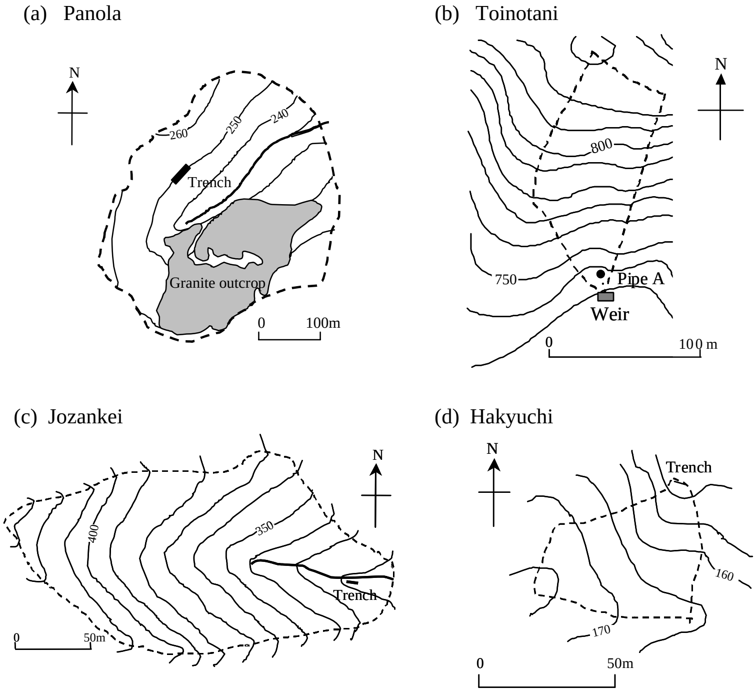

Fig. 1. Maps of (a) Panola, (b) Toinotani, (c) Jozankei and (d) Hakyuchi. Maps for Jozankei and Hakyuchi were compiled from Kitahara et al. (1994) and Ohta et al. (1983), respectively.

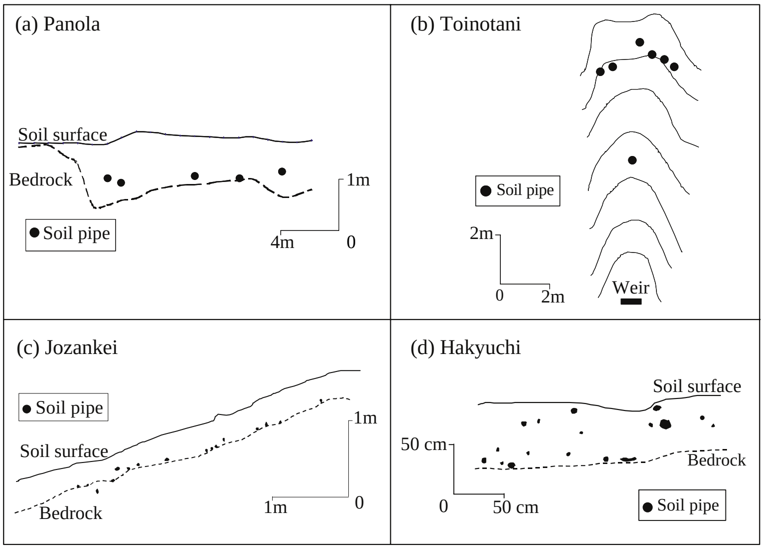

Fig. 2. Soil pipe distribution at the trench face at (a) Panola, (b) Toinotani, (c) Jozankei and (d) Hakyuchi. Soil pipe distribution in (b) are at the lower end of Toinotani. Contour intervals are 1 m. Maps for Jozankei and Hakyuchi were compiled from Kitahara et al. (1994) and Ohta et al. (1983), respectively.

from about 10–60 mm. The total of pipe flow and matrix flow is termed 'hillslope discharge'. Trench outflow from each 2-m wide section and the soil pipes is collected in continuously recording tipping bucket gauges. Additional details of the Panola trench hillslope are presented elsewhere (McDonnell et al., 1996; Freer et al., 1998, 2002; Burns et al., 1998).

2.2. Toinotani

Toinotani is a zero-order watershed located in the northeastern part of the Kyoto Prefecture in the central part of Japan. The catchment is underlain by Paleozoic sedimentary rock, has an area of 0.64 ha and a mean gradient of 36° (Fig. 1(b)). The vegetation consists of a closed secondary forest. The mean annual precipitation is 2885 mm, 30% of which falls as snow. The mean annual runoff in Kamitani Watershed in Kyoto University Forest in Ashiu (adjacent to Toinotani) is 2448 mm (Nakashima and Fukushima, 1994). The soil depth along the axis of the monitored concave hillslope section ranges from 0.2 to 0.8 m. Soils are predominantly brown forest soil. Matrix saturated conductivity and porosity at the depth of soil pipe formation are about 0.23 mm/h and 29%, respectively (Michihata et al., 2001). One surface outlet of a natural soil pipe is observed at 6 m upslope from the weir and six others at about 10 m upslope (Fig. 2(b), Uchida et al., 1999). The outflow of the lowest soil pipe and two of the upper pipes are directed to a 500 cm^3 tipping bucket and measured at 10 min intervals. Fresh bedrock is exposed at the lower portions of the small watershed. At Toinotani, an artificial trench has not been excavated, which is different from other three sites. Since the previous studies in Toinotani reported that the runoff characteristics of pipe flow were changed after a sediment discharge event from the lowest pipe (Uchida et al., 1999), this study used only data after the sediment discharge from the lowest pipe, i.e. after 1994. After the sediment discharge, only two storms produced pipe flow at upper soil pipes. Thus, in this paper, we focus on pipe flow characteristics of the lowest pipe.

The rate of hillslope discharge is measured using a V-notch weir and a water level recorder installed just below the exposed bedrock. The diameters of soil pipes are around 50 mm (as reported by Uchida et al., 1999). Additional details of the Toinotani Experimental Watershed are presented elsewhere (Uchida et al., 1999, 2002; Michihata et al., 2001).

2.3. Jozankei

Jozankei Experimental Watershed is a first-order watershed located in Hokkaido, the northern main island of Japan. The catchment is underlain by schist bedrock, has an area of 2.01 ha and a mean gradient of 37° (Fig. 1(c)). The vegetation consists of a closed natural forest. The mean annual precipitation is 1253 mm, 40% of which falls as snow. The mean annual runoff is 845 mm (Terajima, 2002). The soil depth to the bedrock at the trench face ranges from 0.4 to 0.5 m. Soils are predominantly brown forest soils. The average saturated hydraulic conductivity of the A horizon (0–0.3 m) is 3600 mm/h. Measured saturated hydraulic conductivities below the A horizon range between 3.6 and 360 mm/h (Terajima, 2002). A trench 5 m in length is located along a perennial first-order stream channel (Kitahara and Nakai, 1992). Kitahara and his colleagues report 18 soil pipe outlets at the trench (Fig. 2(c)) and measured the total volume of outflow from the 18 soil pipes using tipping buckets at 10 min intervals. Total hillslope discharge from the trench face is also measured at 10 min intervals (Kitahara et al., 1994). Seventeen of the 18 soil pipe outlets are located immediately above the soil-bedrock interface. The diameters of soil pipe outlets range from 8 to 21 mm (Kitahara, 1994). Additional details of the Jozankei Experimental Watershed are presented elsewhere (Kitahara and Nakai, 1992; Kitahara et al., 1994; Kitahara, 1994; Terajima, 2002).

2.4. Hakyuchi

Hakyuchi Experimental Watershed is a zero-order watershed located in the western part of the Tokyo Prefecture in the eastern part of Japan. The catchment is underlain by Pliocene clay and clayey-gravel deposits. The Hakyuchi hillslope has an area of 0.178 ha and a mean gradient of 27° (Fig. 1(d)). The soil depth to the bedrock along at the base of the zero-order watershed is about 0.7 m (Tsukamoto et al., 1982). Soils are predominantly forest soil and clay loam. The average saturated hydraulic conductivities of the forest soil (0–0.5 m depths from soil surface) and clay loam, which underlies the forest soil, are

3600 and 36–360 mm/h, respectively (Tsukamoto and Ohta, 1988). A trench 2.5 m in length was excavated to bedrock at the lower end of the zero order basin (Tsukamoto et al., 1982). Tsukamoto, Ohta and their colleagues report 18 soil pipe outlets at the trench (Fig. 2(d)) and measured outflow volume from 10 of the 18 soil pipes using tipping bucket at 10 min intervals (Ohta et al., 1983). They also measured the volume of total hillslope discharge from the trench face (Ohta et al., 1983). Eight soil pipe outlets are located within 0.2 m above the soil-bedrock interface; others are located between 0.1 and 0.4 m below the soil surface. The diameters of soil pipe outlets range from 10 to 200 mm (Ohta et al., 1983). Additional details of the Hakyuchi Experimental Watershed are presented elsewhere (Ohta et al., 1983; Tsukamoto et al., 1982, 1988; Tsukamoto and Ohta, 1988).

2.5. Intercomparison of datasets

We used data from the Panola hillslope from the period February 19th 1996 to May 10th 1998 (Tromp-van Meerveld and McDonnell, in review). The total number of storms in this dataset was 147. However, measurable pipe flow was observed during only 50 of the 147 storms. We also used TDR data from an adjacent hillslope at 0.7 m depth to characterize pre-storm wetness. For Toinotani we used data from June 25th to November 27th 1995 and from April 26th to November 26th 1996 (Uchida et al., 1999), with hillslope discharge data available only after September 14th 1995. The number of storms in this dataset was 75. We also used data from four tensiometers, which were called W1, W2 W4 and W6 by Uchida et al. (2002), to characterize the pre-storm wetness at Toinotani. These tensiometers measured soil pore pressure at the soil-bedrock interface (0.42–0.82 m depth) along the longitudinal axis of the bedrock hollow between the perennial spring and a point 10 m upslope from the spring.

The datasets for total rainfall amount, total pipe flow and total hillslope discharge at Jozankei and Hakyuchi come from Table 1 of Kitahara et al. (1994, p. 13) and Table 1 of Ohta et al. (1983, p. 460), respectively. The number of storms for the Jozankei and the Hakyuchi dataset was 19 and 16, respectively. Since the length of the trench face at the four study hillslopes varied (2.5–20 m), we divided the volume of hillslope discharge and pipe flow (expressed in liters) by the length of the trench (expressed in meters), i.e. L/m. The length of the trenches had an impact on the results of the measurements, since the hydrological behaviors varied spatially (e.g. as seen in Williams and Bonell, 1988). We assumed that since these trenches are relatively long in comparison to soil pits (e.g. 20 m wide at Panola) that these trenches are capturing at least some of the spatial variability in pipe flow. We have discussed these issues in previous papers (see for example Freer et al. 2002).

The ratio of the measured pipe flow rate to the measured total hillslope discharge at Hakyuchi ranged between 85.5 and 99.5% (Ohta et al., 1983). Therefore, we assumed that the contribution of pipes in and around the trench face that were not individually measured (and not included in Ohta et al. (1983) data) could be ignored. At Toinotani, soil pipes from which flow was not measured directly, were connected to a water sampler to indicate the presence of water flow. These observations showed that only two storms produced outflow at these soil pipes (Uchida et al., 1999).

3. Results

3.1. Rainfall amount and intensity effects on pipe flow

The relationships between total rainfall and total pipe flow were strongly non-linear for each study hillslope, except for Hakyuchi (Fig. 3). There were not enough storms in the Hakyuchi dataset to examine the occurrence of a non-linear relationships (Fig. 3(d)), but when the rainfall amount was smaller than 20 mm, the total amount of pipe flow was very small, suggesting that the relationship between total rainfall and total flow from soil pipes in Hakyuchi may be non-linear. Significant pipe flow occurred only during storms with total storm precipitation larger than a local total rainfall threshold. These threshold rainfall amounts for Panola and Toinotani were about 55 and 35 mm, respectively. There were not enough storms in the Jozankei dataset to clearly determine this threshold (Fig. 3(c)). However, under small storms (total rainfall amount less than 15 mm), the total amount of pipe flow was very small (Fig. 3(c)), suggesting that this threshold was

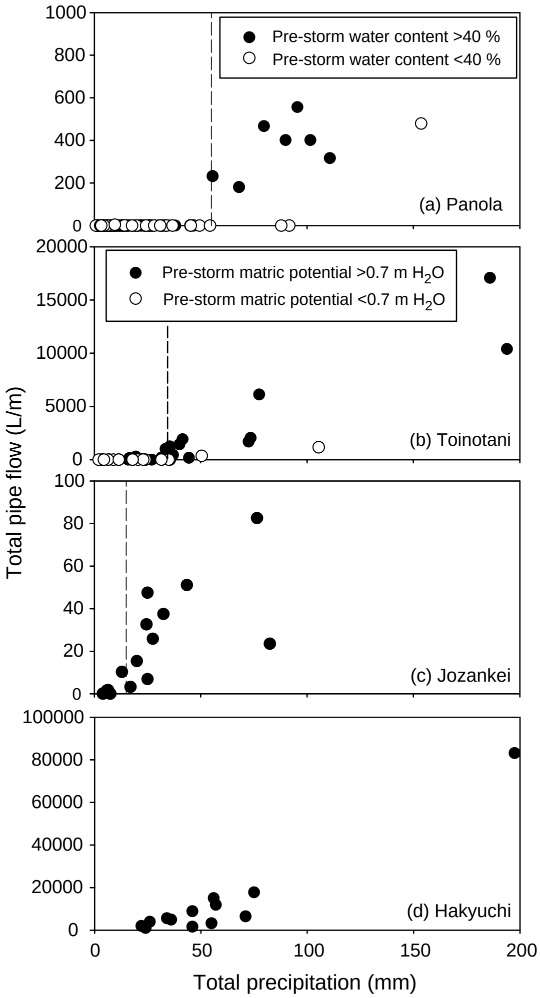

Fig. 3. Relationship between total precipitation and total pipe flow for each storm at (a) Panola (b) Toinotani (c) Jozankei and (d) Hakyuchi. Data for Jozankei and Hakyuchi compiled from Kitahara et al. (1994) and Ohta et al. (1983), respectively. Plots for Panola and Toinotani are classified into two antecedent wetness groups, based on the pre-storm volumetric water content and matric potential, respectively. Broken lines represent the threshold rainfall amounts for significant pipe flow occurrence.

somewhere around 10–20 mm at Jozankei. At all sites, once the total rainfall amount had exceeded the local threshold amount, total pipe flow increased linearly with an increase of total rainfall amount.

TDR data at Panola and tensiometer data at Toinotani facilitated a further refinement of the threshold, based on both total storm precipitation and pre-storm wetness (as defined by the soil matrix volumetric water content or tension). Fig. 4(a) shows that when the pre-storm volumetric soil moisture content at Panola was larger than 40%, the storms larger than 55 mm produced significant pipe flow (>5 L/m). When pre-storm volumetric soil moisture content was smaller than 40%, more than 55 mm of precipitation was necessary to produce significant pipe flow. At Toinotani, when the pre-storm soil matric potential was larger than −0.4 m H_2O, four out of the eight medium size storms (35–50 mm) produced significant pipe flow (>500 L/m). However, when the pre-storm soil matric potential was smaller than −0.4 m H_2O, medium size storms did not produce significant pipe flow (Fig. 4(b)). These results suggest that for both hillslopes, the pre-storm wetness affects the rainfall threshold amount for significant pipe flow occurrence.

Finally, we found a significant difference in the absolute amount of pipe flow per trench length between the side slope sites (Panola and Jozankei) and the hollow sites (Hakyuchi and Toinotani). For example, when the total rainfall amount was about 70 mm, total pipe flow at the side slope sites ranged from 25 to 250 L/m, while that of the hollow sites ranged between 1800 and 18,000 L/m.

3.2. Precipitation intensity effects on maximum pipe flow rate

At Toinotani, the peak pipe flow was related to the peak rainfall intensity, regardless of antecedent wetness conditions. At Panola, some storms with a high peak rainfall intensity (>20 mm/h) did not produce significant pipe flow, suggesting that the peak rainfall intensity alone did not control pipe flow occurrence (Fig. 5(a)). When the peak pipe flow was larger than 1.0 L/h/m, peak pipe flow was associated with the peak rainfall intensity. These results suggest that when total rainfall amount was large enough to initiate significant pipe flow, peak pipe flow rate was sensitive to the peak rainfall intensity.

3.3. Pipe flow as a component of total hillslope discharge

We observed a strong linear relation between storm total hillslope discharge and storm total pipe flow (Fig. 6). At Hakyuchi, the relationship between total pipe flow and total hillslope discharge was close to

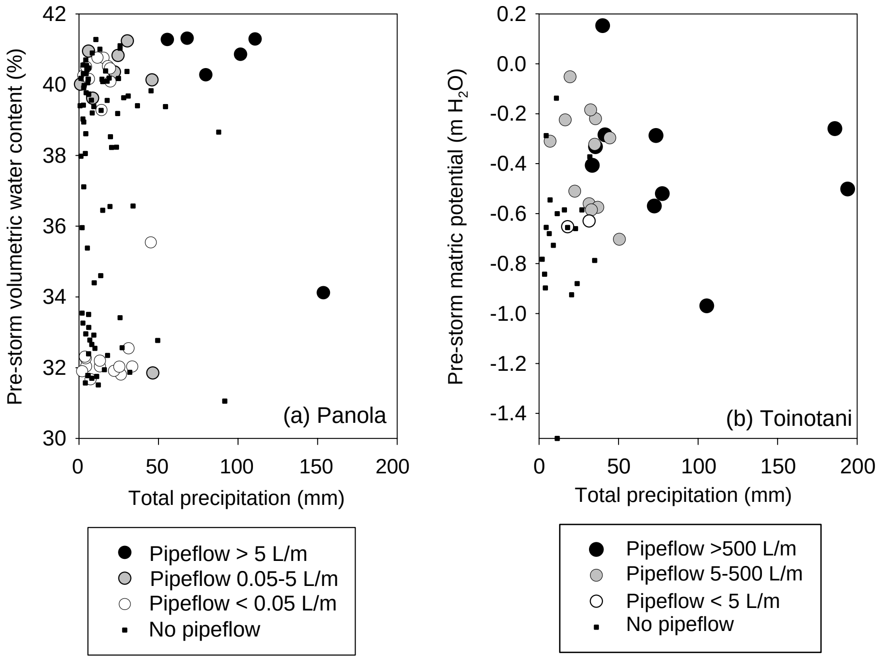

Fig. 4. Relationships between total precipitation, total pipe flow and pre-storm volumetric water content at (a) Panola, and pre-storm matric potential and (b) Toinotani, respectively.

1:1, indicating that pipe flow was the dominant contributor to total hillslope discharge. Data from Toinotani showed a clear threshold of total hillslope discharge necessary before significant pipe flow occurred. When the total hillslope discharge at Toinotani was smaller than 10,000 L/m, total pipe flow was close to zero. When the total hillslope discharge was greater than 10,000 L/m, there was a linear relation between total hillslope discharge and total pipe flow, similar to the other sites.

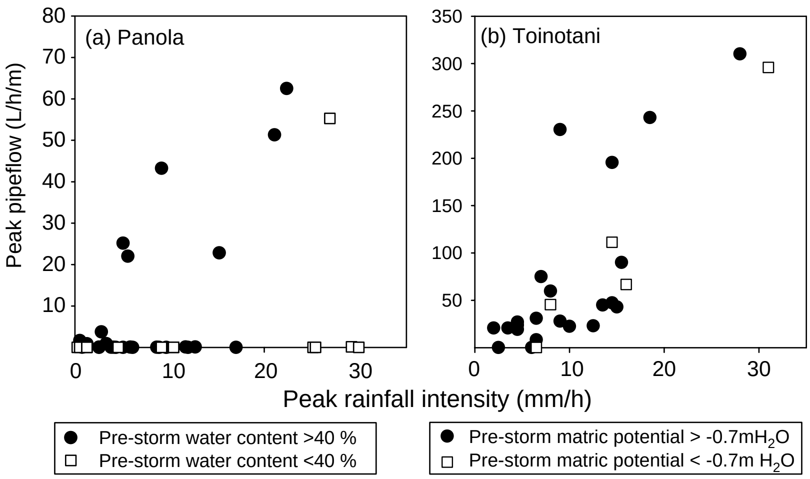

Fig. 5. Relationships between peak hourly rainfall intensity and peak hourly pipe flow rate for storms that produced measurable pipe flow at (a) Panola, and (b) Toinotani.

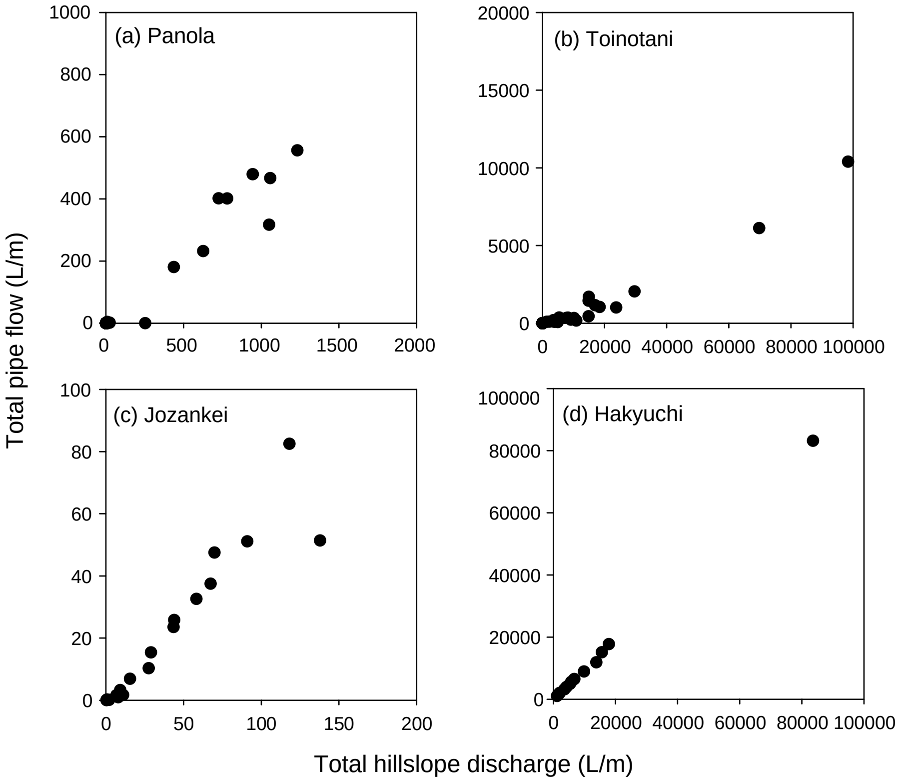

Fig. 6. Relationship between total hillslope discharge and total pipe flow of each storm at (a) Panola, (b) Toinotani, (c) Jozankei, and (d) Hakyuchi. Data for Jozankei and Hakyuchi compiled from Kitahara et al. (1994) and Ohta et al. (1981), respectively.

For storms larger than the precipitation threshold for significant pipe flow to occur, the ratio of pipe flow to total hillslope discharge was almost constant at Jozankei and Hakyuchi (Fig. 7(c) and (d)). At Panola, when the total rainfall amount was large enough for significant pipe flow initiation and the pre-storm volumetric water content was larger than 40%, the ratio of pipe flow to total hillslope discharge was also constant (Fig. 7(a)). At Toinotani, except for two relatively small storms (total rainfall amounts were smaller than 50 mm), the ratio of pipe flow to total hillslope discharge for the storm larger than the precipitation threshold was around 0.1. Precipitation thresholds for significant hillslope flow initiation at Panola, Toinotani and Jozankei were about 55, 40 and 10–20 mm, respectively (see Fig. 3). There were not enough small storms in the data from Hakyuchi to analyze this trend or to estimate the threshold rainfall amount. For storms smaller than the local threshold at Jozankei and Toinotani, the ratio of the pipe flow to hillslope discharge usually increased with increasing storm size. At Panola there was much more variation in this ratio for storms smaller than the precipitation threshold (Fig. 7(a)).

One might expect that at each site the difference between total hillslope discharge and measured pipe flow is due to overland flow and matrix flow. Previous studies on these four hillslopes indicated that the contributions of overland flow to hillslope discharge were negligible (Freer et al., 1998; Uchida et al., 2002; Kitahara and Nakai, 1992; Ohta, 1990). These results indicated that there were linear relations between pipe flow and matrix flow, regardless of antecedent wetness and total rainfall amounts for storms larger than the precipitation threshold, since there were linear relations between pipe flow and total hillslope discharge for storms larger than the precipitation threshold (Fig. 6). In this paper, ‘matrix flow’

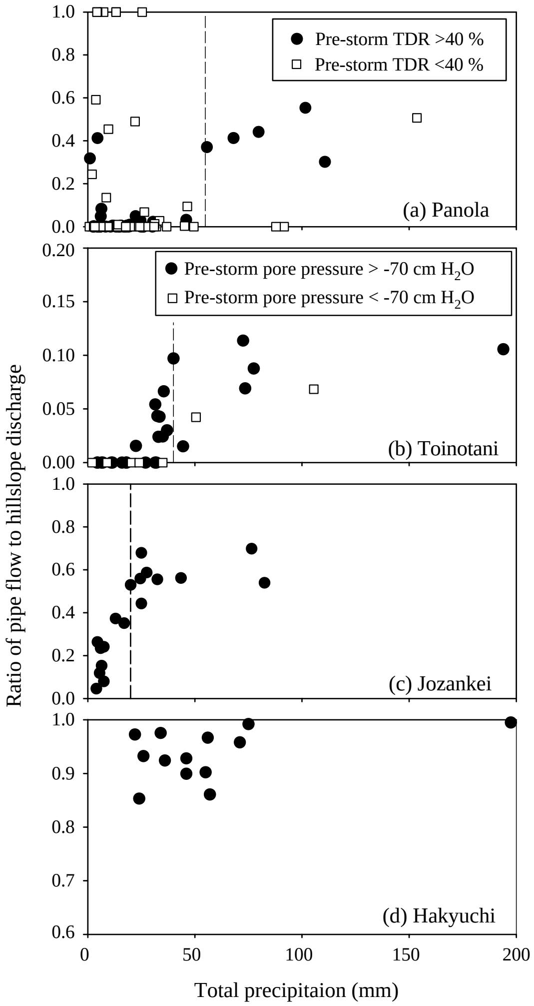

Fig. 7. Relationship between total precipitation and the ratio of total pipe flow to total hillslope discharge of each storm at (a) Panola, (b) Toinotani, (c) Jozankei, and (d) Hakyuchi. Data for Jozankei and Hakyuchi compiled from Kitahara et al. (1994) and Ohta et al. (1981), respectively. Plots for Panola and Toinotani are grouped into two classes, based on the pre-storm volumetric water content and matric potential, respectively. Broken lines represent the threshold rainfall amounts for significant pipe flow occurrence.

included the flow through the relatively small macropores and/or mesopores (e.g. Beven and Germann, 1982), which were not individually measured but contributed to total hillslope discharge.

During storms, the relation between pipe flow and total subsurface storm flow showed some hysteresis (higher pipe flow for a given hillslope discharge on the rising limb than for the same hillslope discharge on the falling limb) (Fig. 8). We should note that hysteresis at Jozankei was reported by Kitahara et al. (1994). At very high subsurface stormflow rates (very intense and large storms), data from Toinotani showed that pipe flow was asymptotic, with a peak maximum pipe flow rate of 325 L/m/h. At that point, pipe flow and total hillslope discharge became decoupled, i.e. total hillslope discharge increased while pipe flow remained at a constant maximum flow rate (Fig. 8). Only the two largest storms produced this relationship in Toinotani. During both of these storms additional pipe flow occurred at the soil pipes located 10 m upslope from the weir (Uchida et al., 1999). This asymptotic pipe flow curve was not observed at Panola. Reasons for not observing this at Panola may include (1) there were no storms large and intense enough in the Panola database to show this maximum pipe flow rate, and/or (2) a maximum drainage capacity for pipe flow does not exist at Panola. We do not have data to check if a limiting maximum pipe flow rate exists at Jozankei or Hakyuchi. Even though total hillslope discharge became unrelated to the pipe flow during the peak runoff of the two largest storms at Toinotani, there was only a small difference in the ratio of total pipe flow to total hillslope discharge between these two largest storms and the other large storms in the dataset. This suggests that the maximum drainage capacity of the soil pipe had a small impact on the ratio of total pipe flow to total hillslope discharge. Our explanation for this is that the period for which pipe flow reached its limiting capacity (and pipe flow rate was unrelated to total hillslope drainage) was relatively short (<2 h) compared to the total length of the storm.

4. Discussion

While some previous pipeflow studies have amassed large numbers of storms in their analyses (e.g. the many papers of Jones and colleagues that have examined hundreds of storms at their sites in Wales) and the 66 storms analyzed by Gilman and Newson (1980), the vast majority of studies to date have been based on a small number of storms and storm sizes. This study draws upon a large number of storms from our four sites (from a low of 16 at

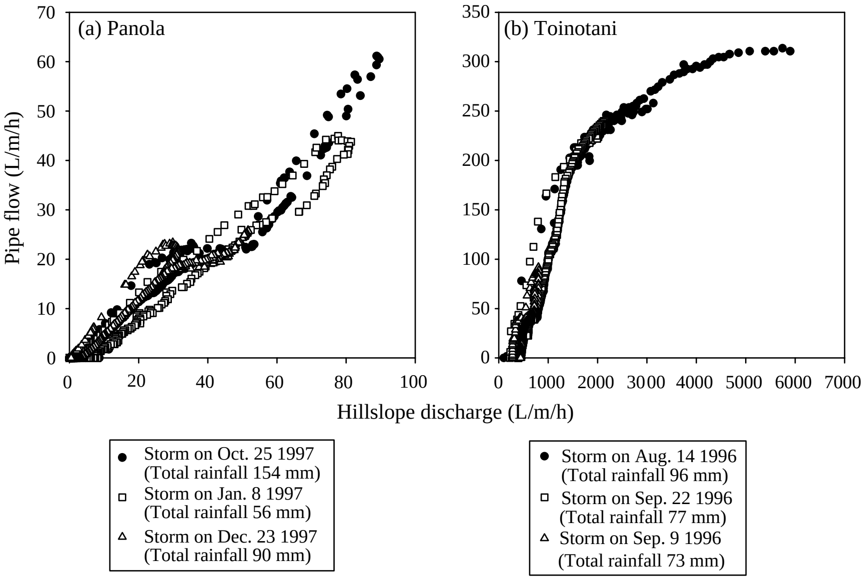

Fig. 8. Relationship between hillslope discharge and pipe flow during single storms at (a) Panola and (b) Toinotani.

Hakyuchi to 147 storms at Panola). Below, we distil some of the dominant controls common to our sites. While we could include myriad details on what is different between our sites, we rather focus on what is similar for controlling pipe flow initiation. This is in keeping with our philosophy that looking for what is similar may be one pathway forward in resolving the first order controls on subsurface flow and lateral pipe flow.

4.1. A decision tree for defining the first-order controls on pipe flow initiation

Our comparison of the four experimental hillslopes in the USA and Japan showed that pipe flow is a large and significant contributor to subsurface stormflow, despite the large differences between sites in topography (side slope vs. head hollow), slope, upslope drainage area, climate, soil pipe geometry and density, and soil matrix saturated hydraulic conductivity. Hillslope total discharge response at each study hillslope was strongly related to pipe flow response. At all sites (although for Hakyuchi this was not clear), the relationship between total rainfall amount and total pipe flow volume was clearly non-linear and threshold-like. The occurrence of significant pipe flow at a given site could be described largely by total rainfall amount and pre-storm wetness. We argue that this demonstrates that total rainfall amount and pre-storm wetness are first-order controls on pipe flow response at any given site.

Once significant pipe flow occurred, the maximum pipe flow rate was affected by the maximum rainfall intensity. We argue therefore that this demonstrates that the rainfall intensity is a second-order control on observed pipe flow response. However, when the pipe flow rate reached the maximum drainage capacity (at Toinotani), pipe flow was no longer influenced by short-term changes in rainfall intensity.

The ratio of pipe flow to hillslope discharge was also related to the occurrence of significant pipe flow response. When the total rainfall amounts were large enough to produce significant pipe flow (i.e. larger than the precipitation threshold), the ratio of pipe flow to total hillslope discharge was almost constant. But, when the total rainfall amount was smaller than the precipitation threshold and significant pipe flow response was not produced, the ratio of the pipe flow to hillslope discharge was dependent on both total rainfall amount and pre-storm wetness and was, overall, more variable.

So how can we organize these observations? We argue that a decision tree may be a useful way to define the hierarchy of controls on lateral pipe flow

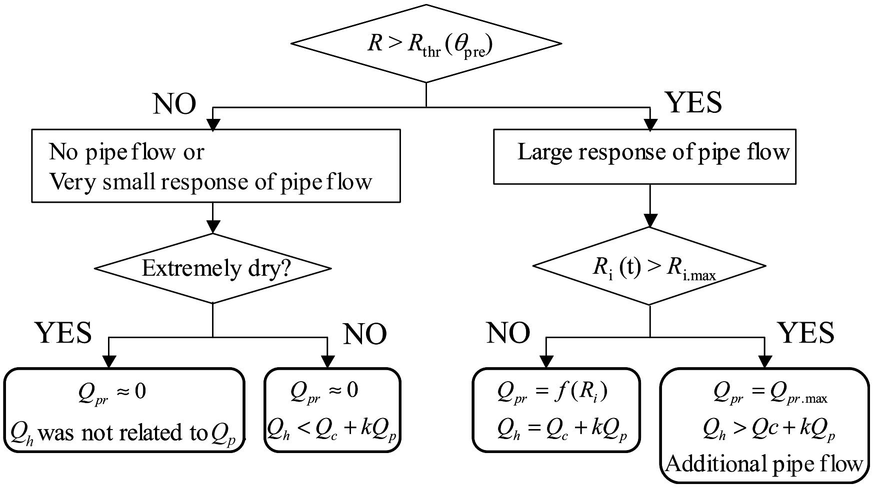

Fig. 9. Decision tree for pipe flow rate and the relationship between pipe flow and hillslope discharge. Symbol R represents total rainfall amount, R_{thr} the threshold total rainfall amounts for pipe flow occurrence and θ_{pre} the antecedent moisture conditions. R_i represents the rainfall intensity and $R_{i.max}$ represents the rainfall intensity that for which the maximum drainage capacity (Q_{prmax}) is reached. Q_{pr} represents the peak pipe flow rate, Q_p represents total pipe flow amount, Q_h represents total hillslope discharge and Q_c represents the minimum hillslope discharge before pipe flow occurs. The k represents the partitioning coefficient between pipe flow and hillslope discharge for storms larger than the precipitation threshold (R_{thr}). The f represents a function between rainfall intensity R_i and peak pipe flow rate (Q_{pr}).

initiation. Given the complexities and idiosyncrasies of each site in our analysis, a decision tree may describe simply, the measurable controls on pipe flow derived from available data and process understanding. It may be a useful organizational framework to summarize and organize the results from this comparative analysis and to help formulate a hierarchy of controls necessary for model development. Fig. 9 shows a decision tree describing pipe flow response and hillslope discharge at the sites described in this study.

Threshold rainfall amounts for significant pipe flow to occur have been reported in a number of studies. Ziemer and Albright (1987), McDonnell (1990) and Luxmoore et al. (1990) reported that ephemeral pipes required some initial rainfall before they began to flow. Wilson et al. (1990) and Sidle et al. (2000)showed that pipe flow was more likely to occur under wet antecedent conditions. Tromp-van Meerveld and McDonnell (in review) showed a rainfall threshold for both matrix flow and macropore flow at the Panola hillslope. These studies support the first criterion in our decision tree in Fig. 9: that total rainfall amount and antecedent wetness conditions are the first descriptors that one needs to define lateral pipe flow. Previous studies have also reported that once pipe flow is initiated, further flow is sensitive to the rainfall intensity (Uchida et al., 2002). Furthermore, the lags in peak pipe flow time-to-peak rainfall intensity are often short (Elsenbeer and Lack, 1996; Uchida et al., 2001). This suggests that pipe flow is often related to the rainfall intensity, once the total amount of rain becomes large enough for pipe flow to occur, supporting the second criterion in our decision tree.

4.2. Controls within the decision tree

The parameters in our decision tree can be classified into two broad categories: 'environmental controls' on pipe flow response, and 'system characteristics' that determine pipe flow response. Total rainfall amount (R), precipitation intensity (R_i) and antecedent wetness conditions (θ_{pre}) are included in the 'environmental control' category (Fig. 9). Threshold rainfall amounts for significant pipe flow to occur (R_{thr}), the hillslope discharge at the start of pipe flow (Q_c), the maximum capacity of pipe flow (Q_{prmax}), the rainfall intensity that produced Q_{prmax} (R_{imax}), the slope of the relation between peak rainfall intensity and peak pipe flow rate (k_p), and the constant ratio of pipe flow to hillslope discharge above the threshold rainfall (k) are grouped into the 'system characteristics' category (Fig. 9).

Some studies on forested slopes have suggested that a minimum groundwater stage was required before a quick response can occur in soil pipes (Roberge and Plamondon, 1987; Terajima et al., 1996), similar to the results in moorland catchments in the UK (Jones, 1981; McCaig, 1983; Sklash et al., 1996). Tsukamoto et al. (1982) reported that soil pipes, located in shallow soil layers required larger total rainfall amounts for the occurrence of pipe flow, compared to the soil pipes in a deeper soil layer. Several studies have proposed that the maximum or limited drainage capacity of soil pipes is determined by the morphological characteristics of soil pipe networks (Tsukamoto et al., 1988; Kitahara, 1994). Uchida et al. (2001) reported in their review that the maximum discharge rates of pipe flows were described by the combination of soil pipe diameter and hillslope gradient. Uchida et al. (1999) indicated that soil pipe morphological change caused by sediment yield from the soil pipe, contributed to a change in the maximum drainage capacity of the soil pipe (Q_{prmax}). Uchida et al. (1999) also reported that the rainfall intensity that produced Q_{prmax} (R_{imax}) increased with the increase of Q_{prmax}. We interpret the results from the present intercomparison study in light of this previous work.

Juxtaposing our intercomparison results with published work, we conclude that the threshold rainfall amounts (R_{thr}), the maximum capacity of pipe flow (Q_{prmax}) and the rainfall intensity that produced Q_{prmax} (R_{imax}) are strongly associated with soil pipe geometry, soil pipe density, soil properties and soil pipe location, i.e. upslope drainage area and soil pipe depth. Nevertheless, we are not able to quantify the relationship between the soil pipe geometry and the values of R_{thr}, Q_{prmax} and R_{imax} well, since morphological information is lacking with regard to the upslope connectivity of soil pipe network systems in the forest soils from the four study sites. Detailed mapping of soil pipe distribution and upslope connectivity were conducted in peaty soils (e.g. McCaig, 1983; Jones, 1987; Carey and Woo, 2000; Holden and Burt, 2002) and at badland sites (e.g. Zhu, 1997). Although recent studies examined the upslope connectivity of soil pipes in forest soils (e.g. Noguchi et al., 1999; Terajima et al., 2000), information about soil pipe geometry in forest soil is still limited.

According to our intercomparison results, when the rainfall intensity was smaller than R_{imax}, the relationship between peak rainfall intensity and peak pipe flow rate (Q_{pr}) was described by a linear relation (Fig. 5). We found a large difference in the slope of this relationship at Panola and Toinotani, despite small difference in the observed soil pipe depth, soil pipe density and soil pipe diameter (Table 1). We argue that this second order control may be a reflection of the very different matrix conductivities, upslope drainage area, soil pipe geometry, and potential differences in the interaction between pipe flow and matrix flow at each site (although we have no data to examine this in greater detail here). In general across the four study hillslopes, both total pipe flow and total matrix flow from the hollow-dominated hillslopes (Toinotani and Hakyuchi) were greater than those in the planar side slope sites (Panola and Jozankei) for a given rainfall input (Fig. 3). These results would suggest that k_p (the slope of the relation between peak rainfall intensity and peak pipe flow)

Table 1
Topography, soil properties and soil pipe geometry for the four study hillslopes

	Panola	Toinotani	Jozankei	Hakyuchi
Upslope drainage area per unit contour length (m^2)	50	3600	38	890
Soil depth (cm)	63	42–82	40–50	70
Slope angle (degree)	13	36	42	27
Saturated conductivity (mm/h)	64	0.23	3.6–360	36–360
Soil pipe density (pipes/m)	0.4	0.5	9.7	11.6
Soil pipe depth (cm)	60–90	45–80	40–50	10–70
Diameters (cm)	1.0–6.0	5	0.8–2.1	1.0–20.0

was strongly affected by the upslope drainage area and upslope topographic convergence. One could argue that given this difference, slope shape should be included in the decision tree. We are now extending our intercomparison work to many new sites, where possibly this distinction can be evaluated and possibly added to the decision scheme.

We found a linear relationship between total pipe flow and the total hillslope discharge for storms larger than the local thresholds (Figs. 4 and 5). Notwithstanding, the slope of this relationship (k) varied considerably from 0.1 at Toinotani to 0.9 at Hackyuchi. The values of k did not appear to be related to the soil pipe location or the pipe diameter but was somewhat related to the soil pipe density (Tables 1 and 2). That is, sites with a high soil pipe density (Hakyuchi and Jozankei) showed larger values of k. Also, it can be assumed that the upslope connectivity of soil pipes affects the value of k.

Except for Toinotani, the values of Q_c, the hillslope discharge at the start of pipe flow, were almost zero. Previous studies in Toinotani reported that during baseflow, flow from the bedrock to the soil layer contributed significantly to the hillslope discharge (Uchida et al., 2002), suggesting that Q_c was associated with the contribution of an upwelling bedrock flow path to the hillslope discharge. Nevertheless, Q_c was very small compared to the peak of total hillslope discharge and to storm total hillslope discharge.

Lastly, in terms of environmental controls, the Panola data showed that when the pre-storm conditions were very dry, the ratio of pipe flow to total hillslope discharge was sometimes greater than k. We did not observe this in the three Japanese catchments. We argue that this difference may be due to climatic differences between the Panola and the Japanese sites, where the Panola catchment experiences extreme seasonality (and therefore antecedent wetness controls on pipe flow), while the Japanese sites vary little in their seasonal soil moisture conditions. Soils at Panola show cracks during the summer and experience hydrophobicity possibly resulting in increased pipe flow during dry periods while total hillslope discharge was very low (Fig. 7). Tromp-van Meerveld and McDonnell (in review) have shown that during the summer months all pipe flow emanated from only one of the five individually measured soil pipes.

In the above paragraphs, we tried to quantify the observed environmental controls and system characteristic parameters in the decision tree based upon differences in the characteristics of the four hillslopes described in this study. Clearly more research and intercomparison of more hillslopes is needed to fully define the controls on the parameters in this decision tree.

Table 2
Parameter values and functions for Panola, Toinotani, Jozankei and Hakyuchi

	Panola	Toinotani	Jozankei	Hakyuchi
Mean $R_{thr}(\theta_{pre})$ (mm)	55	35–40	15–20	About 20
Q_{prmax} (L/h)	>70	300	NA	NA
R_{imax} (mm/h)	>22	25	NA	NA
k_p (L/mm)	20	90	NA	NA
k	0.45	0.1	0.6	0.9

5. Conclusions

We compared the pipe flow response to storm rainfall at four well instrumented sites: Panola (Georgia, USA), Toinotani (Kyoto, Japan), Jozankei (Hokkaido, Japan) and Hakyuchi (Tokyo, Japan) Despite very different hillslope geomorphic characteristics, we found several common pipe flow responses; (1) the relationship between total rainfall amount and total pipe flow volume was highly nonlinear and threshold like at each site, (2) initiation of measurable pipe flow was threshold-dependent, controlled by the total rainfall amount and the pre-storm wetness, (3) once significant pipe flow response occurred, the maximum pipe flow rate was sensitive to the measured maximum rainfall intensity, and (4) the ratio of total pipe flow to total hillslope discharge was constant. We used these results to develop a decision tree that summarizes these intercomparison results to determine the conditions necessary for pipe flow to occur.

Our decision tree (Fig. 9) includes six 'system characteristic' parameters to describe pipe flow and total hillslope discharge: (1) threshold rainfall amounts for significant pipe flow to occur (R_{thr}),

(2) the maximum capacity of pipe flow (Q_{prmax}), (3) the rainfall intensity that produced Q_{prmax} (R_{imax}), (4) the slope of the relation between peak rainfall intensity and peak pipe flow rate (k_p), (5) the slope of the relation between total pipe flow and total hillslope discharge above the threshold rainfall amount (k) and (6) hillslope discharge at the start of pipe flow (Q_c). We examined the first-order control factors for the determination of these parameter values. The value of R_{thr} was associated with the pre-storm wetness and a function of soil pipe geometry, soil properties and soil pipe location. The value of k_p and k appeared to be associated with the upslope drainage area, soil pipe density and connectivity, respectively. Based on previous pipe flow research, we argue that Q_{prmax} and R_{imax} are controlled by the soil pipe geometry, i.e. soil pipe diameter and soil pipe angle. Clearly an intercomparison of more sites is needed to determine the controls on the values of the parameters in the decision tree.

Our analysis of four different hillslopes demonstrates the effectiveness of site intercomparison for extracting common first order controls on complex hillslope processes. For catchment models that use hillslopes as the fundamental model building block, this intercomparison and decision tree approach may be a way for the experimentalist to narrow down the range of complexities and to formulate a hierarchy of controls necessary for model development. This approach may define when hillslopes turn on and off in the landscape, a key factor for water and solute delivery to the stream.

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