Journal of Hydrology (2006) **327**, 627–642

available at www.sciencedirect.com

journal homepage: www.elsevier.com/locate/jhydrol

Functional intercomparison of hillslopes and small catchments by examining water source, flowpath and mean residence time

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Received 27 August 2004; received in revised form 24 February 2006; accepted 27 February 2006

KEYWORDS
Hillslope hydrology;
Intersite comparison;
Hydrometric observation;
Tracer approach

Summary Intercomparisons of hillslopes and catchments in different hydrogeomorphic settings are rare. Those comparison studies that have been completed have focused largely on bulk outflow and chemistry. Here, we present a new functional intercomparison of two well studied hillslopes: one in New Zealand at Maimai and one in Japan at Fudoji. Slope angle, slope length, soil depth, climate and vegetation of both hillslopes are very similar. Thus, questions posed include: In what ways are the hillslopes similar or different as expressed via the combination of throughflow rate, tensiometric response, event/pre-event water partitioning, quickflow rates and mean residence time? How does the apparent difference in soil drainable porosity affect the hillslope response to storm rainfall? How do the apparent differences in bedrock permeability affect the residence time of water at the slope base and catchment outlet? Our results suggest that in steep, wet and thin soil hillslopes, bedrock permeability and water retention characteristics combine to form a first order (main or dominant) control on the baseflow hydrograph and its mean residence time. For storm rainfall totals above about 50 mm, soil drainable porosity appears to be a first order control on the extension of upslope subsurface saturated area and the event water ratio of hillslope discharge in steep, wet and thin soil

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0022-1694/$ - see front matter
doi:10.1016/j.jhydrol.2006.02.037

hillslopes. Although this functional intercomparison is a posteriori, it has yielded information that was not possible from the individual hillslope studies upon which it is based. In particular, it has informed a new, more generalizable, conceptualization of subsurface flow for steep wet hillslopes. We argue that intercomparison of other such hillslopes and small catchments may be a pathway forward for defining first order controls of complex hillslope hydrologic dynamics.

Introduction

The mechanisms of subsurface runoff generation in forested headwater catchments have been debated since the 1930s (see reviews by Dunne, 1978; Bonell, 1998; McGlynn et al., 2002). While individual experimental approaches have evolved considerably over time, combination of hydrometric observations and tracer approaches is now a standard methodology for constraining a sound perceptual model and formal conceptualization of runoff generation in headwater catchments (McDonnell, 2003). Studies of subsurface stormflow in steep wet catchments have shown that channel stormflow is supplied largely by pre-event water moving via subsurface routes to the channel (Buttle, 1994; McDonnell, 2003). Nevertheless, the exact mechanism of rapid pre-event water mobilization remains highly equivocal in most studies and has been shown to originate from a range of hydrological processes, including groundwater ridging (Sklash and Farvolden, 1979), transmissivity feedback (Bishop, 1991), pressure waves (Torres, 2002) and pipe flow (Uchida et al., 1999). Determining these mechanisms a priori has proved very difficult and has led some researchers to reach the rather dire conclusion that each catchment is unique (Beven, 2001).

Most of the published work to date has focused on the study of single hillslopes in individual catchments. Thus, it seems that this field of study has focused on documentation of the idiosyncrasies of new hillslope environments rather than a systematic examination of the first order controls on hillslope hydrology in steep wet environments. Indeed, it has been easier to publish new findings of new mechanisms than simply confirmation that some mechanism or process occurs at *yet another site*. Although research at each intensively studied small basin site *has* (and continues to) produce many valuable insights, it has been difficult to derive general hydrologic principles from these basin-centric approaches (Kirchner, 2003; Weiler and McDonnell, 2004). Jones and Swanson (2001) have called for intercomparison so as to better see/define first order controls.

Intercomparison is not new to catchment hydrology. Indeed, intercomparison is the hallmark of forest hydrology (DeWalle, 2003) where ''paired catchment studies'' have defined differences between a control and treatment. Most intercomparisons to date have focused on ''specific values'' from two or more nearby catchments, such as peak flow (e.g., Dunne, 1978; Jones, 2000), annual water loss (e.g., Bosch and Hewlett, 1982; Komatsu, 2003), subsurface stormflow volume (Freer et al., 2002), the relationship between upslope pore pressure dynamics and hillslope discharge (Uchida et al., 2004) or event water ratio (e.g., Pearce, 1990; Buttle, 1994). Whereas recent work has noted the need for complementary hydrological and hydrochemical information to constrain a functional representation of the hydrological behavior of a catchment (Bazemore et al., 1994; Elsenbeer and Lack, 1996; Rice and Hornberger, 1998), intercomparison of a variety of data from more than one site has not been attempted in the process hydrological literature. Thus, while recent studies combining hydrometric, isotopic, and chemical approaches have successfully identified water sources and storm flow pathways in individual catchments (e.g., Bishop, 1991; Peters et al., 1995; McGlynn et al., 1999; Burns et al., 2001), functional intercomparison has not been attempted.

Here, we present a functional intercomparison of two very well-studied sites–the Maimai catchment in New Zealand (for recent review see McGlynn et al. (2002)) and the Fudoji catchment in Japan (for recent review see Uchida et al. (2003b))–where the similarities of climate, slope angle, length, soil depth, vegetation, are striking (Table 1). These similarities allow us to isolate the different soils and different bedrock geology to explore the first-order (main or dominant) controls on hillslope hydrological response (expressed as differences in soil water retention characteristics and bedrock permeability).

We address the following questions in our quest for functional comparison;

1. In what ways are the hillslopes similar or different as expressed via the combination of throughflow rate, tensiometric response, event/pre-event water partitioning, quickflow rates and mean residence time?
2. How does the apparent difference in soil drainable porosity affect the hillslope response to storm rainfall?
3. How do the apparent differences in bedrock permeability affect the residence time of water at the slope base and catchment outlet?

We draw upon the large body of published hillslope research from the two sites; for Maimai (Mosley, 1979; Sklash et al., 1986; McDonnell, 1990; McDonnell et al., 1990, 1991; Stewart and McDonnell, 1991; McGlynn et al., 2002; McGlynn and McDonnell, 2003) and Fudoji (Uchida et al., 2003a,b; Asano et al., 2002, 2003, 2004). Secondary objectives of this comparison include:

4. What can we learn from the comparison that we did not know before from the individual published investigations and site-specific findings?

Table 1 Summery of data sources

	Unit	Fudoji	Maimai
Annual precipitation	mm	1645[a]	2600
Annual runoff	mm	889[a]	1550
Slope length	m	50	60[b]
Slope gradient	m	37	34
Soil depth	cm	60–120	100–150
Vegetation		Forest	Forest

[a] Data from Kiryu Experimenta Watershed.
[b] Slope length from seep to divide.

5. Can the functional intercomparison approach inform a new more generalizable conceptualization of subsurface stormflow for steep wet hillslopes?

Study sites

Fudoji

The Fudoji zero-order watershed has been the site of ongoing hillslope research since 1997 (Asano et al., 2002, 2003, 2004; Uchida et al., 2003a,b). Fudoji is located in southeastern Shiga Prefecture, central Japan. The catchment is underlain by Tanakami granite and covers an area of 0.10 ha (Fig. 1). Mean gradient in the catchment is 37° and the vegetation consists of dense natural forest, predominately *Chamaecyparis obtusa*. The mean annual precipitation and runoff in the Kiryu Experimental Forest (10 km north of Fudoji) from 1972 to 2001 was 1645 and 889 mm, respectively (Katsuyama, 2002). Nishiguchi et al. (2005) measured soil depth to the bedrock at 20 points in the hillslope, and reported the soil depth ranges from 0.2 to 1.3 m (mean 0.7 m). This depth was measured using a cone penetrometer (Uchida et al., 2003a). The soils are 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 h^{-1}, respectively (Asano et al., 2002). Water retention curves, based on data presented originally by Ohte (1992) are shown in Fig. 3. From the water retention curves a drainable porosity between 0.25 and 0.35 was determined.

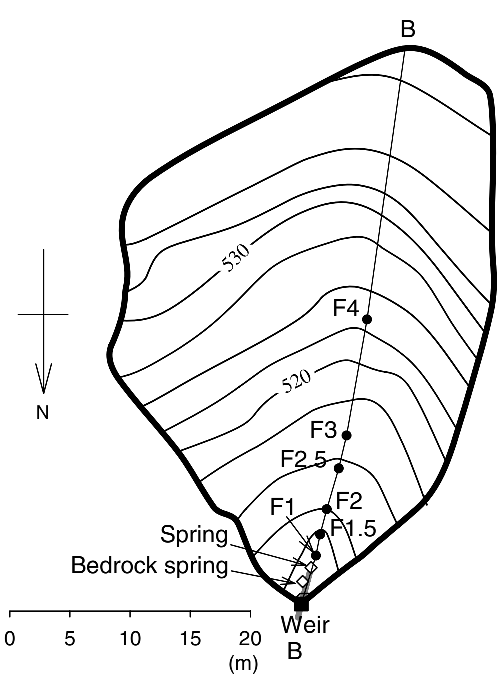

Figure 1 Topographic map of the Fudoji watershed with 2.5 m contour interval.

Two perennial springs contribute to ''hillslope discharge'' at the base of the experimental hillslope: one from the soil matrix and the other from a crack in the bedrock (Fig. 1). The variation in the discharge rate from the bedrock spring was small; observations from April 2000 to July 2001 showed a 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 found at the base of the slope adjacent to the spring. In the small area near to 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, water percolated through the vadose zone and mixed with water emerging from the bedrock (Asano et al., 2002). Other previous studies have shown the importance of bedrock for baseflow hydrological behavior: Uchida et al. (2003a) showed that the ratio of bedrock groundwater to hillslope discharge of Fudoji was about 0.82 for the baseflow periods using a two-component geochemical hydrograph separation. Also, Uchida et al. (2003a) reported that the saturated hydraulic conductivity of bedrock is relatively high (12 mm h^{-1}) was of the same order as those of weathered granite in the Sierra Nevada Range, California (Graham et al., 1997), and the Idaho batholith (Megahan and Clayton, 1986). In contrast, in most of the hillslope area, the soil–bedrock interface was not commonly saturated between events. Nevertheless, most monitored storms produced transient saturation at the soil–bedrock interface. Our previous work suggests that both rain water and pre-event shallow soil water have important effects on the formation of transient saturated groundwater on the upper slope (Uchida et al., 2003b). Additional details of the Fudoji hillslope are presented elsewhere (Asano et al., 2002, 2003, 2004; Uchida et al., 2003a,b).

Maimai

The Maimai research catchments are located on the West Coast of the South Island of New Zealand. McGlynn et al. (2002) provided a review of hydrological research at Maimai. Slopes are short (<300 m), steep (average 34°) (Fig. 2), and have local relief ranging from 100 to 150 m. Mean annual precipitation averages 2600 mm, and produces approximately 1550 mm of runoff (Rowe et al., 1994). A moderately weathered, early Pleistocene conglomerate, known as the Old Man Gravels, underlies the Maimai catchments. The conglomerate is comprised of clasts of sandstone, granite, and schist in a tight clay–sand matrix and is nearly impermeable, with estimates of seepage losses to deep groundwater of only 100 mm y^{-1} (Rowe et al., 1994).

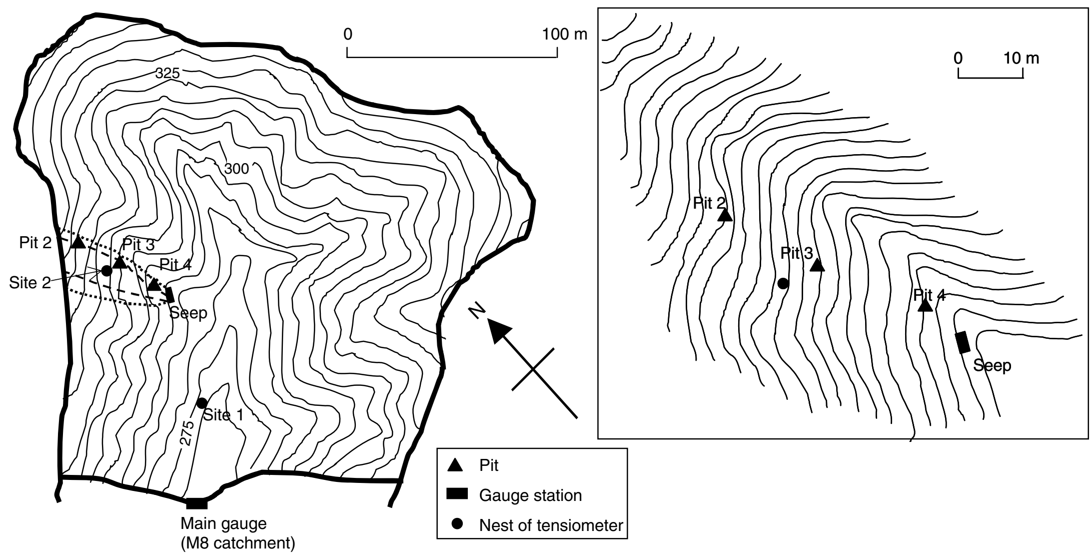

Figure 2 (a) Topographic map of the Maimai (M8) watershed with 5 m contour interval. Dotted and broken lines represent minimum and maximum probable range of the drainage area of seep flow. (b) Close-up map of monitored hillslopes with 2 m contour interval.

Soils overlying the Old Man Gravels are classified as Dystrochrepts and Humults (Pearce et al., 1986). Silt loam textures predominate. Typical soil profiles are characterized by thick, well developed organic horizons (~17 cm), thin, slightly stony, dark grayish brown A horizons, and moderately thick, very friable mineral layers of podsolized, stony, yellow-brown earth sub-soils (~60 cm). Study profiles showed an infiltration rate of 6100 mm h^{-1} for the organic humus layer and 250 mm h^{-1} for the mineral soils (McDonnell, 1990). The soils remain within 10% of saturation by volume during much of the year due to the wet environment and the site specific water retention characteristic. From the water retention a drainable porosity between 0.08 and 0.12 was determined. Water retention curves based on data presented in McDonnell (1990) are shown in Fig. 3. Mosley (1979) and McDonnell (1990) indicated spatial variability of soil depth (mean 0.6 m, range 0.2–1.8 m).

Mosley (1979) found that soil profiles at vertical pit faces in the Maimai M8 catchment revealed extensive macropores

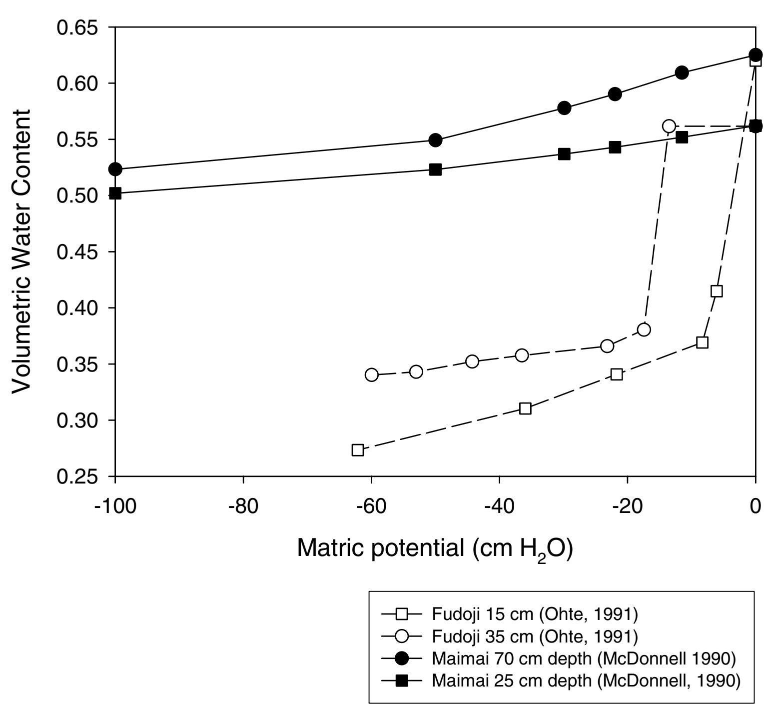

Figure 3 Water retention curves of soil in Maimai and Fudoji.

and preferential flow pathways which formed along cracks and holes in the soil and along live and dead root channels. Preferential flow was observed regularly along soil horizon planes and along the soil—bedrock interface in this study and in more recent research (Mosley, 1979; McDonnell, 1990; Woods and Rowe, 1996; McGlynn et al., 2002). In the Maimai M8 catchment, Woods and Rowe (1996) excavated a 60 m long trench face at the base of a planar hillslope in the Maimai M8 catchment. They measured subsurface flow with an array of troughs. Additional details of the Maimai hillslope are presented elsewhere (Mosley, 1979; Pearce et al., 1986; Sklash et al., 1986; McDonnell, 1990; Rowe et al., 1994; McGlynn et al., 2002).

Comparison methods

The sources of data used are summarized in Table 2. Runoff and soil pore pressure data for Fudoji and Maimai were based on the previous field investigations of Uchida et al. (2003a,b) and McDonnell (1989, 1990), respectively. We analyzed the data from September 1987 to December 1987 for Maimai, and the data from May 1999 to December 2000 for Fudoji. Runoff at Fudoji was measured at the lower end of the hillslope as shown in Fig. 1. Runoff at Maimai was measured at the main gauging station at the M8 catchment outlet (Fig. 2). A transfer function was then developed for converting M8 streamflow to ''seep flow'' (Fig. 2) via regression of M8 main gauge peak flow data against ''seep flow'' data reported in Mosley (1979) (Fig. 4). We did this to eliminate the contribution of riparian area and in-stream flows from the M8 streamflow data for a more comparable juxtaposition with the Fudoji data. The linear relationship was strong ($r^2 = 0.96$) with ''seep flow'' (Q_s) during the comparison period calculated by $Q_s = 0.00495\ Q_m$, where Q_m is the streamflow at main gauge. Since the drainage area of seep flow was somewhat uncertain even from a 5 m DEM, we defined probable range of the drainage area (0.05—0.1 ha) and its associated flow uncertainty in further plots. The ratio of the drainage area of the seep to M8 is around 0.013 and 0.026, although Fig. 4 indicated that the ratio of Q_s to Q_m is about 0.005. A recent study in Maimai by McGlynn and McDonnell (2003) reported that hillslope runoff comprised 2—16% of total catchment storm runoff during a small 27-mm event and 47—55% during a larger 70-mm event. Further, McGlynn and McDonnell (2003) found that less than 4% of the new water collected at the catchment outlet originated from the hillslopes during each event. This suggests differences between processes above the seep and the other elements of the catchments. In this study, we focused mainly on processes above the seep, since there is not enough information about hydrological responses in the riparian area in Fudoji. Quickflow ratios were also defined for the two sites using the standard Hewlett and Hibbert (1967) approach.

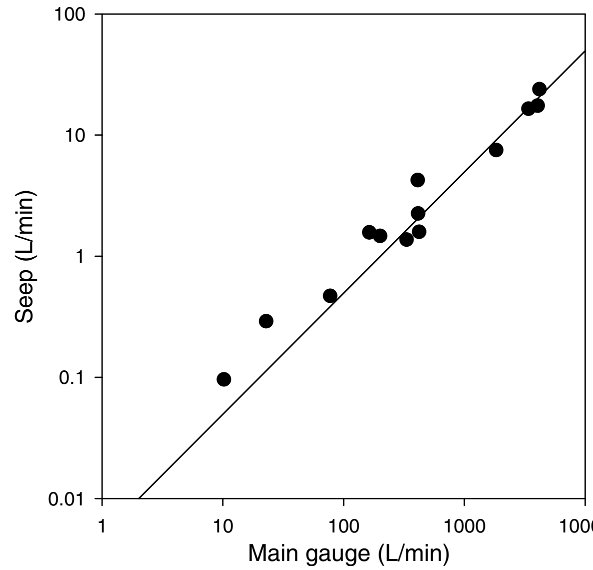

Figure 4 Relationship between seep flow rate and stream flow rate measured at M8 main station in Maimai. Data was compiled from Mosley (1979).

Eight recording tensiometers at Fudoji and seven recording tensiometers Maimai were available for the

Table 2 Source of data

	Period	Reference
Maimai		
Water retention curve		McDonnell (1990)
Tensiometer and streamflow	September—December 1987	McDonnell (1989)
Quick flow	May—June 1978	Mosley (1979)
	September—December 1987	McDonnell (1989)
Pit flow response	May—June 1978	Mosley (1979)
MRT	September—December 1987	Stewart and McDonnell (1991)
New water ratio		Sklash et al. (1986)
Fudoji		
Water retention curve		Ohte (1992)
Tensiometer and streamflow	June—December 1999	Uchida et al. (2003a,b)
Quick flow	June 1997—December 1999	Uchida et al. (2003a)
Groundwater response	June 1997—December 1999	Uchida et al. (2003a)
MRT	January—December 1999	Asano et al. (2002)
New water ratio		Unpublished data

intercomparison. For Fudoji, three different depth tensiometers were located at F1 ($F1_{10}$, $F1_{40}$ and $F1_{86}$) and the others were located at F2 through F3 ($F2_{10}$, $F2_{40}$, $F2_{112}$, $F2.5_{72}$ and $F3_{66}$) (see Fig. 1 for map locations). At Maimai, three different tensiometers were located at Site 1 in the riparian area ($T1_{13}$, $T2_{38}$ and $T3_{78}$) and others were located in the mid-hillslope positions ($T5_{17}$, $T6_{41}$, $T16_{68}$ and $T23_{108}$), see Fig. 2 for map locations. The subscripts of tensiometers refer to the porous cup depth in cm below the soil surface. Further details on instrumentation and data specifics are reported in detail in Uchida et al. (2003a) and McDonnell (1990), respectively.

The flow response data at Pits 2 through 4 at Maimai (published in Mosley (1979)), were used to compute the upslope extension of subsurface contributing area. We used pit flow responses for 13 storms from Mosley (1979). Total rainfall amounts ranged from 2.3 to 104.9 mm. While we lacked a similar data set for Fudoji, we were able to use groundwater level responses at F2 through F4 to define subsurface contributing area and its upslope extent, for comparison purposes. These methods and the data sets are described in detail elsewhere (Asano et al., 2003; Uchida et al., 2003a). The observation period for Fudoji groundwater levels were from May 1997 to December 2000.

Hydrograph separations at Maimai and Fudoji were derived from Sklash et al. (1986) and Uchida et al. (in preparation). Hydrographs at Maimai were separated into two components (event water and pre-event water) using standard deuterium-based two component mixing models. Hydrographs at Fudoji were separated into three components (event water, stored water in soil layer and stored water in bedrock) using standard two tracer (dissolved silica and chloride) three component models. Mean residence time (MRT) of soil water and groundwater were gathered from Asano et al. (2002) for Fudoji and by Stewart and McDonnell (1991) for Maimai. Both used weekly deuterium data and standard convolution integral techniques (and associated system response functions) to compute MRT.

Results

Two month seep flow and tensiometer response

Total rainfall amounts over the two selected periods were almost the same; 435 mm for Fudoji (June and July in 1999) and 499 mm for Maimai (October and November in 1987). Total runoff during selected periods in Fudoji and Maimai are 433 and 340 mm, respectively. In Fudoji, Uchida et al. (2003a) indicate that the drainage area (capture area) of this catchment is greater than the surface drainage area. Baseflow recession curves for hillslope discharge in Fudoji were very gentle (Fig. 5e) compared to the seep flow and streamflow recessions at Maimai (Fig. 6e). This is despite the potential influence of the riparian zone in the M8 catchment-scale streamflow record.

The deep tensiometers at the mid-hillslope ($F2_{112}$,, $F2.5_{72}$ and $F3_{66}$ in Fudoji, $T16_{68}$ and $T23_{108}$ in Maimai) showed strikingly similar response. The tensiometer positions were very similar in terms of distance from the divide (30–39 m from the divide) and the depth (66–112 cm). Tensiometers at Fudoji and Maimai showed generally negative values during base flow conditions, ranging from −10 to −70 cm H_2O (Figs. 5b–d, and 6b,c), except for the wettest period of Fudoji (from late-June to mid-July in 1999). While, most of rainstorms produced transient saturation on both hillslopes at the soil–bedrock interface, all tensiometers were sensitive to rainfall intensity variations through the event, even when pore pressures were positive. Peak pore pressures were mostly in the range 10–40 cm H_2O. The subsurface saturated area dissipated in less than 3 days after storms at both sites.

In contrast to these sites reported above, the tensiometer at $F1_{86}$ at Fudoji showed that a saturated area was present continuously at the base of hillslope (Fig. 5e). This tensiometer remained almost constant at 5 cm H_2O, although hillslope discharge was sensitive to the rainfall intensity. Asano et al. (2002) reported that this constant pore pressure in F1 was controlled by the water emerging from bedrock to the soil layer. This very gentle recession of pore pressure concurs with the baseflow hydrograph of hillslope discharge. While, during the stormflow periods, hillslope discharge was more closely related to soil pore water pressure at $F2_{112}$ through $F3_{66}$ than at $F1_{86}$.

While, the pore pressure in the riparian area of Maimai ($T3_{78}$) exhibited negative values during the baseflow period (similar to hillslope positions), transient saturation formed and was present for several days following each storm at riparian ($T3_{78}$) and hillslopes ($T23_{108}$ and $T16_{68}$). The absolute pore pressure response in the riparian zone was smaller than that of hillslope tensiometers ($T23_{108}$ and $T16_{68}$) and streamflow at Maimai resembled more the pore pressure variations in the mid-hillslope position than in the riparian area.

Event stormflow and tensiometer response

We identified and analyzed a medium sized 35–50 mm storm, with similar rainfall totals, intensities and API_{14} for the two sites (Table 3). These storms also showed similar bi-modal rainfall intensities, where the first peak was larger than the second (Figs. 7 and 8).

The tensiometers at Fudoji rapidly responded throughout the soil profile at the start of the storm (100LT October 7th 1999) due to relatively wet antecedent moisture and high rainfall intensity (Fig. 7). Nevertheless, the variation in $F1_{86}$ was very small. Although the rainfall intensity of the first peak was greater than that in second, both hillslope discharge and $F2_{112}$ pore pressure for the first peak of rainfall was smaller than those for the second peak. This indicates that the peak of both hillslope discharge and pore pressures were affected by peak rainfall intensity and accumulated rainfall amounts. The time lag from peak rainfall intensity to peak hillslope discharge was shorter during the second rainfall burst (<1 h, compared to 2 h for the first).

At Maimai, only shallow tensiometers responded to rainfall at the beginning of storm (Fig. 8). The pore pressures increased at the deeper tensiometers (108 cm) only when the accumulated rainfall exceeded 20 mm. Streamflow at M8 main gauge was more closely related to soil pore water pressure at the deeper zone in the hillslope ($T23_{108}$) than at the riparian area ($T3_{78}$). Like that observed at Fudoji,

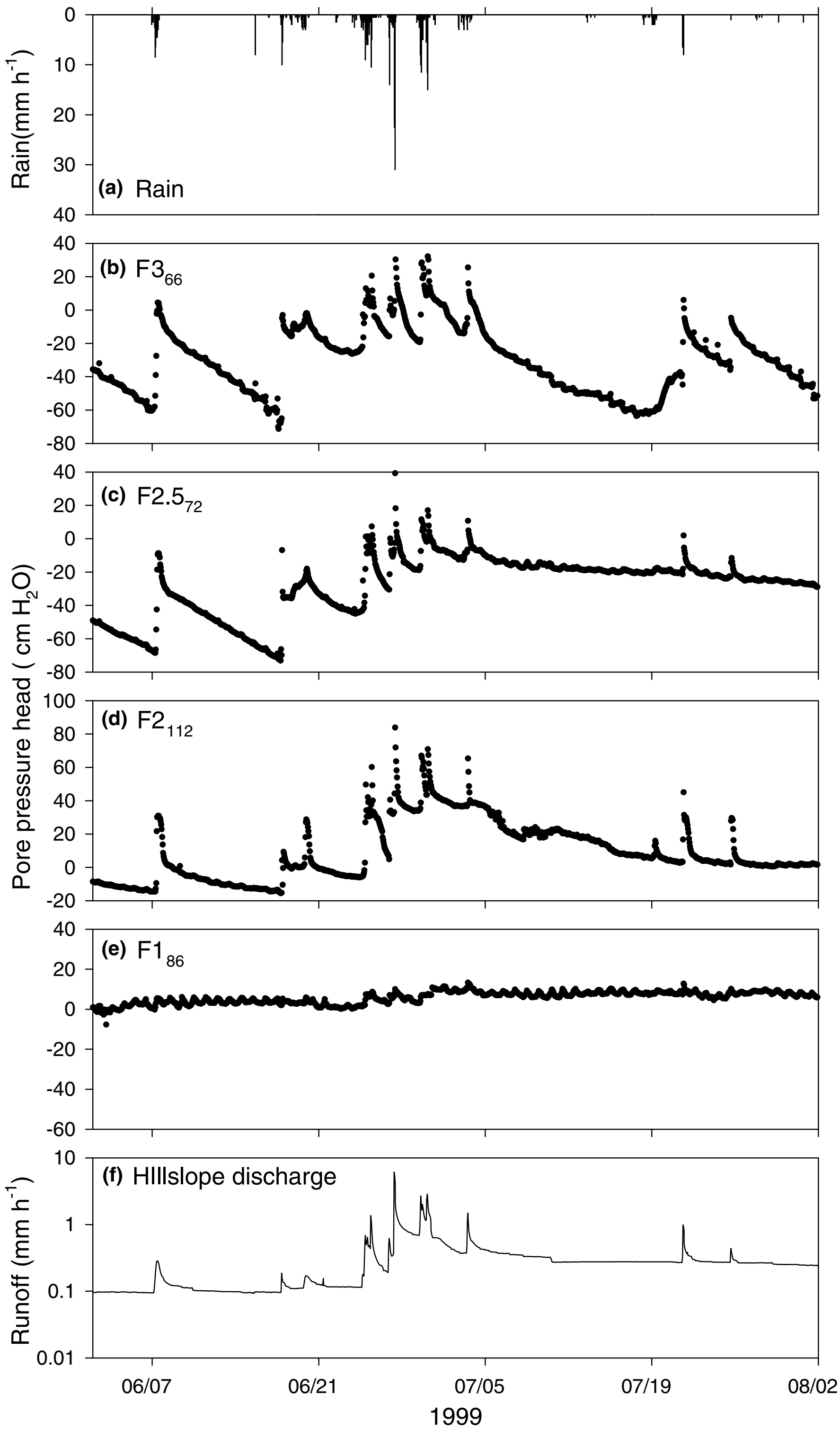

Figure 5 (a) Hydetograph, (b)—(e) temporal variation in pore pressure and (f) discharge rate of hillslope discharge of Fudoji from 2-June to 1-August in 1999.

the rainfall intensity of the first peak was greater than that in second at Maimai. Like Fudoji, both stream flow and pore pressure at the first peak of rainfall was smaller than that for the second peak, with concomitant higher antecedent wetness conditions.

Effects of slope position on rainfall—subsurface water relations

The locations of measured throughflow pits (Maimai) and wells (Fudoji) were very similar in terms of distance

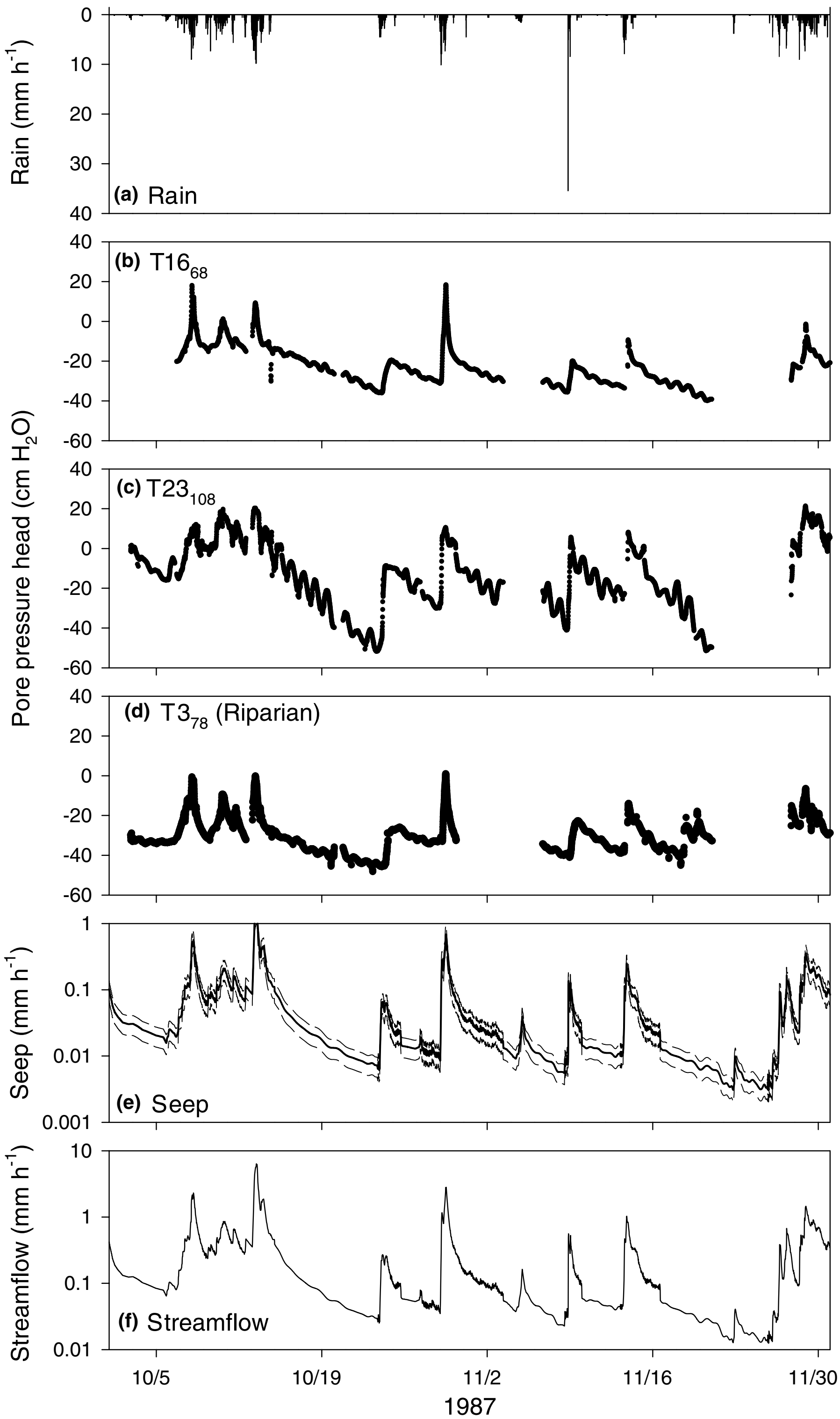

Figure 6 (a) Hydetograph, (b)—(d) temporal variation in pore pressure, (e) discharge rate of seep flow and (f) discharge rate of streamflow in Maimai from 1-October to 30-November in 1987.

from the divide (Fig. 9). At Fudoji, the relationship between total rainfall amount and peak groundwater level showed threshold like response (Fig. 9), regardless of slope position. The total amount of rainfall for generating groundwater level increased in an upslope direction. Only the heaviest storms (>90 mm) produced a transient saturation above the bedrock at F4 (20 m from the divide), while smaller storms (20—40 mm) produced a saturation above the bedrock at F2 (39 m from the divide).

Table 3 Characteristics of storms in Figs. 7 and 8

	Total (mm)	Peak (mm/h)	API_7 (mm)	API_{14} (mm)
Maimai	54.6	9.2	4.7	5
Fudoji	68	19	8.1	8.4

At Maimai, the relationship between total rainfall amount and peak pit flow was also threshold dependent (Fig. 9), but these relationships were similar across all slope positions. Peak runoff volume increased with the increase of distance from the divide (Fig. 9). The threshold rainfall amount for significant pit flow to occur was about 40 mm, regardless of slope position. This threshold rainfall amounts was similar to that of F3 and F2 in Fudoji. These observations are consistent with the results of the tensiometer comparison where F3 tensiometer ($F3_{66}$) response at Fudoji (Fig. 6) was similar to the $T23_{108}$ and $T16_{68}$ tensiometer responses at Maimai (Fig. 5).

Total rainfall—quickflow relation

When the total rainfall amount was smaller than 60 mm, the quickflow (as defined by Hewlett and Hibbert, 1967) generated at Fudoji was similar to that of seep flow in Maimai (Fig. 10). There is some uncertainty in seep flow in Maimai flow due to rather ambiguous definition of the seep ''catchment'' boundary. Nevertheless, even with uncertainty bounds included, the values plotted in Fig. 10 are within the range of Fudoji values. Alternatively, for total rainfall amounts greater than 60 mm, the quickflow of Fudoji was larger than that of seep flow at Maimai (Fig. 10), with rainfall—quickflow being more linear at Maimai for large events. Quick flow at Fudoji increased exponentially with increases in total rainfall amount.

Event water ratios

We analyzed four medium sized rainfall-runoff events for event water ratios (as per standard methods reported in Kendall and McDonnell, 1998). Total amounts and peak intensities ranged from 36 to 49 mm, and from 6 to 9.5 mm/h, respectively (Table 4). These storm sizes were similar also to those selected for the comparison of tensiometer responses. At the both sites, the storm flow was comprised largely of pre-event water. However, there was large difference in the event water ratio at peak runoff: the event water ratio of hillslope discharge at the peak runoff of Fudoji (30—43%) was 4—5 times that of hillslope flow in Maimai (8%). The event water ratio at the peak runoff of the M8 main gauge was 28—30%. During the comparison period, peak event water was the only available descriptor. Recent work by McGlynn and McDonnell (2003) used continuity-based equations and multiple tracer-based mass

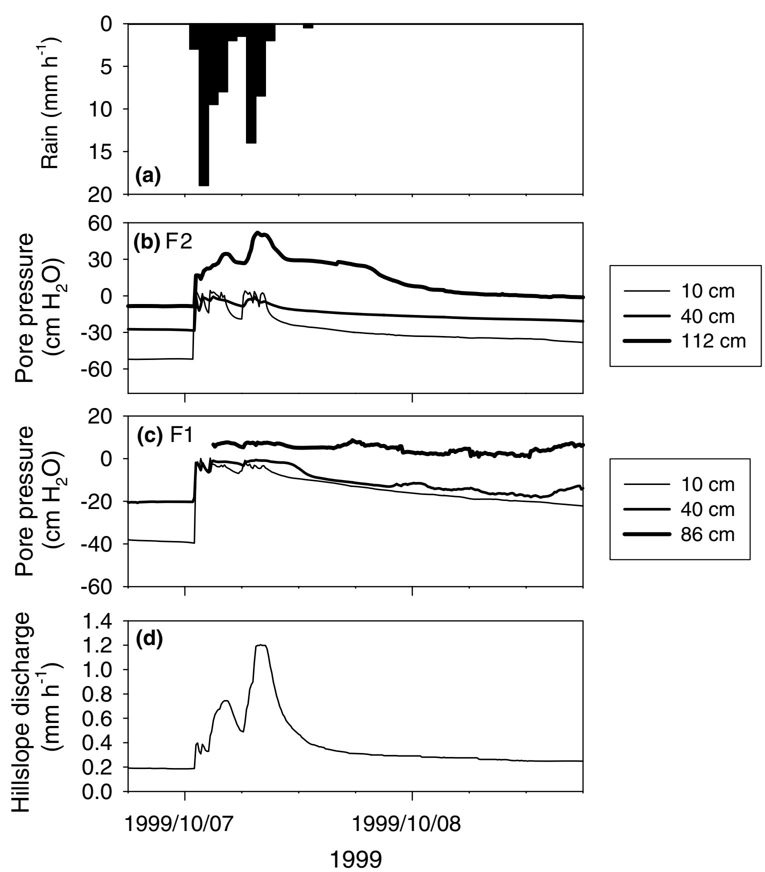

Figure 7 (a) Hydetograph, (b) and (c) temporal variation in pore pressure and (d) discharge rate of hillslope discharge of Fudoji during the storm occurred 6—7 October in 1999.

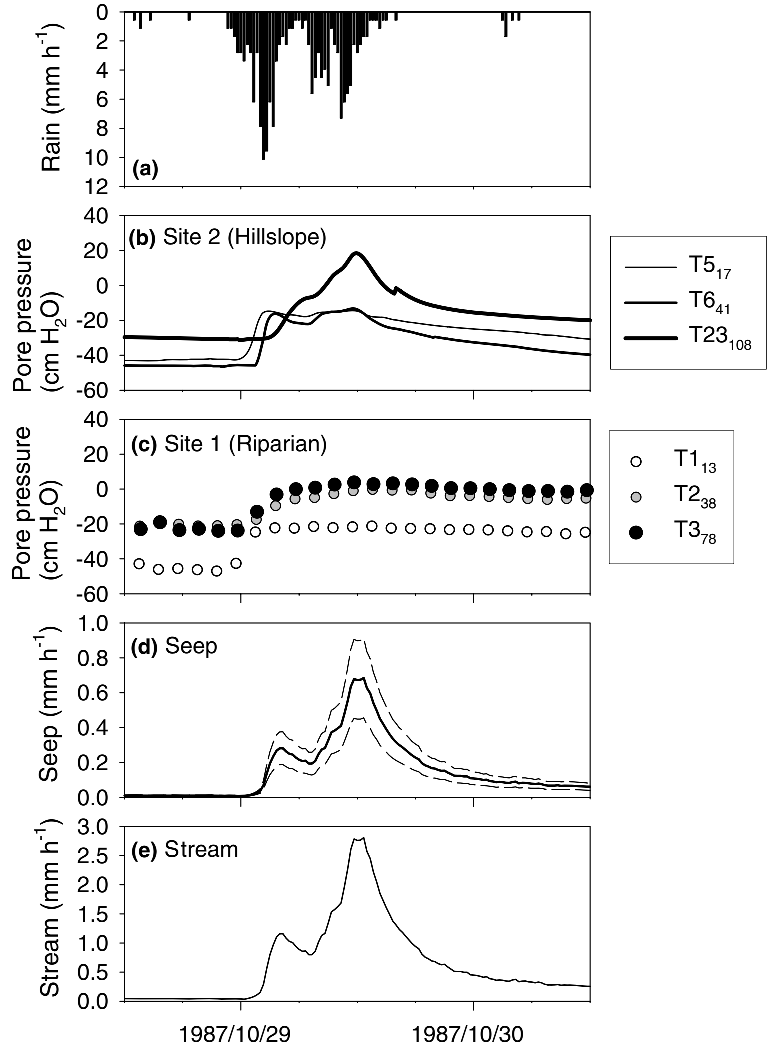

Figure 8 (a) Hydetograph, (b) and (c) temporal variation in pore pressure, (d) discharge rate of seep flow and (e) discharge rate of stream in Maimai during the storm occurred 28–30 October in 1987.

balance mixing model approaches to show that hillslope runoff comprised 2–16% of total catchment storm runoff during a small 27 mm event at Maimai and 47–55% during a larger 70 mm event. Notwithstanding, less than 4% of the new water collected at the catchment outlet originated from the hillslopes during the 70 mm event. McGlynn and McDonnell (2003) also found that for a 27 mm storm event, 84–97% of storm runoff was generated in the riparian zone. Despite the large amount of subsurface hillslope runoff in total storm runoff during their larger event, riparian and channel zones accounted for 96% of new water at the catchment outlet. These findings help to clarify results of the intercomparison work where we compare hillslope event water percentage at Fudoji with stream-based event water percentages at Maimai. The event water ratio for total hillslope discharge at Fudoji (12–19%) was greater than that for the M8 main gauge in Maimai (7–9%). This and McGlynn and McDonnell (2003) suggests that the event water ratio for total hillslope discharge at Fudoji was more than 2 times greater than that of hillslope discharge in Maimai.

Mean residence time distribution

Mean residence times (MRT) computed for lower hillslopes of Fudoji (by Asano et al. (2002)) increased with the increase of the sampling depth (Fig. 11). In other words, water aged vertically at Fudoji. In contrast, there was no clear relationship between sampling depth and MRT in Maimai. MRT distribution (reported originally by Stewart and McDonnell, 1991) was related largely to the distance from the divide (Fig. 11). In other words, water aged in a downslope direction. The maximum MRT in perennial groundwater at Fudoji F1 was about 25 weeks, while the MRT in hillslope seepage at Maimai was less than 8 weeks. The MRT in riparian area of Maimai (9 weeks) was longer than that in the hillslope, but still considerably shorter than that of the base of Fudoji hillslope. While the MRT of 40 cm soil water at Fudoji was 1–3 weeks, soil water at a similar depth at Maimai was 2–6 weeks. The MRT for the Fudoji hillslope discharge was greater than 1 year where Maimai hillslope discharge MRT was approximately 3 months.

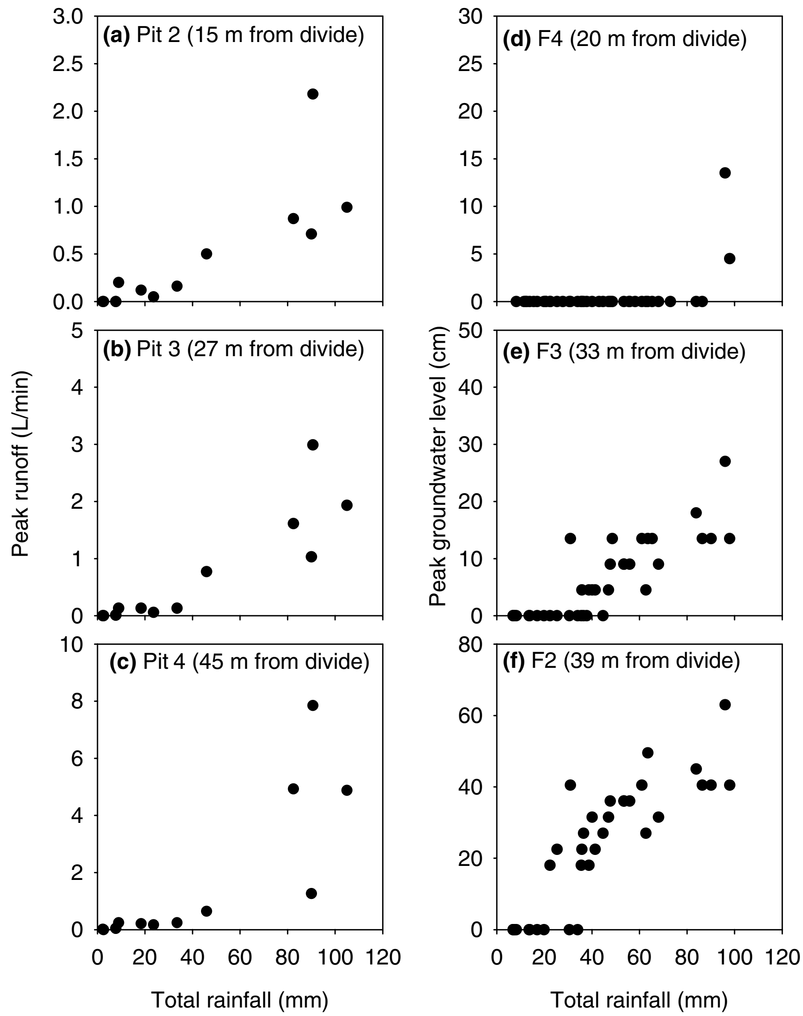

Figure 9 (a)–(c) Relationships between total rainfall amounts and pit flow rate in Maimai. (d)–(f) Relationships between total rainfall amounts and groundwater level in Fudoji.

Discussion

Despite the striking similarities of the Maimai and Fudoji hillslopes and their respective climate settings, there were clear differences during and between events as revealed through the functional intercomparison.

First order control on baseflow behavior

Our functional intercomparison showed that the baseflow recession curve at Fudoji was much lower-angled than Maimai. Also, we found that the MRT of hillslope discharge in Fudoji was 300% longer than Maimai. To aid our interpretation of these differences, Fig. 12 presents a conceptual diagram of water storage in hillslopes, classified into three components: residual water storage, baseflow dynamic storage and stormflow dynamic storage. Here we define residual water storage as the amount of water stored under the lowest flow conditions of a given water year. Baseflow dynamic storage is defined as the difference in water storage between at the lowest flow period and at the transition from storm flow to baseflow (as shown in Fig. 12). Finally, stormflow dynamic storage represents the difference in water storage between the stormflow to baseflow transition and the wettest period of a given water year (Fig. 12). Vitvar et al. (2002) indicated that the slope of their observed baseflow recession curve was related to the baseflow dynamic storage, while baseflow MRT was associated with the mean baseflow water storage (as indicated in Fig. 12). Using this same conceptual framework, our functional intercomparison of the Maimai and Fudoji catchments shows that both mean baseflow water storage and baseflow dynamic storage of the Fudoji hillslope are much greater than those at Maimai.

Next, we portioned water storages in the Maimai and Fudoji hillslopes into two, water storage reservoirs: soil and bedrock. The mid-slope tensiometers at each site indicated that the soil pore water pressure during the baseflow period ranged from −20 to −60 cm H_2O (Figs. 5 and 6). These data, along with known soil water retention data and soil depth data indicate that the mean water storage of soil during the baseflow period at Fudoji (water content ~35%, mean soil depth 0.7 m) is smaller than at Maimai

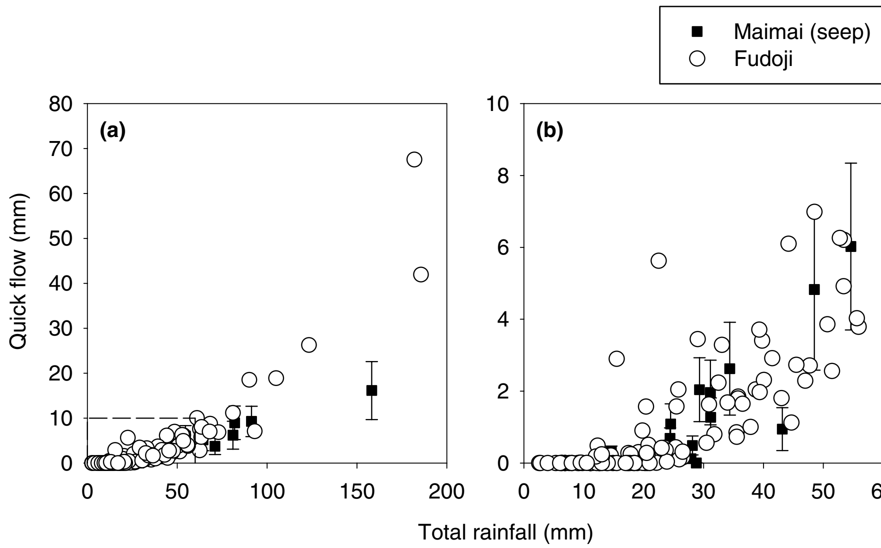

Figure 10 Relationship between total rainfall amounts and quickflow rate. Error bars represents uncertainty associated with uncertainty of drainage area in Maimai.

Table 4 Event water ratio

Total	Date	Total rainfall (mm)	Total streamflow (mm)	New water (mm)	Old water (mm)	New water ratio (%)
Fudoji	1-May-00	36	3.48	0.42	3.06	12
Fudoji	12-May-00	49	3.9	0.74	3.16	19
Maimai (Main gauge)	7-Sep-83	39.8	10.4	2.3	8.1	7
Maimai (Main gauge)	21-Sep-83	43.7	15.8	4.2	11.6	9
At the peak		Peak rainfall (mm/h)	Peak streamflow (mm/h)	New water (mm/h)	Old water (mm/h)	New water ratio (%)
Fudoji	1-May-00	7.6	0.68	0.29	0.39	43
Fudoji	12-May-00	6.2	0.49	0.15	0.34	30
Maimai (Seep)	21-Sep-83	9.5				8
Maimai (Main gauge)	7-Sep-83	6	2	0.6	1.4	30
Maimai (Main gauge)	21-Sep-83	9.5	2.8	0.8	2	28

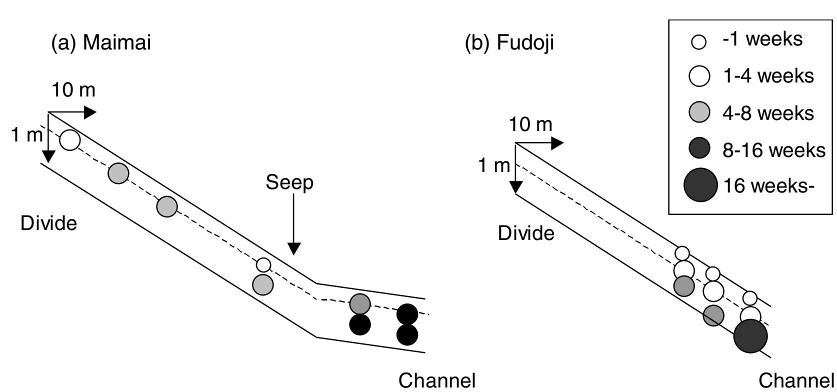

Figure 11 Water mean residence time distribution in hillslopes.

(water content ~55%, mean soil depth 0.6 m). This indicates that the baseflow mean water storage in bedrock at Fudoji is much greater than at Maimai, since MRT data that show that the mean hillslope water storage (both soil and bedrock) is much larger at Fudoji than at Maimai. Tensiometer and water retention curve data indicate that the baseflow

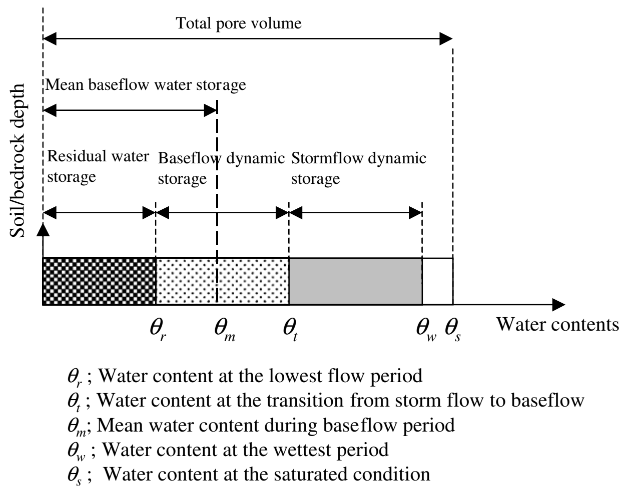

Figure 12 Schematic illustration of residual water storage, baseflow dynamic torage, stormflow dynamic storage and mean baseflow water storage.

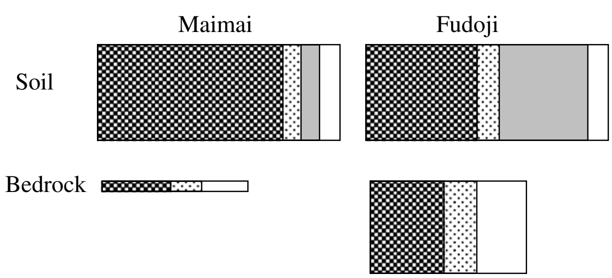

Figure 13 Schematic illustration of water storage dynamics in Maimai and Fudoji. Meaning of pattern and size of boxes are the same as those for Fig. 12.

dynamic storage of soil at Fudoji is similar to Maimai, suggesting that the baseflow dynamic storage of bedrock in Fudoji is much larger than at Maimai. We summarize these results in Fig. 13. Thus, bedrock total pore volume and water retention characteristics appear to be first-order controls of the baseflow hydrograph and MRT of baseflow discharge, while the total soil storage and water retention characteristics appear to be second order control on these behaviors.

Functional intercomparison indicated different directions of ''aging'' of water at the hillslope scale: the MRT in Maimai increased in a downslope direction rather than vertically through the soil profile, whereas the MRT of soil water at Fudoji aged vertically through the profile. These differences might reflect the gross bedrock permeability differences where lateral hydrological connectedness between events appears ''forced'' at Maimai (where the underlying bedrock has very low permeability) whereas vertical communication of water flow at Fudoji proceeds vertically across the soil—bedrock interface. This suggests that at Fudoji, water percolation into the bedrock occurred throughout the baseflow period, indicating that the gross bedrock permeability controls the direction of water flow in soil layer between events.

Functional intercomparison also clarified that the difference between the two sites in terms of subsurface saturated area development. At Fudoji, a perennial saturated area is formed at the toe of the slope, whereas at Maimai, transient groundwater levels at the soil—bedrock interface declined during the baseflow period. Previous studies in Fudoji reported that the water exfiltration from bedrock into soil layer contributed to the formation of the perennial saturated area (Asano et al., 2002; Uchida et al., 2003a). These differences in saturated area formation impact not only on measured baseflow volume and MRT, but also on the water movement direction and spatial groundwater patterns in the overlying soil layers.

First order control on hydrologic behaviors during a medium sized storm

Despite the large difference in the soil water retention curve for each site, there was no significant difference in quickflow rate for medium sized storms (total rainfall amounts of about 50 mm). This would suggest that the change of stored water volume in hillslopes from the start of storm to the end of storm is similar. Although runoff volumes and the bedrock topographic slopes were similar, the upslope extension of subsurface saturated area at Fudoji was considerably smaller than at Maimai. Furthermore, tensiometric responses and water retention curves indicated that the change of water contents in mid-slope position soil layers at Fudoji from the start of the storm to the peak time of pore pressure (~20%) was much greater than at Maimai (~5%), although the cumulative rainfall amounts up until the peak of pore pressure were similar (Fudoji 50 mm, Maimai 48 mm) (Fig. 13). In other words, both hillslopes stored a relatively similar water amount during the storm, but in Maimai, the lateral upslope extension of subsurface saturation is much larger that that in Fudoji, since soil drainable porosity in Maimai is smaller than Fudoji. These results suggest that soil drainable porosity is a first order control on lateral upslope extension of subsurface saturation. This has also been suggested recently by Weiler and McDonnell (2004).

Functional intercomparison of Fudoji and Maimai show considerable difference in event water ratios for the medium storm between seemingly similar steep, wet slopes. Maimai, with its lower drainable porosity, generated a low proportion of event water in the storm hydrograph. Previous studies in both sites reported that the transient groundwater was the dominant source of hillslope discharge in both sites (McDonnell, 1990; Uchida et al., 2003a), indicating that the difference in event water ratio of transient groundwater at peak runoff between Fudoji and Maimai was similar to the event water ratio of hillslope discharge. We computed the possible maximum event water ratio of transient groundwater. To compute possible maximum event water ratio, we assumed that the new water filled all pores (which were not filled by water at the start of the storm), and that the new water mixed completely with stored pre-event water. Possible maximum event water ratio (computed then as the ratio of the pore volume not filled by water at the start of storms to total pore volume) was much greater at Fudoji (~35%) than Maimai (~10%). We do not have complete information about the event water ratio of water supplied via transient groundwater. However, we found that the Fudoji to Maimai ratio of the event water percentage in peak hillslope discharge was 4–6:1, similar to the ratio of the possible maximum event water percentage of transient groundwater (4:1) and the change of water contents in mid-slope position soil layers (4:1). Thus, this intercomparison would suggest that soil drainable porosity is one of first-order controls on the event water percentage of discharged water from wet steep hillslopes. Previous studies in both hillslopes showed that the lateral preferential flow occurred above the soil–bedrock interface in both hillslopes, short-circuiting somewhat any complete mixing with the surrounding water in the soil matrix at lower hillslope (McDonnell, 1990; Uchida et al., 2003b). This means that because of the extension of the lateral preferential flowpath, the event water ratio of the hillslope discharge water is similar to that of transient saturated groundwater. This suggests that once lateral preferential flowpath extended, soil drainable porosity appears to be first order control on the event water ratio of discharged water from wet steep thin soil hillslopes.

What we learn from the functional comparison?

Before this functional intercomparison, we considered that both hillslopes had similar mechanisms of runoff generation, based on previous conceptual models by McDonnell (1990) for Maimai and Uchida et al. (2003a) for Fudoji. Early conceptual models of flow at both hillslopes featured new water infiltrating rapidly into permeable forest soils via vertical preferential flow paths to a soil–bedrock interface, where a perched groundwater zone formed. This produced the mixing of event water with large volumes of stored pre-event soil matrix water; the water in the (transient) saturated zone was then displaced rapidly downslope via soil pipes along the soil–bedrock interface. This conceptual model is now widely acknowledged and accepted in areas with steep slopes, thin soils and matrix hydraulic conductivities above maximum rainfall intensity (Tani, 1997; Sidle et al., 2000; Freer et al., 2002). We thus commenced this intercomparison with the assumption that if the rainfall amounts during a storm were the same, the growth of subsurface saturated areas at Fudoji and Maimai would be similar. Not unexpectedly, our intercomparison showed that vertical pore pressure profiles and their response to medium sized storms at mid-slope positions were similar (Figs. 7 and 8). Surprisingly however, our intercomparison showed that lateral pore pressure development differed markedly between sites, where the extension of the subsurface saturated area at Fudoji was considerably smaller than at Maimai. While the hydrograph separation at both sites concur qualitatively with the review conclusions of Buttle (1994) who summarized that channel stormflow in wet mountainous areas is supplied largely by pre-event water moving via subsurface routes to the channel, our comparison of Maimai and Fudoji suggests that soil drainable porosity is a major control on event water ratio in these environments. All other things being equal (topography, soil depth, vegetation and rainfall magnitude), larger drainable porosity leads to larger soil moisture deficits, allows more storm rainfall to be stored in the soil column and promotes less upslope expansion of subsurface saturation. Larger soil moisture deficits in large drainable porosity soil also leads the large event water ratio of subsurface saturated water. Since the subsurface saturated zone is often the primary source of storm runoff in wet steep hillslopes (McDonnell, 1990; Uchida et al., 2003a), the event water ratio of storm flow appears to be largely a function of soil drainable porosity.

Previous studies at Maimai reported that the bedrock was comprised of extremely low permeability material (firmly cemented conglomerates) (Rowe et al., 1994). Thus, previous studies at Maimai did not pay much attention to the role of bedrock in baseflow hydrological behavior (e.g., McDonnell, 1990). Conversely, at Fudoji, previous studies have shown the importance of bedrock for baseflow hydrological behavior. Uchida et al. (2003a) showed that the ratio of bedrock groundwater to hillslope discharge of Fudoji was about 0.82 for the baseflow periods using a two-component geochemical hydrograph separation. Also, Asano et al. (2002) clarified that the water flow from bedrock into soil layers at the slope base contributed to the formation of perennial saturated areas at the toe slope. Despite these previous efforts at each of our sites, we did not consider any information about bedrock hydrological characteristics that might be contained within the shape of baseflow recession curves (e.g., McDonnell, 1990; Uchida et al., 2003a) and MRT of hillslope discharge (Stewart and McDonnell, 1991; Asano et al., 2002). Although Asano et al. (2002) reported that the difference in MRT direction between Maimai and Fudoji, we did not know what might be the main cause of these differences. Our functional intercomparison presented in this paper suggests that all things being equal (topography, soil depth, vegetation and rainfall magnitude) higher bedrock permeability allows more bedrock aquifer storage (and release) which promotes more sustained baseflow, larger baseflow MRT, and vertical water aging from the soil surface to the aquifer.

Conclusions

Intercomparison of hillslopes and catchments in different hydrogeomorphic settings has been rare to date. This paper has presented a new functional intercomparison of two well studied hillslopes at Maimai, New Zealand and Fudoji, Japan. We examined how these hillslopes were similar or different as expressed by throughflow rate, tensiometric response, event/pre-event water partitioning, quickflow rates and mean residence time. By comparing two seemingly similar sites using records extracted with very similar rainfall amounts, intensities and antecedent wetness conditions, we were able to develop new insight into the first order controls on steep, wet and thin soil hillslope behavior and a more generalizable conceptualization of hydrological processes. We argue that these revelations would not come from basin- or hillslope-specific analysis. Specific findings for these two steep wet hillslopes include:

(1) Baseflow recession curves became gentle with the increase of the dynamic storage of the bedrock.
(2) Baseflow MRT was related to bedrock mean water storage.

(3) The direction of soil water aging was controlled by gross bedrock permeability. Water aged laterally downslope at Maimai where bedrock was largely impermeable and vertically at Fudoji (with no evidence of lateral aging) where bedrock was highly permeable.
(4) The quickflow rate for small to medium sized storms (total rainfall amounts 0–50 mm) was not affected by soil drainable porosity differences, but for events >50 mm total rainfall, drainable porosity was positively correlated with quickflow amount.

Finally, our functional intercomparison leads to the following testable hypotheses, ones we hope may be evaluated in future studies:

(5) The event water ratio of hillslope subsurface stormflow increases with increasing soil drainable porosity.
(6) The extension of subsurface saturated area is negatively related to drainable porosity soil.

The type of functional comparison that we advocate is often difficult with available records from gauged basins and hillslope studies. Differences in instrumentation and types of field observations complicate direct comparisons. While vegetation, climate and topography were very similar at our two sites, these may be features to compare and contrast with other site intercomparisons. We argue that further functional intercomparisons will yield much in the way of new insights into the first order controls on hillslope hydrological processes and quantifiable relationships between site conditions and hydrological behaviors.

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