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Stormflow generation in steep forested headwaters: a linked hydrogeomorphic paradigm

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Abstract:

Headwater catchments are sources of sediments, nutrients, and biota for larger streams, yet the hydrologic pathways that transport these materials remain unclear. Dynamics of stormflow generation related to landform attributes and antecedent rainfall were investigated in a steep forested headwater catchment at Hitachi Ohta Experimental Watershed, Japan. Such headwater catchments are deeply incised: the narrow riparian corridors have limited capacities to store and transmit water to streams. Storm runoff was monitored at several nested scales within the catchment: (1) 2·48 ha first-order drainage (FB); (2) incipient 0·84 ha first-order drainage (FA) comprized of two zero-order basins; (3) 0·25 ha zero-order basin (ZB); and (4) 45 m^2 hillslope segment (HS), including subsurface matrix flow (MF) and preferential flow (PF). Results from applied tracer and staining tests as well as observations of piezometric, tensiometric, and subsurface temperature responses were also employed to elucidate hydrologic pathways during storms. During the driest conditions, water yield from FB was only 1%; runoff occurred as saturated overland flow from the small riparian zone and direct channel interception. For slightly wetter conditions, subsurface flow from the soil matrix augmented stormflow. As wetness increased, two significant non-linear hydrologic responses occurred: (1) threshold response in geomorphic hollows (zero-order basins) where runoff initiated after an accumulation of shallow groundwater; and (2) self-organization and expansion of preferential flow pathways, which facilitate subsurface drainage. Stormflow increases observed during periods of increasing antecedent wetness depend upon temporal and spatial linkages and the unique hydrologic behavior of three components: (1) narrow riparian corridors; (2) linear hillslopes; and (3) geomorphic hollows. These linkages form the basis for an emerging hydrogeomorphic concept of stormflow generation for steep forested headwaters. Knowledge of stormflow response is critical to the assessment of management practices in these headwater areas as well as the routing of water and materials to larger stream systems. Copyright © 2000 John Wiley & Sons, Ltd.

KEY WORDS stormflow generation; hydrogeomorphic concept; preferential flow; self-organization; non-linear systems; geomorphic hollows; riparian zone; macropores; hillslope hydrology; forested catchments

INTRODUCTION

During the past few decades, different paradigms have emerged in attempts to explain stormflow generation in forested catchments. Considerable debate continues regarding the importance of various hydrologic

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pathways and source areas in headwater catchments as well as the interaction of these pathways and source areas with respect to peak runoff, solute transport, surface erosion, and mass wasting. Steep, deeply incised headwaters are particularly important in temperate, subtropical, and tropical forests. These small catchments comprise the source areas and transient sinks for water, nutrients, sediments, and biota that affect greater forest ecosystems and coastal waters worldwide (Tsukamoto, 1963; Dietrich and Dunne, 1978; Pearce *et al.*, 1986; Feger *et al.*, 1990; Wilson *et al.*, 1991). Geomorphic hollows or zero-order basins which often occur in headwaters tend to accumulate shallow groundwater and are sites of repeated landsliding in steep terrain (Dietrich and Dunne, 1978; Sidle, 1984; Tsukamoto and Ohta, 1988; Sidle and Tsuboyama, 1992; Montgomery *et al.*, 1997). Although these headwaters have typically been ignored in current land management schemes, their importance to overall ecosystem function and health is gradually being recognized.

The specification of flow paths in forested watersheds has been elusive because of difficulties in measuring subsurface flow. Instead many studies have employed indirect tracer techniques, particularly using natural isotopes (e.g., Pearce *et al.*, 1986; Moore, 1989; McDonnell *et al.*, 1991; Ross *et al.*, 1994). In steep forested catchments, subsurface flow generally exceeds overland runoff contributions. Tracer investigations have been useful in identifying the relative age of subsurface discharge, but inferences from such studies related to specific flow pathways have generated considerable confusion. Pathway specification based on end member mixing analysis invoked in these tracer studies is fraught with difficulties if intercompartmental mixing within the regolith occurs (DeWalle *et al.*, 1988; Luxmoore and Ferrand, 1993; Sidle *et al.*, 1995; Buttle and Peters, 1997; Noguchi *et al.*, 1997, 1999; Montgomery *et al.*, 1997; Tsuboyama *et al.*, 2000) or if spatial and temporal variabilities in tracer inputs are experienced (McDonnell *et al.*, 1991; Kendall and McDonnell, 1993; Cappellato *et al.*, 1993; DeWalle and Swistock, 1994).

Current stormflow generation models (Tsukamoto, 1963; Hewlett and Hibbert, 1967; Freeze, 1974; Pearce *et al.*, 1986; Beven, 1987; Burgess *et al.*, 1998) do not adequately specify flow pathways. For example, the variable source area concept of streamflow generation that has been widely used in forested catchments (Tsukamoto, 1963; Hewlett and Hibbert, 1967; Kirkby and Chorley, 1967) invokes a dynamic riparian source area that shrinks and expands in response to rainfall and fluctuating water tables. However, the model does not specify flow mechanisms or pathways functioning at different spatial scales. Later studies in moderate to gently sloping basins have cited saturation overland flow and return flow within broad, relatively flat riparian areas as the dominant stormflow generation mechanisms (e.g., Dunne and Black, 1970; Eshleman *et al.*, 1993; Fujieda *et al.*, 1997). Alternatively, Sklash and Farvolden (1979) attributed stormflow generation in such gently sloping basins to a groundwater 'ridging' effect. In steeper forested catchments, other dominant stormflow mechanisms have been cited, including: capillary fringe response (Gillham, 1984); pressure propagation due to entrapped soil air (Yasuhara and Marui, 1994); preferential flow associated with macropores (Mosely, 1979; Tsukamoto and Ohta, 1988; McDonnell, 1990; Tsuboyama *et al.*, 1994b), soil pipes (Jones, 1971; Pond, 1971; Kitahara and Nakai, 1992), deflection over bedrock (McDonnell *et al.*, 1996; Tani, 1997) and channelling through surface bedrock discontinuities (McDonnell *et al.*, 1996; Montgomery *et al.*, 1997; Noguchi *et al.*, 1999). These studies in steep forested terrain safely ignore Hortonian overland flow because of the high infiltration capacity of forest soils.

Although the importance of subsurface flow in steep forested hillslopes is generally acknowledged, the significance of preferential flow pathways as direct links to stormflow production is still questioned. Large discharges from soil macropores and pipes during natural and simulated storms have been measured or inferred at many sites worldwide (Whipkey, 1965; Mosely, 1979; Tsukamoto and Ohta, 1988; Wilson *et al.*, 1990; Kitahara and Nakai, 1992; Turton *et al.*, 1992). Studies with applied conservative tracers have shown that macropore systems increase in importance (Chen and Wagenet, 1992) and may expand during wetter conditions by interacting with surrounding mesopores (Luxmoore and Ferrand 1993; Tsuboyama *et al.*, 1994b). Such expansion may also include a lateral expansion of preferential flow networks by linking in an upslope direction (Tsuboyama *et al.*, 1994b).

Certain isotope and other natural tracer studies have questioned the importance of macropore flow because of proportionally high measured discharges of 'old' water during storm runoff (e.g. Pearce *et al.*, 1986; Sklash *et al.*, 1986). These studies that associated 'old' water discharge with matrix flow and 'new' water discharge with macropore flow may be misleading because of the potential for intercompartmental mixing in the hydrologically active regolith (DeWalle *et al.*, 1988; Luxmoore and Ferrand, 1993; Sidle *et al.*, 1995; Buttle and Peters, 1997; Noguchi *et al.*, 1997, 1999; Montgomery *et al.*, 1997; Tsuboyama *et al.*, 1998, 2000). Later investigations at the study area of Pearce *et al.* (1986) in New Zealand noted predominantly 'old' water discharging from macropores and hypothesized that continuous macropores purge stored 'old' water when shallow groundwater tables rise during storms and intersect these flow paths (McDonnell, 1990). However, the upslope connectivity of such macropore systems was not confirmed. Thus, many inferences related to 'old' and 'new' water estimations, particularly with regards to flow paths, can be questioned.

Insights into hydrogeomorphic linkages are needed to elucidate spatial and temporal attributes of flow paths that affect both headwater and downstream systems, including cumulative impacts of land use (Sidle and Hornbeck, 1991; Sidle *et al.*, 1995; Burgess *et al.*, 1998). As such, the objective of this research is to develop a conceptual model of stormflow generation based on transient hydrologic behavior and linkages among several discrete geomorphic components common to steep, deeply incised headwater catchments. This objective will be addressed by assessing results from surface runoff, subsurface flow (including preferential flow), piezometric and tensiometric response, applied conservative tracer tests, measurements of subsurface temperature fluctuations, and dye staining tests. Emphasis is placed on flow pathways and studies are conducted at different spatial scales to elucidate hydrologic mechanisms.

METHODS

Study site

The diverse field investigations were conducted within a 2·48 ha headwater catchment within Hitachi Ohta Experimental Watershed in Japan at a latitude of 36°34′N and a longitude of 140°35′E (Figure 1). Basin

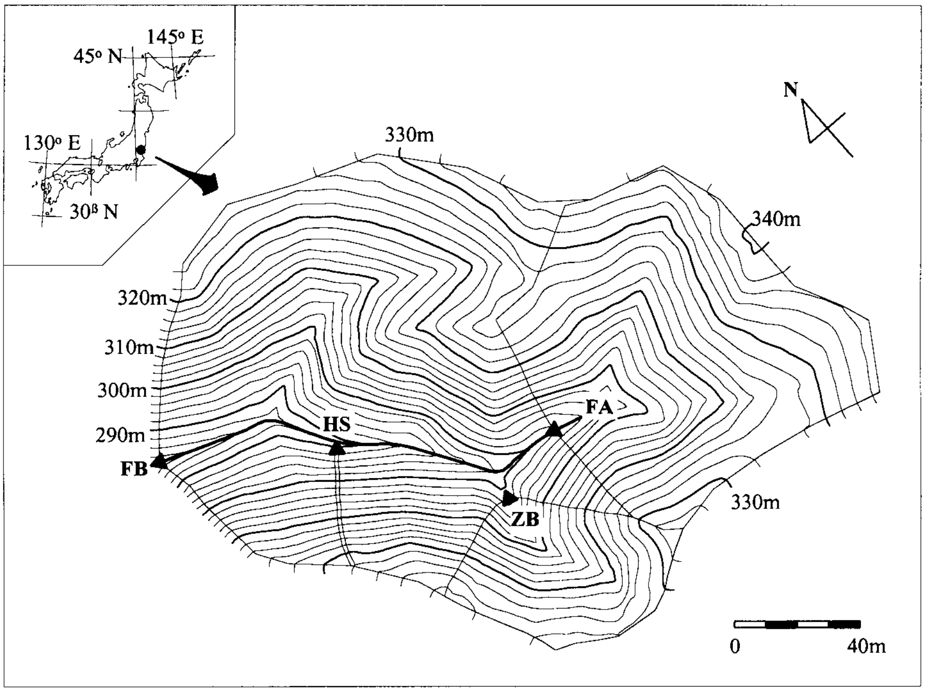

Figure 1. Topographic map of the 2·48 ha catchment at Hitachi Ohta Experimental Watershed, Japan. Nested sub-catchments FA (0·84 ha) and ZB (0·25 ha) as well as the 45 m^2 hillslope segment are shown

elevation ranges from 283 to 341 m. Before the 20th century, the watershed was covered with a natural hardwood forest. The site was clear-cut in the early 1900's and was replanted around 1920 with Sugi (*Cryptomeria japonica*) and Hinoki (*Chamaecyparis obtusa*). Hardwood and various understory species coexist in gaps within this relatively even-aged conifer stand.

Soils, derived from volcanic ash, are well aggregated with a thin, porous organic horizon and have abundant small (2–30 mm diameter) macropores derived largely from decayed root channels and subsurface erosion. The high infiltration capacity and hydraulic conductivity of soils, shallow depth to bedrock, and steep slopes (25–51 °) promote lateral subsurface flow to the exclusion of overland flow (Sidle and Tsuboyama, 1992; Tsuboyama *et al*., 1994b; Sidle *et al*., 1995; Noguchi *et al*., 1999). Average annual precipitation is 1459 mm with two major rainfall seasons: early summer Baiu season and autumn typhoon season. Stormflows during the 1992 typhoon season were continuously monitored in a series of nested hydrologic units consisting of: (1) 2·48 ha first-order drainage (FB); (2) incipient 0·84 ha first-order drainage (FA); (3) 0·25 ha zero-order basin (ZB); and (4) the soil matrix (MF) and preferential flow path (PF) components of a 45 m^2 hillslope segment (HS).

Hitachi Ohta is a typical steep, deeply incised forested basin (Pearce *et al*., 1986; Tsukamoto and Ohta, 1988; Sidle *et al*., 1995; Tani, 1997). The perennial stream channel is incised to bedrock and the total width of the riparian zone ranges from 1·0 to 3·6 m. Soils in this narrow riparian corridor are very shallow and nearly saturated with little water storage capacity. Thus, the riparian zone has a limited capacity to generate saturated overland flow during storms compared to wider corridors in more gently sloping basins (Dunne and Black, 1970; Fujieda *et al*., 1997; Burgess *et al*., 1998). During storms and applied tracer tests there was no evidence of any saturated overland flow emanating from the base of the hillslope (i.e., adjacent to the riparian zone). Average channel gradient is 8·7 ° and sideslope gradients range from 8·5 to 50·6 ° (mean gradient of 32·4 °).

The 0·25 ha zero-order basin (ZB) contains relatively shallow soils, especially in the trough of the geomorphic hollow (Tsuboyama *et al*., 1994a). Forest basin A (FA) is actually comprized of two zero-order basins or hollows that converge about 19 m upstream of the gauging weir of FA. The channel is perennial only about 10 m upstream of the gauging weir (Figure 1). Thus, about 90% of the catchment area for FA is contained in these two geomorphic hollows. Soils in FA are approximately 0·7 m deeper than in ZB (Tsuboyama *et al*., 1994a). Three other zero-order basins exist in FB. Neither discharge nor extensive surveys of soil depth are available for these geomorphic hollows.

Field methods

Streamflow was continuously recorded at calibrated 60 ° V-notch gauging weirs at the outlet of FB and RA. Runoff was also measured at a similar installation at the outlet of ZB where discharge was only observed during storm events. Eight recording piezometers were installed down to bedrock along the longitudinal axis of ZB (Sidle and Tsuboyama, 1992; Tsuboyama *et al*., 1994a, 2000). Additionally, soil temperature profiles (several depths) at two locations along the axis of ZB were monitored during selected storms (Tsuboyama *et al*., 1998, 2000).

A pit was excavated down into bedrock at the base of a relatively linear hillslope segment. The pit was used both for a small-scale tracer study where chloride was applied during different antecedent moisture conditions 2 m upslope of the excavation (Tsuboyama *et al*., 1994b), and for monitoring the outflow from both the soil matrix (MF) and selected macropore groups (Sidle *et al*., 1995). In this paper, we commonly refer to the combined discharge from all preferential flow pathways (i.e., the three macropore groups plus the organic-rich horizon of the soil) as PF. Matric potential at several depths in the soil profile upslope of the pit was measured by recording tensiometers during the tracer tests and selected natural storms (Tsuboyama *et al*., 1994b).

The slope length to the watershed divide above the pit is 49 m with an average gradient of 39 °. The estimated contributing area of the pit based on pit width, slope length, and a topographic survey is 45 m^2. To minimize the effects on the hydrologic contributing area, the pit is assumed to collect outflow that would occur along a streambank even though it is located about 0·5 m outside of the riparian zone. The potential of such an open pit to distort hydrologic potentials upslope (e.g., Knapp, 1973) is acknowledged. Additionally, the potential variability in subsurface discharge along the base of a hillslope is recognized (e.g., Woods and Rowe, 1996). The focus of tracer and staining tests at this 1·2 m wide soil pit was to evaluate specific small-scale flow pathways rather than to attempt to capture the subsurface flow response for the entire hillslope.

Discharge measurements from both the small catchments and soil pit focus on the 1992 typhoon season. While other temporal runoff data were available for these nested catchments, the 1992 season represented a rather unique situation because very little rainfall occurred between the end of the Baiu season and the onset of the typhoon season. Thus, the temporal sequence of storms during the 1992 typhoon season presents a progressive increase in antecedent wetness. Storm discharge from all watershed components is calculated on a unit contributing area basis and expressed in mm h^{-1} of runoff to facilitate direct comparisons. Precipitation was measured by recording and storage rain gauges located in the northern portion of the greater watershed (Sidle *et al*., 1995).

In 1993, following tracer and hydrometric investigations at the soil pit, a combination of staining agents was used to trace preferential flow pathways in the hillslope segment (Noguchi *et al*., 1997, 1999). Approximately one pore volume of a dilute white paint solution was applied at the line irrigation source (located 2 m slope distance above the pit face). After dilute paint application, the 2 m segment of the hillslope was carefully dissected in 10 cm intervals (slope distance) to ascertain the routing of preferential flow in the soil and weathered regolith (Noguchi *et al*., 1999). Additionally, individual macropores >2 mm in diameter were "traced" upslope during excavation (starting at the original pit face) by spraying coloured powdered chalk into the macropore cavities (Noguchi *et al*., 1999). The combination of these two staining techniques allows for an interesting comparison of actual preferential flow paths (white paint staining) with macropore location and distribution (coloured chalk).

HYDROLOGICAL RESPONSE

Water yield patterns

To evaluate the effects of antecedent moisture on overall hydrologic response in FB, rainfall and runoff data for all significant storms during the 1992 typhoon season were analysed. Storms were included if total precipitation exceeded 10 mm and maximum 30-min rainfall intensity exceeded 4 mm h^{-1}. Additionally, sequential storms were separated by at least a 6-h period of no rainfall to be considered discrete events. These criteria produced a sequence of seven storm events beginning on 19 September and ending on 20 October (Table I). Antecedent wetness as indexed by 30-day antecedent rainfall (API_{30}) ranged from 11 mm at the onset of the typhoon season to 187 mm prior to the last storm. This progressive increase in antecedent moisture presents a unique opportunity to evaluate the effect of this important hydrologic variable on runoff response at different scales within the catchment. Maximum 30-min rainfall intensity for the seven storms ranged from 4·6 to 23·6 mm h^{-1}.

Table I. Rainfall characteristics for seven sequential storms during the 1992 typhoon season along with corresponding runoff from Forest Basin B, Hitachi Ohta, Japan

Storm date	Storm length (min)	Total precip. (mm)	Max. 30-min int. (mm h^{-1})	API_{30} (mm)	Runoff from FB (mm)
19 September	930	11·7	4·6	11·0	0·117
26 September	1390	19·5	6·8	21·6	0·316
29 September	90	12·2	16·8	41·1	0·348
30 September	570	23·1	8·4	55·6	1·113
8 October	900	61·4	18·6	88·8	7·068
9 October	110	15·6	23·6	150·2	1·779
20 October	1970	48·0	10·4	187·1	9·383

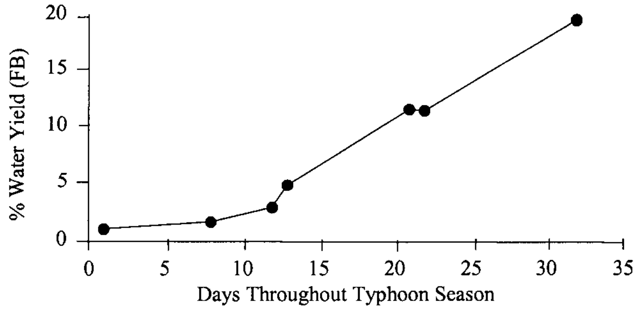

Figure 2. Temporal changes in water yield from basin FB throughout the 1992 typhoon season

Water yields from FB were calculated as the percentage of total storm runoff compared to total precipitation, not adjusted for interception losses. Interception losses from FB are typically 10–15% of total rainfall during summer storms. Baseflow was separated from the runoff hydrographs by projecting a linear separation of slope 2 $m^3 h^{-2} km^{-2}$ from the onset of storm runoff (Hewlett and Hibbert, 1967). Water yield at FB progressively increased from only 1% at the onset of the typhoon season (driest conditions) to almost 20% during the final storm (Figure 2). This increased hydrologic response reflects the cumulative effects of antecedent moisture on storm runoff production.

Riparian zone response

The contribution of the riparian corridor to stormflow, including direct channel interception, was assessed throughout the storm season assuming all rainfall on this corridor would be completely converted to streamflow. Given the narrow dimensions and shallow soil depths in the riparian zone together with the bedrock controlled channel, this assumption appears logical. As noted previously, runoff from FB was only 1% of total rainfall during the first storm of the 1992 typhoon season. However, this small runoff occurred rapidly and coincided with the rainfall hyetograph (Figure 3a). The entire runoff volume from this small storm could be accounted for by saturation overland flow from the narrow riparian corridor and direct channel interception (Figure 4). The 2·5 m wide $\times$105 m long corridor could produce 3·0 m^3 of runoff assuming all rainfall on the corridor was converted to saturated overland flow. Total storm runoff from FB was almost identical: 0·117 mm or 2·9 m^3. Only trivial amounts of subsurface matrix flow (MF) were measured from the soil pit and no response was observed in any of the zero-order basins (Figure 3a). As the season progressed, geomorphic components outside of the riparian zone contributed to increases in water yields in FB (Figure 3b, c, d). Thus, the relative contribution of the riparian zone to stormflow declined rapidly. After the fourth storm (30 September 1992), riparian contributions were $<$10% of the runoff hydrograph from FB (Figure 4). By the end of the typhoon season, the riparian corridor contributed only 5·4% of the stormflow response. These results show that narrow riparian corridors in dissected mountain topography which have small water storage potentials cannot deliver sufficient saturated overland flow to account for wet season stormflow response. Subsurface transport from adjacent hillslopes together with discharge from zero-order basins is clearly necessary to explain observed discharges from FB during later season storms (Table I).

Hillslope response

Hillslope drainage at the excavated soil pit was directly related to antecedent wetness. Within this discussion, we emphasize flow pathways at the hillslope scale and recognize the variability in such pathways across the watershed (e.g., Woods and Rowe, 1996). Thus, we do not attempt to calculate catchment-wide estimates of subsurface flow based on such a small hillslope segment, but rather derive relative estimates of flow response and insights into flow pathways for our study site. During the driest conditions (19 September storm; Figure 3a), subsurface drainage from the hillslope segment was negligible; only 3·4% of the storm

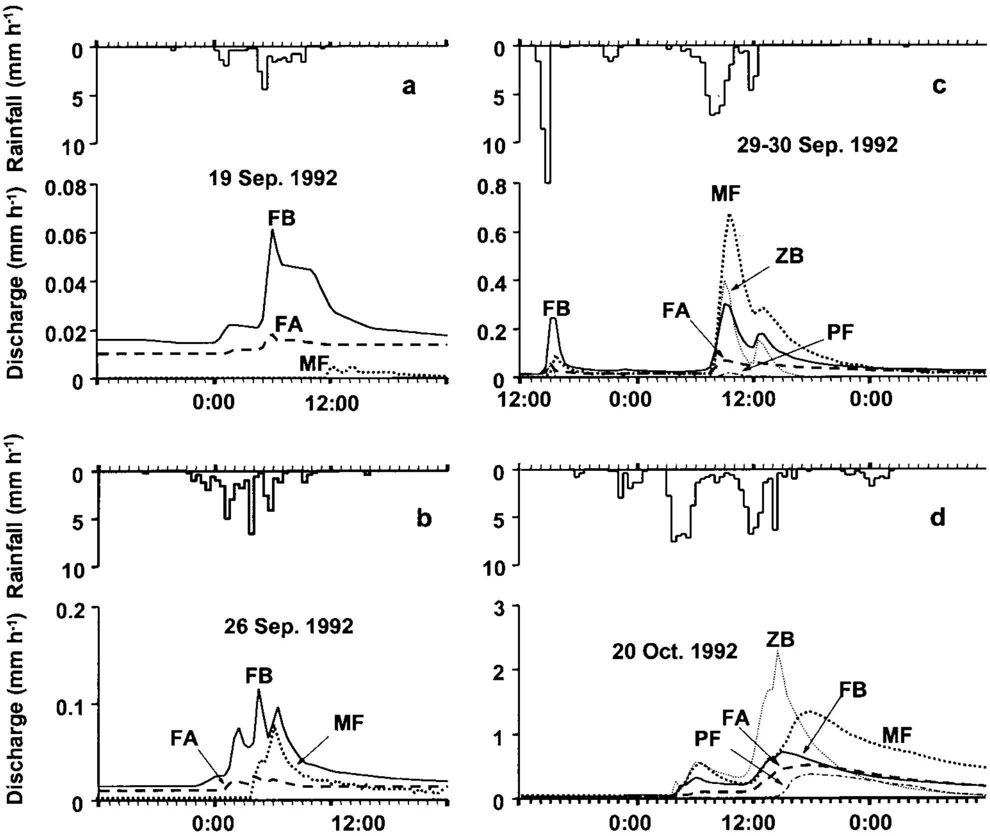

Figure 3. Storm hydrographs in the four nested drainage areas at Hitachi Ohta during selected typhoon storms in 1992: (a) 19 September; (b) 26 September; (c) 29 September and 30 September; and (d) 20 October. Subsurface flow from the hillslope segment was separated into matrix flow (MF) and preferential flow (PF). Storm characteristics, total runoff, and antecedent precipitation are given in Table 1

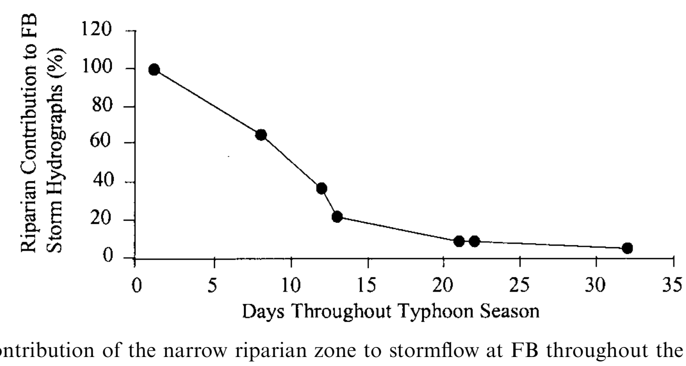

Figure 4. Percent contribution of the narrow riparian zone to stormflow at FB throughout the 1992 typhoon season

runoff from FB based on equivalent areas. No preferential flow occurred. As antecedent wetness increased, the proportion of subsurface flow contributing to storm runoff increased dramatically. Moreover, by the 30 September storm (Figure 3c), preferential flow comprized a small but measurable portion of the subsurface flow ($<2\%$ of subsurface flow). Later in the typhoon season, preferential flow accounted for up to 25% of subsurface flow (Figure 3d). This increase in preferential flow is attributed to an expansion of macropore networks in time and space. Such expansion may occur through a series of complex mechanisms that allow these systems to become self-organized as antecedent moisture increases.

The contributing slope length for subsurface flow from the soil matrix during various storms was estimated by the product of average pore velocity [$\sim$0·5 m h^{-1}; calculated from tracer tests (Tsuboyama *et al.*, 1994b)] and lag time of the mass centroid of the rainfall hyetograph to the mass centroid of the subsurface flow hydrograph. According to these conservative estimates, the lower 1·8 to 8·8 m of hillslope contributed matrix flow during storms; greater contributing slope lengths were associated with wetter antecedent conditions. The small travel distances for matrix flow estimated for early season storms (1·8 to 3·6 m) would be consistent with recharge to the riparian zone described by the variable source area concept (Tsukamoto, 1963; Hewlett and Hibbert, 1967; Kirkby and Chorley, 1967). Measured dye velocities (Noguchi *et al.*, 1999) in the same hillslope suggest that maximum macropore velocity may be up to 20 times higher than average pore velocities derived from tracer tests. Such estimates, coupled with the non-linear flow response of macropore systems, attributed to their self-organized criticality, suggest that preferential flow pathways have the potential to extend long distances upslope during wet conditions.

Zero-order basin response

Zero-order basins are important hydrogeomorphic components of steep terrain. Not only do they reflect the evolution of hillslope processes, but also they act as a shallow groundwater reservoir for headwater stormflow generation (Anderson and Burt, 1978; Sidle, 1984; Tsukamoto and Ohta, 1988; Montgomery *et al.*, 1997; Burgess *et al.*, 1998). During the first two storms of the 1992 typhoon season, no runoff was generated from ZB. Minor runoff was measured during the third storm (Figure 3c), coinciding with a wedge-shaped accretion of shallow groundwater from the base of the hollow. Such wedge-shaped accumulations have been observed during steady-state or gradually changing groundwater conditions (Sidle, 1984; Sidle and Tsuboyama, 1992; Tsuboyama *et al.*, 1994a). In succeeding storms, runoff from ZB progressively increased (Figure 3c, d). During wetter conditions, the groundwater profiles were approximately parallel to the hillslope (i.e., not wedge shaped) just after the storm peak. These findings indicate that a hydrologic threshold must be reached prior to runoff generation from zero-order basins. This threshold is related to soil depth and can be monitored by the accretion of shallow groundwater in the slope.

Basin FA is essentially two zero-order basins that converge into an incipient first-order channel just upstream of the gauging station. Thus, flow measured at FA primarily represents the aggregated flow of these two zero-order basins with minor additional baseflow and stormflow inputs. Soils in FA are typically up to 0·7 m deeper than in ZB, particularly along the upper axes of FA. Stormflow from the two hollows in FA was not significant until the last storm of the 1992 typhoon season (Figure 3d). The response lag reflects the additional time needed to recharge the deeper soils in FA. Even by the last storm of the typhoon season (API_{30} = 187 mm), storm runoff from FA was less than half of that measured from ZB on an equivalent area basis (Figure 3d). The degree of water storage and release from zero-order basins appears to be highly influenced by soil depth.

The effect of different soil depths in basins ZB and FA on hydrologic response can be seen by plotting water yields against API_{30} for the seven typhoon storms of 1992 (Figure 5). Clearly, a hydrologic threshold is reached in ZB after API_{30} exceeds $\approx$40 mm; water yield increases rapidly at first and more moderately thereafter. In FA, water yield begins to slowly increase in the API_{30} range of $\approx$55–85 mm (Figure 5). Since this increase is very small, it is likely related to the drainage from the lower, perennial portion of the catchment (i.e., the $\approx$10% of FA located below the two tributary zero-order basins). Water yield from FA only increases sharply once API_{30} reaches $\approx$150 mm; this threshold may more likely be related to hydrologic response from the two zero-order basins. While it is difficult to relate the spatially variable soil depth in ZB and FA quantitatively to stormflow responses, it appears reasonable that the difference in zero-order basin API_{30} thresholds between ZB and FA ($\approx$110 mm) could satisfy the additional storage requirements in the deeper soils of FA. Such generalizations will require collection of data in additional seasons and zero-order basins of varying depths. It is clear that these hollows, which are sometimes remote from the channel,

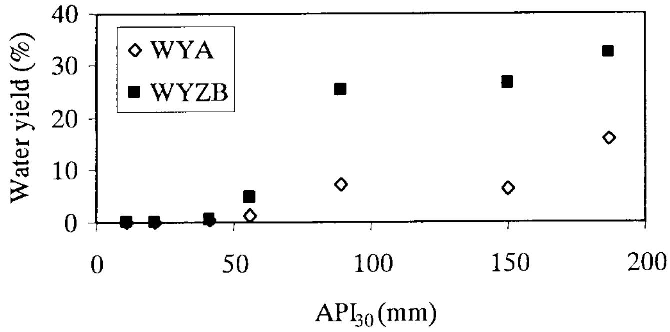

Figure 5. The influence of soil depth differences in ZB (shallow soils) and FA (soils ≈ 0·7 m deeper) on the API_{30} threshold required to initiate runoff from the zero-order basin portion of these drainages

provide important runoff sources when they become connected to the stream during wet antecedent conditions.

HYDROLOGICAL LINKAGES

Preferential flow paths — hillslope scale

Pathways of subsurface flow in hillslopes reflect a complex interaction among the following attributes: antecedent wetness, macroporosity, bedrock characteristics, topography, soil organic matter, perched water tables, matrix permeability, and soil depth. In our site, as is the case in many forested catchments, no overland flow on relatively planar slopes was observed even during the largest and most intense storm events. Additionally, no saturated overland flow emerged above the base of the hillslope. Thus, groundwater 'ridging' (e.g., Sklash and Farvolden, 1979) does not appear to be a viable explanation for any observed stormflow generation at Hitachi Ohta.

Macropore flow generally emerged during the peak and recession limbs of larger storm hydrographs (Figure 3c, d); for lower intensity storms, macropore flow emerged later on the recession limb. These slightly delayed and sometimes pulsating macropore responses (Figure 6) indicate that some hydrologic conditioning occurs that cannot be explained by a simple accretion of groundwater at the lithic contact. Expansion of preferential flow pathways was also noted in Cl^- tracer tests conducted during wet antecedent conditions at the same hillslope site (Tsuboyama *et al.*, 1994b; Sidle *et al.*, 1994). The tracer was appreciably diluted in hydrologically active macropores, thus clearly showing a connectivity upslope of the tracer source. Effective pore volumes calculated from Cl^- breakthrough data were significantly less than values measured *in situ* with tensiometers. Tensiometric readings obtained at several positions and depths in the hillslope segment were rather insensitive to subsurface flow response, particularly preferential flow (Tsuboyama *et al.*, 1994b). Large changes in subsurface discharge were observed during different antecedent rainfall conditions; such conditions could not be captured by changes in matric potential measured in a point grid (Tsuboyama *et al.*, 1994b). It is reasonable to assume that tensiometric readings will not reflect the complex nature of the preferential flow paths, particularly considering the spatial distribution of proposed nodes of interconnection for preferential flow systems.

Comparison of seasonal hydrometric observations (Sidle *et al.*, 1995) from the hillslope segment with results from applied tracer tests (Tsuboyama *et al.*, 1994b), staining tests (Noguchi *et al.*, 1999), tensiometric measurements (Tsuboyama *et al.*, 1994b), and macropore mapping (Noguchi *et al.*, 1997) provide insights into hydrologic linkages at the hillslope scale. Although individual macropores are short ($\leqslant$62 cm), they are often interconnected by physical interaction (see pathway 3, Figure 7), through porous zones of organic matter (pathway 4, Figure 7), exchange with shallow bedrock fractures (pathways 6 and 7, Figure 7), and contact with perched groundwater at a lithic boundary (pathway 5, Figure 7). The staining experiment at the

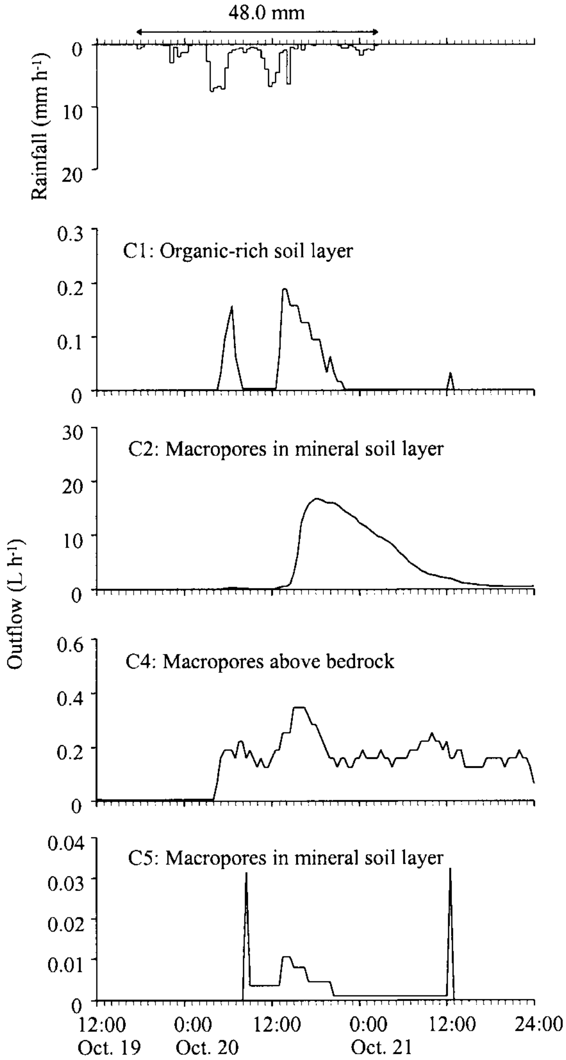

Figure 6. An example of rather erratic preferential flow discharge during the 20 October 1992 storm. Discharge from the most active macropores (C2) was delayed, indicating that "hydrologic conditioning" was needed prior to contributions from this important pathway. Other preferential flow pathways, including the organic-rich horizon, behaved more erratically, indicating discharge from smaller but discrete pathways

same hillslope segment revealed that certain macropores interacted with the surrounding mesopores (pores <1 mm that drain by gravity) to enlarge these preferential flow paths during wet conditions (pathway 2, Figure 7) (Noguchi *et al.*, 1999). This finding corroborated speculations from previous tracer tests (Sidle *et al.*, 1994; Tsuboyama *et al.*, 1994b) as well as theoretical investigations (Chen and Wagenet, 1992; Luxmoore and Ferrand, 1993) and physical evidence during storms. Additionally, preferential flow occurred above the B horizon in the organic-rich soil for short distances (pathway 1, Figure 7). Our investigations also indicate the importance of bedrock or substrate topography as a control over subsurface flow (pathway 8, Figure 7) (Tsukamoto and Ohta, 1988; Sidle *et al.*, 1995; McDonnell *et al.*, 1996; Montgomery *et al.*, 1997; Tani, 1997; Noguchi *et al.*, 1999), particularly preferential flow pathways. Findings from dye staining tests show that the scale at which variations in bedrock topography influence subsurface flow paths may be very small, i.e., $\ll 1$ m; a much smaller scale than previously inferred (McDonnell *et al.*, 1996).

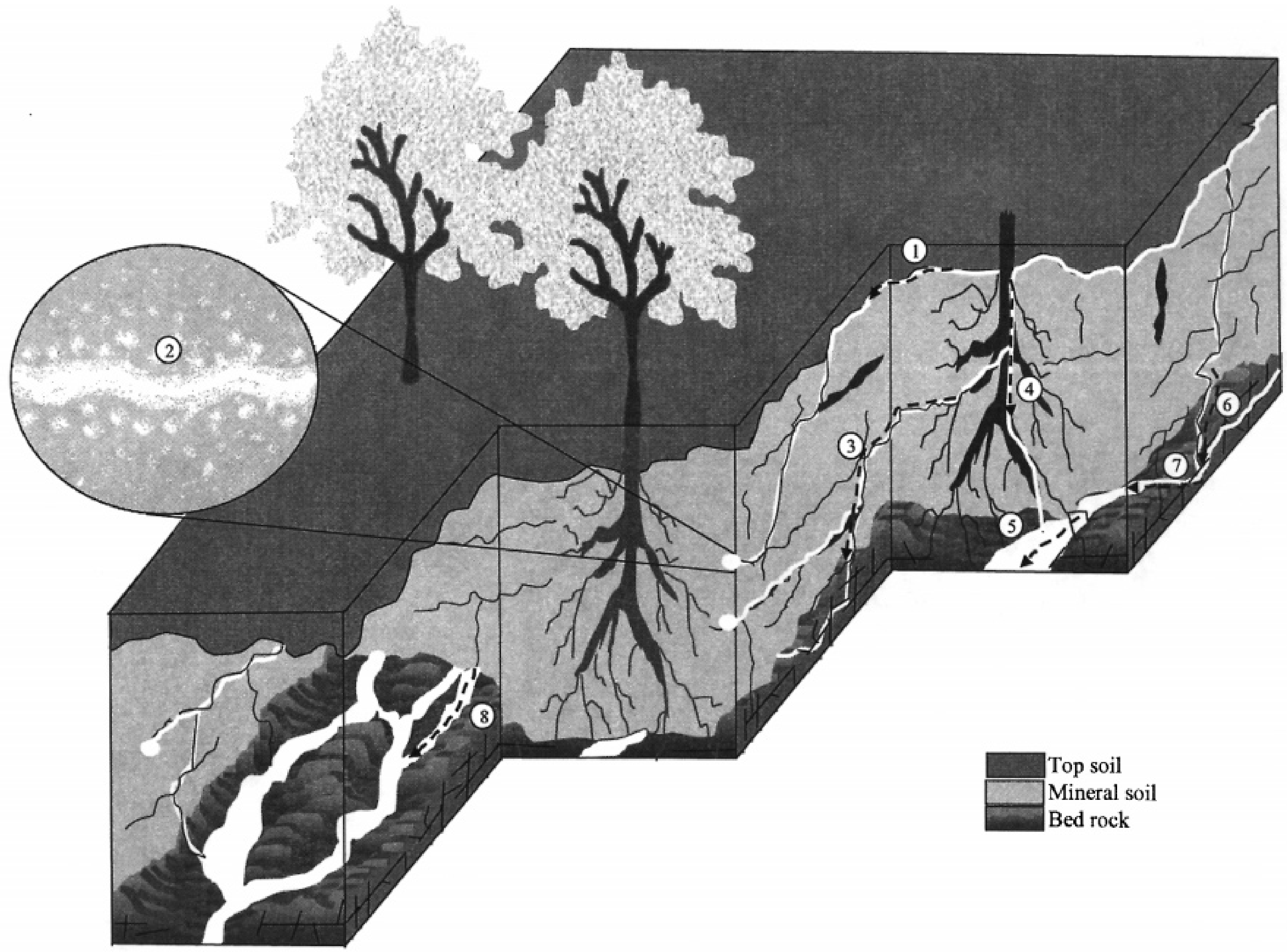

Figure 7. A conceptual model of preferential flow pathways in a hillslope segment based on staining, tracer, and hydrometric tests conducted at Hitachi Ohta. Pathways include (1) preferential flow occurring above the B horizon in the organic-rich soil; (2) macropores interacting with the surrounding mesopores (pores <1 mm that drain by gravity) to enlarge these preferential flow paths during wet conditions; (3) connection of individual macropores by physical interaction; (4) connection through porous zones of buried organic matter, including decayed roots; (5) contact with a perched groundwater at the bedrock or other lithic boundary; (6) preferential flow into and through shallow bedrock fractures; (7) exfiltration of water from shallow bedrock fractures; and (8) flow over microchannels on the surface of bedrock or other substrate (i.e., substrate topography control). White shaded zones represent possible linked or connected preferential flow paths; broken lines delineate specific 'connected' pathways

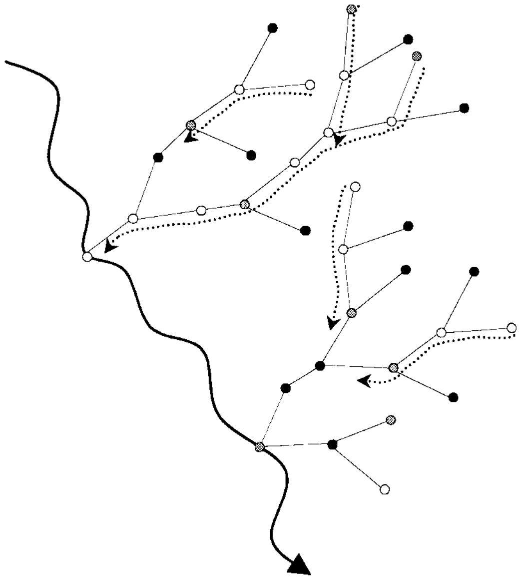

Figure 8. Hypothetical preferential flow network showing nodes of possible pathway interconnections, where: ○ indicates a node that can easily be switched on with only moderate antecedent moisture; ◎ indicates a node that requires very wet conditions to facilitate macropore segment interconnection; and ● indicates a node that essentially will not facilitate preferential flow. Several potential preferential flow travel paths are shown for an example with very wet antecedent conditions (i.e., both ○ and ◎ are switched on)

The concept of linkages among individual short macropores as well as other preferential flow paths via a series of nodes is proposed. Such nodes of interconnection seem to form a backbone of switching mechanisms that determines macropore network expansion. At each junction, the on/off switch appears to be regulated by local soil moisture conditions and is strongly influenced by soil depth, permeability, pore size, organic matter distribution, and substrate topography. Once a node is turned 'on', it becomes an intrinsic part of the preferential flow pathway. The spatial interconnection of macropores at our site was evidenced by several independent field methods and is consistent with results from theoretical (Chen and Wagenet, 1992; Luxmoore and Ferrand, 1993) and other field studies (Tanaka *et al.*, 1988; Tsukamoto and Ohta, 1988; Moore, 1989; McDonnell, 1990; Montgomery *et al.*, 1997; Tani, 1997). A simplified example of a preferential flow network with three levels of nodal switching functions shows that various connective lengths of macropores can occur for the same site wetness (Figure 8). In such a case, nodes that are easily activated may include direct physical linkages between macropores, buried pockets of organic matter, and direct interaction of preferential flow systems with the lithic boundary. Nodes that require very wet conditions to facilitate preferential pathway linkages may include connection through mesopores or pockets of permeable soil. Other nodes may not promote preferential flow (i.e. solid circles in Figure 8); thus subsurface flow would be restricted to matrix flow. Shallower soils should promote preferential pathway linkages because zones of saturation would more likely develop throughout the soil profile. There would be many combinations of such networks of interconnection operating at the hillslope scale as well as in zero-order basins.

Identification of potential connecting nodes of preferential flow systems in the field is problematic. One possibility for simulating such systems would be to generate realistic synthetic distributions of potential flow paths at a given site. In our case, this would include distributions of decayed and live root systems, subsurface erosion channels, fractures in surface of the bedrock, bedrock microtopography, distribution of buried rotten wood, and evidence of hydrologic discontinuities.

Macropores developed in many humid forest soils are quite different in morphology (Noguchi *et al.*, 1997, 1999) and hydrologic behavior (Tsuboyama *et al.*, 1994b; Sidle *et al.*, 1995) than large subsurface soil pipes (Jones, 1971; Pond, 1971; Kitahara, 1992). In pipe-dominated systems, preferential flow is confined by the

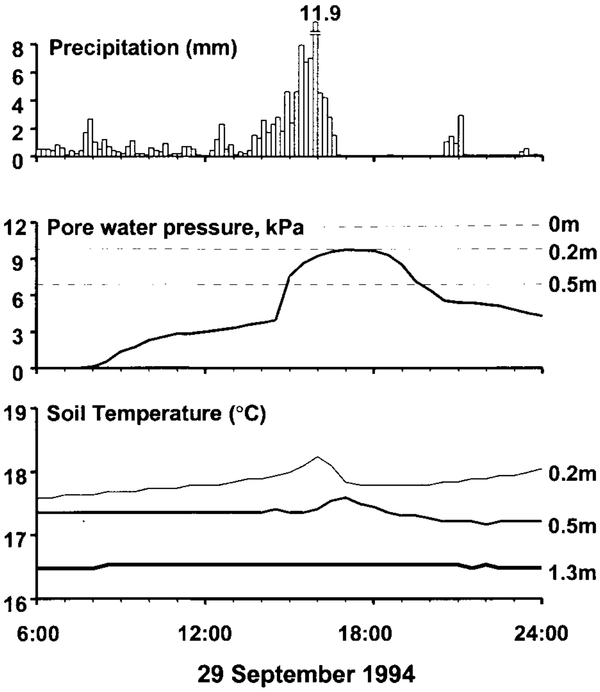

Figure 9. Pore water pressure and thermal fluctuations in the upper portion of the zero-order basin (ZB) during one of the largest (132 mm total rainfall) and most intense (maximum 1-h intensity = 40 mm h^{-1}) storms ever recorded. Soil temperatures in this upper slope profile are specified for 20, 50, and 130 cm depths. Broken lines represent depth below ground level for pore water pressure distributions

pipe morphology; conversely, in many forest soils the macropore network is highly dynamic, becoming self-organized in some hillslope segments as antecedent moisture increases. This self-organizing mechanism would also explain the high spatial variability in subsurface flow noted at some sites (Pearce *et al.*, 1986; McDonnell, 1990; Woods and Rowe, 1996). Indeed, we observed that one of the unmonitored soil pits in FB yielded considerably less subsurface flow during storms.

Zero-order basin to channel linkages

The hydrologic linkage between zero-order basins and streams is needed to specify the timing of runoff contributions from these often remote geomorphic features. The identification of a non-linear (i.e., threshold) response in ZB related to groundwater accretion is significant. Detailed synoptic measurements of stormflow, shallow groundwater response, and soil temperature fluctuations in ZB confirm that development of a groundwater table along the axis of the hollow facilitates the source area linkage from upslope storage to downslope supply needed to augment discharge. This linkage, especially during very wet conditions, is not necessarily from the lower to upper slope position as indicated by the very rapid piezometric response in the uppermost portions of ZB (Figure 9). Such rapid response during very wet conditions provides evidence of convergent flow facilitated by preferential flow pathways (Sidle and Tsuboyama, 1992; Tsuboyama *et al.*, 1994b). Additionally, rapid piezometric response may be facilitated in wet soils by a pressure wave associated with a spike in rainfall intensity that rapidly converts wet unsaturated soil to saturated conditions (Torres *et al.*, 1998).

To further elucidate the hydrologic linkage between hollows and streams, subsurface thermal fluctuations are compared with storm runoff and piezometric response. Short-term fluctuations in soil temperature at the 20 and 50 cm depths were recorded during an intense rainstorm with wet antecedent conditions at two slope positions in ZB. These rapid thermal fluctuations, which occurred even during saturated or artesian conditions, are believed to have resulted from the mixing of colder residual groundwater with warmer infiltrating rainwater (Figure 9). The rapid decline in soil temperature at the upper site (20 cm depth) is likely attributed to a shift in the dominant flow process from infiltration to throughflow. Such throughflow processes (likely facilitated by preferential flow paths) together with resultant rapid groundwater rise could induce mixing in convergent hollows. This abrupt change from an increase to a decrease in soil temperature was also noted at other locations. The measured short-term thermal fluctuations together with the evidence presented from macropore staining and tracer investigations (Tsuboyama *et al*., 1994b; Sidle *et al*., 1994; Noguchi *et al*., 1997, 1999), suggest that inter-compartmental mixing occurs within the soil profile, often incorporating newly infiltrated rain water. Such mixing would invalidate the assumption of temporal invariance of compartmental water signatures, commonly used in end member mixing analysis studies (Pearce *et al*., 1986; Moore, 1989; McDonnell, 1990; McDonnell *et al*., 1991; Eshleman *et al*., 1993; Elsenbeer *et al*., 1995) where inferences related to flow pathways have sometimes been drawn.

The abrupt transition from recharge to discharge measured in ZB and supported by detailed synoptic studies elucidates the temporal hydrologic contributions of these remote basins to the catchment scale. The much more delayed hydrologic response from FB reflects the greater water storage capacity of the deeper soils in this basin that is largely comprized of two geomorphic hollows. Although more research is needed to better understand the relationship between soil depth in hollows and hydrologic response, deeper soil mantles are clearly associated with a lagged response.

CONCEPTUAL HYDROGEOMORPHIC MODEL

A conceptual hydrogeomorphic model for steep, deeply incised headwater catchments is presented based on our findings at Hitachi Ohta Experimental Watershed. This paradigm illustrates the spatially distributed stormflow responses for a temporal sequence of increasing antecedent moisture (Figure 10). During dry conditions, water yields are low and most of the stormflow is generated from channel interception and riparian saturated overland flow (Figure 10a). As wetness increases, flow from the soil matrix of the lower hillslope augments the peak and recession limb of the storm hydrograph (Figure 10b). With increasing wetness, this subsurface flow expands over greater slope distances, preferential flow commences, and moisture thresholds in zero-order basins with shallow soils are reached, triggering runoff (Figure 10c). During very wet conditions, most zero-order basins become linked to the channel system, preferential flow systems expand and significantly enhance subsurface flow, and overland flow contributions from the riparian zone become trivial (Figure 10d). This model is consistent with findings from tracer (Pearce *et al*., 1986; McDonnell, 1990; Elsenbeer *et al*., 1995) and recent topographic modelling approaches (Beven, 1987; McDonnell *et al*., 1996). However, it does refute certain inferences from these studies related to subsurface drainage mechanisms and preferential flow paths.

SUMMARY AND CONCLUSIONS

Here we summarize the results from hydrometric, applied conservative tracer, dye staining, tensiometric, piezometric, and subsurface thermal response tests at Hitachi Ohta Experimental Watershed. Based on these investigations, an improved understanding of stormflow generation in deeply incised headwater catchments is emerging. As antecedent conditions change from dry to wet, the relative proportion of storm runoff attributed to saturated overland flow from the narrow riparian zone decreases abruptly. Conversely, subsurface flow increases as antecedent moisture increases. Zero-order basins exhibit a non-linear response to increasing wetness: they begin to yield storm runoff once a threshold of antecedent moisture has been reached. This threshold appears to be directly related to soil depth. It is hypothesized that as antecedent wetness increases, preferential flow systems begin to self-organize into complex networks involving discrete macropores, lithic contacts, bedrock fractures, buried organic matter, and subsurface topography. From this

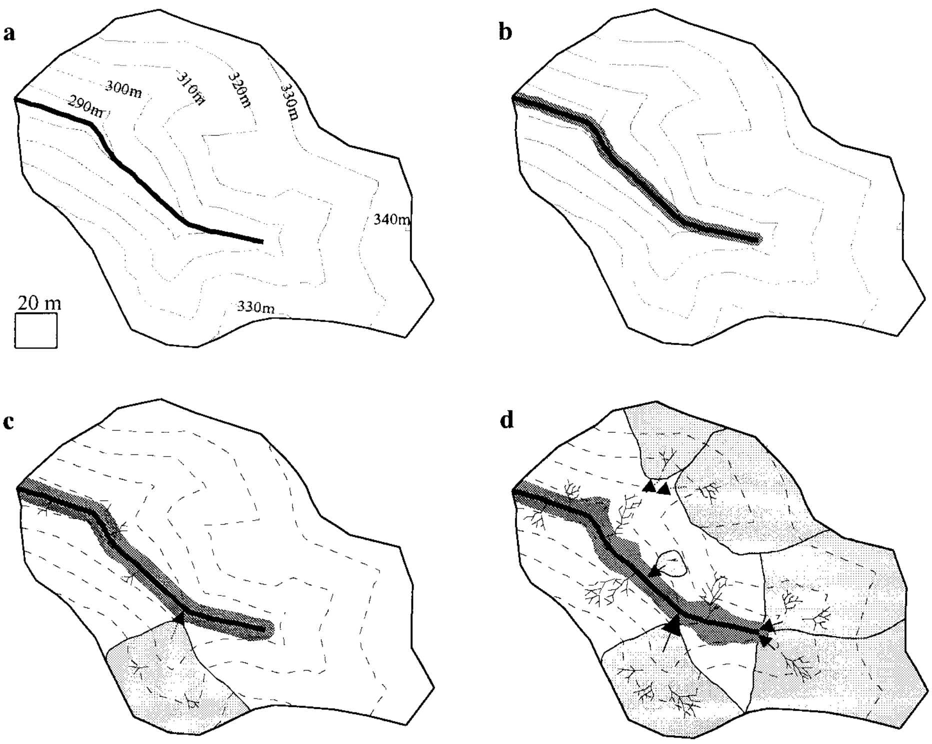

Figure 10. Hydrogeomorphic conceptual model of sources and pathways for stormflow generation during a sequence of increasing antecedent moisture: (a) dry (API_{30} = 0–12 mm); (b) slightly wet (API_{30} = 18–25 mm); (c) wet (API_{30} = 40–50 mm); (d) very wet ($API_{30} > 150$ mm)

better understanding of the temporal and spatial attributes of hydrologic pathways, a hydrogeomorphic concept for stormflow generation is developed (Figure 10).

The spatial and temporal expression of this dynamic hydrologic response is critical to the evaluation of land use within headwater areas (Burgess *et al.*, 1998) and the resulting generation of peak flows and transport of chemicals, sediment, and biota. This conceptual model provides insights into 'hydrologically active' areas in headwater systems. As shown in Figure 10, these regions are not simply extensions of the riparian corridors as implied in the variable-source area concept. Rather these active zones represent linked hydrogeomorphic components of the catchment: riparian zones, linear hillslope segments, and geomorphic hollows or zero-order basins. This model also provides a unique paradigm for spatial (e.g., related to geomorphic components) and temporal (e.g., related to antecedent moisture) scaling of hydrologic processes in addition to offering conceptual advances to the variable-source area model (Tsukamoto, 1963; Hewlett and Hibbert, 1967; Kirkby and Chorley, 1967) for stormflow generation in steep headwaters of temperate, subtropical, and tropical forest ecosystems.

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REFERENCES

Anderson MG, Burt TP. 1978. The role of topography in controlling throughflow generation. *Earth Surface Processes and Landforms* **3**: 331–344.
Beven K. 1987. Towards the use of catchment geomorphology in flood frequency predictions. *Earth Surface Processes and Landforms* **12**: 69–82.
Burgess SJ, Wigmosta MS, Meena JM. 1998. Hydrological effects of land-use change in a zero-order catchment. *Journal of Hydrological Engineering ASCE* **3**: 86–97.
Buttle JM, Peters DL. 1997. Inferring hydrological processes in a temperate basin using isotopic and geochemical hydrograph separation: a re-evaluation. *Hydrological Processes* **11**: 557–573.
Cappellato R, Peters NE, Ragsdale HL. 1993. Acidic atmospheric deposition and canopy interactions of adjacent deciduous and coniferous forest in the Georgia Piedmont. *Canadian Journal of Forest Research* **23**: 1114–1124.
Chen C, Wagenet RJ. 1992. Simulation of water and chemicals in macropore soils. Part 1. Representation of the equivalent macropore influence and its effect on soil water flow. *Journal of Hydrology* **130**: 105–126.
DeWalle DR, Swistock BR. 1994. Differences in oxygen-18 content of throughfall and rainfall in hardwood and coniferous forests. *Hydrological Processes* **8**: 75–82.
DeWalle DR, Swistock BR, Sharpe WE. 1988. Three-component tracer model for stormflow on a small Appalachian forested catchment. *Journal of Hydrology* **104**: 301–310.
Dietrich WE, Dunne T. 1978. Sediment budget for a small catchment in mountainous terrain. *Zeitschrift für Geomorphologie N.F. Suppl*. **29**: 191–206.
Dunne T, Black RD. 1970. Partial area contributions to storm runoff in a small New England watershed. *Water Resources Research* **6**: 1296–1311.
Elsenbeer H, Lack A, Cassel K. 1995. Chemical fingerprints of hydrological compartments and flow paths at La Cuenca, western Amazonia. *Water Resources Research* **31**: 3051–3058.
Eshleman KN, Pollard JS, O'Brien AK. 1993. Determination of contributing areas for saturation overland flow from chemical hydrograph separations. *Water Resources Research* **29**: 3577–3587.
Feger KH, Brahmer G, Zöttl HW. 1990. Element budgets of two contrasting catchments in the Black Forest (Federal Republic of Germany). *Journal of Hydrology* **116**: 85–99.
Freeze RA. 1074. Streamflow generation. *Reviews of Geophysics and Space Physics* **12**: 627–647.
Fujieda M, Kudoh T, de Cicco V, de Calvarcho JL. 1997. Hydrologic processes at two subtropical forest catchments: the Serra do Mar, Sãn Paulo, Brazil. *Journal of Hydrology* **196**: 26–46.
Gillham RW. 1984. The effect of capillary fringe on water-table response. *Journal of Hydrology* **67**: 307–324.
Hewlett JD, Hibbert AR. 1967. Factors affecting the response of small watersheds to precipitation in humid areas. In *Proceedings of the International Symposium on Forest Hydrology*, Sopper WE, Lull HW (eds); Pergamon: New York; 275–290.
Jones A. 1971. Soil piping and stream channel initiation. *Water Resources Research* **7**: 602–610.
Kendall C, McDonnell JJ. 1993. Effect of intrastorm isotopic heterogeneities of rainfall, soil water, and groundwater on runoff modelling. In *Tracers in Hydrology (Proceedings of the Yokohama Symposium, July 1993)*, Peters NE, Hoehn E, Leibundgut Ch, Tase N, Walling DE (eds); IAHS Publ: **215**: Wallingford, UK; 41–48.
Kirkby MJ, Chorley RJ. 1967. Throughflow, overland flow and erosion. *Bulletin of the International Association of Scientific Hydrology* **12**: 5–21.
Kitahara H. 1992. Characteristics of pipe flow in a forest soil. *Journal of the Japanese Society of Hydrology and Water Resources* **5**: 15–25 (in Japanese).
Kitahara H, Nakai Y. 1992. Relationship of pipe flow to streamflow on a first order watershed. *Journal of the Japanese Forestry Society* **74**: 49–54 (in Japanese).
Knapp BJ. 1973. A system for the field measurement of soil water movement. *Technical Bulletin of the British Geomorphological Research Group* **9**: 26 pp.
Luxmoore RJ, Ferrand LA. 1993. Towards a pore-scale analysis of preferential flow and chemical transport. In *Water Flow and Solute Transport in Soils*, Russo D, Dagan G (eds); Springer-Verlag: Berlin; 45–60.
McDonnell JJ. 1990. A rationale for old water discharge through macropores in a steep, humid catchment. *Water Resources Research* **26**: 2821–2832.
McDonnell JJ, Freer J, Hopper R, Kendall C, Burns D, Beven K, Peters N. 1996. New method developed for studying flow on hillslopes. *EOS Transactions of the American Geophysical Union* **77**: 465.
McDonnell JJ, Stewart MK, Owens IF. 1991. Effect of catchment scale subsurface mixing on stream isotope response. *Water Resources Research* **27**: 3065–3073.
Montgomery DR, Dietrich WE, Torres R, Anderson SP, Heffner JT, Loague K. 1997. Hydrologic response of a steep, unchanneled valley to natural and applied rainfall. *Water Resources Research* **33**: 91–109.
Moore RD. 1989. Tracing runoff sources with deuterium and oxygen-18 during spring melt in a headwater catchment, southern Laurentians, Quebec. *Journal of Hydrology* **112**: 135–148.
Mosely MP. 1979. Streamflow generation in a forested catchment. *Water Resources Research* **15**: 795–806.
Noguchi S, Tsuboyama Y, Sidle RC, Hosoda I. 1997. Spatially distributed morphological characteristics of macropores in forest soils of Hitachi Ohta Experimental Watershed, Japan. *Journal of Forest Research* **2**: 207–215.
Noguchi S, Tsuboyama Y, Sidle RC, Hosoda I. 1999. Morphological characteristics of macropores and the distribution of preferential flow pathways in a forested slope segment. *Soil Science Society of America Journal* **63**: (in press).
Pearce AJ, Stewart MK, Sklash MG. 1986. Storm runoff generation in humid headwater catchments, 1. Where does the water come from? *Water Resources Research* **22**: 1263–1272.

Pond SF. 1971. Qualitative investigation into the nature and distribution of flow processes in Nant Gerig. In *Subsurface Hydrology, Rep.* **28**, Institute of Hydrology; Wallingford, UK.
Ross DS, Bartlett RJ, Magdoff FR, Walsh GJ. 1994. Flow path studies in forested watersheds of headwater tributaries of Brush Brook, Vermont. *Water Resources Research* **30**: 2611–2618.
Sidle RC. 1984. Shallow groundwater fluctuations in unstable hillslopes of coastal Alaska. *Zeitschrift für Gletscherkunde und Glazialgeologie* **20**: 79–95.
Sidle RC, Hornbeck JW. 1991. Cumulative effects: A broader approach to water quality research. *Journal of Soil and Water Conservation* **46**: 268–271.
Sidle RC, Tsuboyama Y. 1992. A comparison of piezometric response in unchanneled hillslope hollows: coastal Alaska and Japan. *Journal of the Japanese Society of Hydrology and Water Resources* **5**: 3–11.
Sidle RC, Tsuboyama Y, Noguchi S, Hosoda I. 1994. Subsurface flow through the soil matrix and macropores: results of tracer tests at Hitachi Ohta, Japan. In *Proc. Int. Symp. on Forest Hydrology*, Ohta T (ed.); University of Tokyo: Japan; 225–232.
Sidle RC, Tsuboyama Y, Noguchi S, Hosoda I, Fujieda M, Shimizu T. 1995. Seasonal hydrologic response at various spatial scales in a small forested catchment, Hitachi Ohta, Japan. *Journal of Hydrology* **168**: 227–250.
Sklash MG, Farvolden RN. 1979. The role of groundwater in storm runoff. *Journal of Hydrology* **43**: 45–65.
Sklash MG, Stewart MK, Pearce AJ. 1986. Storm runoff generation in humid headwater catchments, 2. A case study of hillslope and low-order stream response. *Water Resources Research* **22**: 1273–1282.
Tanaka T, Yasuhara M, Sakai H, Marui A. 1988. The Hachioji Experimental Basin Study — Storm runoff processes and the mechanism of its generation. *Journal of Hydrology* **102**: 139–164.
Tani M. 1997. Runoff generation processes estimated from hydrological observations on a steep forested hillslope with a thin soil layer. *Journal of Hydrology* **200**: 84–109.
Torres R, Dietrich WE, Montgomery DR, Anderson SP, Loague K. 1998. Unsaturated zone processes and the hydrologic response of a steep, unchanneled catchment. *Water Resources Research* **34**: 1865–1879.
Tsuboyama Y, Hosoda I, Noguchi S, Sidle RC. 1994a. Piezometric response in a zero-order basin, Hitachi Ohta, Japan. In *Proc. Int. Symp. on Forest Hydrology*, Ohta T (ed.); University of Tokyo: Japan; 217–224.
Tsuboyama Y, Noguchi S, Shimizu T, Sidle RC, Hosoda I. 1998. Intrastorm fluctuations of piezometric head and soil temperature within a steep forested hollow. In *Environmental Forest Science (Proc. of IUFRO Div. 8 Conf., October 1998)*, Sassa K (ed.); Forestry Sciences vol. **54**, Kyoto University, Japan. Kluwer Academic Publisher: Dordrecht, The Netherlands; 475–482.
Tsuboyama Y, Sidle RC, Noguchi S, Hosoda I. 1994b. Flow and solute transport through the soil matrix and macropores of a hillslope segment. *Water Resources Research* **30**: 879–890.
Tsuboyama Y, Sidle RC, Noguchi S, Murakami S, Shimizu S. 2000. A zero-order basin — its contribution to catchment hydrology and internal hydrological processes. *Hydrological Processes* **14**: 387–401.
Tsukamoto Y. 1963. Study on the growth of stream channel. *Journal of the Japanese Society of Forestry* **45**: 186–190 (in Japanese).
Tsukamoto Y, Ohta T. 1988. Runoff processes on a steep forested slope. *Journal of Hydrology* **102**: 165–178.
Turton DJ, Haan CT, Miller EL. 1992. Subsurface flow responses of a small forested catchment in the Ouachita Mountains. *Hydrological Processes* **6**: 111–125.
Whipkey RZ. 1965. Sub-surface stormflow from forested slopes. *Bulletin of the International Association of Scientific of Hydrology* **10**: 74–85.
Wilson GV, Jardine PM, Luxmoore RJ, Zelazny LW, Lietzke DA, Tod DE. 1991. Hydrogeochemical processes controlling subsurface transport from an upper subcatchment of Walker Branch watershed during storm events. 1. Hydrologic transport processes. *Journal of Hydrology* **123**: 297–316.
Wilson GV, Jardine PM, Luxmoore RJ, Jones JR. 1990. Hydrology of a forested hillslope during storm events. *Geoderma* **46**: 119–138.
Woods R, Rowe L. 1996. The changing spatial variability of subsurface flow across a hillside. *Journal of Hydrology (NZ)* **35**: 51–86.
Yasuhara M, Marui A. 1994. Groundwater discharge from a clayey hillslope. In *Proc. Int. Symp. on Forest Hydrology*, Ohta T (ed.); University of Tokyo: Japan; 241–248.

