Hortonian overland flow from Japanese forest plantations—an aberration, the real thing, or something in between?

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Abstract

There is a growing opinion that poorly managed plantation forests in Japan are contributing to increased storm runoff and erosion. Here we present evidence to the contrary from runoff plots at two scales (hillslope and 0.5 × 2 m plots) for several forest conditions in the Mie and Nariki catchments. Runoff coefficients from small plots in untended hinoki forests were variable but typically higher than from better managed or deciduous forests during small storms at Nariki; at Mie, runoff during small events was highly variable from all small plots but runoff coefficients were similar for hinoki plots with and without understory vegetation, while the deciduous plot had lower runoff coefficients. Storm runoff was less at the hillslope scale than the plot scale in Mie; these results were more evident at sites with better ground cover. During the largest storms at both sites, differences in runoff due to forest condition were not evident regardless of scale. Dynamic soil moisture tension measurements at Nariki indicated that during a large storm, flow in the upper organic-rich and root-permeated soil horizons was 3.2 times higher than measured overland runoff from a small hinoki plot with poor ground cover and 8.3 times higher than runoff from a deciduous forest plot. On the basis of field observations during storms, at least a portion of the monitored ‘Hortonian overland flow’ was actually occurring in this near-surface ‘biomat’. Therefore our field measurements in both small and large plots potentially included biomat flow in addition to short-lived Hortonian runoff. Because overland flow decreased with increasing scale, rill erosion did not occur on hillslopes. Additionally, runoff coefficients were not significantly different among cover conditions during large storms; thus, the ‘degraded’ forest conditions appear not to greatly enhance peak flows or erosion potential at larger scales, especially when biomat flow is significant.

Key Words forest hydrology; erosion; biomat flow; preferential flow; scaling; degraded forests; storm runoff

Introduction

An accurate understanding of hydrological pathways during storms is important to assess the interactions of land management practices with export of water, sediment, and nutrients to streams and rivers (e.g. Sidle et al., 2000; Srinivasan et al., 2005; Lyon et al., 2006). Many earlier studies suggested the occurrence of Hortonian overland flow on forest hillslopes was rare or even non-existent (e.g. Whipkey, 1965; Weyman, 1973; Harr, 1977). Later field investigations supported these observations with detailed small-scale measurements of saturated hydraulic conductivity (Ks), soil moisture content and tension, infiltration, subsurface flow, and natural chemical tracers (e.g. Chappell and Ternan, 1990; Chandler and Bisogni, 1999; Elsenbeer and Vertessy, 2000; Schellekens, 2000; Lohse and Dietrich, 2005). When overland flow occurs on humid forested hillslopes, it is generally believed to initiate via return flow, a type of saturation overland flow whereby subsurface water is forced to the surface due to a shallow conducting layer or a hydraulic gradient directed towards the surface or both (e.g. Dunne and Black, 1970; Fujieda et al., 1997; Schellekens et al., 2004; Lin et al., 2006). Also, saturation overland flow is known to be a common runoff pathway in areas where water tables approach the soil surface—e.g. riparian zones and geomorphic hollows (Dunne and Black, 1970; Tanaka et al., 1988;
Masiyandima et al., 2003). However, little research has been conducted on Hortonian overland flow in temperate forest sites.

Changing forest economic conditions in Japan since World War II have caused many plantation forests to be poorly managed. During the post-war recovery period starting in the 1950s and continuing until 1970 many new hinoki (Chamaecyparis obtuse) and sugi (Cryptomeria japonica) plantations were established due to the high demand for timber in Japan (Iwamoto, 2002). These new plantations were encouraged by heavy subsidies from the Japanese government after 1957 (Akao, 2002). As these plantations matured, timber prices declined because Japan began importing cheaper timber from Southeast Asia. Because of this low profitability and a general shortage of forestry workers, more and more plantations have been left untended and unharvested (Iwamoto, 2002). These untended plantations, particularly, hinoki, develop dense stands that tend to exclude understory vegetation and produce only small amounts of litter that are concentrated in the late autumn, and which break down and are easily transported downslope (Sakai and Inoue, 1988; Adu-Bredu et al., 1997). Thus, as unthinned hinoki stands increase in age, ground cover may become more sparse (Miura et al., 2003). These widespread, poorly managed hinoki forests have generated much attention and speculation in Japan related to possible flooding, erosion, and sedimentation associated with increases in Hortonian overland flow (e.g. Onda and Yukawa, 1994; Miura et al., 2003; Onda et al., 2003; Fukuyama et al., 2005). These opinions are in contrast with inferences from Tamai’s (2005) study, which indicate that thinning (i.e. improved management) did not affect stream discharge in hinoki catchments.

Herein, we take a critical look at methods and results of our field investigations conducted on steep hillslopes with different forest cover conditions (hinoki and other cover types) in Japan at two scales to address the prevalence of Hortonian overland flow and other runoff mechanisms during natural rainstorms. We attempt to distinguish true Hortonian overland flow from flow that occurs within the upper organic-rich and root-permeated horizons of these forested sites.

**Revisiting the Process and Measurement of Hortonian Overland Flow**

The original hillslope hydrology model proposed by Horton (1933) assumes that the infiltration capacity of the soil divides rainfall into two components: one which infiltrates into the soil and partly recharges groundwater and is partly returned to the atmosphere via evapotranspiration and the other, which flows overland and directly contributes to stormflow in streams. The proportion of this latter component, which has become known as Hortonian overland flow, can be determined at any time during a storm by measuring the dynamic surface infiltration capacity and comparing this with rainfall intensity data (Horton, 1933). By uniformly extrapolating this relationship over an entire hillslope, it was later proposed that Hortonian overland flow would occur over all hillslopes with surface runoff increasing as a power law for increasing distances downslope and, after some critical flow distance, the shear stress generated by runoff (concentrated into micro-channels) would induce active surface erosion (Horton, 1945). The generation of Hortonian overland flow follows the sequence: (1) a thin film of water forms on the soil surface and initiates surface runoff; (2) surface runoff fills depressions; (3) as the depressions fill, they exude overland flow; (4) overland flow coalesces into micro-channels that eventually form rills and even gullies; and (5) channelized flow is discharged into streams (Figure 1). While the process of partitioning rainfall into

![Figure 1. Conceptualizations of hillslope-scale storm runoff processes for: (a) bare to very sparsely vegetated sites where Hortonian overland flow dominates (e.g. after Horton, 1933); (b) forested sites with thin and possibly intermittent litter cover where extensive biomat flow occurs with spatially limited Hortonian overland flow; and (c) forested sites with deep organic horizons where subsurface flow dominates (e.g. after the concept proposed by Hewlett and Hibbert, 1967)](image-url)
these two simple components (i.e. Hortonian overland flow and recharge/evapotranspiration) has been widely demonstrated to be an inadequate explanation of hydrological processes in humid, vegetated sites where subsurface and saturation flow pathways typically dominate (e.g. Hewlett and Hibbert, 1967; Dunne and Black, 1970; Tsukamoto and Ohta, 1988), the concept of Hortonian overland flow is still valid. The real question that needs to be addressed is the spatial and temporal dynamics of this process as well as its relative magnitude compared to subsurface storm runoff and deep percolation.

Methods employed to measure Hortonian overland flow and distinguish it from subsurface flow are fraught with problems when physical soil conditions promote the lateral movement of water in near-surface, organic-rich soil horizons. As defined by Horton and used by most hydrologists, this flow is strictly a surface phenomenon (Horton, 1933). However, almost all studies that attempt to measure Hortonian overland flow do so by installing some type of collection trough at the downslope end of plots; this trough is typically ‘connected’ to the soil by either sheet metal or a concrete or wood ‘lip’ that is inserted below the soil surface. Given the natural microtopography of most hillslopes, the depth of insertion of this barrier may be at least 2–5 cm. For dry, sparsely vegetated sites (e.g. Bent et al., 1999; Shakesby et al., 2000) this type of installation may not cause a problem for the separation of subsurface and overland flow, but for humid forest hillslopes with relatively thin organic horizons, saturation and preferential flow could occur in this near-surface layer and such installations may collect a portion of this shallow subsurface flow as overland runoff. Steep forest hillslopes with deep organic horizons rarely or ever experience Hortonian overland flow even during large storms (e.g. Whipkey, 1965; Harr, 1977), and subsurface flow within such deep organic horizons normally does not approach the surface.

The Concept of ‘Biomat Flow’

We have developed the concept of biomat flow to describe the movement of stormwater through a near-surface layer on hillslopes—a type of lateral, preferential flow. Biomat flow is defined as subsurface storm runoff within: (1) the loose litter layer; (2) the decomposed portion of the organic horizon; (3) the upper portion of the mineral soil that is permeated by fine, dense root networks; and (4) flow occurring within and below pockets of colluvial organic and mineral materials deposited on hillslopes. Such biomat flow has been measured in other studies with deeper organic horizons where Hortonian overland flow is highly unlikely (Sidle et al., 1995; Kim et al., 2005), but has not been articulated for hillslopes with thin organic horizons where Hortonian flow is often assumed to occur. This concept actually was developed in the field when we observed flow collecting in our surface runoff plots during large storms with no actual Hortonian overland flow occurring. Upon removing the thin (∼1 cm) surface litter layer from a degraded hinoki site during the peak of one large storm, we observed slope-parallel flow just above the mineral soil horizon.

Thus, how we define and measure near surface flow processes affects the interpretation of runoff generation. The specification of flow pathways above and within relatively thin biomes may seem like a moot difference, but it is significantly related to water routing and erosion implications on hillslopes and in catchments. Water flowing through such near-surface biomes will be more rapid than subsurface stormflow in the mineral soil, but much slower than the true Hortonian overland flow. Furthermore, such biomat flow will likely not induce surface erosion due to its relatively lower velocity and consequent shear stress applied to the near-surface soil. And, in fact, the water will largely be in contact with organic materials, not mineral soil particles.

Field Investigations of Overland Flow during Storms

Methods and materials

Herein, we report results from two sites that are part of a large study of the effects of forest management on hydrological response. One study area is a steep (average slope gradient 35°), deeply incised 4.9 ha catchment in Mie Prefecture (latitude, 34°21′N; longitude, 136°25′E), south central Japan. Although steep, hillslopes are relatively short in this headwater catchment; distances from ridges to channels typically range from 20 to 40 m. Elevation within the catchment ranges from 100 to 260 m and mean annual precipitation is 2200 mm. Soils at all sites in Mie are relatively shallow (0.6 to <1.8 m deep) and classified as Cambisols (Inceptisols, known in Japan as brown forest soils). The organic horizon in the dense hinoki stand is either non-existent or <1 cm and consists of loose litter; in the thinned hinoki stand and the deciduous forest, the organic horizons are 1–2 cm and 1–3 cm deep, respectively. All soils have a thin (1–2 cm) A horizon, underlain by progressively deeper B (20–30 cm) and C (30–80 cm) horizons above mantisols bedrock of Jurassic age, mainly weathered and fractured schist. The forest consists of a 40-year-old stand of Japanese cypress (hinoki, C. japonica) with small inclusions of Japanese cedar (sugi, C. japonica) and mixed broadleaf forest. The dominant understory vegetation types are fern (Gleichenia japonica) and evergreen shrubs (e.g. Clevera japonica).

Results from two sizes of runoff plots installed on relatively planar slopes in the Mie catchment are presented: (1) small (0.5 × 2 m) and (2) hillside scale (∼8 × 25.5 m with projected horizontal areas of 108 to 130 m²). The small plots were located within 10 m of the hillside slope at a midslope position. Plastic borders were inserted ∼5 cm into the soil along all sides of the small plots and a trough was inserted several cm into soil (parallel to slope direction) to collect storm runoff. Runoff from these plots was routed to a 200-L plastic tank with a water level sensor; water levels were recorded every 5 min and the tank volume was calibrated to estimate discharge.
In contrast, hillslope scale plots were unbordered along the sides and the ridgeline of the sub-catchment served as the upper boundary. Contributing areas of hillslope-scale plots were estimated based on topography. Plastic troughs were installed along the lower boundary of these runoff plots parallel to the ridge lines and slope contours to collect surface runoff. Flexible aluminum flashing was inserted several cm into the soil to facilitate the effective routing of runoff into the troughs. The troughs were covered with plastic roofs to avoid direct precipitation inputs. Stormflow was routed into a drop-box 45° V-notch weir that was attached to the downslope end of the trough. Water stage near the inlet of the V-notch weir was monitored every 5 min using a water level sensor and stage was calibrated to discharge. Precipitation was measured by a tipping bucket rain gauge situated in an open area 200–300 m away from the runoff plots.

Selected data are presented for three ground cover/overstory conditions at the Mie site: (1) dense hinoki plantation (4500 stems/ha) with very little organic matter on the forest floor; (2) thinned hinoki stand (1500 stems/ha) with a deeper, more continuous organic horizon; and (3) a mixed deciduous forest with a continuous organic horizon. Storm runoff data from large and small plots were collected for variable intervals from late May 2004 through early September 2005.

A second set of data is presented from the 33.9 ha Nariki catchment (latitude, 35°50′N; longitude, 139°10′E) in the outskirts of Tokyo metropolitan area. Altitude of the study drainage ranged from 580 to 840 m asl. Mean annual precipitation and mean air temperature from 1994 to 2004 were 1486 mm and 14.2°C, respectively, based on data collected at the nearby Oume AMeDAS automated weather station. On average, about 80% of total precipitation falls from May to November. The period from November to April is relatively dry, although 10–20 cm of snow periodically accumulates from January to March. The Nariki catchment has steep slopes; mean gradient of the small runoff plots is 38°. Soils are Cambisols (Inceptisols) with similar depth distribution of horizons as the Mie site, underlain by a sequence of mudstone and sandstone (South Chichibu zone). Soils are about 1 m deep underlain by an additional 0.9 m of highly weathered bedrock. Soil organic horizons in all forest types are relatively thin; for the less dense hinoki and deciduous forest cover types, organic horizon depth averaged about 2–3 cm.

Continuous runoff data are presented for small (0.5 x 2.0 m) plots in Nariki catchment; these plots are of the exact same design and installation as in the Mie site, located in midslope positions, and monitored from May through December of 2005 and 2006. One plot was installed in each of the following forest conditions: (1) older (45 year) dense hinoki stand (2000 stems/ha) with very poor ground cover; (2) young (16 year) hinoki stand (1500 stems/ha) with good ground cover; (3) 45-year old sugi stand (1400 stems/ha) with poor ground cover; (4) older (80–100 years) sugi (C. japonica) stand with good ground cover; and (5) mixed deciduous forest with a continuous, but thin, organic horizon. Additionally, adjacent to the deciduous and poor ground cover hinoki plots, recording tensiometers were installed at depths of 20, 40, 60 and 80 cm to assess soil matric potential related to subsurface flow paths. Such detailed measurements allow us to estimate the amount of water percolating vertically into the mineral soil horizons during individual storm events and, with our direct measurements of overland flow and precipitation (uncorrected for gauge catch efficiency), biomat flow can be estimated. Slope parallel unsaturated flow cannot be estimated by this method.

The general climate at both sites is moist and temperate. The largest amounts and intensities of rainfall occur during two periods: (1) the Baiu season from early June to mid-July and (2) the typhoon season from late August through October. The small amount of snowfall at both sites typically does not persist more than one week. Thus, runoff is almost totally controlled by rainfall. Runoff coefficients, the ratio of total storm runoff (in mm) to total rainfall (uncorrected for interception losses), are used to facilitate comparisons between plot sizes (Mie only) and different stand conditions. In both large and small plots at both sites, runoff occurred only during and slightly after rainfall; all runoff was monitored and used in calculations of storm runoff coefficients. Precipitation at the Mie site was well above average in 2004 (annual precipitation in 2004 was 3201 mm), with the highest rainfall occurring during the Baiu and typhoon seasons; in contrast, precipitation in 2005 was only 1383 mm. The range of storm precipitation in the Nariki catchment was narrower compared to the Mie site for the periods monitored.

Results and discussion

Comparison of runoff coefficients from different plots. During all monitored storms at the Mie catchment and most storms in the Nariki catchment, overland flow was measured in all of the small plots, including those in the mixed deciduous forest. On the basis of runoff comparisons of different sizes of plots at the Mie site, it is clear that while runoff was observed during most storms at the hillslope scale, it was consistently much less than storm runoff from small plots (Figure 2). Runoff coefficients during larger storms (>75 mm of total rainfall) typically exceeded 0.08 for small plots, whereas hillslope scale plots rarely experienced runoff coefficients in excess of 0.05. An exception was the dense hinoki stand with little ground cover, where 41% of the storms had runoff coefficients >0.08 at the hillslope scale; however, only four of these storms were large (total precipitation >75 mm), and most had total rainfall <55 mm (Figure 2). The three storms that generated the highest runoff coefficients (0.19, 0.20 and 0.36) from the hillslope-scale hinoki plot with poor ground cover were small (32, 7.6 and 27 mm of rainfall, respectively). It appears that during very large storms, (> 300 mm), the maximum runoff coefficient that can be expected at the hillslope scale is about 0.05. The contrast between
plot scales is more pronounced and consistent with the thinned hinoki forest with good ground cover and the deciduous forest site (Figure 2). Runoff coefficients from the small deciduous plot were >0.10 in 39% of the storms monitored; in the small thinned hinoki plot, runoff coefficients were >0.10 in 81% of the storms. Four of the five storms with runoff coefficients >0.2 in the small deciduous plot had total precipitation <90 mm. For the deciduous hillslope, runoff coefficients never exceeded 0.02; runoff coefficients from the thinned hinoki hillslope were slightly higher during storms, but never exceeded 0.06. The largest storms typically did not produce the highest runoff coefficients from hillslope scale plots under any of the cover types (Figure 2). Runoff coefficients during storms were highly variable in both small and hillslope scale plots. For wetter antecedent conditions, higher runoff coefficients in hillslope plots tended to coincide with peak rainfall inputs during individual storms, while runoff coefficients during large storms preceded by dry conditions were rather high and variable, but not related to rainfall inputs.

For all forest conditions in the Nariki catchment, except hinoki with poor ground cover, runoff coefficients from small plots were <0.16 for all storms monitored from May to December of 2005 and 2006 (Figure 3). In the hinoki plot with poor ground cover, seven storms ranging in size from 8.4 to 41.3 mm had runoff coefficients >0.16; however, runoff coefficients from this plot were <0.10 during five of the six largest storms (>55 mm total precipitation). The young hinoki plot with good ground cover at Nariki experienced the lowest amount of runoff overall with no event producing a runoff coefficient >0.075. Average runoff coefficient for 58 monitored storms was much lower in the young hinoki plot (0.018) compared to other small plots (0.056–0.071) where average coefficients were similar. The sugi plot with good ground cover and the deciduous forest had runoff coefficients >0.1 during eleven and nine storms, respectively; these events tended to be larger than the storms that produced the highest runoff coefficients from both the hinoki and sugi plots with poor ground cover (Figure 3). There was little overall difference between the runoff from sugi plots with good and bad ground cover. The sugi plots with good ground cover had a slightly higher average runoff coefficient (0.066) and one more event that produced a runoff coefficient >0.11 compared to the plot with poor ground cover (0.064). For all plots during the 2-year monitoring period, runoff coefficients tended to be higher during typhoon storms (>3 h duration and maximum 1-h intensity ≥50 mm h⁻¹) followed by low intensity (3–4 mm h⁻¹), long duration (≥10 h) events and thunderstorms. Low intensity, short duration storms typically produced the lowest runoff coefficients. The nine storms with total precipitation >50 mm produced runoff coefficients <0.15 in all plots (Figure 3). For the largest storms in all plots except the hinoki forest with good ground cover, runoff coefficients appeared to reach a maximum at about 0.09–0.12; for the hinoki plots with good ground cover, this maximum was considerably lower (∼0.02) (Figure 3). The higher runoff coefficients observed in the older hinoki stand compared to younger stands of both sugi and hinoki reflect the poorer ground cover condition of this older stand.

Case study of flow pathways—Nariki plots. A detailed analysis of flow mechanisms was conducted for a large storm on 9 August 2006 in two small runoff plots (poor ground cover hinoki and deciduous) in the Nariki catchment near Tokyo based on: (1) dynamic tensiometer measurements adjacent to both plots; (2) saturated hydraulic conductivity measured via falling-head tests in 100 cm³ soil cores (5 cm thick) collected at the 30–35 cm depth; and (3) soil water retention curves derived from soil cores collected at 10–15 cm and 30–35 cm depths. Water release curves were conducted for a low range of tensions because we inferred processes during wet storm conditions from these data (Figure 4). The dynamics of soil water content with respect to suction can be evaluated for the 5 min measurement intervals in terms of effective saturation (S)

$$S = \frac{(\theta_a - \theta_i)}{\theta_s - \theta_i} \quad (1)$$

where $\theta_a$ is actual volumetric soil water content determined from dynamic tensiometric measurements and

![Figure 2. Storm runoff coefficients during various size storm events at Mie (May 2004 to September 2005) in both small (0.5 × 2.0 m) and hillslope-scale plots of: (a) hinoki forest with very poor ground cover; (b) thinned hinoki stand with relatively continuous ground cover; and (c) deciduous forest with continuous ground cover](image)
Figure 3. Storm runoff coefficients from small plots during various size storm events in Nariki catchment during the periods May through December of 2005 and 2006 for the following forest cover conditions: (a) older (³45 yr) hinoki stand with sparse ground cover; (b) 45-yr old sugi stand with sparse ground cover; (c) deciduous forest with moderate ground cover; (d) young (³16 yr) hinoki stand with relatively good ground cover; and (e) old-growth (80-100 yr) sugi stand with very good ground cover.

Figure 4. Water release curves for soil cores sampled at the 10–15 cm and 30–35 cm depths in the hinoki forest site with poor ground cover and the deciduous forest at Nariki catchment.

Net precipitation = overland flow + infiltrated water

\[ Q = \text{Net precipitation} - \text{infiltrated water} \]  

Infiltration = Δstorage + \( Q + BF \)

where \( Q \) is defined as the estimated percolation below the 20 cm depth during the storm based on tensiometer readings at 20 and 40 cm, Δ storage is the change in soil moisture storage in the upper 20 cm of soil (the biomat), and BF is the lateral flux in the biomat. In the water balance calculations for these two small plots, we were able to estimate evapotranspiration during the 9 August 2006 event based on rainfall collected in 4–9 rain gauges situated under each canopy condition compared to a gauge in a nearby open area. Preliminary analysis of throughfall data suggests that the proportion of interception relative to storm precipitation is rather constant over the range of precipitation encountered and does not differ strongly among the various forest stand types and conditions.

Unsaturated hydraulic conductivity \( (K_u) \) during the storm can be estimated as

\[ K_u = K_s \cdot S^\beta \]  

where, \( K_s \) is saturated hydraulic conductivity and \( \beta \) is an empirical constant that is derived by comparing the
total storm water vertical flux (calculated from $Q$ in Equation (3)) against the vertical flux calculated by a Darcy-based function

$$Q_{5\text{min}} = K_s \left( \frac{\theta_{5\text{min}} - \theta_t}{\theta_t - \theta_r} \right)^\beta \cdot A \cdot I_{5\text{min}} \quad (5)$$

where $A$ is plot area and $I_{5\text{min}}$ is the hydraulic gradient estimated in 5 min intervals from tensiometric data; the 5 min subscripts on other variables denote 5 min measurement intervals. For the 9 August 2006 storm data presented herein, $\beta = 3.10$ for the hinoki plot and $\beta = 4.93$ for the deciduous plot. Both of these values are in the range reported by Mualem (1978). We then assume that the difference between infiltrated rainfall and deep percolation ($\Delta S$ measured soil water storage changes) equates to shallow flow in the organic rich horizons (biomat flow; Figure 5). Thus for our example, we assume that the uppermost 20 cm of soil and organic horizons provide the porous media for biomat flow. This method of estimating subsurface flux and pathways has several limitations: (1) water inputs from upslope of the small plots are not considered; (2) tensiometric analysis is one-dimensional (i.e. vertical); (3) potential for vertical preferential flow is underestimated; and (4) the constant $\beta$ is estimated for the entire storm event (i.e. not dynamic). Nevertheless, since water content and hydraulic gradient dynamics are included, this method can be used to assess subsurface flow fluxes and paths.

An example of estimated hydrologic fluxes is presented based on this water budget approach for a large storm on 9 August 2006. This storm produced some of the highest Hortonian overland flow measured from the hinoki plot with poor ground cover in Nariki catchment. The total storm precipitation (77.2 mm) was divided into interception loss, overland flow, biomat flow, deep percolation, and changes in soil water storage in both the hinoki (poor ground cover) and deciduous forest plots (Figure 5). Even for this extreme event, estimated biomat flow was 3.2 times higher than overland flow in the hinoki plot and 8.3 times higher in the deciduous forest plot (Figure 5). The measured runoff coefficients for overland flow from the hinoki and deciduous plots were 0.146 and 0.034, respectively. Overland runoff coincided with rainfall inputs in both plots, but was slightly higher relative to rainfall inputs in the first part of the storm in the hinoki plot (Figure 5). Deep percolation did not occur in the hinoki plot until late in the storm, coinciding with the cessation of biomat flow, whereas in the deciduous plot, deep percolation occurred earlier, but declined after the last storm peak (Figure 5). Storm runoff within the upper 20 cm of soil (defined here as ‘biomat’ flow) was estimated as 46.3 and 28.5% of total rainfall in the hinoki and deciduous plots, respectively, suggesting that much of the rainfall was transported through this highly conductive layer (Figure 5). Most of this biomat flow appeared to occur during the early part of the storm and coincided with peak inputs, while deficits in biomat flow were estimated in the latter portion of storms when low-intensity rainfall occurred (Figure 6). Such deficits represent errors in the water budget calculations attributable to the time step employed and ignoring upslope inputs. Because a portion

![Biomat flow diagram](image)

*Figure 5. Estimated water budget, including surface and subsurface runoff fluxes, interception losses, and changes in soil water storage, for a large storm (77.2 mm) on 9 August 2006 in Nariki catchment. Estimates are based on data from the small, deciduous plot and poor ground-cover hinoki plot.*
of the ‘measured’ overland flow likely occurred in the upper part of the biomat, the surface runoff coefficients (i.e. for Hortonian overland flow) would be lower than measured and the biomat flow may be even higher than estimated.

Deep percolation was considerably higher in the deciduous plot compared to the hinoki plot, but primarily occurred following the peak of the storm in both plots (Figure 6). Soil moisture storage in the upper 20 cm of the hinoki profile increased for a short period during the first peak of the storm; no increase was noted in the deciduous plot. During the second major storm peak and throughout the remainder of the heavy rainfall, soil moisture storage increased in both plots. It is possible that infiltrating water may displace resident water into macropores during periods of increasing soil moisture, thus augmenting preferential flow and deep percolation (Buttle and Turcotte, 1999; Sidle et al., 2000). Soil water storage increased by about 6-6 and 10-1% in the deciduous and hinoki plots during this event.

Discussion of scale issues

If we examine runoff processes at small enough scales, there is ample evidence for Hortonian overland flow. Any rain falling on rocks, rock fragments, or exposed roots and competent woody debris will be almost totally converted into short-lived Hortonian overland flow once evaporation demands and detention storage are met, but this does not imply that overland flow will persist as this runoff typically infiltrates into the adjacent soil. In fact, coarse fragments are known to reduce surface erosion on hillslopes because they tend to decrease the velocity of any overland flow and afford opportunities for infiltration (Poesen et al., 1994). The same can be said for exposed roots and woody debris. Moving from the micro-scale to small plot scale, there remains a bias towards Hortonian overland flow. Small plots are typically installed on relatively smooth slopes that do not contain roughness elements; sites with large wood or rocks would not be selected for small runoff plots, or these materials would be removed. Also, small plots do not capture the more heterogeneous nature of rainfall inputs and log-normally distributed values of hydraulic conductivity and infiltration capacity (Stockton and Warrick, 1971; Warrick and Nielsen, 1980; Woolhiser and Goodrich, 1988; Saghaian et al., 1995; Wainwright and Parsons, 2002; Vigil et al., 2006). The effects of exposed rocks, roots, and organic litter, as well as hydrophobicity, in such plots on small-scale Hortonian overland flow would also be magnified. These attributes, together with the effects of plot borders

![Figure 6. Measured rainfall and overland flow and temporal estimates of soil moisture storage, deep percolation, and biomat flow for the poor ground cover hinoki and deciduous plots in Nariki catchment during the 9 August 2006 storm](image-url)
that concentrate rainwater and truncate preferential flow paths, all tend to promote Hortonian overland flow. Additionally, topographic position can exert a strong control on runoff pathways that is not captured in small plots (Zehe and Flühler, 2001). Once small-scale Hortonian overland flow is generated it may proceed downslope for only very short distances (<1 m to several meters) before re-infiltration (e.g. Vigiak et al., 2006). Additionally, biomat flow that can be partly captured as ‘Hortonian overland flow’ in runoff plots may not persist for long slope distances before infiltrating into deeper soil horizons. Evidence from staining tests conducted in mixed sugi/hinoki forests in Japan clearly showed that even flow paths in organic rich soils (above the mineral soil) are rather short (typically <0.5 m) (Noguchi et al., 1999; Sidle et al., 2001). Thus, water appears to flow via this ‘biomat’ pathway, but frequently will infiltrate deeper into the soil profile when zones of higher $K_s$, mineral soil or more conductive preferential flow paths are encountered (Figure 1(b)). Therefore, this biomat flow provides a buffer against Hortonian overland flow and promotes periodic deep percolation.

The five-fold to order of magnitude reductions in overland flow measured in Mie when moving from the small plot to the hillslope scale attest to this theory; other research confirms such spatial scaling issues (van de Giesen et al., 2000; Joel et al., 2002; Stomph et al., 2002; Cerdan et al., 2004). It is only natural to expect that ‘true’ Hortonian overland flow would be less at the hillslope scale compared to the plot scale. And if we consider that at least a portion of the overland flow measured in our runoff plots (as well as at other sites with similar soil conditions) was actually biomat flow, then this further reduces the likelihood of ‘true’ Hortonian overland flow. Our investigation in Nariki catchment near Tokyo suggests that at least 34 and 55% of net precipitation from large storms flows through the biomat of deciduous and hinoki forest soils, respectively.

**Developing a More Comprehensive Understanding of Near-Surface Conditions and Flow Pathways**

On the basis of our findings and the wealth of process-based knowledge that is accumulating from studies on hydrological scaling (e.g. Sidle et al., 1995; van de Giesen et al., 2000; Joel et al., 2002; Stomph et al., 2002; Cerdan et al., 2004; Vigiak et al., 2006) and preferential flow pathways (Ruan and Illangasekare, 1998; Noguchi et al., 1999; Sidle et al., 2001; Uchida et al., 2001; Lin et al., 2006), it is clear that Hortonian overland flow comprises only a minor component of catchment stormflow at both the Mie and Nariki sites. Further evidence for this is the almost total absence of rill development on hillslopes at these sites. Given the heterogeneous nature of these forest hillslopes, any long-lived overland flow would tend to concentrate and form at least small erosion rills. The lack of such evidence supports our concept that much of the ‘measured’ overland flow is occurring within the thin biomat. This biomat flow buffers both surface runoff and surface erosion because it travels more slowly than Hortonian overland flow due to frictional resistance within the surface soil and has opportunities to infiltrate into the mineral soil as it moves downslope, thus reducing the total storm runoff. Certainly short-term analyses that elucidate the effects of high-intensity pulses of rainfall on runoff processes are needed to fully comprehend these stormflow pathways.

At the onset of storms preceded by dry conditions, some Hortonian overland flow may be attributed to hydrophobicity that develops in surficial organic horizons or soils (Miyata et al., 2007), but scale issues related to the importance of this process are unclear (Shakesby et al., 2000). During the highest intensity periods of larger storms, some Hortonian overland flow may occur, but the spatial extent of this appears to be quite limited, possibly constituting up to only 10–15% of the rainfall inputs at the small scale and a small fraction of this at the hillslope scale. As such, if site disturbances or compaction are precluded, little true Hortonian overland flow is expected to contribute to catchment-scale runoff from deciduous, hinoki, and sugi forest hillslopes in Japan under most circumstances. Maintaining more continuous and deeper organic horizons will obviously provide better buffers against Hortonian overland flow and subsequent surface erosion (Figure 1(c)); however, even very thin and somewhat discontinuous litter layers appear to serve this purpose for most storms (Figure 1(b)).

In summary, the processes of storm runoff in these somewhat degraded forest plantations appear to be dominated by several types of subsurface flow. Firstly, a thin layer of biomat flow develops in the organic-rich or litter horizon (Figure 1(b)). Greater litter or organic horizon depths and densely rooted surface mineral horizons will presumably support more runoff in this zone. The persistence of this biomat flow is not entirely clear, but it may infiltrate into the mineral soil after traveling only short distances downslope based on the presence of preferential flow paths or zones of high $K_s$ (Figure 1(b)). Once the rainfall enters the mineral soil it moves downslope as subsurface stormflow, either within the soil matrix or via preferential flow networks, or it enters into the deeper groundwater reservoirs. The small amount of intense rainfall that does not immediately infiltrate during storms will begin to run off as Hortonian overland flow; however, our evidence suggests that the persistence of this overland flow path is spatially limited many opportunities exist for this runoff to re-infiltrate as water and is routed into the streams (Figure 1(b)). Thus, as noted in other catchment-scale investigations (van de Giesen et al., 2000; Stomph et al., 2002; Cerdan et al., 2004), the role of Hortonian overland flow progressively decreases from the plot scale to the hillslope and finally to the catchment scale, and biomat flow appears to decrease the connectivity of overland flow and surface erosion from hillslopes to channels even in degraded forests.
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