Peak flow responses and recession flow characteristics after thinning of Japanese cypress forest in a headwater catchment

Bui Xuan Dung¹, Takashi Gomi², Shusuke Miyata³ and Roy C. Sidle⁴

¹United Graduate School of Agriculture Science, Tokyo University of Agriculture and Technology, Japan
²Department of International Environmental and Agricultural Science, Tokyo University of Agriculture and Technology, Japan
³Disaster Prevention Research Institute, Kyoto University, Ujigawa Open Laboratory, Japan
⁴Ecosystem Research Division, US Environmental Protection Agency, Office of Research and Development, USA

Abstract:

We evaluated the effects of forest thinning on peak flow and recession characteristics of storm runoff in headwater catchments at Mie Prefecture, Japan. In catchment M5, 58.3% of stems were removed, whereas catchment M4 remained untreated as a control catchment. Storm precipitation and runoff was monitored from June 2004 to January 2007 for the pre-thinning period (113 events) and from March 2007 to June 2009 for post-thinning (103 events). Based on paired-catchment analysis between M5 and M4, volumes of peak flow did not increase significantly after thinning. Recession constant K increased, while recession time of storm runoff did not differ between pre- and post-thinning periods. Storm hydrograph recession tended to be more gradual (i.e., higher K values) after thinning due to increases in available soil water associated with higher net precipitation and decreased evapotranspiration. The lack of changes in peak flow can be attributed to the minimal soil disturbance during thinning. Our hydrograph analysis in paired catchments indicates that thinning may alter specific internal hydrological pathways, such as subsurface flow and groundwater flow.

KEYWORDS hydrograph analysis; forest thinning; Japanese cypress forest; peak flow; recession flow; internal flow paths

INTRODUCTION

During the past few decades, a number of hydrological investigations in forest catchments focused on evaluating the effects of forest management on peak flow (e.g., Rothacher, 1973; Hudson, 2002; Guillemette et al., 2005) and recession characteristics (Hewlett and Helvey, 1970; Rothacher, 1973; Tallaksen, 1995; Carey and Woo, 2001). However, findings from these studies varied due to uncontrollable factors such as topography, size of storm events, soil characteristics, forest types, and harvesting methods. For instance, clearcutting nearly half of a watershed in Washington, USA did not change peak flows (Duncan, 1986). On the other hand, annual peak flow was reduced by 32% following total clearcutting in the western Cascades of Oregon (USA), in part due to greater canopy interception of snow and more rapid melting compared to less accumulation and slower melting on the ground surface of clearcuts (Harr and McCorrison, 1979). Harvested areas, road locations, and skid trail installation vary amongst study sites, which affect runoff response due to these combined forest management activities (DeWalle, 2003; Guillemette et al., 2005).

Another study in the western Cascades of Oregon generated controversial discussions over analytical methods and interpretations related to the evaluation of forest management on peak runoff. Initially, Jones and Grant (1996) claimed that forest harvesting increased peak flow by as much as 50% in small basins (< 1 km²) and by 100% in larger basins (> 60 km²). Analyzing the same data set, Thomas and Megahan (1998) demonstrated that peak runoff did not increase in large basins, but peak runoff in small basins increased 2-fold when comparing pre- and post-harvesting periods. Reanalysis of these data were also conducted by Beschta et al. (2000) and Alila et al. (2009) to try to clarify these effects.

Other aspects of the effects of forest management on storm runoff responses have been evaluated by hydrograph analyses, including response time with respect to precipitation, rising limb patterns, and recession limb characteristics (Griffiths and Clausen, 1997; Carey and Woo, 2001). Response time with respect to precipitation reflects the wetness of soil and topography of the catchments (Dingman, 1994). Patterns of the rising limb of hydrographs, including time to the peak, correspond to the intensity and duration of precipitation (Carey and Woo, 2001). Recession flow patterns, including the slope of recession hydrographs, reveal behavior of water storage which affects stream flow and low flow characteristics (Hall, 1968; Tallaksen, 1995; Sugiyama, 1996; Griffiths and Clausen, 1997). Among these hydrograph parameters, recession analysis tended to be used more often for evaluating forest harvesting effects on soil-water availability (Hewlett and Helvey, 1970; Carey and Woo, 2001) in addition to peak flow characteristics (Hewlett and Helvey, 1970; Ziegler et al., 2001).

Despite numerous studies to identify the effects of forest management on runoff characteristics, few have demonstrated the effect of thinning on hydrograph shape including both peak runoff and recession characteristics. Forest thinning has been proposed as a management practice to enhance the hydrologic function in forested catchments
(Onda et al., 2010). In most thinning operations, the ratio of stems removed is uniformly distributed, while in clearcutting and partial cutting operations, all of stems are removed in the harvested unit. Therefore, it is difficult to extrapolate findings from clearcut and partial cut studies to thinned forested catchments. For instance, Rahman et al. (2002, 2005) showed that peak flow did not increase after 33% and 6.4% thinning in 27 ha catchments in Japan. A 40% increase in peak flow was noted after a 70% thinning in a 40 ha catchment in North Carolina (Grace et al., 2006).

To understand how the dominant hydrological pathways change due to thinning, both peak flow and recession characteristics should be examined. Therefore, we applied a paired-catchment approach and recession analysis to quantify changes in hydrograph behavior associated with thinning.

## METHODOLOGY

### Study site and paired-catchment experiment

This study was conducted in two headwater catchments (M4 and M5) that drain Japanese cypress (Chamaecyparis obtuse) plantations located in the central Mie Prefecture (34°21'N, 136°25'E), south-central Japan (Figure 1). The climate in this area is moist and temperate, with two rainy seasons: the Baiu season from June to July and the typhoon season from late August to October. Mean annual precipitation and air temperature are approximately 2000 mm and 14°C, respectively. Drainage area of catchments M4 and M5 are 0.19 and 0.35 ha, respectively. The study catchments are deeply incised, with Cambisols soils ranging in depth from 0.6 to 1.8 m (Gomi et al., 2008). The A horizon is approximately 25–30 cm thick and the thickness of the underlying B horizon varies depending on the hillslope position (Gomi et al., 2008). Prior to thinning, stand densities of Japanese cypress were similar in catchments M4 (3500 stems ha⁻¹) and M5 (3475 stems ha⁻¹). The ground surface of catchment M5 had sparse understory vegetation coverage, whereas the majority of catchment M4 was covered by fern (Gleichenia japonica) (Gomi et al., 2010) (Figure 1).

A paired-catchment experiment was used to examine the effects of forest thinning on runoff response. Catchment M4 remained unthinned as a control catchment, whereas experimental thinning was conducted in catchment M5. After a 3-year calibration period from 2004 to 2007, 58.3% of the stems (43.2% of the basal area; mostly small diameter) in catchment M5 were cut by chainsaws and carefully placed parallel to slope contours to minimize soil disturbance from transporting thinned trees (Figure 1). Although forest thinning is generally conducted to improve understory vegetation growth, the understory vegetation did not significantly recover until the end of our 27-month monitoring period (Dung et al., 2011).

Outflow from catchments M5 and M4 was monitored using 5 and 3 inch width Parshall flumes, respectively. The flumes were fixed on the exposed channel bedrock and sealed to avoid leakage of stream water. Thus, we assumed that all of the storm flow and baseflow was captured at the flumes. Water level was monitored in the flumes and discharge was calculated using the formula for the specific size of Parshall flume based on water depth (Herschy, 1985).

Precipitation was measured by a tipping bucket rain gauge at an open area about 150 m away from the catchment. Because the thinning operation was conducted in February 2007, we divided the observation period into pre-treatment from June 2004 to January 2007 and post-treatment periods from March 2007 to June 2009.

### Hydrograph analysis

Three types of hydrograph analysis were conducted: (1) hydrograph separation (Hewlett and Hibbert, 1967); (2) peak flow response (Beschta et al., 2000); and (3) recession pattern estimation (Carey and Woo, 2001). These analyses provide a qualitative evaluation of the dominant runoff pathways; values estimated from these analyses correspond to the different internal hydrological processes. For instance, quick runoff was estimated by hydrograph separation (Hewlett and Hibbert, 1967) and defined as the part of runoff that enters streams, during and immediately after precipitation ceases, via overland flow and rapid subsurface runoff (primarily through preferential flow; see Sidle et al., 2000). Delayed runoff was defined as subsurface water movement through the soil matrix and bedrock outflow.

Peak flow was analyzed based on the paired-catchment approach (Brown et al., 2005). The paired-catchment approach was applied to examine the effect of thinning on peak flow based on an assumption that rainfall and runoff responses between treatment and control catchments remained consistent during the pre- and post-thinning periods. Because the catchments were small (< 1 ha), storm events in control and treated catchment were similar in time, duration, intensity, or spatial extent (Alila et al., 2009). Additionally, the dominant internal hydrological processes were similar between the two catchments and remained consistent before and after treatments (Gomi et al., 2010; Dung et al., 2012). Thus, a paired-catchment approach was deemed valid and reliable for the analysis using the equations.

![Figure 1](image-url)
that follow; first a linear regression model developed for the pre-thinning data;

\[ y = \beta_0 + \beta_1 x + \varepsilon \] (1)

where \( y \) is the observed peak flow for the treated catchment M5 in a given time, \( x \) is the corresponding value of peak flow in the control catchment M4, \( \beta_0 \) and \( \beta_1 \) are parameters estimated by ordinary least squares linear regression, and \( \varepsilon \) is the random error, which is assumed to be independently and normally distributed with constant variance. Next, we estimated post-thinning peak flow (\( \hat{y} \)) in catchment M5 based on the equation (1). Finally, we estimated the residual (\( T_e \)) as the observed peak flow (\( y \)) subtracted by estimated peak flow (\( \hat{y} \)):

\[ T_e = y - \hat{y} \] (2)

Because peak flow was not significantly autocorrelated from one value to other, we assumed that the linear model for the paired-catchment study was robust to ascertain treatment effects.

Recession analysis is indicative of water availability as stored at the catchment scale (Hall, 1968; Tallaksen, 1995). The recession hydrograph is assumed to be derived from the sum of outflow from quick and slow discharge reservoirs within the catchment. Recession times (\( T \), hour) and recession constants (\( K \)) were determined using hydrograph recession analysis (Carey and Woo, 2001); the exponential decrease in flow on the recession limb was defined as,

\[ Q(t) = K t Q_{peak} \] (3)

where \( t \) is time from the peak discharge in each storm event and \( Q_{peak} \) is the peak discharge in each storm event. When a later storm occurred before the recession of a prior event, the trend line of the observed recession was extrapolated to estimate the end point of discharge for the earlier event. The parameter \( K \) (ranging from 0 to 1) indicates shape of the recession curve. Higher \( K \) values suggest more gradual recession limbs. We fitted \( K \) values for each storm using a least squares method (Miyata et al., 2010). Recession time (\( T \)) is the time from a point at which the slope of the exponentially decreasing recession hydrograph became distinctly flatter to a point when stream flow decreased to the discharge level prior to the storm event. Because subsequent storms sometimes started prior to cessation of a prior event and thus, appropriate recession times (\( T \)) could not be obtained for these events, we were able to use 88 and 99 storm events for this analysis in the pre- and post-thinning periods, respectively.

We delineated storm events as separated by an inter-storm period with no-rain for at least 12 hr. Because catchment runoff decreased quickly after precipitation ceased, a 12-hr period without precipitation was sufficient to distinguish storm events (Gomi et al., 2010; Dung et al., 2012). We applied a two-sample Student’s t-test to assess differences in residuals (\( T_e \)), recession times (\( T \)), and recession constants (\( K \)) between the pre- and post-thinning periods. All statistical analyses were performed using the R-software package (Crawley, 2005).

RESULTS AND DISCUSSION

Rainfall-runoff response

Mean annual precipitation during our monitoring period from 2004 to 2009 was 1987 mm. Mean annual precipitation was somewhat higher in the pre-thinning period (1987 mm) than that in the post-thinning period (1732 mm) (Figure 2). In the control catchment M4, mean annual runoff was 403.2 mm in the pre-thinning period and 286.7 mm in the post-thinning period. Mean annual runoff coefficients in control catchment M4 during the pre- and post-thinning periods were 18.4 and 16.6%, respectively. In contrast, mean annual runoff from the thinned catchment M5 during the pre- and post-thinning periods was 655.1 mm and 978.5 mm, respectively; corresponding mean annual runoff coefficients were 32.8% and 56.2%, respectively. Of the 216 storm events during the entire monitoring period, 113 were in the pre-thinning period and 103 occurred after thinning (Table SI; Figure 2). The maximum storm precipitation during the pre-thinning period was 345.6 mm on 28–29 September 2004; during the post-thinning period the maximum storm precipitation was 263.9 mm (13–15 July 2007; Table SI; Figure 2).

Storm runoff responded rapidly to precipitation input

Figure 2. Precipitation and hydrological response in catchments M4 and M5 during the monitoring period from June 2004 to June 2009: (a) precipitation, (b) catchment runoff, and (c) catchment runoff coefficient. No catchment runoff data was collected from 23 November 2007 to 6 February 2008.
throughout the monitoring period. Increased rainfall intensity corresponded to increased storm runoff (Figure 2). Mean storm runoff from catchments M5 and M4 was 12.9 and 6.2 mm, respectively (Figure 2b). Storm runoff coefficients for M5 ranged from 0.4% to 98.7%, with a mean of 32.3%, whereas the runoff coefficients of M4 (control) ranged from 0% to 69.9%, with the mean of 9.9% (Figure 2c).

During both the pre- and post-thinning periods, quick runoff from catchments M5 and M4 increased dramatically when total storm precipitation exceeded 80 mm (Figure S1). This pattern was also reported in the same watershed during different observation periods (Gomi et al., 2010; Miyata et al., 2010). Despite the removal of forest stems, threshold behavior for the observed increase in quick runoff during storms remained similar between the pre- and post-thinning periods, suggesting that the dominant storm runoff pathways remained unchanged after thinning. Nevertheless, rainwater that percolated into the soil and was delivered to the stream as subsurface storm flow was the dominant runoff pathway in this catchment.

**Peak flow and recession characteristics**

Peak flow responses to storm precipitation did not increase after thinning and also between the treated (M5) and control (M4) catchments (Table S1). In catchment M5, the mean peak flow (± standard deviation; SD) was 1.3 ± 1.5 mm h⁻¹ and 0.8 ± 1.7 mm h⁻¹ in the pre- and post-thinning periods, respectively. The mean peak flow from catchment M4 was 1.4 ± 1.1 mm h⁻¹ in the pre-thinning period and 0.6 ± 1.3 mm h⁻¹ in the post-thinning period.

Peak flow from catchment M5 was significantly correlated with flow from catchment M4 (Figure 3a). Residuals of peak flow (Tₑ) were generally positive with means of 0.1 ± 0.6 mm h⁻¹ and 0.07 ± 0.6 mm h⁻¹ in the post- and pre-thinning periods, respectively (Table SII; Figure 3b). Hence, treatment effects between the pre- and post-thinning periods did not significantly differ at the 95% confidence level (Table SII). A cumulative frequency distribution curve of the treatment effects also showed that observations exceeding two standard errors tended to be similar between the pre- and post-thinning periods (Figure S2).

The mean recession time (T) in the thinned catchment (M5) was 23.4 (SD: ± 30.5) and 29.8 (SD: ± 34.6) hr during the pre- and post-thinning periods, respectively (Table SIII). In the control catchment (M4), mean recession time in the pre-thinning period was 9.1 ± 18.4 hr, while that for post-thinning was 12.5 ± 22.7 hr. The shorter recession time in catchment M4 compared to the treated catchment suggests that less available water was stored in catchment M4 (Hewlett and Helvey, 1970; Tallaksen, 1995).

The mean recession constants (K) estimated for catchment M5 were 0.84 (± 0.18) in the pre-thinning period and 0.93 (± 0.11) in the post-thinning period (Table SIII). Mean K values (± SD) for catchment M4 were 0.64 ± 0.27 and 0.59 ± 0.31 in the pre- and post-thinning periods, respectively. Because both recession times (T) and constants (K) differed substantially between catchments M4 and M5, we did not conduct statistical analysis for T and K between catchments M4 and M5. However, recession constants between pre- and post-thinning periods in catchment M5 were significantly different; this pattern was not true in the control catchment M4 (Table SII; Figure S3). Recession times were similar for pre- and post-thinning periods in both catchments (Table SII).

**Effects of forest thinning on hydrological processes**

Recession hydrographs responded differently before and after forest thinning, while peak flow response was similar for these periods. Hydrograph analysis indicated that removal of stems altered internal hydrological pathways within the catchments. Storm flow consists of several hydrological components such as direct precipitation on the channel, infiltration-excess overland flow, biomat flow, saturated overland flow, subsurface storm flow, and bedrock ground water flow (Sidle et al., 2000; Gomi et al., 2010; Sidle et al., 2011). Our previous studies indicated that the amount of overland flow did not differ significantly before and after the thinning based on runoff from 8 × 25 m hillslope plots installed in both catchments (Dung et al., 2011). Miyata et al. (2010) also suggested that subsurface storm flow dominated near the peak of storm hydrographs. Using field observation and numerical models, Kim et al. (2011) and Sidle et al. (2011) also noted that subsurface flow was the dominant flow component in forested zero-order basins in Japan.

Because net-precipitation (i.e., throughfall) increased and evapotranspiration decreased after thinning, net availability of soil water increased. Increased baseflow after forest harvesting management has also been summarized in a comprehensive review (Moore and Wondzel, 2005). In catchment M5, net precipitation was estimated to increase 9.8% (corresponding to a 137.1 mm increase in annual precipitation) due to thinning based on an equation developed by Komatsu et al. (2008). Estimated evapotranspiration potentially decreased by 21% (corresponding to a 293.8 mm decrease in annual evapotranspiration) based on

![Figure 3](image-url)
findings by Kolb et al. (2009). Although some overland flow occurred on the hillslope, the increased net precipitation also infiltrated into the soil matrix and was delivered to the stream via throughflow and preferential flow paths (Sidle et al., 2000; Dung et al., 2011; Sidle et al., 2011). Such changes in available water only altered the recession constant K and the available baseflow volume after thinning in catchment M5 (Dung et al., 2012).

The lack of significant changes in peak flow after the thinning can be attributed to the minimal site disturbance during thinning. Thinning was conducted by forest workers using chainsaws with very little disturbance of the soil surface. Some thinned timbers and branches were placed parallel to slope contour. Thus, our study site was affected only by the removal of trees and we could evaluate the changes in net precipitation and evapotranspiration on runoff. On the contrary, clearcutting (particularly ground-based) generally creates soil disturbance by heavy machinery and forest roads. For instant, peak flow increased from 28 to 128% in Pacific Northwest catchments where greater than or equal to 70% of the forest stand was clearcut because of soil disturbances and brush burning (Krygier and Harr, 1972). In the Western Cascades of Oregon, forest harvesting with 2 to 3% of the area in roads increased peak flows from 50 to 100% (Jones and Grant, 1996). Based on field results and previous studies, Guillemette et al. (2005) demonstrated that increases in peak flow were attributed to the hydrological connectivity of overland flow via skid trails and roads. Forest harvesting in these studies was conducted by ground-based machinery with skid trails and road ditches along streams. Such forest practices caused soil compaction and reduced infiltration capacity, producing greater overland flow that led to increases in peak flows (Sidle and Drlica, 1981; Ziegler et al., 2001). Our study was able to isolate the effect of only tree removal and associated soil disturbance on storm runoff.

**SUMMARY AND CONCLUSIONS**

Our paired-catchment analysis revealed that thinning 58.3% of the forest stand with minimal soil disturbance did not alter either peak flow or recession time, but increased the recession constant. Increases in net precipitation and decreases in evapotranspiration increased the net availability of soil water and resulted in increases in baseflow. Because subsurface flow dominated the storm runoff processes in headwater basins, changes in available soil water resulted in a slower recession phase during storm hydrographs. In the thinned catchment, soil disturbance was minimized and the thinned timber was placed parallel to slope contours to help prevent surface runoff. Thus, peak flows and recession times during storms did not change due to forest thinning unlike in prior studies where contiguous blocks of timber were clearcut (e.g., Krygier and Harr, 1972; Jones and Grant, 1996; Guillemette et al., 2005). Therefore, findings of our study confirmed that forest cover by itself does not control or alter peak flows.

Maximizing the utilization of timber together with minimizing environmental impacts has been recommended for appropriate watershed management (FAO, 2005). Our results of experimental forest harvesting suggest that to minimize the impact of harvesting operations on peak runoff, careful site preparation is essential to guide of forest management in steep terrain of Japan. Further investigation is needed at the catchment-scale to identify and reduce the confounding effects of land management on watershed processes.

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**SUPPLEMENTS**

Table S1. Storm precipitation and peak flow characteristics
Table SII. Summary of statistical analysis for peak flow, time recession, and K-values
Table SIII. Recession analysis for storm events

| Figure S1. The relationship between total storm precipitation and quick runoff in the thinned (M5) and control (M4) catchments during the pre- and post-thinning periods. |
| Figure S2. Cumulative frequency distributions for pre- and post-thinning differences between observed and estimated peak flow based on paired-catchment analysis. |
| Figure S3. (a) Time recession of stream flow and (b) K-values of catchments M5 and M4 during the pre- and post-thinning periods. Lines within and adjacent to the box plots indicate the mean and standard deviation, respectively. n shows number of storm event was analyzed. |

**REFERENCES**


