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Effects of Forest Thinning on Direct Runoff and Peak Runoff Properties in a Small Mountainous Watershed in Kochi Prefecture, Japan

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Abstract: Single catchment experiment was used to assess the effects of thinning on direct runoff and peak runoff properties in a small mountainous watershed of Kochi prefecture, Japan. The watershed is covered with commercial plantations of Japanese cedar (*Cryptomeria japonica*), Japanese cypress (*Chamaecyparis obtusa*), red pine (*Pinus densiflora*) and oak (*Quercus* spp.). Following an initial pre-thinning period (1996-1999), stream flow measurements were continued over a comparable post-thinning period (2000-2003) and linear regression models were developed for the two periods to assess the effects of a thinning operation conducted during December 1999 to January 2000. We hypothesized that the regression model for the pre-thinning period is still valid for the post-thinning period and tested this utilizing the Chow's F Test. A 95% prediction interval was calculated for the pre-thinning regression models to evaluate changes in individual observations of the post-thinning period. The results suggest that the thinning, carried out on 19.25% of the watershed area removing only 6.35% of total timber volume, did not cause noticeable effects on direct runoff and peak runoff. Concentration time was found to be decreased after thinning for some storm events. The study revealed that hydrometric method is not enough for detecting noticeable effects of a small thinning operation on direct runoff and peak runoff properties.

Key words: Single catchment experiment, hydrograph, linear regression model

INTRODUCTION

Mountains and uplands are recognized as the water towers of the world, providing reliable supplies of freshwater to lowland areas[1]. Forests play the crucial role in the filtration of precipitation by the forest canopy and floor and ensure the release of steady water flows even in the driest months. Thus, Mountainous forested watersheds are important in the hydrological cycle. The effects of timber harvest or thinning on streamflow have been the subject of many studies, often with conflicting results. Since forested watersheds become more intensively managed and attempts are made to minimize adverse impacts, research on hydrological response of watersheds due to forestry activities is becoming increasingly important.

Bosch and Hewlett[2] updated Hibbert's[3] review of catchment experiments to determine the streamflow response of vegetation changes and suggested that the response depends on the region's mean annual precipitation and on the precipitation for the year under treatment. They also suggested that the response is greatest in high-rainfall areas and is, however, shorter-lived than in low-rainfall areas due to rapid regrowth of vegetation. Bruijnzeel[4,5] reviewed the hydrological effects of forest cover transformation in the humid tropics and concluded that: carefully executed light selective harvesting of tress (upto 20% removal of biomass) has little (if any) effect on stream flow; removal of natural forest cover may result in a considerable increase in water yield (upto 800 mm/yr), depending on the amount of rainfall received and the degree of surface disturbance; there is a decline in runoff with time associated with reforestation.

Bent[6] reported large difference of timber harvest effects on total flow, direct runoff, base flow and ground-water recharge in two different watersheds, although total basal area was reduced by similar percentages. He suggested that the difference was due to: the location of the forest treatments within the experimental watersheds; the percentage of areas affected by the forest treatments in the experimental watersheds;

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the types of regrowth in the treated areas of the experimental watersheds; the time separating the periods of forest treatments. According to Harr[7], the size of peak flows may be increased, decreased or remain unchanged after timber harvest, depending on what part or parts of the hydrologic system are altered, to what degree and how permanent the alteration is by timber harvest activities.

The highly variable and site-specific response of the timber harvest activities on runoffs has led more watershed experiments worldwide. The aim of this study was to assess the effects of forest thinning on direct runoff and peak runoff properties in a small mountainous watershed of Kochi prefecture, Japan.

MATERIALS AND METHODS

Study area: The study area was at the Kawai watershed located in the upstream region of the Shimanto River on the Shikoku Island, Japan at 33°21' 45"N and 132°54' 03"E, which is 48 km to the north of Nakamura city and about 2 km away from Yusuhara town of Kochi prefecture (Fig. 1). The watershed drains an area of 27.38 ha. The elevation varies from 455 to 925 m. The watershed is underlain by tertiary sedimentary rocks of sandstone and mudstone alternates in the Shimanto belt. The area has warm to temperate rainy climate with four distinct seasons based on the climatic condition: summer (June-September), fall (October-November), winter (December-February) and spring (March-May). Snow falls occasionally during winter. Temperature had significant seasonal variation, with the maximum and the minimum monthly mean values of 24.2 and 2.6°C in August and January, respectively, during the study period (1996-2003).

Most of the precipitation is rain often associated with typhoons and frontal storms. Annual rainfall averaged 2908.6 mm at the watershed outlet during the study period, out of which 58.6% occurred in the summer. The highest total annual rainfall occurred in 1999 (4752 mm) and the lowest in 2001 (2140 mm) (Fig. 2). The average monthly rainfalls in the pre- and post-thinning periods are presented in Fig. 3. The significant monthly and yearly variations of rainfall largely influenced the hydrological response of the watershed in the two periods.

Vegetation type and treatment: Kawai watershed is covered with commercial plantations of Japanese cedar (*Cryptomeria japonica*), Japanese cypress (*Chamaecyparis obtusa*), red pine (*Pinus densiflora*) and oak (*Quercus* spp.). All of the plantations of different species were established during 1960-1961. A thinning operation was carried out over 5.27 ha of the watershed area from December 1999 to January 2000. Out of 2062 m^3 timber volume in the thinned area, 680 m^3 were removed through skyway for commercial use. On an equivalent basis, thinning was conducted on 19.25% of the watershed area and only 6.35% of the total timber volume was removed from the forest.

Instrumentation: Stream stage heights through sharp-crested 90° V-notch weir were monitored continuously in Kawai watershed with a water depth probe and the average values were recorded on an automatic data logger at an interval of 10 min during the study period (1996-2003). An autographic rain gauge was installed for recording the amount of rainfall at the same interval with the stage height measurement in Kawai watershed. The stage height data were converted to the runoff in millimeter per hour (mm/h) equivalents.

Data analysis: Single catchment experiment was used to assess the effects of thinning on direct runoff and peak runoff properties of storms. Following an initial calibration or pre-thinning period (1996-1999), streamflow measurements were continued over a comparable post-thinning period (2000-2003) to assess the thinning effects. Many of the storm events during the study period were deemed unacceptable for analysis because of multiple inseparable peaks, which is common in Kawai watershed due to typhoons and long-duration storm events. For analyzing the effects of thinning on direct runoff, 24 storm events were selected in each of the pre- and post-thinning periods. Twenty seven storm events were selected in each of the pre- and post-thinning periods for analyzing the effects of thinning on peak runoff properties.

Hydrograph separation into direct runoff (that part of runoff which enters the stream promptly after the rainfall) and base flow (the sustained fair-weather component of runoff) is based on the method described by Hong *et al.*[8] (Fig. 4). They suggested that the storm runoff decays with an exponential constant of 0.024 h^{-1} from several hours after rainfall to one or two days later and then continues to decay with a constant of 0.011 h^{-1}. The point, where these two decay lines cross each other on the recession limb of the log-scale hydrograph, is considered as the end of direct runoff. A line projected from the initial rise of storm runoff to the end point of surface runoff divides the storm runoff into surface runoff and base flow.

For assessing the effects of thinning on direct runoff, multiple linear regression models were developed separately for the pre- and post-thinning periods using 6 predictor variables, which were found to be strongly correlated with direct runoff. For analyzing the effects of thinning on peak runoff properties, simple linear regression models were used. Because hydrological data tend not to be normally distributed, many literatures suggested a logarithmic transformation of hydrological data[9]. To determine whether logarithmic transformation

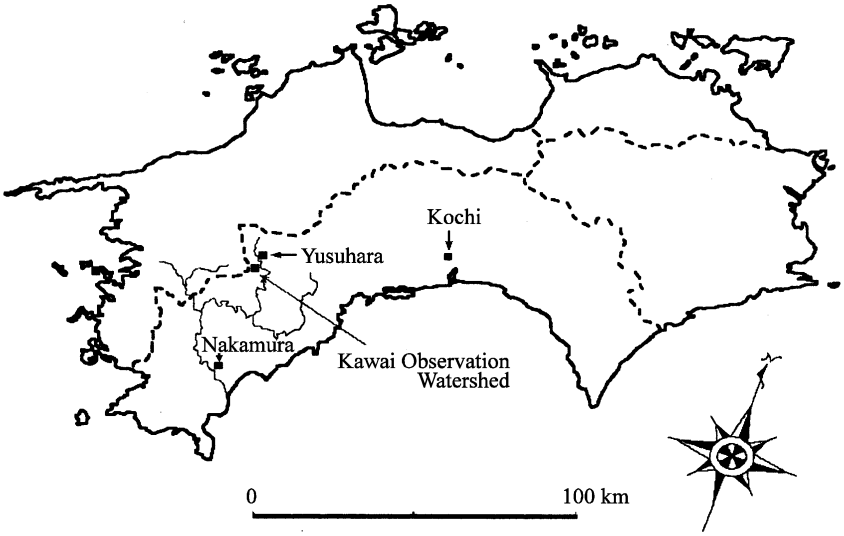

Fig. 1: Kawai observation watershed in kochi prefecture of Japan

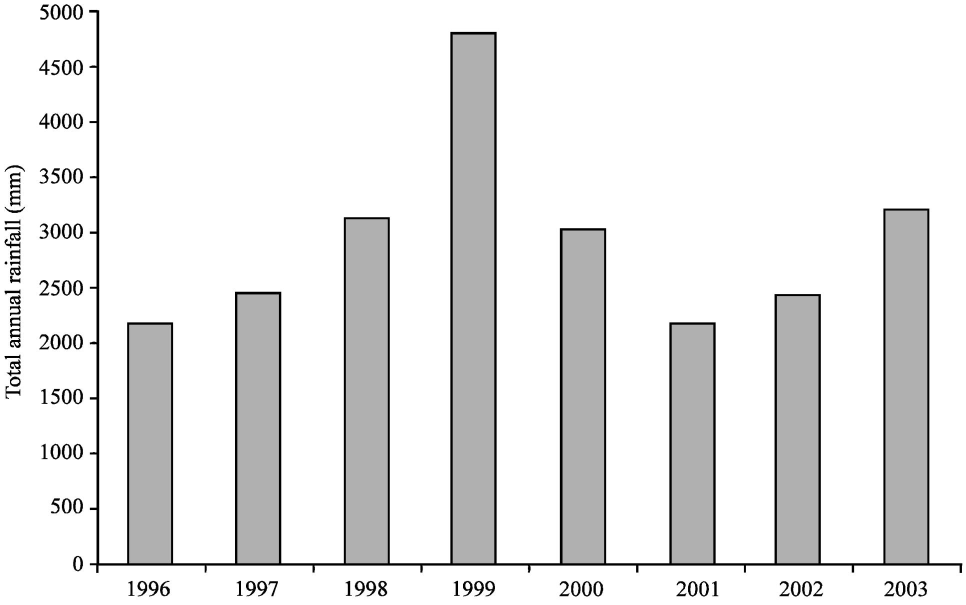

Fig. 2: Total annual rainfall in Kawai watershed (1996-2003)

should be applied, residuals of the regression models were tested for normality by Chi-square Test for untransformed and transformed data. Logarithmic transformation was done on both predictor and response variables to get best fitted simple linear regression models that have approximately normally distributed residuals and that represent more nearly linear relationships between the variables.

We hypothesized that the multiple/simple linear regression model for the pre-thinning period is still valid for the post-thinning period and tested this hypothesis utilizing the Chow's F Test[10]. A 95% prediction interval was calculated for the pre-thinning regression model. Any point of response variable that fell above or below the upper or lower prediction level, respectively, was deemed to have been increased or decreased by thinning.

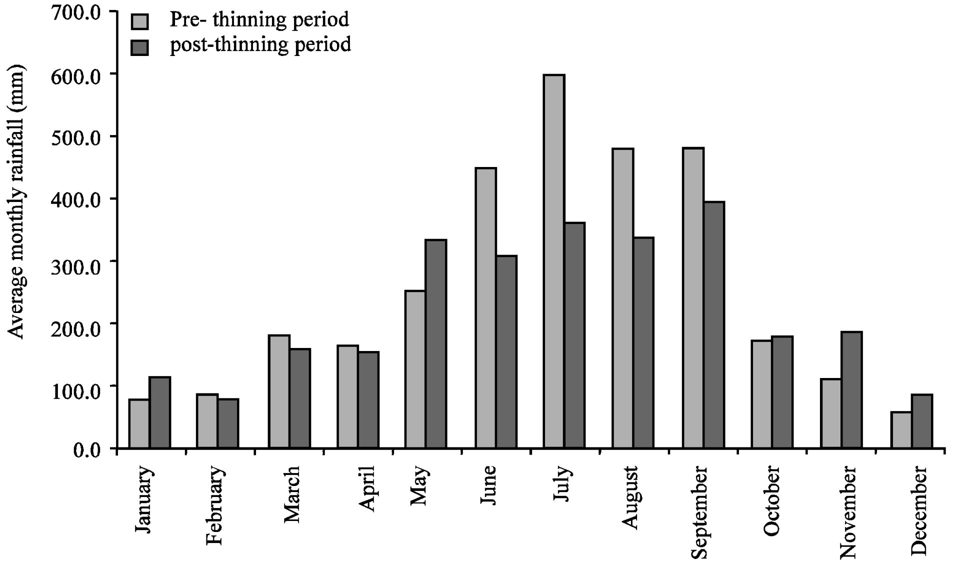

Fig. 3: Average monthly rainfall in the pre- and post-thinning periods

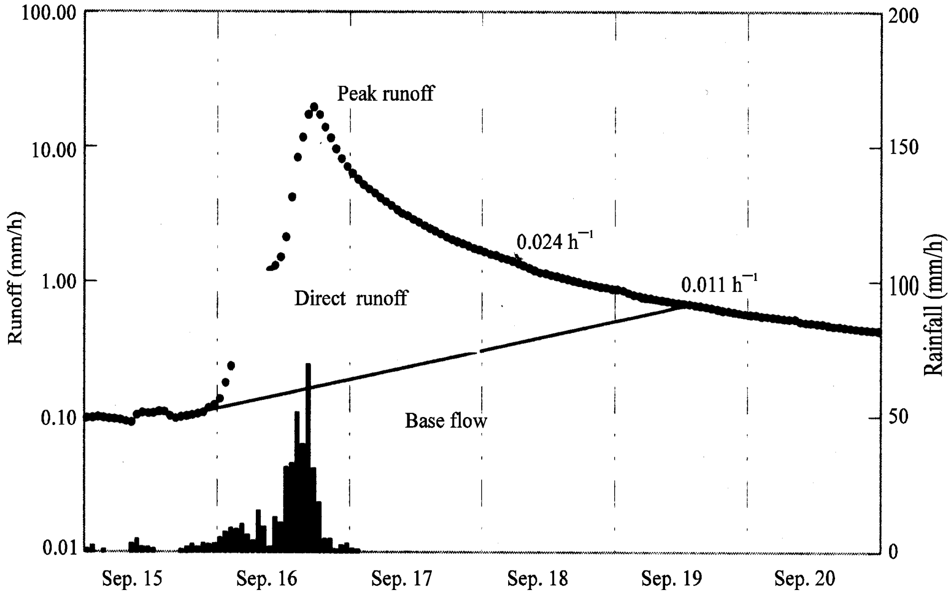

Fig. 4: Separation of strom hydrograph (September 15-20, 1997)

RESULTS

Effects of thinning on direct runoff: Direct runoff is the amount of flow resulting directly from a rainfall or snowmelt event but arbitrarily limited in duration, which usually includes channel interception, overland flow and interflow[11]. In determining the effects of thinning it was assumed that,

$$Q_d = f(R, R_i, R_{max}, T_r, T_{Qd}, D_o) \quad (1)$$

Where, Q_d is direct runoff (mm), f is the function, R is total amount of rain (mm) in the storm event, R_i is the average rainfall intensity (mm/h), R_{max} is the maximum hourly rain (mm/h), T_r is the duration of the storm event (h), T_{Qd} is the duration of direct runoff and D_o is the deficit of soil moisture (mm). D_o is an antecedent index of soil moisture condition and was calculated by the following equation:

$$D_o = \sum (E_p i - ri) \quad (2)$$

Table 1: Summary of multiple linear regression models for direct runoff (Q_d) and Chow's test result

		Regression coefficients							Chow's Test	
Regression	n	b_1	b_2	b_3	b_4	b_5	b_6	R^2	F	p
Calibration	24	0.801	-5.868	0.242	-1.497	0.306	-0.459	0.992		
Post-thinning	24	0.796	-1.954	-0.691	-1.067	0.176	-0.771	0.988	0.720	0.754

The b coefficients represent multiple linear regressions of the form: $Q_d = b_1 R + b_2 R_i, + b_3 R_{max} + b_4 Tr + b_5 T_{Qd} + b_6 D_o$

Where, E_p = daily potential evapotranspiration (mm) calculated by Penman[12] equation through the computer program of Miura and Okuno[13] ; r = daily rain (mm), if any, in small amount; I = antecedent days (from the next day of previous storm event to the previous day of the storm event under consideration). If (E_p – r) is negative at any antecedent day, that was considered zero.

We developed pre- and post-thinning multiple linear regression models for direct runoff using the variables indicated on the right side of Eq. 1 as predictor variables. The Chow's Test failed to detect any significant variation between the pre- and post-thinning multiple linear regression models for direct runoff (Table 1). A 95% prediction interval calculated for the pre-thinning regression model showed that all of the observed direct runoff data in the post-thinning period fell within the prediction interval. Therefore, no effect of thinning on direct runoff was found.

Effects of thinning on peak runoff properties:

Concentration time: Concentration time is a fundamental watershed parameter. It is used to compute the peak discharge for a watershed. According to Kadoya and Fukushima[14], concentration time can be calculated from the following equations:

$$T_p = CA^{0.22} (R_e)^{-0.35} = CA^{0.22} (f_p R_{tp})^{-0.35} \quad (3)$$

$$f_p = R_e / R_{tp} \quad (4)$$

Where, T_p is the concentration time (min), C is a coefficient depending on land use; R_e is effective rainfall intensity and is equal to the peak runoff of a storm (mm/h); A is the area of the watershed (km^2); R_{tp} is the average rainfall intensity during T_p (mm/h), f_p is the runoff coefficient.

We calculated T_p and other variables using the above equations. The pre- and post-thinning regression models for T_p were developed using R_e as the predictor variable to assess the impact of thinning on T_p. The regression relationships in the two periods are shown in (Fig. 5a). The Chow's F Test showed that there is no statistical difference between the pre- and post-thinning regression models (Table 2). The 95% prediction interval calculated for the pre-thinning regression model is shown in (Fig. 5b), which reveals that few points of post-thinning T_p has fallen below the lower prediction level, thereby, decreases of concentration time for some storm events in the post-thinning period.

Peak runoff: A peak runoff (Q_p) is defined as the maximum instantaneous flow that result from an individual storm (Fig. 4). According to the theory of rational formula, peak runoff is a function of the average rainfall intensity during the time of concentration (R_{tp}). Therefore, pre- and post-thinning linear regression models were developed using Q_p as the response variable and R_{tp} as the predictor variable to assess the effect of thinning on peak runoff. The regression relationships in the two periods are shown in Fig. 6.

The Chow's F Test shows that there is no variability between the pre- and post-thinning regression models (Table 3). A 95% prediction interval calculated for the pre-thinning regression model suggested that, no post-thinning peak runoff fell above the upper prediction limit. Therefore, no significant effect of thinning on peak runoff was found.

DISCUSSION

A marked reduction in the stand density of a forest due to thinning or timber harvest can be expected to cause an immediate reduction of total evapotranspiration. Reduction in the canopy cover would also result in decease of interception losses, resulting in more water reaching the soil. This in turn would lead to a wetter

Table 2: Summary of simple linear regression models for concentration time (T_p) and Chow's test result

Regression	n	R^2	b_0	b_1	Chow's F	p
Pre-thinning	27	0.254	5.274	-0.323		
Post-thinning	27	0.071	5.104	-0.227	0.399	0.673

The b coefficients represent simple linear regressions of the form: $\log (T_p) = b_1 + b_2 \log (R_e)$

Table 3: Summary of simple linear regression models for peak runoff (Q_p) and Chow's test result

Regression	n	R^2	b_0	b_1	Chow's F	p
Pre-thinning	27	0.729	-2.710	1.266	1.567	0.219
Post-thinning	27	0.602	-2.607	1.110		

The b coefficients represent simple linear regressions of the form: $\log (Q_p) = b_1 + b_2 \log (R_{tp})$

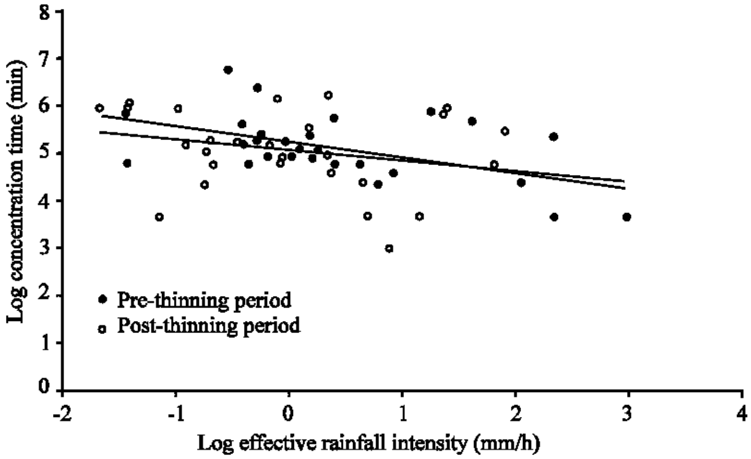

Fig. 5 a: Linear regression relationship between concentration time (T_p) and effective rainfall intensity (R_e) in the pre- and post-thinning periods

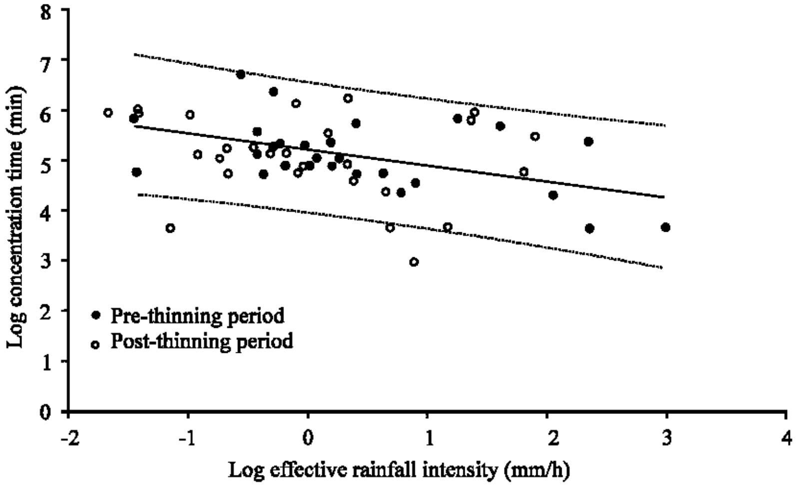

Fig. 5 b: Pre-thinning regression (solid line) and 95% prediction interval (dashed lines) for the pre-thinning regression between concentration time (T_p) and effective rainfall intensity (R_e)

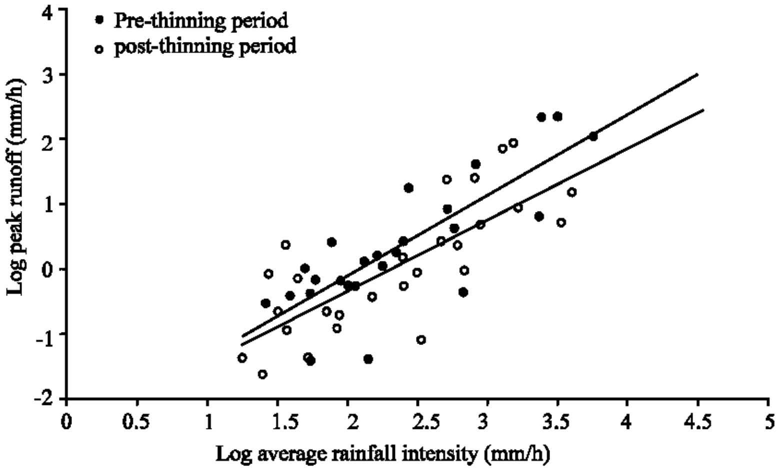

Fig. 6: Linear regression relationship between peak runoff (Q_p) and average rainfall intensity (R_{tp}) in the pre- and post thinning periods

watershed and an increase in direct runoff and peak flow. However, there are many climatic factors that influence direct and peak runoffs, namely, type of precipitation (rain, snow, frost etc.), rainfall intensity, rainfall amount, rainfall duration, distribution of rainfall over the drainage basin, direction of storm movement, antecedent precipitation and resulting soil moisture, other meteorological and climatic conditions that affect evapotranspiration, such as temperature, wind, relative humidity and season etc. During the study period, climatic factors varied largely from year to year (Fig. 2 and 3).

Large variability of climaticconditions in the pre- and post-thinning periods made it difficult to distinguish the effects of thinning on the direct runoff and peak runoff properties in the single catchment experiment.

Thinning usually causes rapid growth of the remaining trees and a full recovery of the leaf area index and, consequently, interception losses in the thinned stand. The vigorous trees that remain after thinning would make use of extra available moisture, restricting the potential increase in streamflow over time[15]. In general, changes in annual water yield from harvesting of less than 20% watershed area or forest cover can not be determined by stream flow measurement[16], which is also likely to be true for determining changes in direct runoff and peak runoff. On an equivalent basis, thinning was carried out on 19.25% area of the watershed area and only 6.35% of the totaltimber volume was removed from the forest during the thinning operation. Therefore, no noticeable increase of direct runoff and peak runoff after thinning is attributable to the small percentage of timber removal from the forest.

The concentration time is usually influenced by surface roughness, slope and overland flow pattern. Although no impact of thinning on overland flow or surface runoff was found, a change in surface roughness caused by thinning might have been influenced the decrease of concentration time for some of the storm events in the post-thinning period.

The reduction of number of stems resulted in a smoother surface in the thinned forest area which caused a decrease in travel time of the flow and eventually decrease in concentration time noticeable for some of the storm events.

This study revealed that hydrometric method is not enough for detecting noticeable effects of a small thinning operation on direct runoff and peak runoff properties of storm events. McMinn and Hewlett[17] suggested that logically the effects of zero treatment (timber harvest) must be zero and we must carry forward the assumption that ever smaller percentage reductions in forest cover will produce effects in expected water yield. Therefore, alternative methods should be examined to detect noticeable changes in direct and peak runoff properties due to small reduction of forest cover in the future research.

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