Model Analysis of Forest Thinning Impacts on the Water Resources During Hydrological Drought Periods

Running Title: Thinning impacts on water resources

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Abstract

In Japan, there has recently been an increasing call for forest thinning to conserve water resources from forested mountain catchments in terms of runoff during prolonged drought periods of the year. How their water balance and the resultant runoff are altered by forest thinning is examined using a combination of 8-year hydrological observations, 100-year meteorological data generator output, and a semi-process-based rainfall-runoff model. The rainfall-runoff model is developed based on TOPMODEL assuming that forest thinning has an impact on runoff primarily through an alteration in canopy interception. The main novelty in this analysis is that the availability of the generated 100-year meteorological data allows the investigations of the forest thinning impacts on mountain catchment water resources under the most severer drought conditions. The model is validated against runoff observations conducted at a forested mountain catchment in the Kanto region of Japan for the period 2010–2017. It is demonstrated that the model reproduces temporal variations in runoff and evapotranspiration at inter- and intra-annual time scales, resulting in well reproducing the observed flow duration curves. On the basis of projected flow duration curves for the 100-year, despite the large increase in an annual total runoff with ordinary intensifying thinning, low flow rates, i.e., water resources from the catchment in the drought period in the year, in both normal and drought years were impacted by the forest thinning to a lesser extent. Higher catchment water retention capacity appreciably enhanced the forest thinning effect on increasing available water resources.

Keywords: forest management, coniferous plantation, evapotranspiration, TOPMODEL, low-flow, stochastic rainfall model

1. INTRODUCTION

Forested headwaters supply water resources to billions of people at a global scale, which are derived from a balance between runoff from the catchment and water use by vegetation (McDonnell et al., 2018). Thus, it has been expected that some forest management has the potential to optimize water yield from the headwater catchment (Andréassian, 2004; Grant, Tague, & Allen, 2013). In Japan, forests cover ~70% of the total land area with the majority situated in the mountain region, and the forested headwaters play a significant role in supplying water to lowlands. Therefore, there has been a strong need to utilize forest management for sustainable water supply from mountains even if under drought conditions (Forestry Agency, 2019).

Forest thinning is among the most effective silvicultural treatments of forest management to increase water availability for humans (Ganatsios, Tsioras, & Pavlidis, 2010; Hawthorne, Lane, Bren, & Sims, 2013; G. Sun, Caldwell, & McNulty, 2015). The forest thinning effects on the catchment hydrology would be primarily due to changes in evapotranspiration (ET), induced by alterations to the forest canopy-atmosphere processes (Komatsu, Tanaka, & Kume, 2007; X. Sun et al., 2014). As runoff is originated from net precipitation input to the catchment water storage, soil physics related to the water holding capacity and conductivity can supplementarily alter the thinning effects on the water availability (Moreno, Gupta, White, & Sampson, 2016; Zhang, Deng, Yang, & Shangguan, 2016). Here, we emphasize that to quantify the hydrological effect of forest thinning, we should take into consideration the combined effects of the ET change and the soil physics properties on the runoff from the studied catchment.

There have been numerous findings of the relationships between forest cover change and runoff responses based on observational and experimental studies (Bosch & Hewlett, 1982; Brown, Zhang, McMahon, Western, & Vertessy, 2005). However, generalizing these findings and predicting the water yield after forest thinning in either catchment by observations alone have been difficult because of varieties of climate, vegetation type, geology, and topography (McDonnell et al., 2018; Saksa, Conklin, Battles, Tague, & Bales, 2017). What is less certain is the forest thinning effects on increasing both minimum seasonal streamflow rate during the dry periods of the year and extremely low streamflow rate during the prolonged drought periods (see Smakhtin, 2001). Note that it should be also difficult to obtain so sufficient long-term climate data that can explain the influence of an extraordinary drought on the thinning effects.

Our goal is to investigate how forest thinning affects water yield from a headwater catchment, especially under abnormally severe and common drought conditions. Toward this goal, we use 100-year meteorological data generated by observed precipitation statistics, a semi-process-based rainfall-runoff model (a modified TOPMODEL; cf. Beven & Kirkby, 1979), and detailed catchment-hydrology observations conducted over an 8-year period. Prior to accessing the thinning impacts in terms of low-flow hydrology, the model is first validated with the field observations at a forested mountain catchment in the Kanto region of Japan, described next.

2. STUDY SITE AND OBSERVATIONS

2.1 Site Description

This study was carried out in the Oborasawa Experimental Watershed (OEW), a 55-ha forest headwater catchment in the Tanzawa mountains, in the Kanto region of Japan (35°28'N, 139°12'E, 439–872 m a.s.l.). The catchment is steep with a mean slope (± standard deviation [SD]) of 34.9 ± 9.0°. The soil is classified as Cambisol having a large portion of volcanic ash and has a high infiltration capacity at the surface ranging from 100 to 600 mm h^{-1} (Oda, Suzuki, Egusa, & Uchiyama, 2013). The mean soil depth (± SD), observed by a cone penetration test, was 1.64 ± 0.97 m (n = 217; Yokoyama, Uchiyama, & Mitsuhashi, 2014). The underlying bedrock beneath the soil is tuff, composed mainly of volcanic breccia, and is classified as Cenozoic sedimentary rock. There exists weathered bedrock with fissures below 40 m depth from the surface, and its hydraulic conductivities depend on the degree of weathering, ranging from 4.7×10^{-5} to 2.6×10^{-6} cm s^{-1} (Yokoyama, Uchiyama, Sato, & Yamane, 2013).

The mean annual precipitation (P) for the period 2010–2017 was 2954 mm. Large rainfall events occur generally during the rainy season from mid-June to early July (584 ± 206 mm for the 2-month June–July; mean ± SD) and the typhoon season from September to October (921 ± 235 mm). Snowfall only occurs once or twice a year from January to March, only accounts for a small percentage of total annual precipitation, and has limited influence on runoff. The mean annual air temperature (T_a) was 11.6°C in 2010–2017, with a minimum mean daily T_a of −2.5°C in January and a maximum mean daily T_a of 24.4°C in August. The mean daily vapor pressure deficit (VPD) averaged over daylight hours (06:00–18:00 LT) reached a maximum of 1.6 kPa in May.

Forest in the OEW consists mainly of coniferous plantation stands, and the bare land ratio is less than 1%. Approximately two-thirds of the forested areas are composed of conifers, i.e., *Cryptomeria japonica* D. Don and to a lesser extent, *Chamaecyparis obtusa* Endl. (a vegetation survey in 2007; Uchiyama, Nakajima, Yokoyama, & Yamanaka, 2014). The remaining one-third is fragmented areas of deciduous broadleaved trees, e.g., *Cercidiphyllum japonicum* Sieb. et Zucc. and *Aesculus turbinata* Blume. The averaged stand density (S_d) and leaf area index (LAI) over the catchment were estimated to be 1280 trees ha^{-1} and 3.8 m^2 m^{-2}, respectively.

2.2 Hydrological and Micrometeorological Observations

A 49-ha subcatchment (referred to as Catchment A) of the OEW is devoted to catchment-scale water budget observations. A previous study using the annual chloride balance method (Oda et al., 2013) assumed little bedrock drainage and inter-catchment groundwater flow, which was ca. 5% of annual runoff and almost negligible, in Catchment A, although the recently accumulated observation data suggest that the bedrock drainage and/or spring could be larger than the previous estimation (data not shown here).

The data from the 2010–2017 observations were used for this study. The stream water level was measured every 10-min by a pressure type water level gauge (ATM_N type, Koshin Denki, Tokyo, Japan) installed at a V-notch weir in Catchment A, and was converted to volumetric runoff (Q_V) with an empirical relationship between the water level and actual Q_V. Then, specific discharge, hereinafter referred to as runoff (Q), was obtained by dividing Q_V by contributing catchment area. The P was continuously measured every 10-min with a 0.5 mm tipping-bucket rain gauge (N78, Nippon Electric Instrument, Tokyo, Japan) at the open ridge in Catchment A.

Solar radiation (R_s) and relative humidity (RH) and T_a were measured every 10-min at the open ridge of Catchment A using a pyranometer (SL-30, Azbil, Tokyo, Japan) and a relative humidity probe (HT-20, Azbil, Tokyo, Japan), respectively. The VPD was calculated as a saturated vapor pressure of T_a minus an actual vapor pressure estimated from RH, and then, was averaged over daylight hours (06:00–18:00 LT).

3. METHODOLOGY

We discuss first the rainfall-runoff model development, validating the model, and parameterization, and then proceed to discuss its usage for assessing the forest thinning effect on runoff regimes under normal and abnormal drought conditions following the precipitation statistics. For the model validation, the observed meteorological variables time series were used to drive the model calculation; however, in our model simulations for the severe drought impact—only precipitation statistics were available thereby necessitating a stochastic representation such as the flow duration curve (cf. Yokoo & Sivapalan, 2011). The generation of 100-year meteorological data and the connections to the flow duration outputs are also discussed.

3.1 Rainfall-Runoff Model

Given little bedrock drainage and inter-catchment groundwater flow, the *Q* can be expressed as the function of soil water storage, following the original TOPMODEL concept (Beven & Kirkby, 1979). In this study, TOPMODEL was modified to account for the forest thinning impact on ET and the resultant *Q*. Note that according to our preliminary approximate estimate of the time lag between *P* and *Q* at a daily time scale in the study catchment, we did not take into consideration water storage capacity in the root or vadose zone (e.g., Beven, Lamb, Quinn, Romanowicz, & Freer, 1995) for this modification.

The vertically integrated continuity equation describes the catchment water balance (Figure 1) to compute the catchment average saturation deficit $\overline{D_s}$ (mm), given by

$$\frac{d\overline{D_s}}{dt} = T_r + I_c + Q_{¿} + Q_{¿} - P, \qquad (1)$$

where t is time (day), T_r is transpiration rate (mm day^{-1}), I_c is interception rate (mm day^{-1}), Q_{over} is overland flow (mm day^{-1}), and Q_{sub} is subsurface flow (mm day^{-1}). Saturation deficit at a given point i (D_{s_i}; mm) can be calculated as:

$$D_{s_i} = \overline{D_s} + m\left(\overline{TI} - TI_i\right), \qquad (2)$$

where m is a soil parameter replacing ϕ / f, in which ϕ is soil porosity and f defines the decrease of saturated hydraulic conductivity with depth, and $\overline{TI}$ and TI_i are the topographic indices TI as the catchment average and the value at a given point i, respectively. TI is defined as ln $(a/\tan\beta)$, in which a is contributing catchment area per unit contour length and β is the local slope. For the TI computation in this study, using a 1-m gridded digital elevation model (DEM), all pits were made level with theoretically elevation increments (Ao, Takeuchi, Ishidaira, Yoshitani, & Fukami, 2003) and the multiple flow direction algorithm was adopted (Quinn, Beven, Chevallier, & Planchon, 1991).

[Insert Figure 1]

Q_{over} and Q_{sub} in Equation (1) are respectively given by

$$Q_{¿}=\frac{1}{N}\sum_{i=1}^{N} max\left(0,-k_t D_{s_i}\right) \tag{3}$$

and

$$Q_{¿}=T_{max}e^{-\overline{TI}}e^{\frac{-\overline{D}_s}{m}}, \tag{4}$$

where N is the number of grids in the DEM of the studied catchment, k_t is a time constant, and T_{max} is a soil parameter representing the transmissivity, which replaces K_0/f, in which K_0 is the saturated hydraulic conductivity at the surface.

3.2 Evapotranspiration Modeling

The ET model, incorporated into the rainfall-runoff model in this study, comprises T_r and I_c models based on the formulations by Momiyama, Kumagai, and Egusa (2019). In general, the boundary conductance of conifers is sufficiently large, and Kumagai, Tateishi, Shimizu, and Otsuki (2008) confirmed *Cr. japonica* canopies are aerodynamically well coupled to the atmosphere. Hence, we used a modified McNaughton and Black (1973) expression to compute the daily T_r rate given by

$$T_r=12\times 3600\times \alpha\frac{\rho_a c_p VPD}{\rho_w \lambda\gamma}G_s, \tag{5}$$

where α is a limiting parameter for T_r, ρ_a is the density of dry air (kg m^{-3}), c_p is the heat capacity of air (J kg^{-1} K^{-1}), ρ_w is the density of water (kg m^{-3}), λ is the latent heat of vaporization of water (J kg^{-1}), and γ is a psychrometric constant (Pa K^{-1}). The G_s is the monthly mean surface conductance (mm s^{-1}), which was calculated from the inverse form of Equation (5) with the monthly mean T_r. Note that the T_r was calculated by subtracting the estimated I_c (described later) from the monthly mean ET derived from the short-term water budget method at the studied catchment (cf. Momiyama et al., 2019). Here, given the daily estimation in the mid-latitude zone, the T_r rate per second was summed over daylight hours (= 12 h × 3600 s) with mean daytime VPD (Pa).

Major uncertainties for driving Equation (5) are G_s and α which are generally functions of environmental variables, e.g., R_s (W m^{-2}) and VPD in kPa for G_s and soil moisture for α. Here, the monthly mean G_s in the studied catchment is expressed using a multiplicative-type function (e.g., Jarvis, 1976):

$$G_s=4.30\times 10^{-3}\overline{R_s}\times\left(1-5.78\times \ln\,\overline{VPD}\right), \tag{6}$$

where an overbar denotes a monthly mean value. According to Tadaki's (1976) report, in Japan, LAI of common coniferous plantations can be estimated to be at least > 3.0, and foliage amount per ground area in forests with closed canopy is independent of the forest thinning intensity and the stand density. Thus, we assumed that the G_s is conservative against changing LAI at post-thinning (cf. Kelliher, Leuning, Raupach, & Schulze, 1995). To facilitate the interpretation of the influence of drought conditions on T_r and the resultant Q, we assumed the following:

$$\alpha = \begin{cases} 0, & for\ \overline{D_s} > D_{sx} \\ 1, & for\ \overline{D_s} \leq D_{sx} \end{cases}, \tag{7}$$

where D_{sx} is $\overline{D_s}$ at plant wilting point. That is, α abruptly decreases to zero under severe drought conditions and has unity for wet conditions.

Komatsu et al. (2007) found a moderate relationship between the I_c ratio, which represents the I_c loss divided by annual P, and the S_d from 12 previous studies throughout Japan ($R^2 = 0.42$), leading to

$$I_c = P \times \left(4.98 \times 10^{-5} S_d + 0.12\right). \tag{8}$$

Kumagai et al. (2014) suggested that Equation (8) might be applicable to estimates at a more detailed time scale, and thus we assumed that the daily I_c loss can be estimated using Equation (8) with daily P. It should be noted that the estimated I_c ratio in Equation (8) (= 0.184, in which S_d = 1280 trees ha^{-1}) for the studied catchment is consistent with the preliminary observations at the several sites in the OEW (0.14–0.25).

3.3 Model Calibration

To estimate model parameters, i.e., m, T_{max}, D_{sx}, and $\overline{D_{s0}}$ (an initial value of $\overline{D_s}$), Q in the modified TOPMODEL was calibrated by comparing the simulated Q with the 8-year observation through the shuffled complex evolution (SCE-UA) algorithm (Duan, Gupta, & Sorooshian, 1993; Duan, Sorooshian, & Gupta, 1992). Given the importance of low streamflow in this study, we used Nash–Sutcliffe efficiency (Nash & Sutcliffe, 1970) criterion with inverse Q values (NSE_{inv}) as an evaluation function for the optimization (Pushpalatha, Perrin, Moine, & Andréassian, 2012), given by

$$NSE_{inv} = 1 - \frac{\sum_{j=1}^{n} \left(\frac{1}{Q_{oj}} - \frac{1}{Q_{mj}} \right)^2}{\sum_{j=1}^{n} \left(\frac{1}{Q_{oj}} - \overline{\left(\frac{1}{Q_{oj}} \right)} \right)^2}, \tag{9}$$

where n is the total number of time steps, subscript j denotes each time step, Q_o and Q_m are observed and simulated Q, respectively, and overbar denotes ensemble mean.

We performed four types of calibrations to examine which model parameters dominate the model reproducibility for observations (see Table 1). Case A optimizes all four parameters, i.e., m, T_{max}, D_{sx}, and $\overline{D_{s0}}$, taking into consideration groundwater runoff, Q_{sub}, and soil moisture limitation for T_r. Cases B and C assume not accounting for Q_{sub} (T_{max} = 0) and the soil moisture limitation ($D_{sx} \rightarrow \infty$), respectively, and optimize remaining parameters, i.e., m, D_{sx}, and $\overline{D_{s0}}$ for Case B and m, T_{max}, and $\overline{D_{s0}}$ for Case C. Case D takes into consideration neither Q_{sub} nor the soil moisture limitation, optimizing only two parameters, m and $\overline{D_{s0}}$.

[Insert Table 1]

3.4 Numerical Experiments

Given that forest thinning would change ET primarily through the alteration of I_c and impact Q (Komatsu, 2020), numerical experiments examining the hydrological impacts of forest thinning will be based on changing the variable S_d in Equation (8) in this study.

For simulation purposes, meteorological data in the period of 100-year with 2-year for spin-up were constructed using random numbers generated from probability distributions representing current P characteristics at the site. The current P characteristics were taken from 8-year P records collected in 2010–2017. As a result of the rainfall-runoff model simulations with the 100-year meteorological data, 100-year time series of Q (and additionally, the other hydrological components, e.g., ET) can be computed. From the simulated time series of Q, flow duration curves for the 100-year and the low-flow domain in each year can then be obtained. Shifts in the low-flow rate of each year within the 100-year can then be readily related to thinning intensities and soil physics.

The P time series were constructed as follows: in each month, the frequency of rainfall events was determined by the Markov chain method (cf. Gabriel & Neumann, 1962), and then, the amount of rainfall when rainfall occurs was assumed to be an independent random variable, expressed by a mixed exponential distribution (cf. Wilks & Wilby, 1999). It is logical to anticipate that P changes lead to concurrent changes in other meteorological variables such as VPD and R_s because of increased or decreased atmospheric moisture content and cloud cover. Here, the daily mean VPD values related to daily P were obtained as random numbers generated by Weibull distributions representing the probability density functions of the VPD in five bin ranges of the P. Also, the daily mean R_s related to the VPD were obtained in the same manner as for the VPD but using Weibull distributions of the R_s in five bins of the VPD for each month.

In each flow duration curve of the 100-year simulation, the flows within the ranges of 20–70% and >70% time exceedance were referred to as 'Intermediate flows' and 'Low flows', respectively (cf. Yilmaz, Gupta, & Wagener, 2008). Besides, the simulation years when the averaged flows in the 'Low flows' domain of the simulated flow duration curves for Case B and S_d = 1280 trees ha^{-1} are the lowest and 50th the lowest were referred to as 'Drought year' and 'Normal year', respectively. We investigate the shifts in flows of Intermediate flows and Low flows corresponding to changes in S_d and/or soil physics under Normal year and Drought year conditions.

4. RESULTS

4.1 Validation of the Rainfall-Runoff Model

At a yearly time scale, we estimated ET by catchment water balance between P and Q and divided the ET into T_r and I_c by subtracting the I_c estimated using Equation (8) from the ET (Figure 2). Given little bedrock drainage in the studied catchment and the Q expressed as the function of catchment water storage, a previous study (Momiyama et al., 2019) estimated monthly mean daily ET over the 8-year observation campaign using the short-term water budget method (see Linsley, Kohler, & Paulhus, 1958; Suzuki, 1985) (Figure 3).

[Insert Figure 2]

[Insert Figure 3]

As a result of comparisons among NSE_{inv} for Cases A–D, we found that NSE_{inv} for Cases A and B are almost the same (0.827) and the highest, suggesting that Case B, which neglects the effect of Q_{sub} on Q, i.e., the parameter T_{max}, performed the best (Table 1). Also, NSE_{inv} for Cases C and D are almost the same (0.749) and still an acceptable value for the reproduction of the data, although the value is less than that for Case B. This suggests that for the simulation of water balance in this studied catchment using this rainfall-runoff model, a model parameter calibration of the only m is sufficient, and adding another model calibration of D_{sx} contributes to the reproduction skill of this model. Thus, hereinafter we use Cases B and D for the model investigations.

Daily variations in calculated Q and ET with the parameter set in Case B (see Table 1), forced by observed meteorological variables, are compared against observations for January 1, 2010, to December 31, 2015, in Figure 3. The model well reproduced observed Q and ET despite all the simplifying assumptions. Figure 4 further compares simulated flow duration curves, which were made of calculated Q forced by the 8-year observed and the 100-year generated meteorological data with the parameter set in Case B (see Table 1), against flow duration curves made of the 8-year observed Q. In terms of averaged Q over the Low flow domain (Q_{LF}) and the Intermediate flow domain (Q_{IF}) in Figure 4, there were no significant differences between both mean and variance of the 8-year observed Q_{LF} and those of the 8-year (p = 0.93, t-test; p = 0.49, F-test) and the 100-year (p = 0.61, t-test; p = 0.52, F-test) modeled Q_{LF}, and between those of the 8-year observed Q_{IF} and those of the 8-year (p = 0.84, t-test; p = 0.87, F-test) and the 100-year (p = 0.36, t-test; p = 0.50, F-test) modeled Q_{IF}. This confirms the successful reproduction of the stochastic characteristics of both actual Q_{LF} and Q_{IF} using the 100-year generated meteorological variables.

[Insert Figure 4]

4.2 Thinning Impacts on Runoff

Figure 5 shows simulation results on relationships between S_d and Q and ET using the 100-year generated meteorological data and Cases B and D parameter sets (see Table 1). A decrease in S_d increased Q owing to a reduction in ET, despite the small thinning effects on increases in Q_{LF}, in both Normal year and Drought year. In general, with decreases in S_d, increasing ratios of Q were lower than decreasing ratios of ET, and this tendency became more pronounced for Q_{LF}. Also, comparing simulation results of Cases B and D, the soil water deficit control on T_r (see Equation 7) was found to contribute to enhancing Q_{LF} more appreciably than Q_{IF} in Normal and Drought years (Figure 5).

[Insert Figure 5]

Before the investigation on the forest thinning impacts via alterations of ET and soil physics properties, we evaluate a single hydrological effect of the catchment soil physics (here, referred to as catchment water retention capacity, m in Equation 2) on Q with changing the parameter m in Case D (Figure 6). While simulated Q was relatively robust to an increase in m, the smaller m compared to the reference value (0.0517 m; see Table 1), i.e., the smaller catchment water retention capacity, significantly reduced Q_{LF}. Figure 7 compares the simulation results of relationships between m and increases in Q_{LF} and Q_{IF} due to the thinning in Normal and Drought years. There was somewhat exponential saturation in the relationships: high values of increases in Q_{LF} and Q_{IF} in higher m (> 0.0517 m), and drastically decreases in the values with m decreasing (Figure 7). Again, the hydrological effects of the forest thinning on increasing water resources were confirmed to be very small under severe drought conditions. It is interesting to note that unlike the other cases, the runoff growth rate (i.e., the ratio of runoff after to before thinning) for Q_{LF} in the Drought year decreased and became constant with increasing m (Figure 7c, d). This is because a majority of Q_{LF} might be derived from catchment stored water and hence intrinsic Q_{LF} before thinning, especially in the Drought year, tends to decrease with decreasing m.

[Insert Figure 6]
[Insert Figure 7]

5. DISCUSSION AND CONCLUSION

5.1 Validating the Model

Forest thinning will firstly increase net precipitation (P_{net}) into the surface soil layer via a reduction in I_{c}, and then increase Q with changing consumption of the surface water storage by the T_{r} and forest floor evaporation (E_{f}). Thus, we assume how to describe the thinning impact on ET, i.e., $I_{\mathrm{c}} + T_{\mathrm{r}} + E_{\mathrm{f}}$ is the most critical in modeling total water balance amenable to forest thinning.

Komatsu (2020) asserted that forest thinning significantly affects I_{c} and least changes $T_{\mathrm{r}} + E_{\mathrm{f}}$. Also, he suggested that in terms of the robust $T_{\mathrm{r}} + E_{\mathrm{f}}$, some cancellations emerge; an intense thinning decreases stand-scale T_{r} but increases E_{f} with increasing canopy openness and incident radiative energy to the forest floor. While, some previous studies (e.g., Gebhardt, Häberle, Matyssek, Schulz, & Ammera, 2014; X. Sun et al., 2014) reported an increase in individual-scale T_{r} after thinning probably because of relaxing remaining trees from resource competitions, which might result in the little change in stand-scale T_{r}. In this study, according to Kelliher et al. (1995), we formulated the stand-scale T_{r} characteristics, i.e., the G_s (Equation 6), to be conservative against LAI or S_d after thinning. Although how the T_r characteristics are altered by thinning has been still unclear, our assumption on the conservative G_s would be equivalent to Komatsu's (2020) assertion on the conservative T_r + E_f.

As a result, a submodel describing the thinning impact on I_c can be assumed to control a majority of the simulated ET under forest thinning conditions. To estimate daily values of I_c, we employed the I_c model (Equation 8) which was originally developed by Komatsu et al. (2007). In reality, although the I_c ratio in Equation (8) on the present S_d condition for the study catchment was within a range of preliminary short-term observations at multiple plots, it overestimated the measured value at our single long-term intensive ET observation plot in the same catchment (see Fujime, Kumagai, Egusa, Momiyama, & Uchiyama, 2021). On the other hand, Shinohara, Levia, Komatsu, Nogata, and Otsuki (2015) reported that immediately after thinning at their site in Japan, I_c decreased to a greater extent than the estimations by Equation (8). These could lead to the underestimation of an increase in P_{net} due to thinning. Despite successful reproduction of the actual Q by using the estimated P_{net} and tuning soil physics parameters in the present model, the appropriate estimation of the catchment-scale I_c altered by forest thinning remains controversial and requires more technically difficult examinations.

When considering T_{max} = 0 in the TOPMODEL (see Equations 3 and 4) used to reproduce the total runoff (Q) from the studied catchment (see Cases B and D in Table 1), a lumped rainfall-runoff model, the so-called tank model (Sugawara, 1972, 1995), can be compatible with the TOPMODEL. Neglecting detailed information on soil moisture dynamics distributed over the catchment, multiple discharges (q_i) from a single tank were assumed as:

$$Q = \sum_{i=1}^{N} q_i = \sum_{i=1}^{N} max\{0, a_i(H - h_i)\}, \tag{10}$$

where N is the number of discharge holes of the tank, i identifies each discharge hole, a_i and h_i are fitting parameters, and H is the current depth of water in the tank. Note that h_i represents the height of the discharge hole i from the bottom of the tank. A comparison between Equations (3) and (10) allows us to derive the following relationships:

$$a_i = \frac{k_t}{N}, \tag{11}$$

$$H = -\overline{D_s} + C, \tag{12}$$

and

$$h_i = m\left(\overline{TI} - TI_i\right) + C, \tag{13}$$

where C is a constant to make H and h_i positive, and a_i is found to be a constant independent of i. Further, we confirmed that the soil parameter m in the TOPMODEL denotes catchment water retention capacity because an increase in h_i delays the start of discharge from the stored water in the tank, and h_i can be linearly related to m in Equation (13). Indeed, a decrease in m reduced the calculated Q_{LF}, i.e., baseflow through the increasing flood following precipitation (Figure 6). Again, at least in this studied catchment, tuning only one soil physics parameter m can provide sufficient reproducibility of actual Q (Table 1). This suggests that catchment water storage is a major driver of the Q from the studied catchment.

Despite few historical records on the Q impacted by forest thinning treatments, several previous studies demonstrated that in the temperate zone, percentages of annual Q increase to annual P due to thinning (ΔQ: %) ranged from 1.3 to 6.2% and from 2.0 to 15% when ca. 30 and 50% of the stems in the catchments were removed, respectively (Baker, 1986; Bosch & Hewlett, 1982; Bren, Lane, & Hepworth, 2010; Hawthorne et al. 2013; Jayasuriya, Dunn, Benyon, & O'Shaughnessy, 1993; Lesch & Scott, 1997). In Japan, Kubota, Tsuboyama, and Nobuhiro (2018) reported that a 3-year mean ΔQ after thinning from 2229 to 1132 trees ha^{-1}, which is identical to ca. 50% thinning, was 3.2% at the *Ch. obtusa* catchment. The simulations by our rainfall-runoff model, that is, the modified TOPMODEL in this study, estimated ΔQ after thinning from 2229 to 1132 trees ha^{-1} and from 1500 to 1000 trees ha^{-1} (ca.30% thinning) to be 5.2 and 2.4%, respectively (cf. Figures 5 and 7), falling within the range of actual records. Thus, we assumed that the rainfall-runoff model would have a sufficient ability to examine the forest thinning impacts on water resources in forested catchments.

Note that the I_c modeling can be assumed the most important for the simulations to examine the thinning impact on ET (Komatsu, 2020). Here, we adopted the I_c model with the best performance for changing S_d, i.e., thinning intensities (Komatsu et al., 2007). In other words, the I_c model would allow us to best simulate P_{net} corresponding to a large variety of thinning intensity. Furthermore, our rainfall-runoff model well reproduced the 8-year Q observation, in particular, the Q_{LF} record (see Figure 4). This ensures that the model can successfully simulate Q, especially Q_{IF} and Q_{LF}, with the changing P_{net} input to the catchment surface. Therefore, using this model simulation, we can expect a highly reliable prediction of Q_{IF} and Q_{LF} regimes affected by forest thinning, discussed next.

5.2 Analyzing the Model Simulations

Many previous studies on how water supply from forested headwaters will increase through a decrease in the forest water use due to forest harvesting have been performed using empirical and experimental methods (see McDonnell et al., 2018). In Japan, both policymakers and people have anticipated conservation and optimization of water resources from forested headwaters by appropriate forest management, mainly expecting to maintain the water supply in a shortage of precipitation, i.e., Q_{LF} and further, one in the Drought year. However, without sufficient scientific evidence, the policy recommendations about forest thinning for increasing available mountain water resources have been claimed (cf. Fujimori, 2006). In our present study, the rainfall-runoff model was validated by previous observational studies, and stochastic treatments for P regimes enabled us to examine the thinning impacts on hydrological processes under Low flows conditions in both Normal and Drought years (see Kumagai et al., 2004; Yokoo & Sivapalan, 2011). For example, the simulated increases in Q_{LF} and Q_{IF} due to thining from 3000 to 1000 trees ha^{-1} (hereinafter, referred to as ΔQ_{LF} and ΔQ_{IF}, respectively) without the T_r regulation were 0.22 and 0.57 mm day^{-1}, respectively in the Normal year and 0.12 and 0.50 mm day^{-1}, in the Drought year (Figure 5). This revealed that the policy recommendations have been exaggerated, especially concerning Low flows and Drought year conditions.

The D_{sx} obtained for Cases A and B (Table 1) mean sensitive water use regulation against small $\overline{D_s}$ in the studied forest catchment composed of *Cr. japonica*, *Ch. obtusa*, and various hardwood species. On the other hand, Kumagai et al. (2008) indicate that *Cr. japonica* tends to have little regulation of tree water use even during the sporadic periods of severe soil drying, expecting $D_{sx} \rightarrow \infty$ (see Table 1) for a single *Cr. japonica* species stand. Then, it is instructive to consider the forest manipulation effects on hydrology from the supposition that changing forest stand status from 3000 trees ha^{-1} without the T_r regulation to 1000 trees ha^{-1} with the T_r regulation denotes a forest thinning with changing the species composition such as from a single *Cr. japonica* species stand as “a heavy drinker” to a multi-species stand like the studied catchment as “a miser”.

Given this forest manipulation, ΔQ_{LF} and ΔQ_{IF} were 0.32 and 0.57 mm day^{-1}, respectively in the Normal year and 0.45 and 0.67 mm day^{-1}, in the Drought year (Figure 5). The base parameters set was obtained assuming a multi-species stand, i.e., actually studied catchment, as Case B, while the parameters set of Case D assumes a single *Cr. japonica* stand, which is a very common forest stand type in Japan. Here we have to note that the m

optimized for Case D adjusts Q without water use regulation by trees, and therefore is larger than the one for Case B (Table 1). Hence, based on the Case B parameter set, which was determined for actual Q data, Q_{LF} and Q_{IF} without the water use regulation and with the same m as Case B would be smaller than those in Case D, implying that the estimated ΔQ_{LF} and ΔQ_{IF} could be minimum predicted values. This suggests that the forest thinning with the conversion of the species might be promising forest management for sustainable mountain water resources, especially under severe precipitation shortage conditions.

The review study by Smakhtin (2001) on vegetation cover change impact on hydrology suggested that afforestation might decrease total annual Q due to a drastic reduction in Q_{LF}, while as its reverse effect, forest harvesting might increase total annual Q by increasing the seasonal Q_{LF}. Furthermore, he might find that it is difficult to determine which decrease or increase in Q_{LF} could be caused by the forest harvesting because the reduction in ET could increase soil moisture storage and surface Q, possibly leading to reducing recharge to groundwater storage and the resultant Q_{LF}. The notable insight that emerges from the possibility for reducing Q_{LF} due to forest thinning requires taking into consideration an interaction between soil physics properties and altered ET by thinning as a forest-water resources management.

To find the best forest thinning practice for sustainable water resources from forested catchments, we need more general information on how thinning may affect Q under a large variety of P amount conditions and soil hydrological conditions. As Saksa et al. (2017) partly mentioned, the observational study alone would not be sufficient to detect thinning effects on Q under P shortage conditions and to examine the interaction between soil characteristics and vegetation canopy processes. Using a watershed-scale monthly water balance model, G. Sun et al. (2015) succeeded in quantifying the impact of forest thinning practice on water yield over the United States under current and future climate scenarios but only considered the altered ET by a reduction in LAI via thinning. Likewise, Saksa et al.'s (2017) modeling study investigated well the thinning impacts on the water balance of forested headwater basins influenced by the high temporal variability of P. Moreno et al. (2016) further investigated the thinning impacts on hydrological processes affected by the thinning operation-induced changes through direct the canopy process effects and the collateral soil compaction effects in a large-scale basin, with taking into consideration inter- and intra-annual and spatial variations in P. However, it should be noted that despite the well-examined effects of soil characteristics altered by the thinning operations, they did not attempt to examine the relationships between the thinning impacts and variation in soil characteristics possible over forested catchments.

In this study, using a combination of the 8-year hydrological observations, the 100-year stochastic-generated meteorological data, and the semi-process-based rainfall-runoff model, we could demonstrate the combined effects of soil physics parameter m and the altered ET by thinning on Q_{LF} and Q_{IF} in Normal and Drought years, consequently suggesting the optimal thinning intensity corresponding to a variety of soil physics conditions m (Figure 7). We found that forest thinning would primarily increase Q_{LF} and Q_{IF} at the catchments with larger values of m, i.e., higher water retention capacity. This, in part, is attributed to the fact that at a catchment with low water retention capacity, P_{net} cannot contribute to Q_{LF} and Q_{IF} but to rapid runoff even though a reduction in ET by thinning increases P_{net}. This also suggests that to gain the best hydrological benefit from forest thinning, it is important to refrain from forest treatment actions to lose soil water retention capacity such as soil compaction. Here, we emphasize that assuming the simplified TOPMODEL that can be optimized with a single parameter, m, can apply to the studied catchment, we can find the best practice of forest thinning for sustainable forested mountain water resources. In short, if m for a subject catchment can be obtained as prior information, the present study can help the ground-level forest and water managers to decide thinning intensity at the catchment and will be further attractive to the policymakers having a mission to improve forest ecosystem services and resilience.

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DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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TABLES

TABLE 1 Calibrated model parameters and Nash–Sutcliffe efficiency criterion with inverse runoff values (NSE_{inv}) for each Case

Cases	m (m)	T_{max} (m^2 h^{-1})	D_{sx} (m)	$\overline{D_{s0}}$, (m)	NSE_{inv}
A	0.0493	0.0628	0.222	0.247	0.827
B	0.0445	NA	0.177	0.203	0.827
C	0.0520	0.00248 [a]	NA	0.236	0.749
D	0.0517	NA	NA	0.233	0.749

[a] Parameterized at the detection limit.

FIGURE LEGENDS

FIGURE 1 Schematic diagram of the rainfall-runoff model used in this study.

FIGURE 2 Annual water balance in the studied catchment. Q, T_r, and I_c denote runoff, transpiration, and interception, respectively, and the sums of them are precipitation.

FIGURE 3 Precipitation (upper panel), observed (closed circles) and modeled (solid line) runoff (middle panel), and observed (grey zone, representing the range of middle quartiles of the data) and modeled (solid line) evapotranspiration (lower panel) in the studied catchment. The model simulation was conducted using the parameter set in Case B (see Table 1). The observed daily evapotranspiration rates were obtained as monthly-mean values in an averaged single annual variation in the period 2010–2017, estimated by the short-term water budget method. Note that the single annual variation repeatedly appears every year. Daily-computed evapotranspiration rates were converted to 31-day moving average values, resulting in the modeled daily evapotranspiration rates.

FIGURE 4 Flow duration curves made of observed runoff in 2010–2017 (red lines) and modeled runoff using observed climatic data in 2010–2017 (green lines) and generated climatic data for 100-year (grey lines). The model simulations were conducted using the parameter set in Case B (see Table 1).

FIGURE 5 Modeled relationships between stem density and runoff (red solid lines) and evapotranspiration (blue broken lines) using 100-year generated climatic data. Both thick lines with shaded zone and thin lines with ranges between upper and lower dotted lines represent averages with the upper 10–90% values, modeled with (Case B) and without (Case D) taking into consideration the effect of soil water deficit on transpiration, respectively (see Table 1). Columns (a, c) and (b, d) are model results for intermediate flows and low flows situations, respectively, and rows (a, b) and (c, d) are ones for the normal year and the drought year, respectively.

FIGURE 6 Daily precipitation (upper panel), and modeled daily runoff (lower panel) using m = 0.0517 (thick solid line), m = 0.07 (thin solid line) and m = 0.03 (thin broken line) in the studied catchment in 2014. The model simulations were conducted changing the only m in parameters in Case D (see Table 1).

FIGURE 7 Relationships between the parameter *m* and increases in runoff (a, b) and runoff growth rate (c, d) after thinning. The model simulations were conducted changing the only *m* in parameters in Case D (see Table 1). Columns (a, c) and (b, d) represent changes in the values due to alterations of stand density, 1500 to 1000 trees ha^{-1} and 2229 to 1132 trees ha^{-1}, respectively. The relationships are compared between intermediate flows and low flows situations and between the normal year and the drought year. Vertical dotted lines denote the *m* estimated for the actual data (0.0517 m).