Chapter 7

Improvement of the Flood-Reduction Function of Forests Based on Their Interception Evaporation and Surface Storage Capacities

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Abstract Forests have a flood-reduction function that reduces flood peak flow and delays the flood peak time. In the mountains of Japan, artificial forests planted between the 1950s and 1970s are widespread; however, many of these forests are not well managed. The effective use of the flood-reduction function of forests as a remarkable approach for river basin management has been discussed for several years. In this study, two aspects of the water cycle in forests were explored: the interception evaporation process in the forest canopy and the groundwater storage process on the forest slope. A runoff model was applied to the hydrological data obtained in several forest basins with different characteristics to evaluate the effects of the processes. In the case of the Japanese cedar plantations studied, it was suggested that the improvement of interception evaporation capacity and surface storage capacity by conversion to mixed forests and selective logging would significantly reduce the peak flood discharge on a timescale of approximately 20–30 years.

Keywords Forest · Flood-reduction function · Interception evaporation · Surface runoff · Selective cutting

7.1 Introduction

The influence of climate change is conspicuous in Japan. Severe flood disasters occur almost annually in various regions of Japan. Forests in Japan account for approximately 70% of the land, while 40% of the forests are artificial forests comprising coniferous trees. These forests are distributed at mountainous areas,

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which are the source areas of streams. Therefore, heavy rain in mountainous forests has become a major cause of flood disasters. Forests have a flood control function for storing a part of the rainfall and delaying runoff discharge from their basins. This contributes toward decreasing the quantity of flood flow. As forests are part of the green infrastructure, an effective use of the flood-reduction function for disaster prevention has been previously discussed.

Generally, it is recognized that forest soil plays a principal role in the flood-reduction function. Since forest soil has a large void structure, forests can store a significant amount of rainwater as compared with other land cover types. Therefore, methods used to strengthen the flood-reduction function, such as thinning of forests and conversion of vegetation structure, have been discussed. However, it has been pointed out that the flood-reduction function of forests is not sufficiently effective for large floods (Laurance 2007). It is also extremely difficult to increase the thickness of the soil layer, which determines the water storage capacity. The soil formation speed has been reported in the range of 0.05–0.2 mm/year (Amundson et al. 2015); it is estimated that a significant amount of soil is washed away by heavy rainfall in the steep Japanese mountains. Therefore, the increase in the thickness of the surface soil layer will not be able to adapt to the large-scale heavy rainfall that is predicted to accompany the rapid progression of climate change. In addition, it is difficult to incorporate this method in flood control plans, since the plans in Japan are developed for the subsequent 20–30 years. Two methods that can improve the flood-reduction function of forests in a relatively short period of time include enhancement of interception evaporation capacity and enhancement of ground surface storage capacity. These two processes are examined and their effects are discussed using a rainfall-runoff model.

7.2 Rainwater Runoff Mechanisms in Mountainous Forests and Measures to Improve the Flood-Reduction Functions of Forests

Figure 7.1 shows the rainwater runoff processes in a mountainous forest. First, the interception evaporation on the forest crown or canopy affects the rainfall. Some raindrops are intercepted by the branches and leaves, wherein they become microscopic particles and drift through the air. The interception evaporation process was strongly affected by the multilayered structure around the crown. The rainwater lost through interception evaporation reduces the flood amount and its peak flow. This forest property can be effectively improved by forest management through planting, thinning, and felling of trees.

Thereafter, the rainwater that reaches the ground surface will then infiltrate the soil layer if its intensity is below the infiltration and storage capacity of the soil. Rainwater that infiltrates the soil becomes groundwater and contributes to subsurface runoff components, flowing out relatively slowly as compared to the

Fig. 7.1 Rainwater runoff processes in mountainous forest

surface runoff components. This process is generally recognized as the key role of the flood-reduction function of forests. However, rainwater becomes a surface runoff component when the rainfall intensity increases beyond the infiltration and storage capacity of the soil layer. The surface runoff component immediately flows down a slope, resulting in a flood. The flood-reduction function of the forest then reaches its limit. The infiltration and storage capacity are determined by the thickness of the forest soil layer. Therefore, it would be extremely difficult to increase the storage capacity of the soil because a period greater than 100 years is necessary for recovery of soil layer thickness (Ogawa et al. 2011).

Surface flows account for most of the peak flood discharge during heavy rainfall events that can cause flood disasters. It flows down forest slopes under the influence of the amount of understory vegetation and the roughness of the ground surface. Therefore, a forest with significant ground surface roughness can decrease the speed of surface runoff flow. Consequently, the surface runoff component is stored on the ground surface for a short time. The amount of water storage on the ground contributes to the reduction and delay of the flood peak flow. For instance, the management of understory vegetation is important for increasing the ground surface roughness. This can be actualized by daily forest management, and the effects are expected to manifest rapidly.

In this study, two aspects were explored: the interception evaporation process in the forest canopy and the water storage process on the ground surface. Based on hydrological observations and analysis using a rainfall-runoff model for two forest areas with different forest characteristics, the possibility of improving the flood-reduction function of forests by enhancing the operation of these two hydrological processes is discussed.

7.3 Runoff Model for Evaluating Flood-Reduction Function

The tank model is used as the runoff model in this study, as shown in Fig. 7.2. The author refers to it as the two-stage tank model with separated surface flow (Tamura et al. 2006). The model is broadly divided into a surface tank (soil layer) and a groundwater tank (bedrock layer) to represent the infiltration, storage, and runoff processes of rainwater in forest soils, as well as the various runoff components: surface runoff, subsurface runoff, and groundwater runoff. Rainfall input to the model is either the amount of throughfall that reaches the ground surface or the amount of rainfall multiplied by the percentage of throughfall (the reciprocal of the interception evaporation rate). A characteristic feature of this model is that the surface runoff coefficient is calculated from the average slope, average slope

Fig. 7.2 Two-stage tank model with separated surface flow

Fig. 7.3 Location of the study sites

length, and roughness of the forest slope (Eq. 7.1). The coefficients of the tank model, including the surface roughness, are identified as a set of parameters that can uniformly reproduce multiple flood hydrographs obtained from field observations; these are used in flood simulations to compare the flood-reduction functions of forest basins.

$$\lambda_o = 2.52 \times 10^{-3} \cdot I_s / \left\{ r_{\max}^{0.8} (N \cdot L_s)^{1.8} \right\} \quad (7.1)$$

where λ_o is the surface runoff coefficient (/h), L_s is the slope length, I_s is the average slope (m), N is the surface roughness ($\text{m}^{-1/3} \text{ s}$), and $r_{\max}$ is the observed maximum rainfall intensity considered as the maximum surface runoff intensity (mm/h).

7.4 Enhancing Interception Evaporation Capacity Through Afforestation

In the upper basin of the Dozan River, which is one of the prevailing tributaries of the Yoshino River on Shikoku Island (Fig. 7.3), a large copper mine (Besshi-doan) had been operated from 1691 to 1973. A significant number of trees had been felled for copper refinement business, and a substantial quantity of soil had been washed away from the mountains. A severe flood was caused by a heavy rain-related typhoon in August 1899, and several people lost their lives. Thereafter, a large-scale tree plantation was created, and the vegetation was restored (Sumitomo group Public Affairs Committee 2021).

The flood-reduction function of the Tomisato dam basin, including the Besshi Copper Mine area, was evaluated at the beginning of the twenty-first century when the vegetation had recovered for approximately 100 years after the beginning of

large-scale planting. A runoff model was used in the evaluation to describe the water cycle processes in a forested basin (Tamura et al. 2008). In this study, the water storage capacity of the soil layers and the interception evaporation effect were estimated; Figs. 7.4 and 7.5 show the calculation results. The characteristics of the flood-reduction function of the basin were examined by comparing its runoff results with those of the Sameura dam basin, because it is located next to the Tomisato dam basin and has similar geology and vegetation. The role of interception evaporation is very important during the forest recovery stage (Fig. 7.4). The simulation results demonstrate that the flood peak flow would increase by 50%, compared to the current condition, if clear-cutting was performed in the Tomisato dam basin. The rate of increase of the flood peak flow is higher than that of the Sameura dam.

This is because the runoff model estimated that the interception evaporation rate of the current Tomisato dam basin is larger than that of the Sameura dam basin, and the thickness of the surface soil layer of the current Tomisato dam basin is much smaller than that of the Sameura dam. In other words, if clear-cutting is implemented in the Tomisato dam basin, the large amount of rainfall lost due to interception evaporation will reach the ground surface, but the thin soil layer will quickly become saturated, resulting in an increase in peak flood discharge. Figure 7.5 shows the maximum groundwater storage volume for the two basins under the clear-cut conditions (the situation is shown in Fig. 7.4b). It shows the incremental storage from the start of rainfall to the time of peak flood flow in the surface and groundwater tanks shown in Fig. 7.2. The possibility that the thickness of the soil layer at the Tomisato dam basin has not recovered sufficiently since the start of the planting program is shown in Fig. 7.5. Nevertheless, the fact that the peak flood discharge in the Tomisato dam basin is lower than that in the Sameura dam basin (Fig. 7.4a) suggests that the interception evaporation in the flood-reduction function of the current Tomisato dam basin is quite effective. This can be considered as the greatest effect of the large-scale afforestation project in terms of flood reduction.

As a result, it can be concluded that the enhancement of interception evaporation capacity is more effective than the enhancement of soil layer thickness as a means of improving the flood-reduction function of forests in a short period of time. In addition, it is important to avoid excessive thinning and clear-cutting in forest management when applying this method to basins with poor forest soil layer thickness, such as the Tomisato dam basin.

7.5 Enhancing the Interception Evaporation Capacity and Surface Storage Capacity by Vegetation Conversion

The upper basin of the Naka River is notable for the production of Kito-sugi Japanese cedar. This basin is known to be a high precipitation area, with an annual precipitation of approximately 3000 mm. The Hashimoto forest is located in the upper district of the Naka River (Fig. 7.3), wherein selection cutting forestry was

Fig. 7.4 Comparison of flood hydrographs under current and clear-cut conditions to evaluate the impact of interception evaporation considering Typhoon No. 23 in 2004 (summarized from Tamura et al. 2008)

performed from the 1980s and broadleaf trees were preserved. Its forest type is a mixed forest consisting of conifers and broadleaf trees, with a multilayered crown structure. The standard thinning rate is approximately 30% in common cedar artificial forests in Japan, but the rate of the Hashimoto forest ranges from 15% to 20%. However, due to the mixture of various aged trees and species, the canopy is not dense and the understory vegetation is rich (Fig. 7.6a).

The flood-reduction function of the Hashimoto forest was evaluated using a runoff model (Tamura et al. 2020). The effects of the interception evaporation capacity and the ground surface storage capacity in the Hashimoto forest, a mixed conifer and broadleaf forest, were discussed and compared with those in the

Fig. 7.5 Estimation of maximum groundwater storage in forested basins using the two-stage tank model with separated surface flow considering Typhoon No. 23 in 2004 (summarized from Tamura et al. 2008)

Fig. 7.6 Trees and understory vegetation at the observation sites

Shirakawatani experimental forested basin. Shirakawatani is a Japanese cedar forest where general Japanese forestry (large-scale planting and felling) is performed (Fig. 7.6b), and its geological features and topography are similar to those of the Hashimoto forest. The model parameters of the interception evaporation rate and surface roughness obtained from the runoff analysis of the Hashimoto forest

Table 7.1 Main parameters of the in-line two-stage tank model for simulating the conversion of Japanese cedar artificial forest to mixed needle and broadleaf forests

Parameter	Hashimoto	Shirakawatani	
	Mixed needle and broadleaf forests	Artificial cedar forest (current condition)	Mixed needle and broadleaf forests (simulation)
Interception evaporation rate	25	14	25
I (%)			
Ground surface roughness	1.8	1.2	1.8
N ($\text{m}^{-1/3}$ s)			
Apparent surface thickness	137	100	100
γD (mm)			
Groundwater supply coefficient			
λ_g (/h)	0.05	0.01	0.01
Final infiltration rate	6.45	1.45	1.45
f_* (/h)			
Soil saturation capacity	168	40	40
h_1 (mm)			

were applied to the Shirakawatani experimental forested basin model to study the improvement of flood-reduction function of a general cedar artificial forest by converting it into a mixed needle-hardwood with only selective logging. The model parameters for the two basins, as well as the parameters when the Shirakawa valley is changed to a mixed needle-hardwood forest, are listed in Table 7.1.

The flood-reduction function of the Hashimoto forest is greater than that of the Shirakawatani. Runoff simulation using the same rainfall pattern as shown in Fig. 7.7 for both runoff models showed that the peak flow rate in Hashimoto forest area was 22% lower than that in Shirakawatani (Fig. 7.8). When the interception evaporation capacity rate of the Hashimoto forest model was applied to the Shirakawatani model, the peak flood discharge in the Shirakawatani decreased from 66.8 mm/h to 56.3 mm/h. In addition, when the surface roughness parameter of the Hashimoto forest was applied to the Shirakawatani model, it was further reduced to 50.9 mm/h. As a result, the peak flood discharge was estimated to be 24% lower than that for the current Shirakawatani model.

The flood-reduction function of the Hashimoto forest is higher than that of the Shirakawatani owing to several factors. In the Hashimoto forest, cedar trees of different ages and broad-leaved trees of various species are mixed; the canopy is multilayered. The density of the canopy of the multistoried forest seems to be sparse in the vertical space. The thinning rate in the Hashimoto forest is low, but sunlight reaches the forest floor easily. This is a favorable condition for understory vegetation. Therefore, the interception evaporation rate and the surface roughness are high, and it is assumed that a high flood-reduction function is demonstrated in the Hashimoto forest.

Fig. 7.7 Rainfall patterns used to evaluate the Hashimoto forest and Shirakawatani experimental forested basin (Tamura et al. 2020)

Fig. 7.8 Comparison of flood hydrographs between Hashimoto forest and Shirakawatani experimental forested basin under current conditions (summarized from Tamura et al. 2020)

Fig. 7.9 Flood hydrographs of the Shirakawatani experimental forested basin under the condition that the interception evaporation rate and surface roughness are changed by the conversion to mixed needle and broadleaf forest (summarized from Tamura et al. 2020)

The results suggest that the flood-reduction function of cedar forests with poor understory vegetation, such as those in the Shirakawatani experimental forested basin, can be improved on a timescale of approximately 20–30 years by conversion to mixed forests with only selective logging (Fig. 7.9).

7.6 Methods and Limitations of Early Enhancement of Flood Mitigation Functions of Forests

In this study, the reinforcement measure for the flood-reduction function of forests and the expected effects were discussed in terms of interception evaporation in the forest canopy and water storage on the forest ground surface. These methods have two advantages compared to the restoration of soil layer thickness. First, they are achieved easily via daily forest operations. Second, the effects can be expected to be realized in 20–30 years. However, the expected effect is still restrictive (10–20% reduction of the flood peak runoff) for heavy rainfall events that are targeted by the flood control plan. In addition, because the interception evaporation rate observed in forests has changed owing to a rainfall event (Tanaka et al. 2005), it is believed that the flood-reduction function of forests fluctuates due to forest site and structure. For utilizing the flood-reduction function of a forest in river basin management, a thorough understanding the characteristics of this function is required.

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