HYDROLOGICAL CHARACTERISTICS UNDER DECIDUOUS BROADLEAF AND EVERGREEN CONIFEROUS FORESTS IN CENTRAL JAPAN

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ABSTRACT: In Japan, many natural or secondary forests of the deciduous forest type have been converted to evergreen coniferous forests for plantation agriculture. This conversion should have an influence on the hydrological conditions. Thus, in order to reveal the difference in hydrological characteristics between deciduous broadleaf and evergreen coniferous forests, a 10-year hydrological observation was conducted at two small paired catchments. The results show that the annual discharge from the deciduous forest was higher than that from the coniferous forest. However, the peak discharge, the direct runoff during rainfall events and the runoff coefficient were higher in the coniferous forest than in the deciduous forest. In addition, the snow depth in the deciduous forest was higher than that in the evergreen coniferous forest due to the difference in canopy interception between the two forests. The forest canopy and the floor vegetation might be the most important factors in determining all of these hydrological characteristics. This research confirms that deciduous broadleaf forests are better able to foster water resources and control flooding than evergreen coniferous forests.

Keywords: Flow duration curve, Snow depth, Deciduous broadleaf, Evergreen coniferous

1. INTRODUCTION

The water cycle is a key function that links other processes in forest ecosystems. However, it is difficult to understand the hydrological processes since they are influenced by a myriad of biophysical factors such as topography, geology and vegetation [1]. Amongst these factors, the vegetation cover has an important influence on the hydrological processes through rainfall interception, collection and storage by the foliage, and the subsequent loss by evaporation, sometimes resulting in an enhanced loss of water in the hydrological cycle [2, 3].

After World War II, many natural or secondary forests in Japan were changed to coniferous plantation forests for the purpose of timber production. The plantations were dominantly formed by converting broadleaf forests to coniferous forests [4]. Changing the vegetation type has a significant impact on the hydrological cycle in the watershed scale [5]. Moreover, most of the mountainous regions located upstream of agricultural and urban areas are covered by forests in Japan. From the viewpoint of water resource management, the forested areas are considered to be water sources [6, 7] and are closely linked to downstream ecosystems [8]. Thus, when establishing policies for water resource management, how the conversion of broadleaf forests to coniferous forests influences the hydrological conditions should be considered.

In previous studies, the annual runoff of two types of forests at the same basin was measured by a long-term observation while the forest was being converted from a deciduous broadleaf type to an evergreen coniferous type [9, 10]. It was concluded that the annual runoff (long-term runoff) in broadleaf deciduous forests is higher than that in coniferous evergreen forests in regions with high winter precipitation. However, these studies could not compare the hydrological characteristics of the two forest types directly due to the fact that the weather conditions were not the same. By comparing the runoff characteristics of two types of forests in the plot scale and analyzing only the final data [11,12], other studies have shown that short-term runoff characteristics, such as surface runoff and peak discharge, were higher from coniferous evergreen forests than from broadleaf deciduous forests. However, the studies could not explain the annual characteristics in the basin scale.

Contrary to other studies, the present study contains a direct comparison of the hydrological characteristics of paired catchments with different vegetation through an examination of 10 years of observation data. Thus, it enables a more direct evaluation of the hydrological characteristics in broadleaf deciduous and evergreen coniferous forests. In addition, the present study is expected to provide useful information for forest management.

2. MATERIALS AND METHODS

2.1 Study Site

The study site is the Kuraiyama experimental forest at Gifu University (137°11´-137°14´E and 35°58´-36°01´N), which is located in Gero City, Gifu Prefecture, Japan (Fig. 1). The elevation lies in the range of 820-1,451 m a.s.l. The management office is located at an elevation of 750 m. The yearly minimum, maximum and average air temperatures observed at the office are -10°C, 30°C and 10°C, respectively. The annual precipitation is about 2,400 mm. According to the Köppen climate classification system, the climate at the study site is classified as the Cfa type. A rainy season from late June to mid-July and a typhoon season from August to October are the typical characteristics of a Cfa climate zone. In particular, typhoons can produce high rainfall and sometimes cause disastrous landslides and/or debris flows in the region. The bedrock is Nohi rhyolite, shallowly covered by brown forest soil. While the main observations were carried out at the paired catchments of the C1 and D1 basins, supplemental observations were also carried out at the C2 and D2 basins for use as reference data.

The basic characteristics of the four basins are summarized in Table 1. The C1 basin is mainly covered by an evergreen coniferous forest, whose dominant tree species is Japanese cypress (*Chamaecyparis obtusa*). The basin is located southeast of the experimental forest station. Its elevation lies in the range of 926-1,278 m and its area is 0.6 km^2. 74% of the basin is covered by a 40- to 50-year-old artificial coniferous forest, 18% is covered by a broadleaf forest, and 8% is covered by a natural coniferous forest. The D1 basin is mainly covered by a deciduous broadleaf forest, whose dominant species is *Quercus* spp. The basin is located to the south of the C1 basin. The elevation lies in the range of 909-1, 278 m and its area is 0.73 km^2. 77% of this basin is covered by a deciduous broadleaf forest, 14% is covered by a 50- to 70-year-old artificial coniferous forest, and 9% is covered by a natural coniferous forest. The forest floor is also covered with a high density of bush, sasa bamboo grass and a litter layer.

The C2 basin is covered by an evergreen coniferous forest located at an elevation from 1, 088-1,312 m and its area is 0.21 km^2. The D2 basin is a deciduous broadleaf forest, which is located near the C2 basin. The elevation lies in the range of 1,037-1,228 m and its area is 0.09 km^2. 73% of the basin is covered by a broadleaf forest.

2.2 Measurements

2.2.1 Discharge

In order to measure the discharge from each basin, a right-angle triangular weir was built and a water level logger (HOBO-U20, Onset Computer Corporation) was installed at the downstream end of each basin. The data utilized for our analysis were taken from 1st November 2007 to 15th April 2018 (total of 3819 days). The recording intervals were 10 minutes from November to May (winter season) and 3 minutes from May to November (other than the winter season). The discharge can be calculated from the water level using the following formula [13]:

$$Q = KH^{\frac{5}{2}}$$
$$K = 1.354 + \frac{0.004}{H} + \left(0.14 + \frac{0.2}{\sqrt{W}}\right)\left(\frac{H}{B} - 0.09\right)^2$$

where, Q: discharge (m³/s), K: discharge coefficient (-), H: overflow depth (m), W: weir height (m), and B: weir width (m).
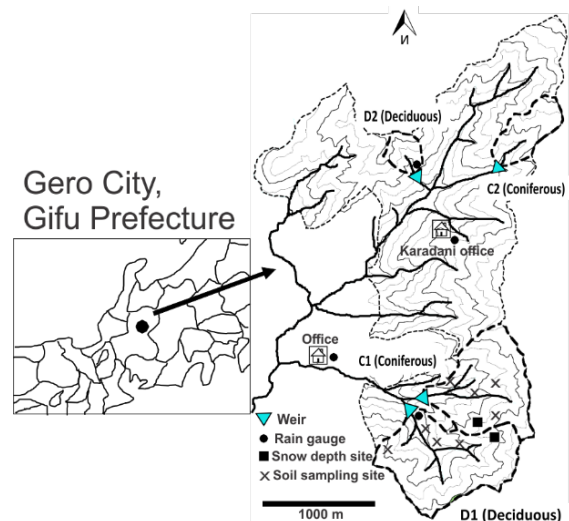

Fig.1 Location of four basins in Kuraiyama experimental forest, Gifu Prefecture, Japan

Table 1 Characteristics of four basins

Parameters		C1	D1	C2	D2
Basin area (km^2)		0.61	0.73	0.21	0.09
Main stream length (km)		1.01	1.21	0.71	0.37
Total stream length (km)		3.75	3.63	1.2	0.37
Main stream slope		0.35	0.31	0.32	0.46
Coefficient of basin shape		0.60	0.49	0.41	0.69
River channel density (km^{-1})		6.15	4.97	5.71	4.11
Maximum altitude (m)		1278	1278	1312	1228
Minimum altitude (m)		926	909	1088	1037
Altitude difference (m)		352	369	224	191
Vegetation type upper: area (km^2) lower: rate (%)	Broadleaf deciduous	0.11 18	0.56 76	- -	0.07 73
	Plantation coniferous	0.45 75	0.1 14	- -	0.02 27
	Natural coniferous	0.04 7	0.07 10	0.21 100	- -

2.2.2 *Precipitation*

Two rain gauges were set up inside the experimental forest stations. One gauge was set up at the downstream end of the D1 basin for the analysis of the C1 and D1 basins. The other gauge was set up at the downstream end of the D2 basin for the analysis of the C2 and D2 basins. However, these two rain gauges could not observe snowfall. Therefore, the precipitation during the winter period was obtained by a heater rain gauge which was set up at the management office. All these rain gauges were of the tipping bucket type with a minimum observed value of 0.5 mm.

2.2.3 *Soil analysis*

Soil samples were collected inside the C1 and D1 basins. There were four sample sites inside each basin. The soil samples were collected from three different depths, 0-10 cm, 10-30 cm and 30-60 cm, with three replications for analyzing the following parameters: (a) soil texture (determined with the hydrometer method based on Stoke's law), (b) soil organic carbon (measured by the Walkey and Black Method [14]), (c) particle density (measured by the pycnometer method), (d) permeability (using a 100-cc core sampler and the falling head method based on Darcy's law) and (e) soil pH (1:5) (measured by a pH meter: D71-s, Horiba Corporation).

2.2.4 *Snow depth observation*

Changes in the snow depth during winter were estimated by handmade instruments composed of an aluminum pole, 2 m in length, with 16 temperature sensors (HOBO pendant logger: UA-002-64, Onset Computer Corporation) at 10-cm intervals from 0 cm to 150 cm in height. Changes in the snow depth could be estimated by the changes in temperature measured by each sensor installed at different heights above the ground surface. The principle of the measurement method was the same as that of the equipment proposed by Fujihara et al. [15].

One aluminum pole was set up inside each of the C1 and D1 basins, respectively, and the air temperature at each height above the ground surface was measured at one-hour intervals only during the winter season from 2013 to 2018.

3. RESULTS

3.1 *Soil Properties*

The soil texture of all the layers of both basins was classified as sandy loam (Table 2), suggesting that the parent materials were almost the same. The soil particle densities in the two basins were low (around 2 g/cm^3) compared to mineral soil, which means that the soil contained much organic matter. The organic matter at a depth of 0-10 cm in the C1 basin (23.4%) was higher than that in the D1 basin (17.5%), while the organic matter at a depth of 10-60 cm in the D1 basin (13.4-11.6%) was higher than that in the C1 basin (7.5-4.6%). This indicates that the organic matter in the C1 basin was concentrated only in the surface soil due to the accumulation of hardly decomposable fallen leaves. In the D1 basin, however, the organic matter was distributed to the deep soil layer because the understory was dead and decomposed. It supplied a great deal of organic matter throughout the whole soil profile. The soil permeability in the D1 basin was higher than that in the C1 basin and decreased with depth. The soil pH in both basins was almost the same and close to the neutral value (pH 7.0).

3.2 Flow Duration Curve

The flow duration curve (FDC) represents the relationship between the magnitude and the frequency of the daily streamflow for a particular river basin, providing an estimate of the percentage of time a given streamflow was equal to or exceeded a historical period [16].

Fig. 2 shows FDCs for the D1 and C1 basins, based on the daily specific discharge over 3,455 days from November 2007 to December 2017. Some data (259 days) are missing due to a sensor error. The three-month discharge, D_{25} (probability of exceedance: 25%), the six-month discharge, D_{50} (50%), the nine-month discharge, D_{75} (75%), and the droughty discharge, 355-day discharge, $D_{drought}$ (97%), are important for water resource management [17]. Each discharge, D_{25}, D_{50}, D_{75} and $D_{drought}$ of the D1 basin was 5.57, 2.85, 1.63 and 0.73 mm/day, respectively, which was higher

Table 2 Soil properties of D1 (deciduous) and C1 (coniferous) basins

Parameters (unit)		D1 basin (deciduous)			C1 basin (coniferous)		
Soil depth	(cm)	0-10	10-30	30-60	0-10	10-30	30-60
Soil texture		Sandy loam	Sandy loam	Sandy loam	Sandy loam	Sandy loam	Sandy loam
Organic matter (C-org)	(weigh%)	17.5 ±5.99	13.40 ±6.05	11.60 ±4.16	23.24 ±8.67	7.53 ±2.67	4.62 ±2.69
Particle density	(g/cm^3)	2.07 ±0.18	2.14 ±0.16	2.14 ±0.16	1.80 ±0.15	1.92 ±0.18	1.96 ±0.18
Permeability	(cm/hour)	8.81 ±4.11	5.75 ±3.43	4.20 ±3.28	5.41 ±4.20	4.99 ±3.2	3.69 ±2.60
pH		7.06 ±0.17	7.14 ±0.18	7.13 ±0.19	7.18 ±0.11	7.20 ±0.17	7.30 ±0.11

than that of the C1 basin (4.53, 2.05, 1.07 and 0.44 mm/day). The average daily discharge estimated from the FDC was 5.39 mm/day in the D1 basin, which was also higher than the C1 basin (4.76 mm/day). However, all the daily discharge values with frequency less than 4.86% in the C1 basin were higher than those in the D1 basin.

Fig. 3 also shows FDCs of the pair catchments, the D2 and C2 basins, based on the daily specific discharge over 1,462 days for the same duration. However, many data (2,252 days) are missing in the C2 and D2 basins due to a sensor error or frequently occurring mudslides. Therefore, all the results obtained from the FDCs of the C2 and D2 basins could not be directly compared with the results obtained from the curves of the C1 and D1 basins. The discharge values for D_{25}, D_{50}, D_{75} and $D_{drought}$ of the D2 basin were 10.20, 6.19, 4.39 and 2.55 mm/day, respectively, which were higher than those of the C2 basin (9.85, 5.49, 3.29 and 1.44 mm/day). The average daily discharge estimated from the FDC was 10.08 mm/day for the D2 basin, which was larger than for the C2 basin (9.59 mm/day). Almost all the daily discharge values with frequency less than 14.6% in the C2 basin were higher than those in the D2 basin.

3.3 Characteristics of Hydrograph

Fig. 4 shows one of the representative hydrographs for each of the four test basins observed from 13th to 15th October 2014, which has one peak of discharge by a rainfall event of more than 100 mm.

The peak discharge in the C1 basin (coniferous) was higher than that in the D1 basin (deciduous). However, after the rainfall event ended, the runoff discharge decreased more rapidly in the C1 basin than in the D1 basin, which showed that the gradient of the recession curve was higher in the C1 basin than in the D1 basin. The relation between the runoff discharge of the C1 basin and that of the D1 basin was reversed around six hours after the peak discharge, when the discharge of the D1 basin was higher than that of the C1 basin.

While the shapes of the hydrograph of the C2 and D2 basins look almost the same, the discharge during the flood duration (from 21:00 on 13th October to 11:00 on 14th October) was higher in C2 than D2 just like the hydrograph of the C1 and D1 basins, as described above. The peak discharge of C2 was 1.69 $m^3/s/km^2$, which was a little higher than D2 (1.61 $m^3/s/km^2$). And the runoff discharge starting ten hours after the peak discharge became higher in D2 than C2.

Furthermore, almost all the hydrographs under the various amounts of rainfall showed the same pattern. This suggests that deciduous forests can mitigate floods better than coniferous forests.
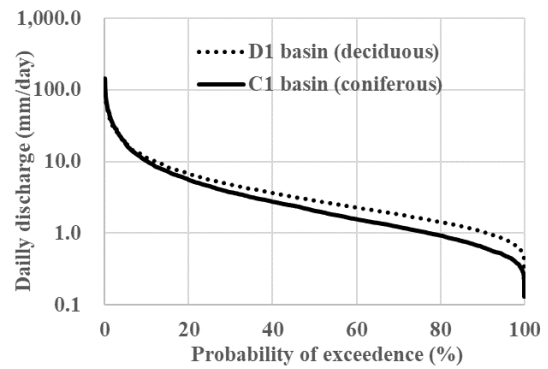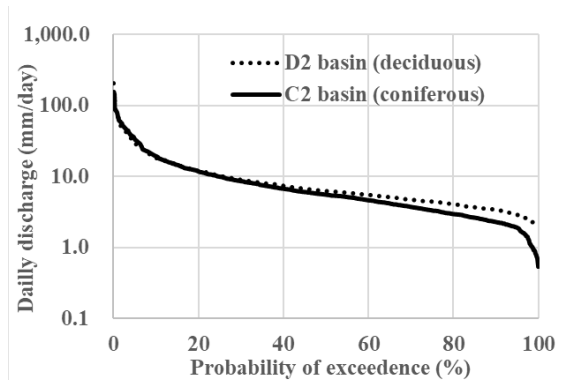

Fig.2 Flow duration curves of D1 and C1 basins
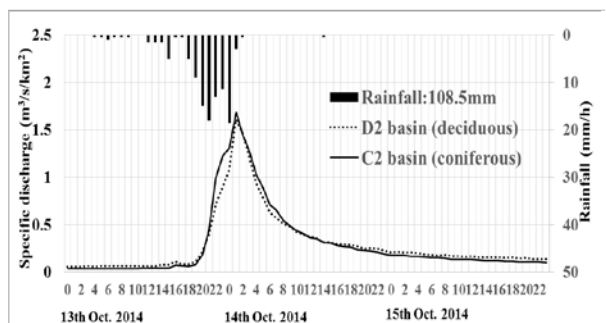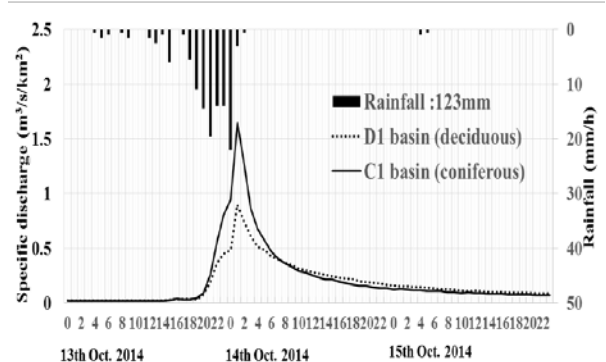

Fig.3 Flow duration curves of D2 and C2 basins

Fig.4 Hydrographs of four test basins

3.4 Peak Discharge

Fig. 5 shows a comparison between the peak discharge of the deciduous basin and that of the coniferous basin during the rainfall events. Based on this figure, the peak discharge from the

coniferous basin was higher than that from the deciduous basin. In comparing the C1 and D1 basins, the peak discharge from the C1 basin is 1.49 times higher than that from the D1 basin based on a linear regression with R^2 of 0.96. Moreover, a comparison between the C2 and D2 basins shows that the peak discharge from the C2 basin is 1.16 times higher than that from the D2 basin based on a linear regression with R^2 of 0.92.

3.5 Direct Runoff and Runoff Coefficient

The streamflow from a rainfall event is generally composed of two components, direct runoff and base flow. Direct runoff is defined as the runoff caused directly by a rainfall or snowmelt event; it usually forms the major part of the flood hydrograph. Base flow is defined as the part of the streamflow that is not attributable to direct runoff from precipitation or melting snow; it is usually sustained by groundwater.

Thus, the two components were separated by a straight line between the rising point just after the rainfall had started and the gradient changing point between the reduction coefficients of 0.024 h^{-1} and 0.011h^{-1} on the hydrograph after the rainfall had ended [18,19]. In this research, direct runoff is defined as the total discharge above the straight line drawn by the above-mentioned method.

Fig. 6 shows the relation between the rainfall and the direct runoff of each basin with the same rainfall events. Based on the linear regression equation, the initial loss (the amount of rainfall before the direct runoff occurs) is estimated by taking the x value when the linear regression equation intercepts the x-axis. The initial loss from the C1 basin is 32.2 mm (=14.8/0.46), which is almost the same as the value for the D1 basin (34.4 mm=13.4/0.39). And the initial loss from the C2 basin is 23.7 mm (=15.9/0.67), which is also almost the same as the value for the D2 basin (25.9 mm =15/0.58), but it is lower than the values (32.2 and 34.4 mm) for the C1 and D1 basins. These results suggest that the initial loss is less influenced by the forest type and much more strongly influenced by the basin area. This implies that the larger the area is, the larger the initial loss will be. On the other hand, the gradient parameter of the linear equation for the C1 basin is 0.46, which is larger than the value for the D1 basin (0.39). And the gradient for the C2 basin is 0.67, which is also larger than the value for the D2 basin (0.58). These results suggest that the gradient parameter is larger in the coniferous basin than in the deciduous basin when the basins have the same area.

Fig. 7 shows the relation between the amount of rainfall and the runoff coefficient of the coniferous and deciduous forest basins under the same rainfall event.
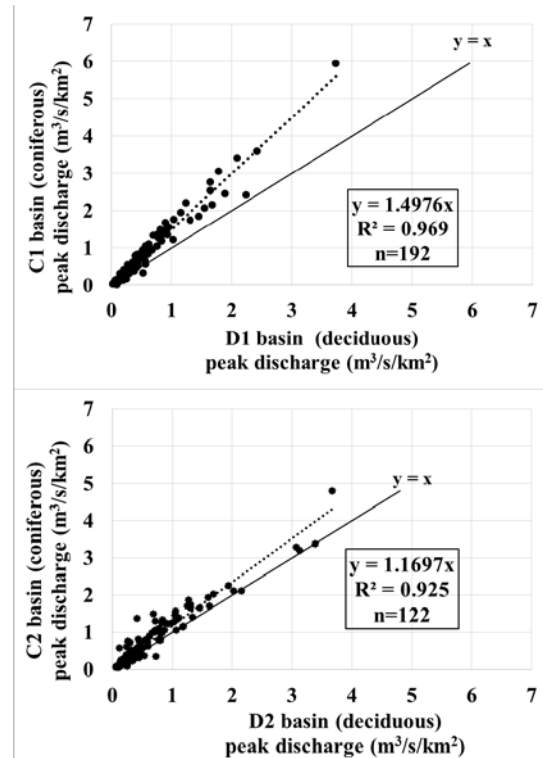

Fig. 5 Comparison of peak discharge between coniferous and deciduous basins
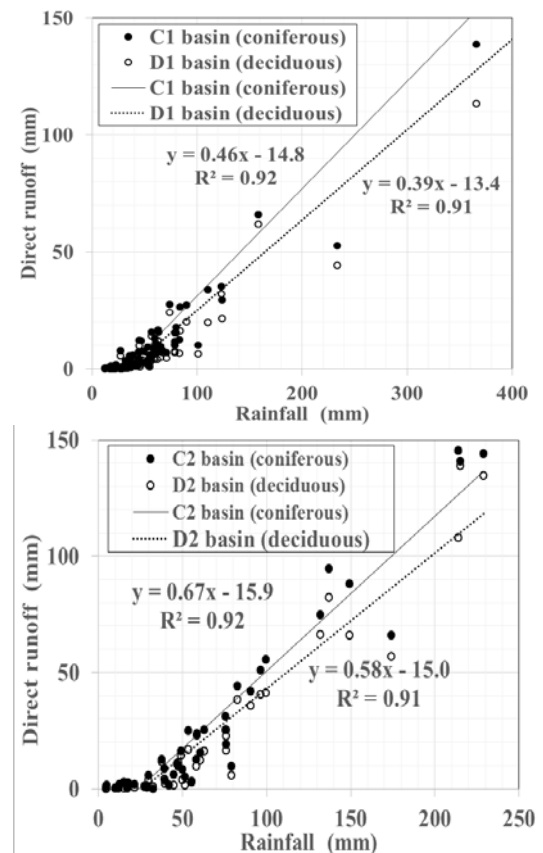

Fig. 6 Relation between rainfall and direct runoff of coniferous and deciduous basins
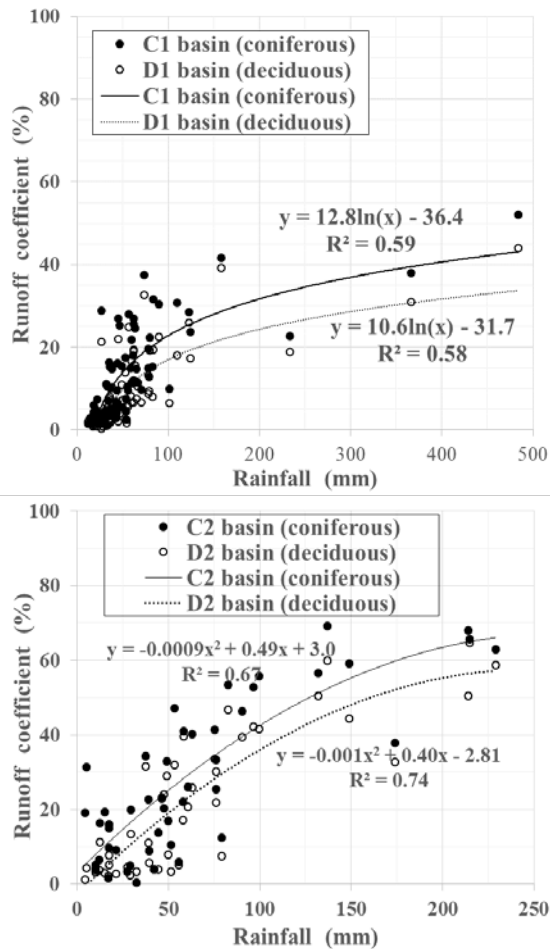
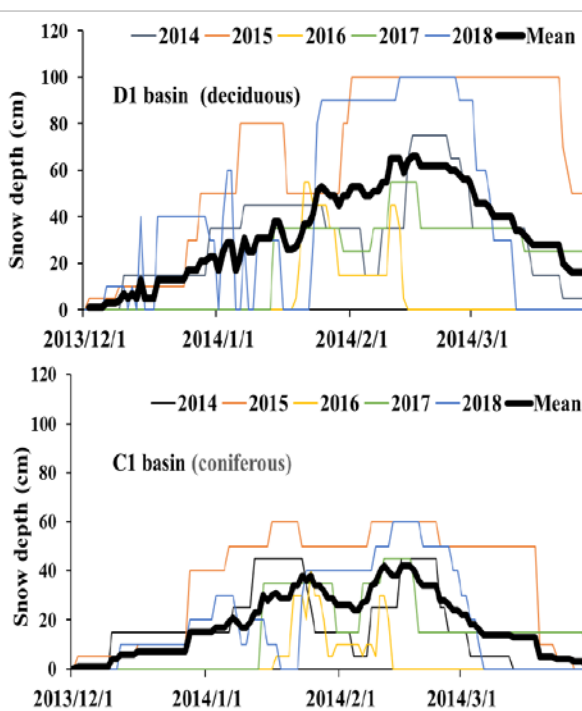Fig.7 Relation between rainfall and runoff coefficient

Fig. 8 Snow depth in D1 (deciduous) and C1 (coniferous) basins

The runoff coefficient is a dimensionless value relating the amount of direct runoff to the amount of precipitation received. It generally has a larger value for areas with low infiltration and high runoff (pavements and steep gradients), and a smaller value for permeable, well-vegetated areas (forests and flat lands). The runoff coefficient tends to increase as the amount of rainfall increases in all basins. The average runoff coefficient for more than 150 mm of rainfall is 38.6 and 58.6% for the C1 and C2 basins, respectively. These values are higher than those for the D1 (33.3%) and D2 (51.7%) basins in the deciduous forest. Furthermore, these values are also strongly influenced by the basin area, which implies that the smaller the area is, the larger these values will be.

3.6 Snow Depth

Fig. 8 shows the changes in snow depth during the winter seasons from 2014 to 2018. The bold black line represents the average snow depth over five years. The snow depth fluctuated a lot every year. The highest snow depths were found in 2015 and 2018, but the snow started to melt faster in 2018 than in 2015. And the lowest snow depth was recorded in 2016. However, it is clear that the snow depth in the D1 basin was higher than that in the C1 basin.

4. DISCUSSIONS

Our results showed that the annual discharge in the deciduous forest was higher than that in the coniferous forest during the observation period. The phonological difference between deciduous broadleaf and evergreen coniferous forests might contribute to this difference. While the trees in evergreen coniferous forests always keep their leaves, those in deciduous broadleaf forests lose almost all of their leaves in autumn, as shown in Figs. 9 a) and d). Due to the absence of leaves in deciduous broadleaf forests during the winter season, more snow can reach the ground. In contrast, the canopy in evergreen coniferous forests intercepts much of the snow; and thus, less snow reaches the ground.

On the other hand, in the non-winter periods, the shape and configuration of the leaves affect the LAI (leaf area index) and the water storage [20, 21]. It is well known that flat leaves (deciduous species) store water as a thin coating, while needle-type leaves (coniferous species) store water in the capillary spaces between the leaves [21]. The water stored by mature deciduous trees with and without leaves measures 0.2-2 mm and 0.03-0.8 mm, respectively [22], and 0.1-4.3 mm for mature coniferous trees [23]. In addition, previous observations have revealed that the annual

Fig.9 Forest condition in C1 (evergreen coniferous) (top) and D1 (deciduous broadleaf) (bottom) (left: forest floor, right forest canopy in autumn)

evapotranspiration in coniferous forests is higher than that in deciduous forests [9, 10, 19]. These facts are consistent with our results, namely, that the annual discharge in deciduous forests is higher than that in coniferous forests. Moreover, this difference might be due to the difference in canopy characteristics, resulting in the difference in evapotranspiration.

The differences in direct runoff and peak discharge during rainfall events result from not only the leaf characteristics, but also the structure of the branches. Coniferous trees have multilayers of branches, which make the canopy look crowded, and narrow hard leaves called scales or needles which are almost evergreen. The multilayers of the branches and the evergreen leaves of coniferous trees block solar radiation from reaching the soil surface. This, in turn, inhibits the growth of the understory on the forest floor due to the low light intensity. Deciduous trees, on the other hand, shed their leaves each autumn and the branches are broadly distributed in the air (not in multilayers). This charters a great deal of solar radiation to the forest floor and promotes the growth of grass and/or shrubs.

It can be seen in Fig. 8 c) that the dominant vegetation of the understory cover in the D1 basin is Sasa bamboo grass where the root systems are well-developed [24]. This kind of condition helps to enhance the preferential flow in the soil [25]. The forest floor in the C1 basin, on the other hand, has a lower density understory vegetation cover (Fig. 8 a) [26], and lower organic matter and soil permeability compared to the D1 basin (Table 2).

It was previously mentioned that the root systems, organic matter and litter floor increased the infiltration rate [27], which decreased the

proportion of direct runoff to total rainfall. In addition, it was reported that the highest final infiltration rate was found in the deciduous plot with 321 mm/h, while the cypress and cedar plots had lower infiltration rates of 76.4 mm/h and 173 mm/h, respectively [12].

Furthermore, the existence of understory vegetation could decrease and delay the speed of the surface runoff, which would reduce the peak discharge in the deciduous basin to a greater degree than in the coniferous basin.

5. CONCLUSIONS

Based on the findings of this study, it was seen that the runoff discharge in the deciduous broadleaf forest was higher than that in the evergreen coniferous forest. The peak discharge (Fig. 5), direct runoff (Fig. 6) and runoff coefficient (Fig. 7) in the deciduous broadleaf forest were lower than those in the evergreen coniferous forest. The snow depth in the deciduous broadleaf forest was thicker than that in the evergreen coniferous forest (Fig. 9). All those hydrological characteristics were influenced by the conditions of the canopy and the forest floor. It was confirmed in this research that deciduous broadleaf forests are better able to foster water resources and to control flooding than evergreen coniferous forests.

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