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SEPARATION OF RAINFALL INTERCEPTION AND TRANSPIRATION FROM ANNUAL EVAPOTRANSPIRATION IN FORESTED WATERSHEDS

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In case that interception evaporation and transpiration of forested watersheds can not be directly observed, a method of separately estimating annual interception evaporation and transpiration is studied and proposed. The 365 days in a year are mainly divided into two groups: rainy days having interception evaporation and non-rainy days having transpiration. Then daily interception evaporation is calculated from rainfall and potential evaporation determined by the temperature, and effect of annual change of forest condition is also considered. Three parameters of the method are determined by using observed multi-year data of precipitation, runoff and temperature in four watersheds in Japan, giving acceptable results of annual evapotranspiration. Finally the changing patterns of interception evaporation and evapotranspiration are analyzed, demonstrating the sensitivity to rainfall and forest change. This method is applicable to the separation of interception and transpiration from the whole evapotranspiration.

Key Words : *Interception evaporation, transpiration, separation, rainfall, temperature, oasis effect*

1. INTRODUCTION

It is widely accepted that the evapotranspiration in a forested watershed is mainly consisted of the interception evaporation during rainy days and the forest transpiration during non-rainy days. For watersheds or large-scale watersheds, however, direct observation of interception evaporation and transpiration is impossible, and the separation of interception and transpiration from evapotranspiration has not been well understood. As a result, annual evapotranspiration is seldom used to allocate the interception evaporation in rainy days and transpiration in non-rainy days, which are important for estimation of long-term runoff, although the annual evapotranspiration can be estimated by annual water budget (precipitation minus runoff). Furthermore, in order to assess the role of interception evaporation on reducing floods, the evapotranspiration obtained by water budget method should be separated into interception evaporation and transpiration.

Forest resources of Japan have dramatically increased since 1955,[1)2)] because of the afforestation policy after the world war, the fuel revolution from woods to gas fuel and the timber imports of other countries beginning in 1961. The national growing stock of trees in 1995 has become 1.9 times of the stock in 1956, although the forested area has not evidently changed. And among the stock changes, the stock of broadleaf trees has increased to 1.2 times of that in 1956, while the stock of conifer trees has increased up to 2.7 times. It can be thought that a similar and big change in tree type, tree area and growing stock has happened in a prefecture or a watershed during the 40 years.

In general, the evapotranspiration volume is proportional to the surface area of trees' leaves, and the leaf area is proportional to the growing stock of trees. As a result, evapotranspiration in a watershed changes annually as the tree type and growing stock change annually. In fact, the annual evapotranspiration of the Nagayasuguchi Dam watershed in Tokushima Prefecture, which is obtained from precipitation and runoff data, shows an evident tendency of increase corresponding to the rapid increase of tree stock, as illustrated later.

Unfortunately, it is very difficult to get the quantitative data on annual changes in decades of tree type, tree area and stock at watershed scale, and to develop a quantitative relation of evaporation or transpiration to these tree characteristics. Therefore in this paper, a separation method is proposed to get interception evaporation and transpiration by only using daily rainfall and temperature data, without using the quantitative data of forest characteristics.

2. INTERCEPTION EVAPORATION AND TRANSPIRATION ESTIMATION

First of all the daily interception evaporation and transpiration are discussed and calculated, then annual interception and transpiration are estimated.

Interception evaporation is supposed to occur on rainy days, and daily evaporation is expressed as follows.

$$e_I = r \qquad (r < r_c) \qquad or \qquad e_I = r_c + \alpha(t)\cdot(r - r_c) \qquad (r > r_c) \tag{1}$$

where e_I is the daily interception evaporation, r is the rainfall in a day, r_c is a parameter called the storage capacity of canopy, and $\alpha(t)$ is a function of time t and is called the interception-evaporation coefficient. Equation (1) means that when rainfall volume is less than the storage capacity, all the rainfall is intercepted by the canopy and is evaporated in the day, otherwise a part of rainfall is intercepted by the canopy, and evaporation from intercepted rainfall is affected by rainfall intensity and the interception-evaporation coefficient $\alpha(t)$.

The coefficient $\alpha(t)$ is defined as

$$\alpha(t) \equiv A\cdot f(t)\cdot h_I \tag{2}$$

where A is a coefficient (constant for a watershed), $f(t)$ is a function reflecting the year-by-year change of the coefficient, t is the time of year, and h_I is the potential evaporation value for the day and is calculated with the Hamon formula (h=0.14D^2Q, here D is the possible maximum sunshine duration, Q is the saturated air humidity at daily-mean temperature).

From equations (1) and (2) it is seen that the interception evaporation e_I in a rainy day is determined by the canopy storage capacity r_c (reflecting canopy's property), rainfall intensity r, timely changing function $f(t)$ (relating to canopy's change) and potential evaporation h_I (reflecting meteorological condition) [3) 4)].

On the other hand, transpiration is supposed to happen in non-rainy days, and transpiration also appears in a rainy day if the rainfall is less than the potential evaporation. The daily transpiration is expressed as

$$e_T = \beta(t)\cdot h_T = B\cdot[f(t)]^{\delta}\cdot h_T \qquad (r < h_T) \tag{3}$$

in which $\beta(t)$ is called transpiration coefficient and changeable with season or year, B and δ are coefficients, and h_T is the potential evaporation in a day for those days when transpiration happens and is also estimated by the Hamon formula.

Then annual evapotranspiration is expressed as the sum of annual interception evaporation and transpiration which are the sum of daily values.

$$E = E_I + E_T = \sum e_I + \sum e_T \tag{4}$$

where E is the annual evapotranspiration, E_I is the annual interception evaporation, and E_T is the annual transpiration.

Substituting equations (1), (2) and (3) into equation (4) can give an integrated formula,

$$E^* = A\cdot R^* + B \tag{5}$$

The E* is a non-dimensional item for annual evapotranspiration E, which is written as

$$E^* = (E - r_c\cdot N_c - \sum_{r<r_c} r)/[f^{\delta}(t)\cdot H_T] \tag{6}$$

where N_c is the number of days when rainfall is less than the canopy storage capacity, and H_T is the sum of daily potential evaporation of all non-rainy days with the transpiration occurred.

The R* is a non-dimensional item for annual rainfall (including those rainy days with its rainfall larger than the canopy storage capacity) and written as,

$$R^* = f^{1-\delta}(t)\sum_{r>r_c} h_I(r - r_c)/H_T \tag{7}$$

Equation (5) may be seen as a linear relationship between annual non-dimensional evapotranspiration E* and rainfall R*.

When the function $f(t)$ and canopy storage capacity r_c are determined to a giving watershed, parameters A and B in equation (5) can be obtained by a linear regression analysis, using observed multi-year data of annual evapotranspiration (e.g. precipitation – runoff), daily rainfall and daily mean temperature.

Finally, the obtained B is used to estimate annual transpiration with equation (3). The obtained A is used to derive the interception-evaporation coefficient $\alpha(t)$ from equation (2), and then annual interception evaporation can be estimated by equation (1).

In above way the interception evaporation and transpiration can be separated out from annual evapotranspiration.

3. APPLICATION

Four watersheds in Japan are selected for case studies, their locations are shown in **Fig. 1**, and their characteristics such as area and forest type are listed in **Table 1**. The watershed of Nagayasuguchi Dam is located at the upstream of Naka River in the southern Tokushima Prefecture, with area of 494 km^2, covered mainly by conifer trees, and having seventeen rainfall gauges; the watershed of Shimizubata is located at the upper and middle part of the Fuji River basin mainly in Yamanashi Prefecture, with area of 2,179 km^2, dominant of conifer trees, and having ten rainfall gauges; the Fukuchi Dam watershed is located at Okinawa Prefecture, with small area of 32 km^2, covered by evergreen broadleaf trees, and having three rainfall gauges; and the Hanayama Dam watershed is located at the Miyagi Prefecture, with area of 127 km^2, mainly covered by deciduous broadleaf trees, and having three rainfall gauges. Therefore these four watersheds are different in area, forest type, mean altitude and climatological regime. The basic time period of water budget analyses is one year for the former three watersheds, and the annual change of water storage can be neglected. The unit time is four months (July through October) for the fourth watershed due to snowfall and snow melt in the winter and spring, and the water storage change is supposed to be negligible.

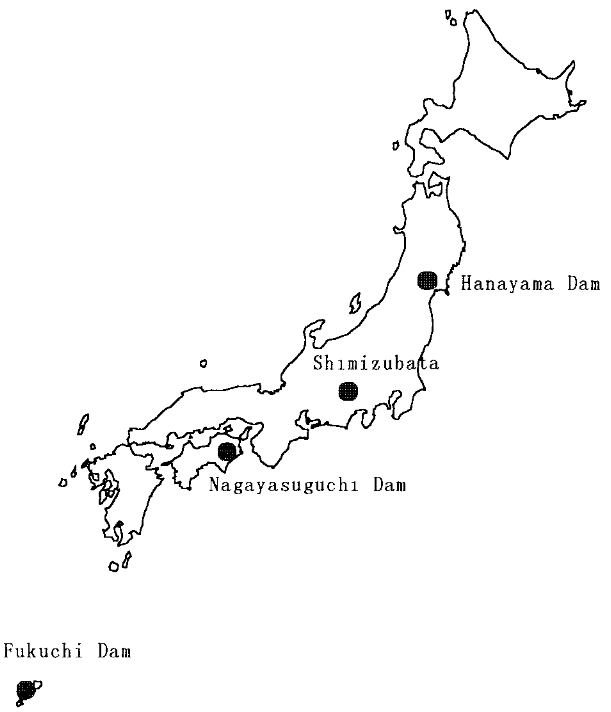

Fig. 1 Locations of four watersheds.

In order to obtain the values of parameters r_c, A and B, many years of data are used. The data sample size of each watershed is shown in **Table 2**. Means of precipitation and potential evapotranspiration, regression results (r_c, and the means of $\alpha(t)$ and $\beta(t)$) for parameters, and regression accuracy are also listed in **Table 2**.

Table 1 Outline of forested watersheds of study

Watershed (Prefecture)	Area (km^2)	Forest Type	Mean Altitude (m)	Latitude	Period of Water Budget
Nagayasuguchi Dam (Tokushima)	494	Conifer	785	33.7	Annual (Jan – Dec)
Shimizubata (Yamanashi)	2197	Conifer	999	35.7	Annual (Jan – Dec)
Fukuchi Dam (Okinawa)	32	Evergreen broadleaf	159	26.2	Annual (Jan – Dec)
Hanayama Dam (Miyagi)	127	Deciduous broadleaf	512	38.3	4-months (Jul – Oct)

Table 2 Results of regression analysis

Watershed	Sample Size	Precipitation (mm)	Potential H (mm)	Mean of α	Mean of β	r_c	δ	Correlation Coefficient	Standard Error (mm)
Nagayasuguchi Dam	27 (1967-1993)	3418	646	0.08	0.64	1.3	0.0	0.921	71
Shimizubata	30 (1960-1992)	1363	583	0.21	0.47	0.5	0.5	0.820	94
Fukuchi Dam	12 (1979-1990)	2393	1078	0.14	0.55	0.6	0.3	0.963	89
Hanayama Dam	32 (1958-1990)	847	302	0.18	0.37	0.3	0.0	0.835	43

Table 3 Used functions of $f(t)$

Watershed	f(t)	
Nagayasuguchi Dam	$f(t)=(t-1964)^{0.5}$	$(1965 \leqq t)$
Shimizubata	$f(t)=\exp\{0.05(t-1960)\}$ $f(t)=1.92\exp\{-0.03(t-1973)\}$	$(1960 \leqq t<1973)$ $(t \geqq 1973)$
Fukuchi Dam	$f(t)=1-\exp\{-0.14(t-1978)\}$	$(t \geqq 1979)$
Hanayama Dam	$f(t)=\exp\{0.03(t-1958)\}$ $f(t)=6.55\exp\{-0.13(t-1975)\}$	$(1958 \leqq t<1975)$ $(t \geqq 1975)$

Table 4 Means of E_{obs}, E_I and E_T, and correlation coefficient between residual (E_{obs}-E_I-E_T) and potential H_T

Watershed	Period of Water Budget	E_{obs} (mm)	E_I (mm)	E_T (mm)	Corr. Coeff. of (E_{obs}-E_I-E_T) and H_T
Nagayasuguchi Dam	Jan-Dec	701	484	217	0.011
Shimizubata	Jan-Dec	522	296	226	0.046
Fukuchi Dam	Jan-Dec	771	530	241	0.033
Hanayama Dam	Jul-Oct	226	172	54	0.056

Mathematical formations of function *f(t)*, used in estimation of interception evaporation, are listed in **Table 3**. An accurate formulation of function *f(t)* can not be drawn out because of the shortage of data relating to annual forest change. However the changing pattern can be determined by watching the timely process of annual evapotranspiration. The evapotranspiration increases monotonously in some duration and decreases monotonously in other duration. Then a linear relation or exponential relation is applied to reflect timely change of *f(t)*.

The results of $\alpha(t)$, $\beta(t)$ and r_c are reasonable compared with corresponding values in forest hydrology researches[5]. The correlation coefficients of estimated and actual evapotranspiration (also listed in **Table 2**) are higher than 0.79, and the standard errors of evapotranspiration volume are less than 20%. All of these show that the estimation method proposed above is applicable to those watersheds.

Multi-year means of actual evapotranspiration E_{obs} (obtained by the water budget), estimated interception evaporation E_I and transpiration E_T are obtained and listed in **Table 4**. In order to check the accuracy of estimation, the residual between actual and estimated evapotranspiration is analyzed, and the correlation coefficient of the residual (E-E_I-E_T) and potential transpiration H_T is shown in **Table 4**. A large value of the coefficient means a remarkable estimation error. The fact that all coefficients of four watersheds are close to zero demonstrates further the applicability of equation (5).

4. ANNUAL VARIABILITY OF INTERCEPTION EVAPORATION AND EVAPOTRANSPIRATION

Estimated evapotranspiration, interception evaporation, transpiration, and observed evapotranspiration in each year are illustrated in **Fig. 2(a)**, **Fig. 2(b)**, **Fig. 2(c)** and **Fig. 2(d)** for the four watersheds respectively. The corresponding ratio of interception evaporation (E_I) to potential evaporation (H_I) during interception period, and ratio of total evapotranspiration (E) to potential evapotranspiration (H) are also shown in these figures. It is seen that the estimated evapotranspiration (interception + transpiration) is comparatively close to the observed one.

Interception evaporation and evapotranspiration in the Nagayasuguchi Dam watershed have an

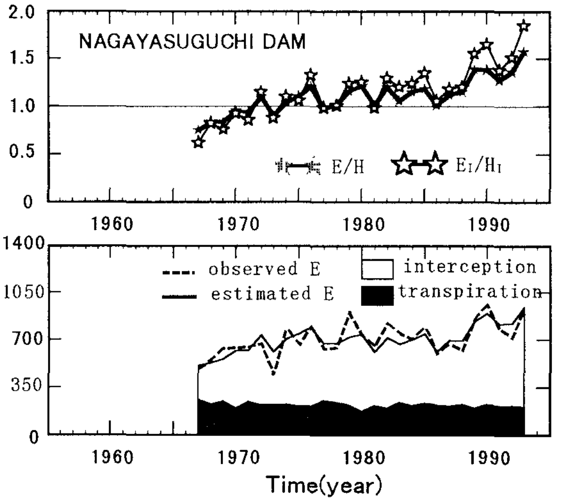

Fig.2(a) Annual changes in Nagayasuguchi Dam.

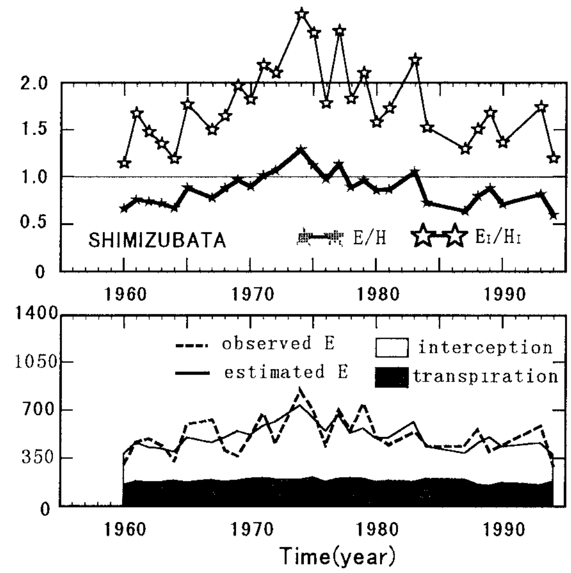

Fig.2(b) Annual changes in Shimizubata.

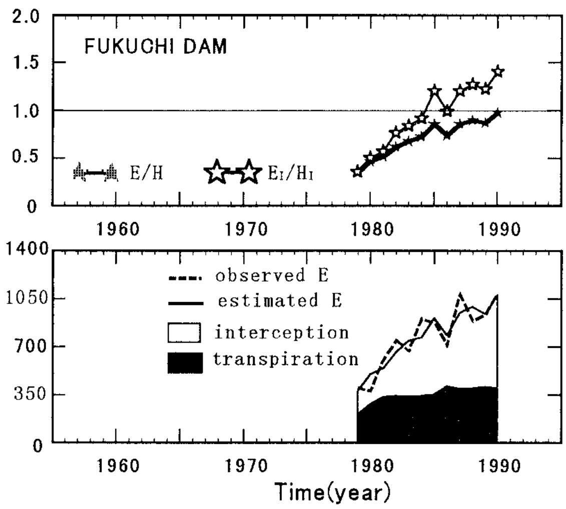

Fig.2(c) Annual changes in Fukuchi Dam.

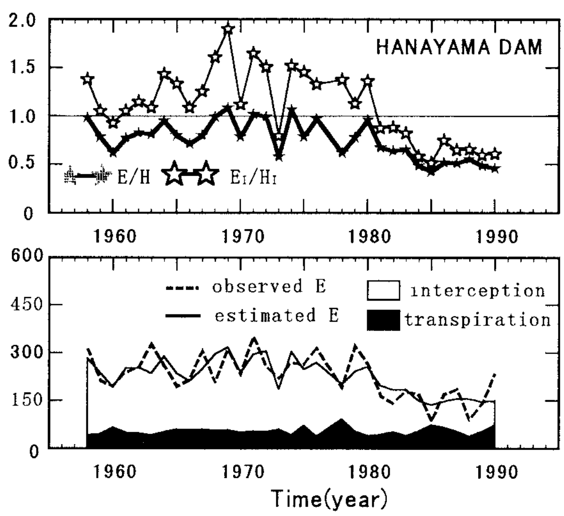

Fig.2(d) Annual changes in Hanayama Dam.

evident increase tendency with time of year, as shown in **Fig. 2(a)**. But the precipitation and mean temperature did not have such kind of tendency. The evapotanspiration has become nearly doubled from 1958 to 1993, mainly because the conifer trees got more and more condensed and doubled in leaf area [4]. The ratios of interception and evapotranspiration varied similarly and close to each other in values. But transpiration did not change evidently. In recent years the interception takes possess of over half of evapotranspiration amount.

Interception and evapotranspiration in the Shimizubata watershed have also changed with time (see **Fig. 2(b)**), first increasing during 1959-1973 then decreasing during 1973-1993. Unfortunately the forest alteration in that period is not known. And different from the situation of Nagayasuguchi Dam, the ratio E_I/H_I of interception to potential evapotranspiration is much bigger than the ratio E/H of evapotranspiration.

As shown in **Fig. 2(c)** for the Fukuchi Dam watershed, interception evaporation and evapotranspiration had a changing tendency rather similar to that of Nagayasuguchi Dam. But the ratio of interception increased faster than the ratio of evapotranspiration did. The main reason for the changes is that the growing stock of trees became 2.1 times during period of 1966-1990.

Tendency for the Hanayama Dam watershed as shown in **Fig.2(d)** is somehow similar to that of the Simizubata, with an increase at first and then a decrease. A cutting of deciduous trees happened after 1980, and might have resulted in the decrease in evapotranspiration. To reveal the reasons causing such kind of tendency needs more information on forest change and landuse variability.

Furthermore, estimated transpiration volume is usually less than the corresponding potential evapotranspiration for the four watersheds, which is coincident with the common knowledge obtained from experiments[6]. As for the ratio E/H of evapotranspiraton to potential evapotranspiration, some past work [7] has pointed out that the ratio can commonly exceeds unit one in local sites of arid regions, as the result of oasis effect, and has guessed that this phenomenon might appear at watershed scales in humid regions like tropical forests. Results of ratio E/H for present four watersheds in Japan are shown in **Fig.3(a)**, which is around 1.0 and similar to the results of the former work for humid temperate regions [7].

This phenomenon (E/H exceeds 1.0) can not be explained by the current theory of energy balance which assumes a horizontally uniform surface. But a net horizontal transfer of energy, the advection, may happen remarkably in non-uniform forests or hilly topography. The energy can be transferred to the forest by the advection, which is called the oasis effect[8], and can bring on the additional evaporation beside the net radiation.

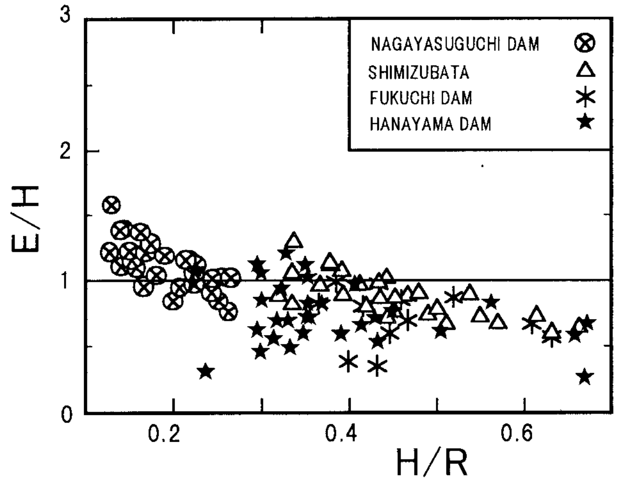

Fig.3(a) Relation of E/H to H/R.

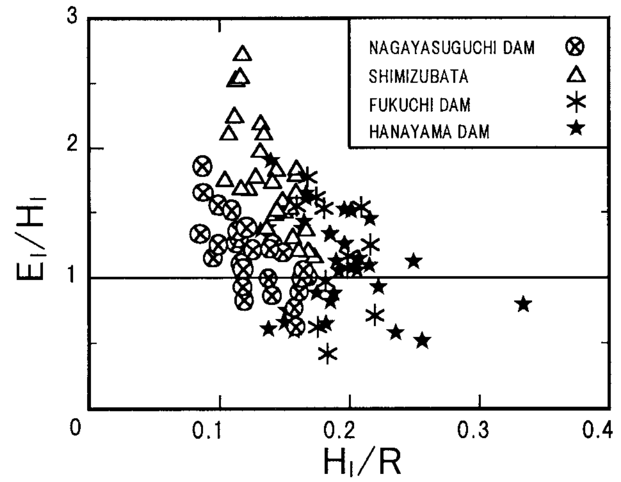

Fig.3(b) Relation of E_I/H_I to H_I/R.

Moreover, which component (interception evaporation or transpiration) is exceeding the potential evapotranspiration has not been understood. This study made a try to understand it, by means of separating interception and transpiration. The ratio of interception evaporation to corresponding potential evapotranspiration is larger than 1.5 for many years in the four watersheds, as shown in **Fig. 3(b)**, no matter what the forest type is. In other words, it is the interception evaporation that results in those ratio values larger than 1.0.

5. SUMMARY

First, the method proposed in this paper separates annual interception evaporation and transpiration for a forested watershed, based on data of watershed-averaged precipitation, runoff discharge and temperature. The estimated evapotranspiration for four watersheds is close to the observed one, demonstrating the applicability of the method. Second, although the watersheds are different in forest characteristics, the ratio of transpiration to potential evapotranspiration does not evidently change year-by-year, compared with the ratio of interception evaporation to potential evapotranspiration. Third, analyses of annual changes of interception, transpiration and evapo-transpiration highlight that interception evaporation is much sensitive to rainfall and forest change, and possesses an important part in the evapotranspi-ration change, for coniferous or broadleaf trees in Japan. And the ratio of interception to potential evapotranspiration is affected by forest type, growth process, management and landuse change. Finally, the ratio of transpiration to potential evapotranspiration falls into a common range of 0.4-0.7, but the ratio of interception to potential evapotranspiration may exceed 1.5 with forest's alteration.

The phenomenon of dramatically changing evapotranspiration will be further studied.

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REFERENCES

1) Ministry of Agriculture, Forestry and Fisheries: Statistical Yearbook , 1957.
2) Forestry Agency: Statistical Handbook of Forestry, 1998.
3) Alfiansyah, Y., Yoshida, H. and Hashino, H.: The estimation of rainfall interception loss using Hamon's potential evapotranspiration and linear regression, *J. Japan Society of Hydrology & Water Resources*, Vol.11, No. 2, pp.141-149, 1998. (in Japanese with English summary)
4) Hashino, M.: Water circulation and conservation function in forest, *Lecture Notes of the 33rd Summer Seminar on Hydraulic Engineering, Course A*, JSCE, pp.A-3-1-A-3-19, 1997. (in Japanese)
5) Tsukamoto, Y.: *Forest Hydrology*, Buneido Press, 1992. (in Japanese)
6) Tsukamoto, Y.: *Forest Hydrology*, Buneido Press, p.92, 1992. (in Japanese)
7) Tsukamoto, Y.: *Forest Hydrology*, Buneido Press, p.98, 1992. (in Japanese)
8) Federer, C. A.: Measuring forest evapotranspiration – theory and problems, *Readings in Forest Hydrology*, Eschner, A. R. and Black, P. E. eds., MSS Information Corporation, pp.159-185, 1975.

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