森林流域蒸発散量推定へのPENMAN-MONTEITHモデルの適用

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著者	鈴木, 雅一 福嶌, 義宏 Rampisela, D.A.
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論　文

Application of the Penman-Monteith Model to the Estimation of the Evapotranspiration Rate of a Forested Watershed

Dorothea Agnes Rampisela,* Masakazu Suzuki,* and Yoshihiro Fukushima*

Rampisela Dorothea Agnes, Suzuki, Masakazu, and Fukushima, Yoshihiro : **Application of the Penman-Monteith model to the estimation of the evapotranspiration rate of a forested watershed J. Jpn. For. Soc. 72: 1〜10, 1990** The procedures for the prediction of aerodynamic and canopy resistances of the Penman-Monteith model are described. These resistances are predicted using the long-term average rates of transpiration and evapotranspiration by the Water-Budget method as standard data. The hourly micro-meteorological data observed from September 1986 to August 1987 on the Kiryu Experimental Watershed is utilized for the evapotranspiration estimations. The estimated evapotranspiration rate by the Penman-Monteith model is compared with the rates that resulted by using the Thornthwaite, Hamon, and Penman methods. The seasonal trend of Penman's evapotranspiration factors, the coefficient to fit the potential rate into the actual rate calculated for a forested watershed are quite different compared with the seasonal trend for pastureland. The peculiarity of the Penman-Monteith model with its separation of the transpiration and evaporation of intercepted rainfall periods in the procedures made this model the best for estimating the evapotranspiration rate of a forested watershed.

ドロテア　アグネス　ランピセラ・鈴木雅一・福嶌義宏：**森林流域蒸発散量推定へのPenman-Monteithモデルの適用　日林誌 72：1〜10, 1990**　森林流域からの蒸発散量を気象記録から推定するためにPenman-Monteithモデルを適用することを試みた。このモデルでは空気力学的抵抗 R_a と表面抵抗 R_c の二つのパラメータが含まれており，これらを水収支測定と樹冠遮断量測定結果から得られている蒸発散量とモデルによる計算値が適合するように定めた。用いた記録は桐生試験地における既報の水収支，遮断量測定量と1986年9月から1987年8月の樹冠上での気象記録である。 R_c についてイギリスのトウヒ林，マツ林で報告されているものとほぼ同様の日変化，季節変化を与えることで，年量とその季節変化が水収支観測と適合する蒸発散量を得た。また，Penman, Thornthwaite, Hamon法に基づく可能蒸発散量から蒸発散係数を求めると，草地などで報告されている季節変化とは異なったが，蒸発散量を遮断蒸発量，蒸散量に分けて推定するPenman-Monteithモデルを用いた検討結果より，この差異は森林での遮断蒸発量に因っていることが示された。

I. Introduction

It was presumed that evaporation from vegetation with an unlimited water supply is controlled primarily by meteorological factors. Recent evidence has shown that evaporation is affected by many more factors than was previously thought, especially for a forest which has special characteristics. The Penman-Monteith model, although theoretically capable of giving accurate estimates of evaporation loss from any crop, is seldom used. Usually this is not because of a scarcity of the necessary meteorological data, which is becoming increasingly available from reliable automatic weather stations, but because of the lack of information and knowledge of crop aerodynamic and surface resistances. In this study, the aerodynamic and canopy resistances were predicted using the long-term average rate of transpiration and the evapotranspiration rate with the Water-Budget as standard data. The applicability of the Penman-Monteith model in estimating the evapotranspiration rate of a forested watershed also is discussed and compared with other commonly used models in Japan.

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* Fac. Agric., Kyoto University, Kyoto 606 京都大学農学部

The study was done using hourly micrometeorological data, continuously observed on a forested watershed from September, 1986 to August, 1987. This data was supported by some additional estimated parameters from previous studies.

II. Methods

1. Study site and instrumentation

The study area is situated in the southern part of Shiga Prefecture, Japan, located at 34° 58′ N, 136° 00′ E and at an altitude of about 190～225 m as shown in Fig. 1. The total area of the watershed is 5.99 ha and is covered by a closed forest of Japanese red pine (akamatsu, *Pinus densiflora* S. and Z.) and Japanese cypress (hinoki, *Chamaecyparis obtusa* (S. and Z.) Endl.). The average height of the trees was 12 m.

Temperature and net radiation were measured at 12 m height and windspeed was measured at the top of 16 m tower. A rain gauge was placed on the ground about 200 m from the tower.

2. Mean evapotranspiration rate by Water-Budget method as standard data

Climatic data, especially precipitation and discharge records, were available for the watershed covering a long period of time. Based on this data, SUZUKI and FUKUSHIMA (1985) reported the average monthly evapotranspiration rate by the Water-Budget method for the 1972～1981 period. Based on the fact that the seasonal trend of the daily evapotranspiration is nearly the same from one year to another, the average for 1972～1981 was used as the standard evapotranspiration rate data.

The average monthly transpiration rate of the watershed was estimated from the observed interception rate and the evapotranspiration noted above as reported by SUZUKI *et al.* (1979 a, b). The reported transpiration rate also was used as the standard transpiration rate.

3. The PENMAN-MONTEITH model

The PENMAN-MONTEITH model requires more detailed data and involves many steps of predictions and analysis. The main point of this analysis is to separate whether transpiration or evaporation of intercepted rainfall has occurred, in relationship to the canopy wetness condition. Transpiration is considered to have occurred only when the canopy is in a dry condition, and the calculated rate represents the evapotranspiration rate of the area. During the wet condition of the canopy, transpiration is zero, and the evapotranspiration rate is represented by the evaporation rate of intercepted rainfall. To determine the canopy wetness condition, the Interception Model shown in Fig. 2 is used. This is the model that was used by SUZUKI *et al.* (1979 b) for estimating the rainfall interception rate derived from the measurements of throughfall and stemflow on the Kiryu Watershed. The input data is the observed rainfall. When rainfall occurs, water is stored in the tanks of this model. During this period the canopy is considered to be in the wet condition

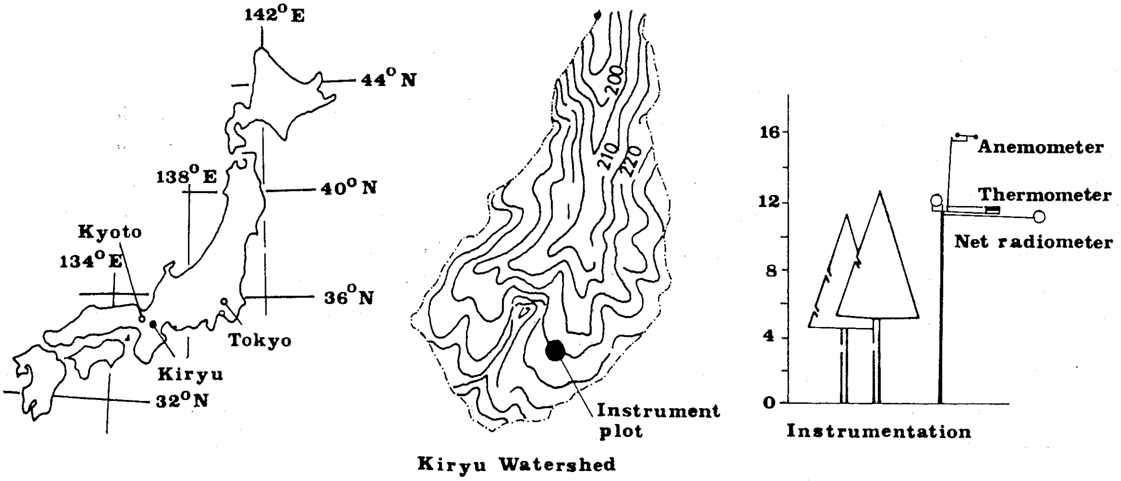

Fig. 1. Study site and instrumentation

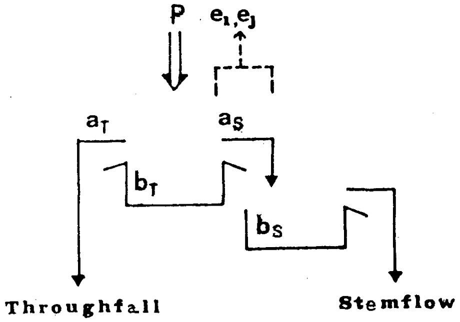

Fig. 2. Interception model
P, Rainfall intensity (mm/h) ; a_T, Throughfall coefficient (0.81) ; a_S, Stemflow coefficient (0.11) ; b_T, Water storage depth on foliage and branches (1.44 m) ; b_S, Water storage on stems (0.53 mm) ; e_i, Evaporation rate during rain period (0.1618 mm/h) ; e_j, Evaporation rate after rain period (0.1618mm/h).

(completely or partially wet), and the transpiration is considered to be zero. The stored water diminishes according to the evaporation intensity. When the tanks in this model are empty, the canopy is assumed to be completely dry, and it is considered that transpiration occured.

a. The PENMAN-MONTEITH equation (MONTEITH, 1965)

$$\lambda E=\frac{\Delta(R_n-G)+\rho_a C_p(e_a^*-e_a)/R_a}{\Delta+\gamma(1+R_c/R_a)} \qquad (1)$$

where E, evapotranspiration rate ; λ, latent heat for vaporization ; Δ, the slope of the saturation water vapor pressure curve at the air temperature ; R_n, net radiation flux ; G, soil heat flux ; γ, the psychrometric constant ; ρ_a, density of the air ; C_p, specific heat of air at constant temperature ; e_a, vapor pressure of the air ; e_a^*, saturated vapor pressure at the temperature of the air ; R_a, aerodynamic-resistance ; R_c, canopy-resistance. There are two unknown parameters, R_a and R_c, which cannot be measured directly and have to be estimated. Some submodels are required for the application of this equation to the forest condition. In this study, we determined the functional relationship of these parameters and the meteorological factors by curve fitting between the calculated rate using the PENMAN-MONTEITH equation and the standard rate by the Water-Budget method previously reported. Procedures for estimating the aerodynamic and canopy-resistances will be discussed consecutively. The available energy (R_n-G) is considered to be equal to the net radiation (R_n) because the soil heat flux (G) is negligible for a soil surface covered with a crown-closed forest.

b. Determining the aerodynamic-resistance parameter

Among the unknown parameters, aerodynamic-resistance (R_a) can be estimated first because another parameter (R_c) is equal to zero during the wet canopy period.

Aerodynamic resistance is related to the vertical wind profile,

$$R_a=\frac{[\ln((z-d)/z_0)]^2}{k^2u(z)} \qquad (2)$$

where z, reference height of the anemometer ; d, zero plane displacement ; z_0, roughness length ; k, von KARMAN's constant ; $u(z)$, mean windspeed at height z.

Usually, parameters z_0 and d are determined by wind profile observation above the canopy. However, because of insufficient information about the wind profile on the watershed, parameters z_0 and d were determined by the following procedures :

1. Estimation A : This is an estimation of the rainfall interception rate using the Interception Model in Fig. 2 with a constant evaporation-intensity of 0.1618 mm during and after rain as e_i and e_j, respectively. This model is quite simple and independent of climatological factors, and it was calibrated in the same watershed by SUZUKI *et al.* (1979 a, b).

2. Estimation B : Using the same model as in Fig. 2 but considering that the evaporation rate depends on the climatological factors, the evaporation rate calculated by the PENMAN-MONTEITH Eq. with $R_c=0$ is used. Parameters z_0 and d are required in this equation and can be developed by trial and error.

3. The accumulated evaporation rate of the intercepted rainfall calculated by Estimation B is compared with the rate calculated by Estimation A. When the rate calculated by estimation B nears the rate of estimation A, the values of z_0 and d used in Estimation B can be regarded as suitable values.

The available windspeed data was measured at 16 m. To find the windspeed at 12 m the following estimation was used :

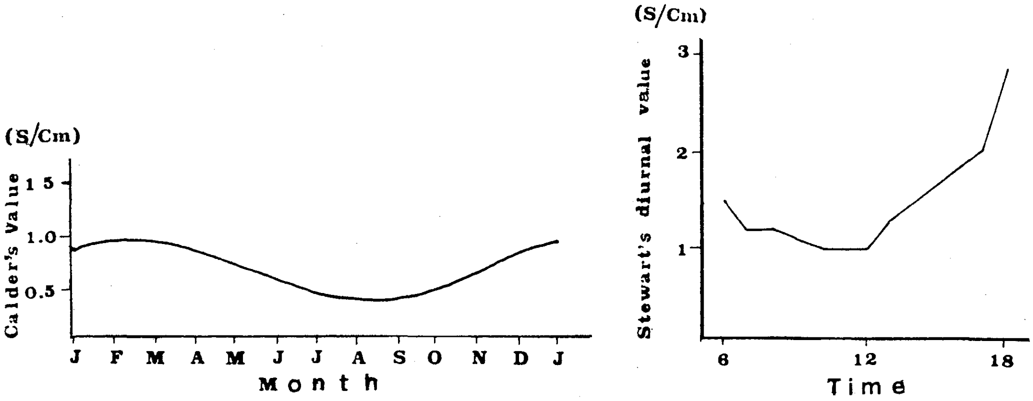

Fig. 3. CALDER's seasonal variations and STEWART's diurnal course of canopy-resistance

$$u(12)=u(16)\frac{(\ln(12-d)-\ln z_0)}{(\ln(16-d)-\ln z_0)} \tag{3}$$

c. Determining the canopy-resistance parameter

When the canopy is in a dry condition, transpiration occurs, and the canopy-resistance parameter value is required for Eq.(1). Is this study, the canopy-resistance parameter was estimated from the following equation:

$$R_c=\frac{S\times a(t)\left[1-A\cos\left(2\pi\frac{D-M}{365}\right)\right]}{1-B(e_a^*-e_a)} \tag{4}$$

where D, the number of days, since the 1st of January; M, the number of the day when R_c is a minimum; A, the annual amplitude of the modulation of canopy-resistance; B, the dependence of canopy-resistance on the vapor pressure deficit; $a(t)$, the diurnal variation factor at time (t) of the day; S, multiplied factor of $a(t)$ to match the total annual rate.

This is a combination model of the diurnal course and the seasonal variation in R_c. The diurnal course reported by STEWART and THOM (1973) and the seasonal variation model reported by CALDER (1977) are shown in Fig. 3. In this equation, there are four unknown parameters: A, S, M, and B. Because the information about the seasonal variation of R_c is limited, the annual amplitude and phase modulation of canopy-resistance indicated as parameters A and M are given the same value as reported by CALDER ($A=0.3$, $M=222$ day). As CALDER's original equation is for calculating the daily mean value of R_c, in Eq. (4) the $S\times a(t)$ is introduced instead of the constant 0.745 in CALDER's. The diurnal course value of R_c at each time of day translated from the figure presented by STEWART and THOM (1973) is given as $a(t)$ in Eq. (4). The daily mean rate of $a(t)$, averaging 6:00 am to 15:00 pm, is 0.75, a value nearly equal to CALDER's constant. Parameter S is introduced for adjusting the daily average rate of R_c to optimize the annual total rate in application of the model. Considering the variation of the dependence of stomatal-resistance on vapor pressure for different species, it is necessary to determine Parameter B particularly. Thus, these two parameters, B and S, are determined as follows:

1. Several parameter sets of B and S are sought out by using the annual total evapotranspiration rate calculated by the Water-Budget method as a standard rate.
2. The most matching parameter set of B and S is selected by checking the amplitudes of the seasonal variations in the evapotranspiration and transpiration rates, with the standard rate determined by the Water-Budget method.

III. Results

1. Meteorological records from September 1986 to August 1987

Monthly values of observed meteorological factors are shown in Fig. 4, and seasonal variation by daily

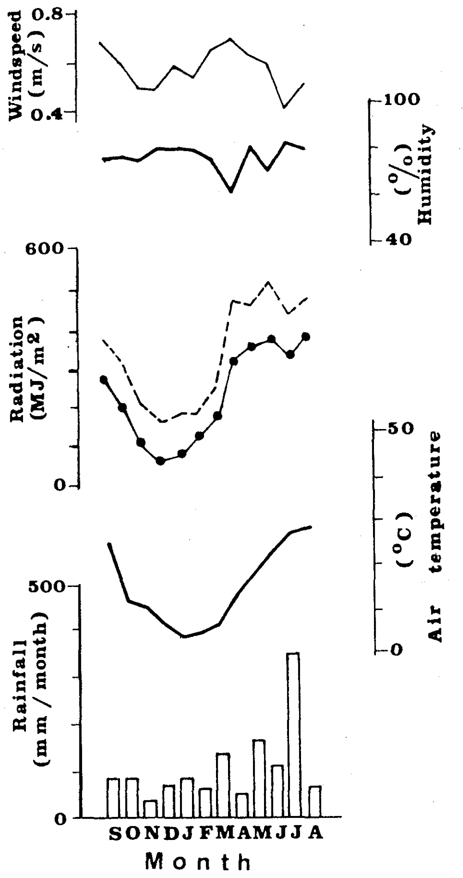

Fig. 4. Monthly rate of the observed meteorological-factors, September 1986~August 1987

----, Short-wave radiation ; ●-●, Net radiation.

rates are seen in Fig. 5.

The highest monthly mean temperature (26.3°C) was in August where as the lowest was in January (3.0°C). The total annual precipitation was about 1,322 mm of which about 50 % fell during the May~July period as the rainfall rate. The monthly mean rate of windspeed was about 0.4~0.8 m/s with the slowest in July and the fastest in April and September. In contrast to windspeed rates, the lowest humidity occurred in April and the greatest in July. Net radiation varied from 53.88 MJ/m²/month during January to 373.2 MJ/m²/month during August. The smallest value of shortwave radiation was recorded in January ; this agrees well with the net radiation, but the largest value was recorded in June, it was about 504.70 MJ/m²/month.

2. *The predicted aerodynamic-resistance parameter*

Utilizing the Interception model shown in Fig. 2, the evaporation rate of intercepted rainfall was calculated with the constant evaporation rate of e_i and e_j=0.1618 mm/h (Estimation A). Parameter z_0 and d were determined by trial and error. When the rate of the calculated evaporation (Estimation B) nears the accumulated evaporation of the intercepted rainfall rate calculated by Estimation A, z_0 and d will have been determined correctly.

The accumulate evaporation of intercepted rainfall calculated by Estimations A and B using these values is presented in Fig. 6. This figure shows that the accumulated rate of constant evaporation agrees well with the accumulated rate of calcu-

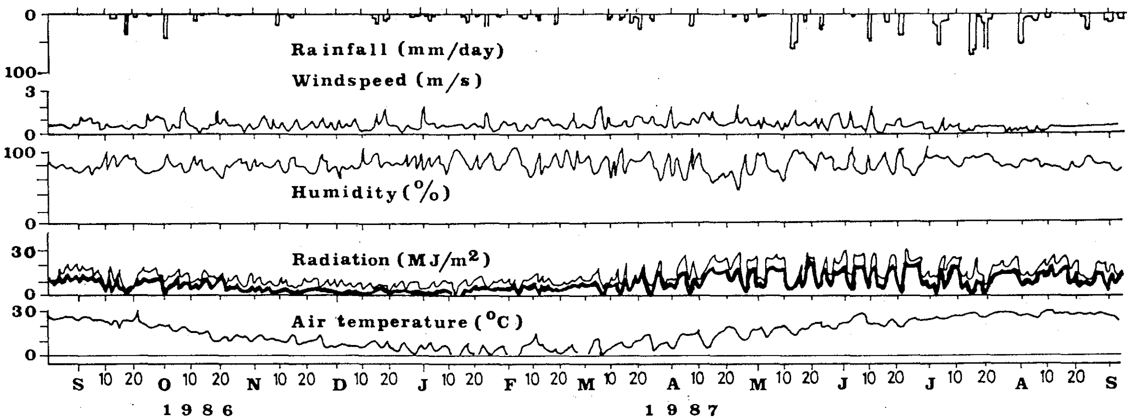

Fig. 5. Seasonal variation in the daily rates of the observed meteorological factors, September 1986~August 1987

——, Short-wave radiation ; ——, Net radiation.

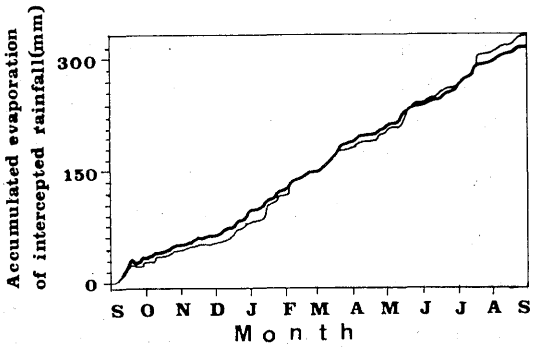

Fig. 6. Comparison of the accumulated-evaporation rates of intercepted rainfall calculated by Estimations A and B
——, Estimation A ; ——, Estimation B.

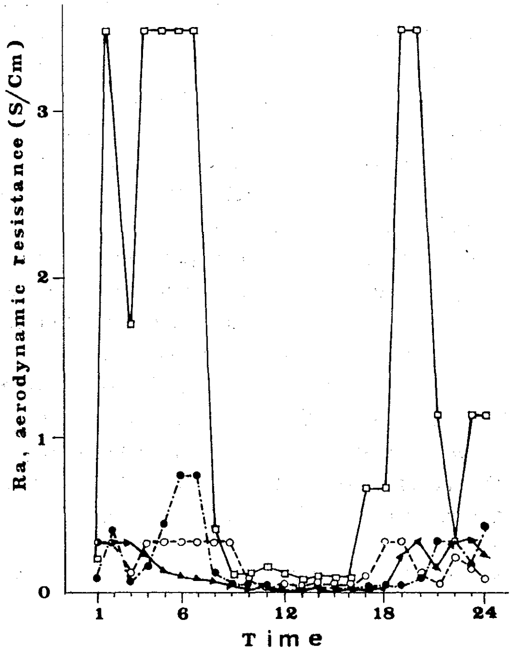

Fig. 7. Diurnal variations of the calculated R_a for one fine day of each season
●—•—●, Apr. 4 ; □——□, Feb. 2 ; ○······○, Jul. 29 ; ▲——▲, Sept., 9.

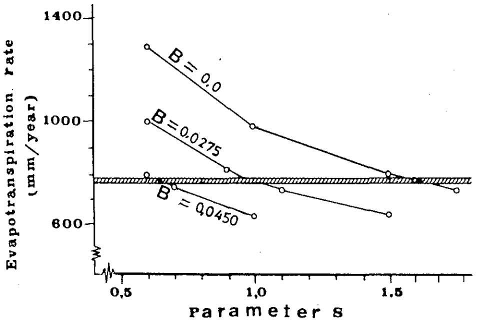

Fig. 8. The combination sets of Parameters B and S for the prediction of the canopy-resistance parameter and the calculated evapotranspiration rates

lated evaporation. This showed that the value of $z_0=2.5$ m and $d=8.0$ m ($z_0/H=0.208$ and $d/H=0.667$) can be utilized in Eq. (2) to predict the aerodynamic-resistance. The diurnal variation of the calculated R_a for one fine day in each season is illustrated in Fig. 7 which shows that there was a relatively greater fluctuation during the night, but during the day the rate was less than 0.3 m.

3. The predicted canopy-resistance parameter

a. On the watershed the standard annual evapotranspiration rate was set at 770 mm as observed by the Water-Budget method.

b. Using the value of Parameter $B=0.045$ as reported by CALDER (1977) and the value of $S=1$ as reported by STEWART and THOM (1973), and by gradually reducing the former to zero, some combination sets of Parameters B and S for Eq. (4) were obtained and three are presented in Fig. 8. These three combination sets of Parameters B and S resulted from the annual evapotranspiration rates being close to the standard annual evapotranspiration rate which resulted from using the Water-Budget method. They are the combination sets of $B=0.045$ and $S=0.65$, $B=0.0275$ and $S=1.0$, and $B=0.0$ and $S=1.62$.

c. The amplitude of seasonal variation was checked by comparing the monthly evapotranspiration and the transpiration rates obtained by the Water-Budget method with the rate calculated by using the three selected combination sets of Parameters B and S. The comparisons illustrated in Fig. 9a and b show that the combination of $B=0.0275$ and $S=1.0$ resulted in the amplitudes closest to the standard rates. Using these parameter values, the canopy-resistance, R_c was predicted by Eq. (4) The predicted diurnal values of R_c as presented in Fig. 10 show relatively small rates in the morning, increasing sharply after midday. The minimum rates appearing from 7 : 00 am to 9 : 00 am on two of four clear days presented in this figure show slight differences compared with STEWART's curve of R_c because of the effect of the vapor pressure deficit in Eq. (4). The predicted R_c values are acceptable for this evapotranspiration estimation.

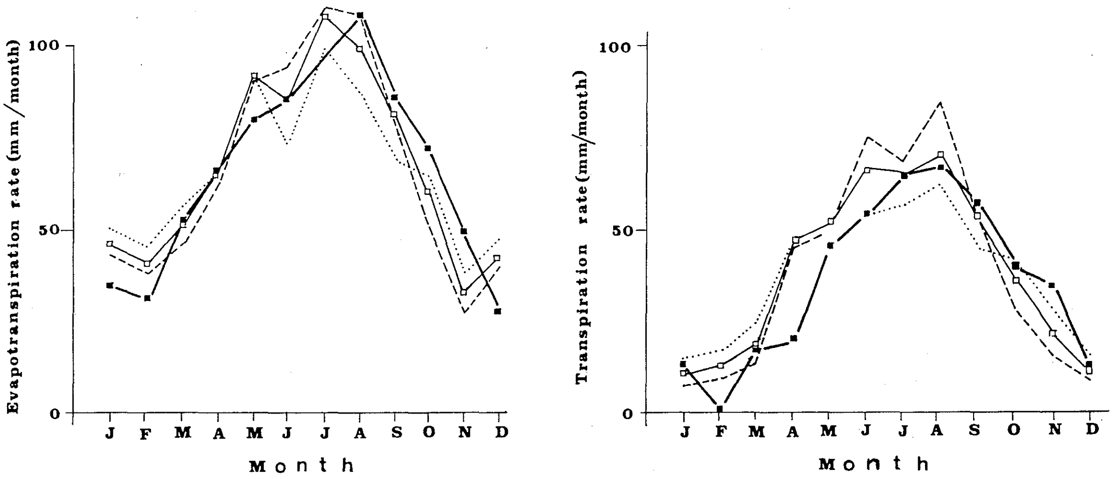

Fig. 9. The seasonal variations of the evapotranspiration rates and the transpiration rates calculated by the three selected combination sets of Parameters B and S and the standard rate by the Water-Budget method

■——■, Water-Budget; □——□, $B=0.0275$ and $S=1.0$; ———, $B=0.00$ and $S=1.62$; ·········, $B=0.0450$ and $S=0.65$.

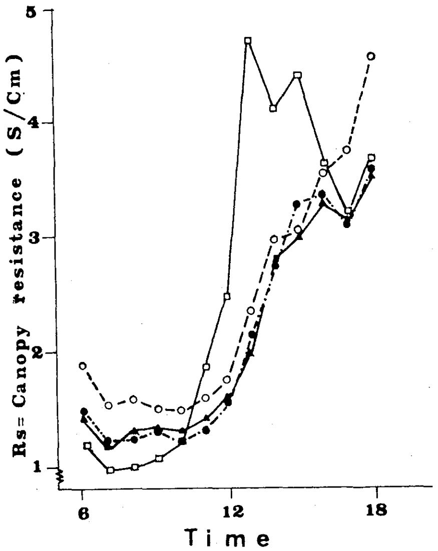

Fig. 10. Diurnal variations of calculated R_c for one fine day of each season

●-·-●, Apr. 4; □——□, Feb. 2; ○——○, Jul. 29; ▲——▲, Sept. 9.

IV. Discussion

1. *Evaluation of the evapotranspiration rate by the PENMAN-MONTEITH model*

The calculated annual evapotranspiration rate using the predicted R_a and R_c is 778.42 mm, an equal rate to the standard rate of 770.90 mm calculated by Water-Budget method. However, the calculated monthly evapotranspiration rates as illustrated in Fig. 11, showed slight differences between the monthly rates. The climate deviation of the 1986～1987 period from the 10-year average of 1972～1981 can be consider as one of the reasons.

2. *Comparisons with other commonly used models*

The commonly used models of THORNTHWAITE, HAMON, and PENMAN also were calculated for the same period. All of these methods are based on the potential evapotranspiration concept.

The THORNTHWAITE method is very simple, using average monthly temperature data and a day-length factor. HAMON's (1961) simple equation is similar to THORNTHWAITE's, but also can be used to estimate the daily evapotranspiration rate. PENMAN (1948) provides a practical method for estimating losses from grass and low crops, given basic meteorological variables. It has proved reliable with a wide range of environmental conditions. The total annual potential evapotranspiration rate calculated by THORNTHWAITE method (764.20 mm) and HAMON method (778.81 mm) were close to the standard rate (770.90 mm). The total annual-potential rate calculated by the PENMAN method is about 140 mm/year greater than the standard rate. RUTTER (1967) reported that PENMAN's equation was not suitable for application to forests mainly because it did not consider the physiological control

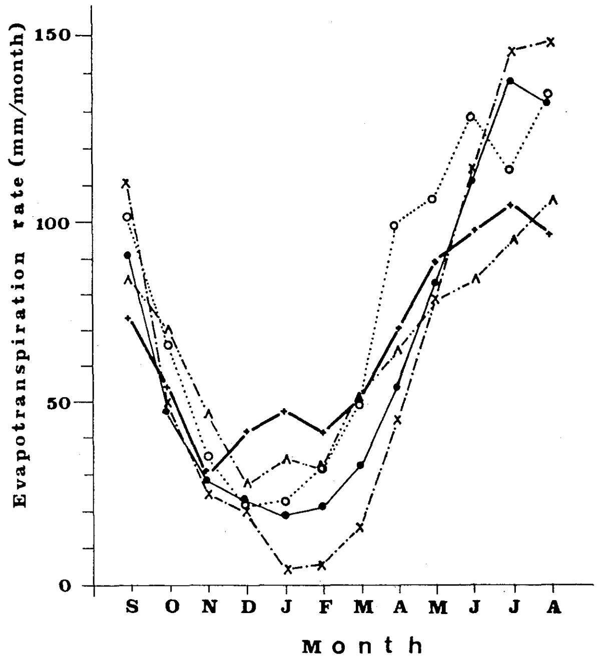

Fig. 11. The seasonal variation of the evapotranspiration calculated by the THORNTHWAITE, HAMON, PENMAN, and PENMAN-MONTEITH methods compared with the standard rate by the Water-Budget method

∧-•••-∧, Water-Budget (annual actual rate=770.90 mm)*; +——+, PENMAN-MONTEITH (annual calculated actual rate=778.42 mm)**; o······o, PENMAN (annual potential rate=912.38 mm)***; ●——●, HAMON (annual potential rate=778.81 mm)***; ×—•—×, THORNTHWAITE (annual potential rate=764.20 mm)***.

* Average evapotranspiration rates (1973~1981) by SUZUKI, and FUKUSHIMA (1985). ** Calculated rate using Parameter $B=0.0275$ and $S=1$ in the canopy-resistance model for Sept. 1986~Aug. 1987. *** Calculated rate for Sept. 1986~Aug. 1987.

of the transpiration processes. GASH and STEWART (1975), and also CALDER (1977), showed that the rate of transpiration can be much less than the potential rate, even if there is a plentiful supply of water, because the biological control imposed by canopy-resistance always has a significant effect. The amplitude of seasonal variations illustrated in Fig. 11 show a tendency to be underestimated during the late autumn to winter period and to be overestimated during the summer. NAKAGAWA (1984) also reported underestimation in the winter and overestimation in the summer when using the THORNTHWAITE method.

As suggested by PENMAN, to find the actual rate, some "evapotranspiration factors" must be introduced into the potential rate. Many experiments about the variation values of evapotranspiration factors have been made and reported, but their behavior is still unclear. The evapotranspiration factors for each model are calculated and presented in Fig. 12a. All of the methods had larger values in the winter and smaller values during the summer for the evapotranspiration factors on the Kiryu Experimental Watershed. ISHII (1988) reported the evapotranspiration factors for the HAMON method calculated for the Higashiyama Watershed located in Central Japan, not far from the Kiryu Watershed. The comparison of the evapotranspiration factors for the HAMON method on both watersheds as illustrated in Fig. 12b, showed that both values agreed well with each other. The evapotranspiration factors of the PENMAN method for pastureland in Japan reported by NAKAGAWA (1984) are compared with the evapotranspiration factors of the same method for the Kiryu Watershed in Fig. 12c. This figure shows a marked difference between the two seasonal trends of evapotranspiration factors. Where as the latter is greater in the winter, the former is smaller.

The seasonal trend of the evapotranspiration factors calculated on the Kiryu Watershed are shown in Fig. 12b can be regarded as the standard course for forested watersheds in Central Japan. Therefore, the difference in the seasonal trend as shown in Fig. 12c has to be explained in terms of the difference in the vegetation on the ground surface.

If the evapotranspiration factors of the PENMAN method, $f=E_a/E_p$ (E_a, actual evapotranspiration rate; E_p, potential evapotranspiration rate), are translated into the PENMAN-MONTEITH concept, the evapotranspiration factors become

$$E_a/E_p=E_t/E_p+E_i/E_p$$

or

$$f=f_t+f_i$$

where E_i, evaporation rate of intercepted rainfall; E_t, transpiration rate; f_i, interception factor; f_t,

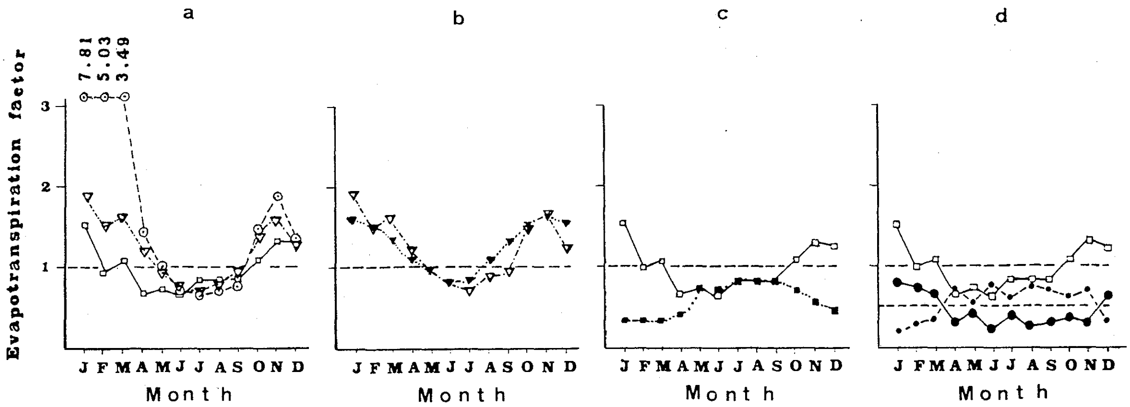

Fig. 12. Comparisons of the evapotranspiration factors in the THORNTHWAITE, HAMON, and PENMAN methods

a. For each method
b. For the HAMON method on the Kiryu and Higashiyama Watersheds
c. For the PENMAN method on Japanese pasture land and on the Kiryu Watershed
d. For the PENMAN method with indicated ratios of the PENMAN-MONEITH method on the Kiryu Watershed

⊙, Evapotranspiration factors of the THORNTHWAITE method for the Kiryu Watershed; ▽, Evapotranspiration the factors of the HAMON method for the Kiryu Watershed; □, Evapotranspiration factors of the PENMAN method for Kiryu Watershed; ▼, Evapotranspiration factors of the HAMON method for the Higashiyama Watershed (ISHII, 1988); ■, Evapotranspiration factors of the PENMAN for pasture in Japan (NAKAGAWA, 1984); ●, Ratio of the intercepted rainfall rate to the total evapotranspiration rate by PENMAN-MONTEITH method for the Kiryu Watershed; •, Ratio of transpiration to the total evapotranspiration rate by the PENMAN-MONTEITH method for the Kiryu Watershed.

transpiration factor.

In Fig. 12d, the PENMAN's evapotranspiration factor, f, is compared with f_i and f_t of the PENMAN-MONTEITH method for the Kiryu Watershed. This figure suggest that the seasonal trend of f_t is not far from PENMAN's f for pastureland and the large values of f in the winter for the forested watershed are caused by the evaporation of intercepted rainfall in the winter (contribution of f_i). This means that PENMAN's method is unapplicable to a forest if the intercepted rainfall rate is not considered. This fact also supported the importance of separating the period of transpiration and evaporation of intercepted rainfall and of the capability of the PENMAN-MONTEITH method in estimating the forest evapotranspiration rate.

V. Concluding Remarks

1. Our optimization procedure can be utilized for the prediction of aerodynamic and canopy resistances. In our study, the model utilized for the prediction of aerodynamic-resistance already was checked by the observed interception rate of evaporation data. It also is important to make a cross check of the model utilized in the prediction of canopy-resistance. This model can be checked, for instance, by the observed transpiration data.

2. A more detailed procedure which also involves optimizing the Parameters A and M in the canopy-resistance model (Eq. 4) is suggested. The application of other canopy-resistance models also is important to make sure that the model used is the best.

3. The seasonal trend of the PENMAN evapotranspiration-factors, the coefficients to fit the potential rate into the actual rate, for pasture is quite different from a forested watershed. This difference is explained in terms of the contribution of the evaporation of intercepted rainfall on the forested watershed.

4. Compared to other models, the PENMAN-MONTEITH model is most applicable for estimating the evapotranspiration rate of a forested watershed. The peculiarity of this model in separating the periods of

transpiration and evaporation of intercepted rainfall in the estimation, is an important procedure. The accuracy of the Interception Model used in our study in determine this period also is a decisive factor.

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