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A SIMPLE METHOD FOR SEPARATELY EVALUATING DAILY EVAPORATION AND TRANSPIRATION IN FORESTED AREA

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SYNOPSIS

A simple method for separately evaluating daily evaporation and transpiration is described in this study. The method consists of two mathematical models: One model is a daily evaporation model for evaluating daily rainfall interception loss in rainfall events applying Geostationary Meteorological Satellite-Infrared (GMS-IR) and daily temperature data; the other one is a daily transpiration model making use of GMS-Visible data, daily temperature, and monthly rainfall data. These models are applied to the data from Shirakawatani Experimental Forested Basin on Shikoku Island, Western Japan. Daily evaporation and transpiration - evaluated by the models - are in good agreement with the obtained data. Hence, the above-mentioned method is employed in practice.

INTRODUCTION

Evapotranspiration is most important for the hydrological circulation in water resources planning and management. The influence of tropical rain forest areas on global-scale hydrological circulation was investigated. Generally, such areas are found in developing countries that are equipped only with poor hydro-meteorological observation networks. The evaluation of evapotranspiration for a large-scale area is essential for the analysis of the water balance. However, it is impossible to obtain any spatially average data at this stage. Therefore, it is necessary to develop a simple method requiring a small number of meteorological data that are easily obtained even in developing countries. Several methods for evaluating evapotranspiration have been suggested using satellite remote sensing data: Tada et al. (11), evaluation of evapotranspiration in a forested basin (NDVI from AVHRR data of NOAA); Inoue et al. (6) took advantage of infrared and reflectance data (LANDSAT MSS data); Sado et al. (9) and Running et al. (8), (LANDSAT TM data). However, evaporation and transpiration are derived from different hydrological processes, and occur in both temporally and spatially different conditions. Therefore, they should be evaluated separately to be more precise. Up-to-date few practical methods for such evaluation have been known.

In this study, daily evaporation and transpiration models are the first step of a methodology for analyzing the water balance for a large-scale area. The authors developed a daily rainfall model for a large-scale area applying the Geostationary Meteorological Satellite – Infrared (GMS-IR) and cloud amount data in order to evaluate the water balance (1). Henceforth, the water balance in a forested basin is analyzed by the following models: A daily rainfall model, a daily evaporation model, and a daily transpiration model. The daily evaporation and transpiration models mentioned above are applied to the data from a forested basin in Japan. Validity of the two models is examined by comparing the correlation between observed and estimated data of daily evaporation and transpiration. Applicability and feasibility of the models are also investigated.

STUDY SITE AND DATA

The study site is Shirakawatani Experimental Forested Basin (33°52'N, 133°40'E) located ~100 km west of Tokushima City on Shikoku Island, Western Japan as shown in Fig. 1. Shirakawatani Basin has an area of 23ha, altitudes ranging from 740m to 1140m, and a mean slope angle of 21.5°. The predominant tree species is Japanese cedar (*Cryptomeria japonica*) covering sixty percent of the area, while the other forty percent are covered by deciduous broad-leaved forest.

Rainfall was measured with a tipping bucket rain gauge at S1 in Fig. 1. Throughfall was recorded with two tipping bucket rain gauges and a throughfall trough, with an area of 7.2m^2, under a 32-year old Japanese cedar at S2. Stemflow was obtained from measured rainwater captured by a vinyl collar that was sealed to the stem of the Japanese cedar by means of a tipping bucket rain gauge at breast height (1.3m).

Common meteorological parameters (air temperature, relative humidity, wind speed, net radiation, and solar radiation) were taken about 2 m above the canopy using instruments mounted on a 22 m observation tower. Duration of sunshine data was supplied by the Ikeda Dam Group Operation Office (Water Resources Development Public Corporation) located 21 km northeast off the basin.

The Japanese Geostationary Meteorological Satellite - 5 (GMS-5) was launched at a point (0°N, 140°E) and ~36,000km away from the earth in 1993. GMS covers the whole hemisphere. Instruments for the observation of VISSR (Visible and Infrared Spin Scan Radiometer), UHF, and S band antennas are located on the top. The VISSR measures visible and infrared radiation in wavelength bands of 0.55 – 0.75μm and 10.5 – 12.5μm respectively. The minimum scale of GMS-IR and GMS-VIS data supplied as WE-FAX (Weather-Facsimile) image data generally are 0.05° x 0.05° (~ 5km x 5km) in size. GMS-IR and GMS-VIS data are obtained as integer values of 16 levels ranging from 0 to 15. GMS-IR data (*IR*) are an index of brightness temperature given as an absolute

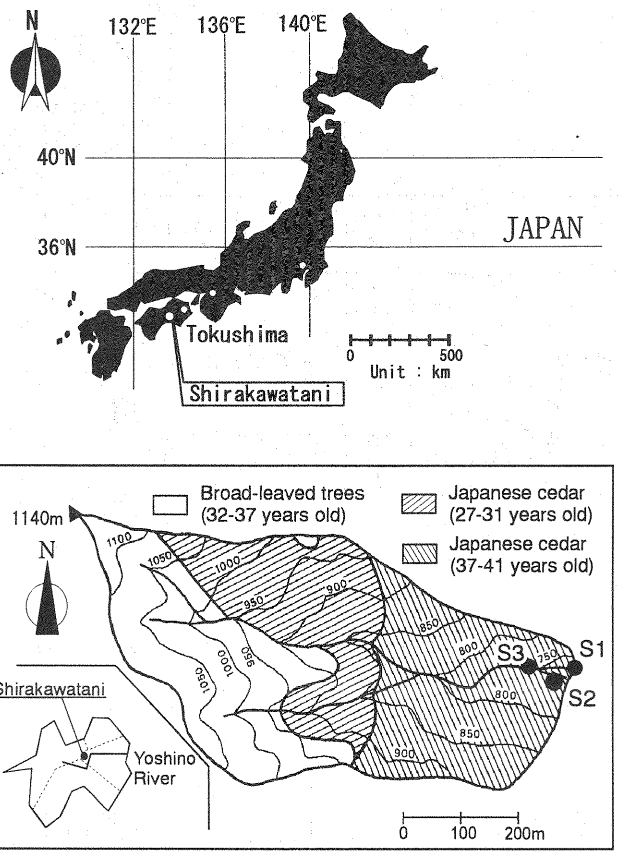

Fig. 1 Shirakawatani Experimental Forested Basin

temperature ranging from 0 K – 402 K on the top of the clouds. GMS-VIS data (*VIS*) are an index of reflectance on the ground surface on clear days and on the top of the clouds on cloudy days respectively. Usually, most data are reported every hour. Shikoku Island is divided into 24 grids the size of which is 0.25° x 0.25° (G1 – G24) as shown in Fig. 2. The Shirakawatani Experimental Forested Basin shown in Fig. 1 belongs to G7. According to the afore-mentioned models, GMS-IR data were provided in each grid by average data from each pixel. It is presumed that level 6 of GMS-IR data (254.41K – 261.41K) defines the occurring rainfall (1). As illustrated in Fig. 3 GMS-VIS data used for evaluating daily duration of sunshine were arranged in nine pixels of WE-FAX image data. They were made up of one pixel including Shirakawatani Basin and the other eight pixels surrounding it.

The minimum scale of cloud amount data are 1° x 1°: ~100km x 100km. The data are arranged as integer values ranging from 0 to 100. Its definition of time amounts to one hour. However, the data are obtained in the shape of magnetic tapes monthly. Due to cloud amount data being a second

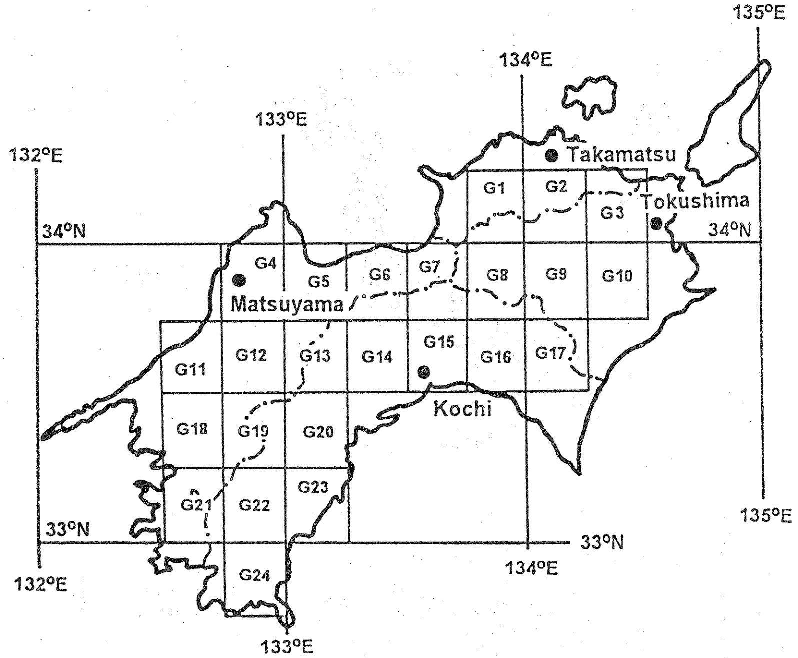

Fig. 2 Grids of WE-FAX image in Shikoku Island

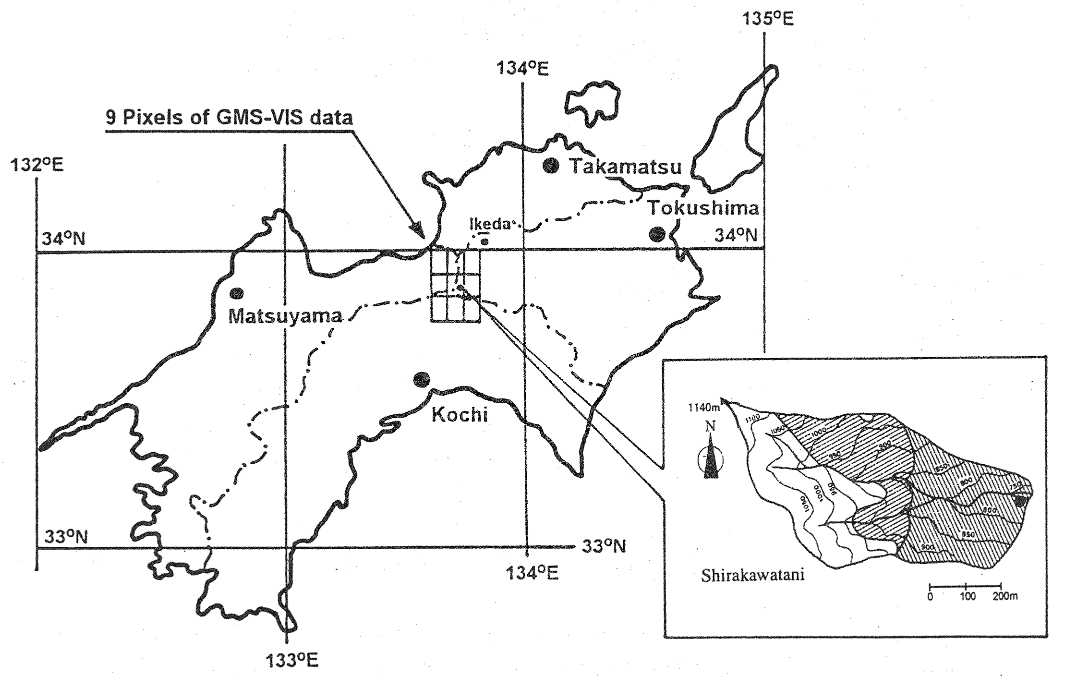

Fig. 3 Shirakawatani Experimental Forested Basin and 9 pixels of GMS-VIS data

product of GMS-IR data, it takes one month to process original unchanged GMS-IR data. They are supplied in three different categories: 1) upper layer *UL* (<400hPa), 2) lower layer *LL* (>400hPa), and 3) whole layer *WL*. As GMS-IR, GMS-VIS and cloud amount data are provided as polar stereo pictures, original coordinates have to be transformed into the correct ones by affine transformation in order to apply the data to maps.

All GMS WE-FAX data were prepared for August, October, and November of 1990 and July, August, and September of 1991.

METHODOLOGY

GMS Daily Rainfall Model

A daily GMS rainfall model using GMS-IR and cloud amount data was developed to provide daily rainfall data for the daily evaporation model. Basic indices for the daily rainfall model are GMS-IR data *IR* and cloud amount data *UL, LL, WL*. In the afore-mentioned model the cool spot rate *Fc* is defined in each grid in Eq. 1:

$$Fc = \frac{Number\ of\ pixels\ where\ IR\ data\ are\ greater\ than\ level\, 6\ in\ a\ grid}{Total\ number\ of\ pixels\ in\ a\ grid} \tag{1}$$

Fc is supposed to be an index implying the degree of concentration of rainfall. GMS-IR data and other derivative indices, such as *Fc*, were used independently in previous models (Arkin et al. (3), Takeuchi et al. (12) etc.). *CL* defined as the difference between *UL* and *LL* is also considered an explanatory variable. A notable feature of this model is the combination of the basic indices that are introduced into the model as explanatory variables. The explanatory variables are IR, Fc, $1/Fc$, $IR \cdot Fc$, IR/Fc and CL. The daily rainfall model represents a multiple regression equation of daily rainfall and explanatory variables. Terms up to the third order are considered for each explanatory variable as follows:

$$R = k_0 + \sum_{j=1}^{3} k_{1j}(IR)^j + \sum_{j=1}^{3} k_{2j}(Fc)^j + \sum_{j=1}^{3} k_{3j}(1/Fc)^j + \sum_{j=1}^{3} k_{4j}(IR \cdot Fc)^j + \sum_{j=1}^{3} k_{5j}(IR/Fc)^j + \sum_{j=1}^{3} k_{6j}(CL)^j \tag{2}$$

where k_{ij} (i = 0, 6, j = 1, 3) = regression coefficients; and R = daily rainfall (mm/day).

Daily rainfall data from Shirakawatani Experimental Forested Basin are given as ground truth data in order to identify parameters. Optimum regression coefficients are determined and significant explanatory variables are selected using a stepwise regression analysis method (4). Detailed features of the model are described in the quoted paper (1).

Daily Evaporation Model

Eq. 3 expresses the daily evaporation model:

$$I = b + aE_H R \tag{3}$$

where I = daily rainfall interception loss (mm/day); E_H = Hamon's potential evapotranspiration (mm/day); R = daily rainfall (mm/day); and a and b = regression coefficients. The original model (2) was developed in order to evaluate rainfall interception loss within rainfall events referring to Horton's model given in Eq. 4:

$$I = V + KeT_R \tag{4}$$

According to Eq. 4 I = rainfall interception loss in rainfall events (mm); e = constant evaporation rate (mm/hr); T_R = rainfall duration (hr); V = rainfall interception loss after rain ceases (mm); and K = coefficient corresponding to leaf areas. Thus, Ke refers to the actual evaporation rate taking leaf areas into account during rain. The first and second terms in Eqs. 3 and 4 indicate evaporation during rain and after rain ceases respectively.

In Horton's model, the evaporation rate during rain is constant. Both rainfall intensity and air temperature are not considered with regard to the evaporation process. Subsequently, the model is apt to underestimate rainfall interception loss during heavy storm events in the summer (2). Daily rainfall R is equal to the product of average rainfall intensity r and rainfall duration T_R. The relation $Ke \approx aE_H r$ is derived from the second terms in Eqs. 3 and 4. Unique features of the model are: 1) Effect of rainfall intensity on evaporation rate during rain is considered in the second term of Eq. 3, and 2) Hamon's potential evapotranspiration varying with air temperature is adopted as a reference evaporation. The coefficients a and b are model parameters. Daily air temperature and daily rainfall are required for parameter identification. Optimum parameters are determined by minimizing the square sum of the estimated error of the daily evaporation. Detailed features of the model are described in the paper (2) listed in the references.

Daily Transpiration Model

The ratio of actual daily transpiration E_{Td} is defined as transpiration factor $\Phi_d = E_{Td} / E_H$ in this model in contrast to Hamon's potential evapotranspiration E_H. The actual daily transpiration that cannot be measured in the forest, is given by a Heat Pulse Transpiration Model (HPTM) (5) developed by the authors. The HPTM was developed in order to evaluate transpiration independent of evaporation using micrometeorological data and heat pulse velocity as an index of sap flow. It has been confirmed that monthly variations of the transpiration factor can be expressed by a regression equation applying the monthly average meteorological parameters: Net radiation, air temperature, vapour pressure deficit and wind speed from a practical point of view (7). In the daily transpiration model, there are the following explanatory variables: Daily solar radiation on the ground surface Qg, daily air temperature T, and monthly rainfall R_m. The model expresses a multiple regression equation of transpiration factor and considers each variable up to the third order. The stepwise regression method determines optimum regression coefficients and selects significant explanatory variables. In developing countries, meteorological data such as solar radiation and duration of sunshine are not easily found, but air temperature and rainfall are obtained.

Daily solar radiation on the ground surface Qg is easily obtained from the top of atmosphere Qa, daily duration of sunshine n, and possible daily duration of sunshine N using a linear regression equation (10) in the following manner: Eq. 5 is obtained for one year, because it is known that seasonal change of the coefficients in Eq. 5 is negligible:

$$Qg = Qa\left(0.18 + 0.55\frac{n}{N}\right) \quad (5)$$

In this model, daily duration of sunshine n is estimated using GMS-VIS data VIS (13) as shown in Eq. 6:

$$n = \beta + \alpha\, VIS \quad (6)$$

where α and β = regression coefficients.

The transpiration factor for the daily transpiration model Φ_d is given in Eq. 7:

$$\Phi_d = l_0 + \sum_{j=1}^{3} l_{1j}(R_m)^j + \sum_{j=1}^{3} l_{2j}(T)^j + \sum_{j=1}^{3} l_{3j}(Qg)^j \quad (7)$$

where R_m = monthly rainfall; T = daily air temperature; Qg = daily solar radiation; and l_{ij} (i = 1, 3) = regression coefficients.

Daily transpiration E_{Td} is given in Eq. 8:

$$E_{Td} = \Phi_d \cdot E_H \quad (8)$$

RESULTS

Estimation of Daily Rainfall

The GMS daily rainfall model was applied to the data >5 mm/day. They were obtained in the grid G7 according to Fig. 2. The selected explanatory variables were Fc^3, Fc^2, $1/Fc$, IR/Fc, $(IR/Fc)^3$, CL and CL^3. The most significant variables were Fc^3, Fc^2, $1/Fc$ as reported by Alfiansyah et al.(1). It is noteworthy that, Fc corresponding to the degree of concentration of rainfall, is included in the above significant explanatory variables. Determination coefficient (r^2), standard deviation (SD), and estimation error rate (ER) are quoted in Table 1. The estimation error rate is defined by normalizing standard deviation using mean value. The determination coefficient and standard deviation were 0.918 and 14.8mm respectively, when the model was applied to data from 1990 and 1991. As the mean value of daily rainfall was about 65mm/day, an estimation error rate of 22.9 percent occurred.

Table 1 Determination coefficient (r^2), standard deviation (SD), and estimation error rate (ER) of daily rainfall

Year	r^2	SD (mm)	ER (%)
1990 & 1991	0.9175	14.8	22.9
1990	0.9595	14.2	15.0
1991	0.6633	15.1	33.6

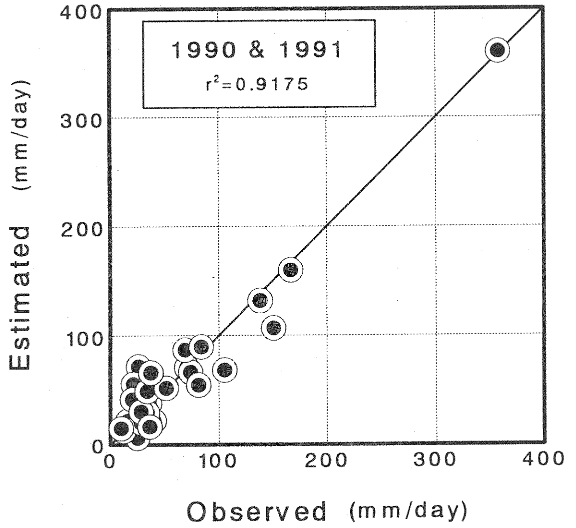

Fig. 4 Comparison between estimated and observed daily rainfall

If the model was applied to data prepared in 1990, a large determination coefficient and a small estimation error rate resulted. The results from 1991 were not very precise, because there were few heavy storms, and the data ranged from 0mm to 100mm.

Fig. 4 shows a comparison and significant agreement between estimated and observed daily rainfall. It was found that 1) daily rainfall was apt to be underestimated in events of daily rainfall >50 mm and 2) it tended to be overestimated in events of daily rainfall <50mm.

Estimation of Daily Evaporation

Daily evaporation was evaluated by the model in 1990 and 1991 using daily rainfall given in the GMS daily rainfall model. The model was applied to daily rainfall >1.5mm. Identified values of a and b are 1.86 and 3.0 respectively. The determination coefficient (r^2), standard deviation of

Table 2 Determination coefficient (r^2), standard deviation (SD), and estimation error rate (ER) of daily evaporation

Year	r^2	SD (mm)	ER (%)
1990 & 1991	0.9111	3.72	25.6
1990	0.9704	2.85	14.5
1991	0.6724	3.73	33.4

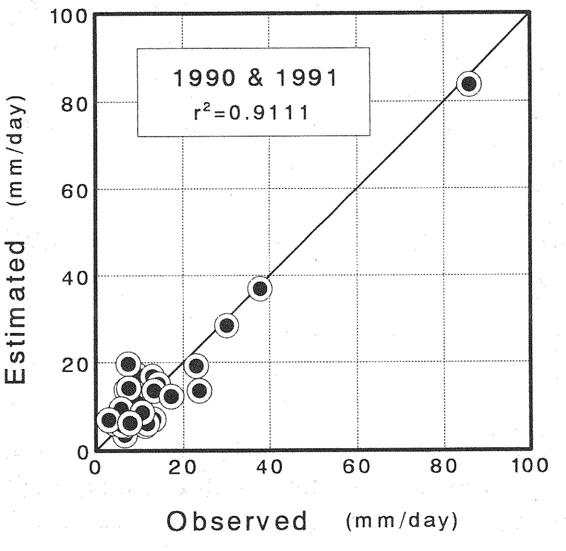

Fig. 5 Comparison between estimated and observed daily evaporation

estimated error (SD), and estimation error rate (ER) are quoted in Table 2; r^2 and SD obtained in 1990 and 1991 were 0.911 and 3.72mm respectively. As a mean value of daily evaporation was 14.5mm, an estimation error rate of 25.6 percent was the result. The statistics are almost the same as those for daily rainfall.

Daily evaporation in the Shirakawatani Basin resulted in rainwater balance; daily rainfall - daily throughfall - daily stemflow. A further comparison and good correlation are shown in Fig. 5.

Estimation of Daily Transpiration

Table 3 shows the identified regression coefficients α and β in Eq. 5, determination coefficient (r^2), standard deviation (SD), and estimation error rate (ER) if Eq. 5 is applied to the data from 1991 to 1994. With the exception of December, the determination coefficients ≥ 0.70.

Table 3 Regression coefficients, determination coefficients (r^2), standard deviation (SD), and estimation error rate (ER) of daily duration of sunshine

Month	α	β	r^2	SD (mm)	ER (%)
January	14.03	-2.16	0.70	1.27	30.0
February	15.55	-2.08	0.70	1.40	25.6
March	15.67	-1.88	0.75	1.26	20.3
April	17.48	-1.96	0.86	1.01	13.5
May	16.80	-1.67	0.84	1.15	15.9
June	14.86	-1.77	0.72	1.53	27.4
July	14.62	-1.63	0.87	0.94	13.4
August	14.51	-1.67	0.79	1.16	17.4
September	16.06	-2.00	0.84	1.04	15.6
October	16.94	-2.47	0.76	1.18	18.0
November	15.98	-2.36	0.74	1.20	21.8
December	12.68	-2.01	0.59	1.45	38.9

Table 4 Determination coefficients (r^2), standard deviation (SD), and estimation error rate (ER) of daily duration of sunshine

Month	Jan.	Feb.	Mar.	Apr.	May	Jun.
r^2	0.60	0.80	0.93	0.88	0.72	0.75
SD (mm)	0.15	0.10	0.15	0.16	0.17	0.13
ER (%)	10.4	11.2	10.2	11.0	16.8	13.7

Month	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
r^2	0.79	0.73	0.66	0.86	0.81	0.49
SD (mm)	0.06	0.05	0.08	0.05	0.12	0.29
ER (%)	11.2	8.80	12.3	10.1	15.1	29.8

Table 5 Identified parameters and selected explanatory variables for daily transpiration model

Month	Jan.	Feb.	Mar.	Apr.	May	Jun.
Sample size of data	16	41	39	77	70	59
Constant	-0.020	1.280	1.290	6.510	-3.840	-0.060
R_m			-2×10^{-4}	**-0.043**	0.032	0.005
R_m^2		**-6×10^{-5}**		**8×10^{-5}**		
R_m^3			**-2×10^{-8}**		-3×10^{-7}	**-1×10^{-8}**
T	0.550	**-0.077**	**-0.043**	**0.041**	**0.032**	**-0.064**
T^2	**-0.023**	0.057		-0.012	-0.003	
T^3	0.023	-0.008	9×10^{-5}	3×10^{-4}		1×10^{-5}
Qg	**0.029**	**0.040**	-0.229	-0.023	**0.088**	**0.055**
Qg^2			**0.018**	0.002		
Qg^3	**-0.002**	-7×10^{-6}	-4×10^{-4}		**-4×10^{-5}**	-3×10^{-5}

Month	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Sample size of data	59	57	66	72	42	24
Constant	-1.680	1.530	4.740	1.260	-2.650	-0.170
R_m	**3×10^{-4}**	4×10^{-4}	-0.010			
R_m^2				**-3×10^{-5}**	**4×10^{-4}**	
R_m^3		**-3×10^{-10}**	3×10^{-8}			
T	**0.169**	**-0.051**	**-0.168**	**-0.058**	-0.102	**-0.052**
T^2			**0.003**	0.001	0.014	**0.035**
T^3	**-1×10^{-4}**	9×10^{-6}			**-6×10^{-4}**	**-0.006**
Qg	-0.017	**0.007**	**0.030**	**0.076**	-0.271	0.301
Qg^2		-8×10^{-5}		-0.004	**0.033**	
Qg^3	2×10^{-5}		-1×10^{-5}	8×10^{-5}	-0.001	-0.002

Note: Bold figures indicate the three most significant explanatory variables selected by stepwise regression method

In Figs. 6(a) and 6(b) there is significant correlation between GMS-VIS data and daily duration of sunshine except for December.

Daily duration of sunshine from 1991 to 1994 as stated in Eq. 5 was used for determining solar radiation on the ground *Qg* as given in Eq. 6. *Qg* was used as an explanatory variable of Eq. 7 for evaluating transpiration factor Φ_d. Finally, daily transpiration from 1991 to 1994 was evaluated according to Eq. 8. Regression coefficients of the daily transpiration model are quoted in Table 4. Table 5 shows results of the model of monthly data. With the exception of December, most of the determination coefficients >0.70 and standard deviation <0.15mm. Figs. 7(a) and 7(b) show a comparison and good correlation between evaluated and observed transpiration factors except for December.

DISCUSSION

Most of the daily rainfall data values were <100mm. There was only one data value >100mm in 1991, while the maximum daily rainfall of ~360mm was recorded in 1990. The difference of determination coefficients and standard deviations between 1990 and 1991 may be due to different characteristics of data. The scattering range of data from 1990 is wider than 1991, and the numbers of data are more than in 1991. A storm event in 1990 might have had great influence on the selection of explanatory variables and tuning of regression coefficients. In this study, average GMS data are found in an area of $0.25^{\circ} \times 0.25^{\circ}$, and compared with rainfall data from an observatory. Subsequently, a precise evaluation of daily rainfall cannot be expected. Daily rainfall was evaluated up to a certain extent as the standard error rate was about 20 percent.

The daily evaporation model was originally developed to evaluate rainfall interception loss during a rainfall event. In this study, it was found that the model could be applied to daily evaporation due to rainfall interception on the canopy. The model requires daily air temperature close to the ground for evaluating Hamon's potential evapotranspiration. Air temperature is one of the most fundamental meteorological parameters and is easily obtained even in developing countries. It is necessary to estimate air temperature with satellite remote sensing data such as GMS. In the future, efforts should be made to develop a method evaluating average air temperature in a large area with satellite remote sensing data. At present, daily evaporation is obtained by rainwater balance based on rainfall, throughfall, and stemflow. A mean value of daily evaporation was 14.5mm in this study. The latter is an overestimated mean value for one year. It should be noticed, however, that the mean value is estimated only on the canopy basis. It was not evaluated for a whole day in the course of one year, but only for days with daily rainfall of >1.5mm.

Daily duration of sunshine is evaluated monthly using GMS-VIS data with great accuracy. Precision is required especially between March and October when transpiration is active in order to evaluate solar radiation during the course of one year.

The daily transpiration factor is also evaluated monthly applying daily solar radiation derived from daily duration of sunshine, daily temperature, and monthly rainfall. For this reason, the results are quite sufficient for practical application. Daily temperature and daily solar radiation were major model parameters throughout the years. However, monthly rainfall was also required in order to

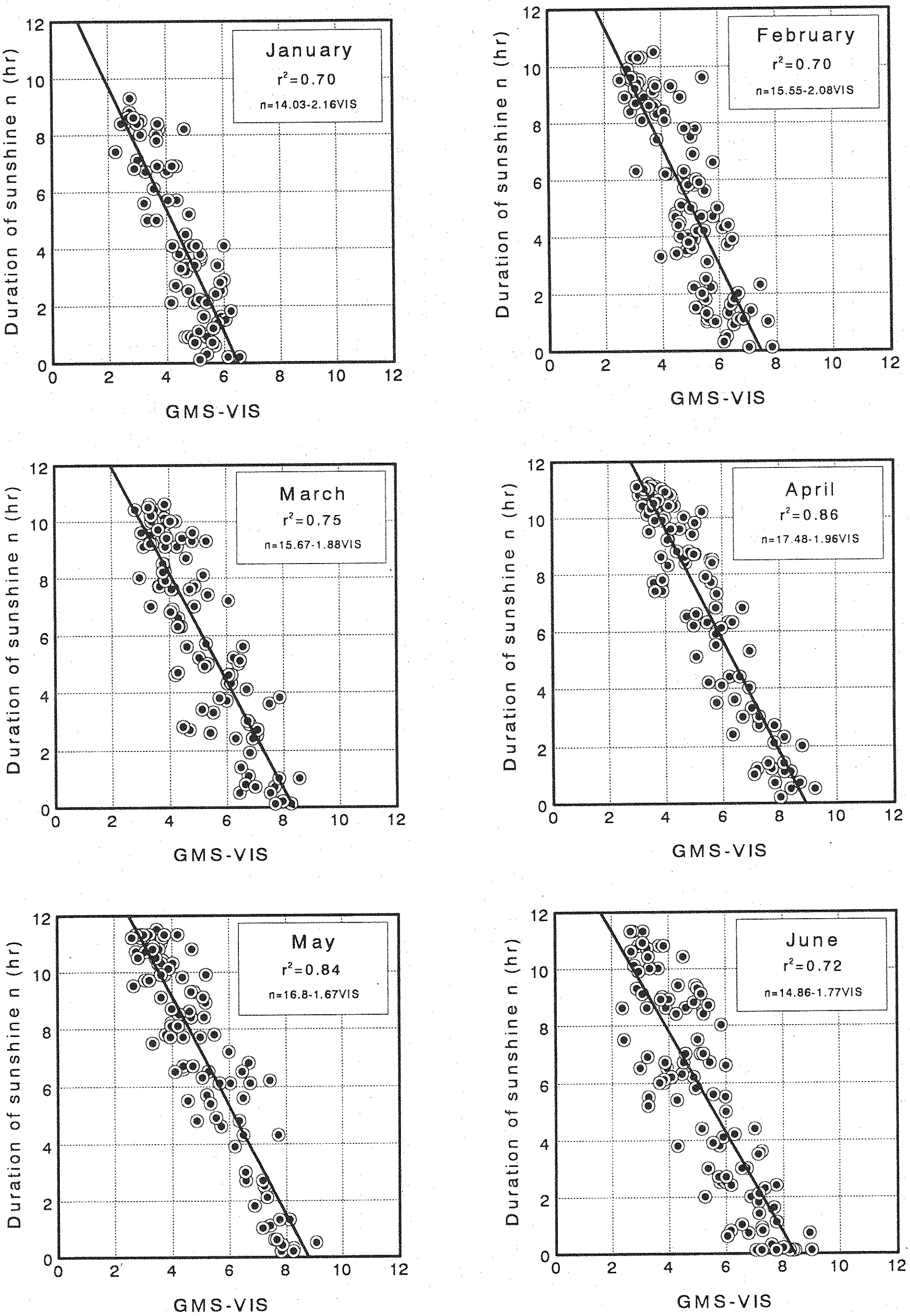

Fig. 6(a) Comparison between GMS-VIS data and daily duration of sunshine from January to June

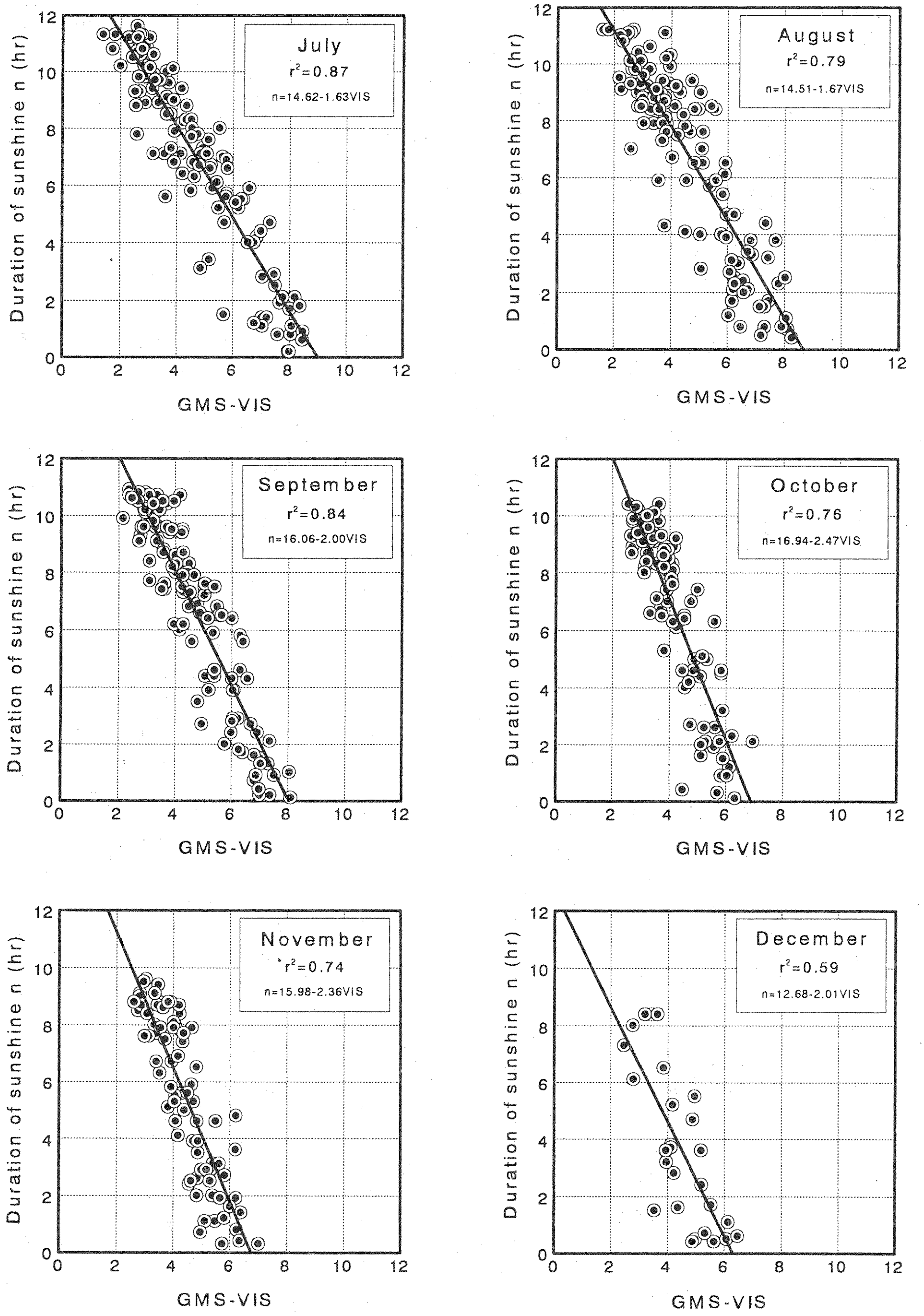

Fig. 6(b) Comparison between GMS-VIS data and daily duration of sunshine from July to December

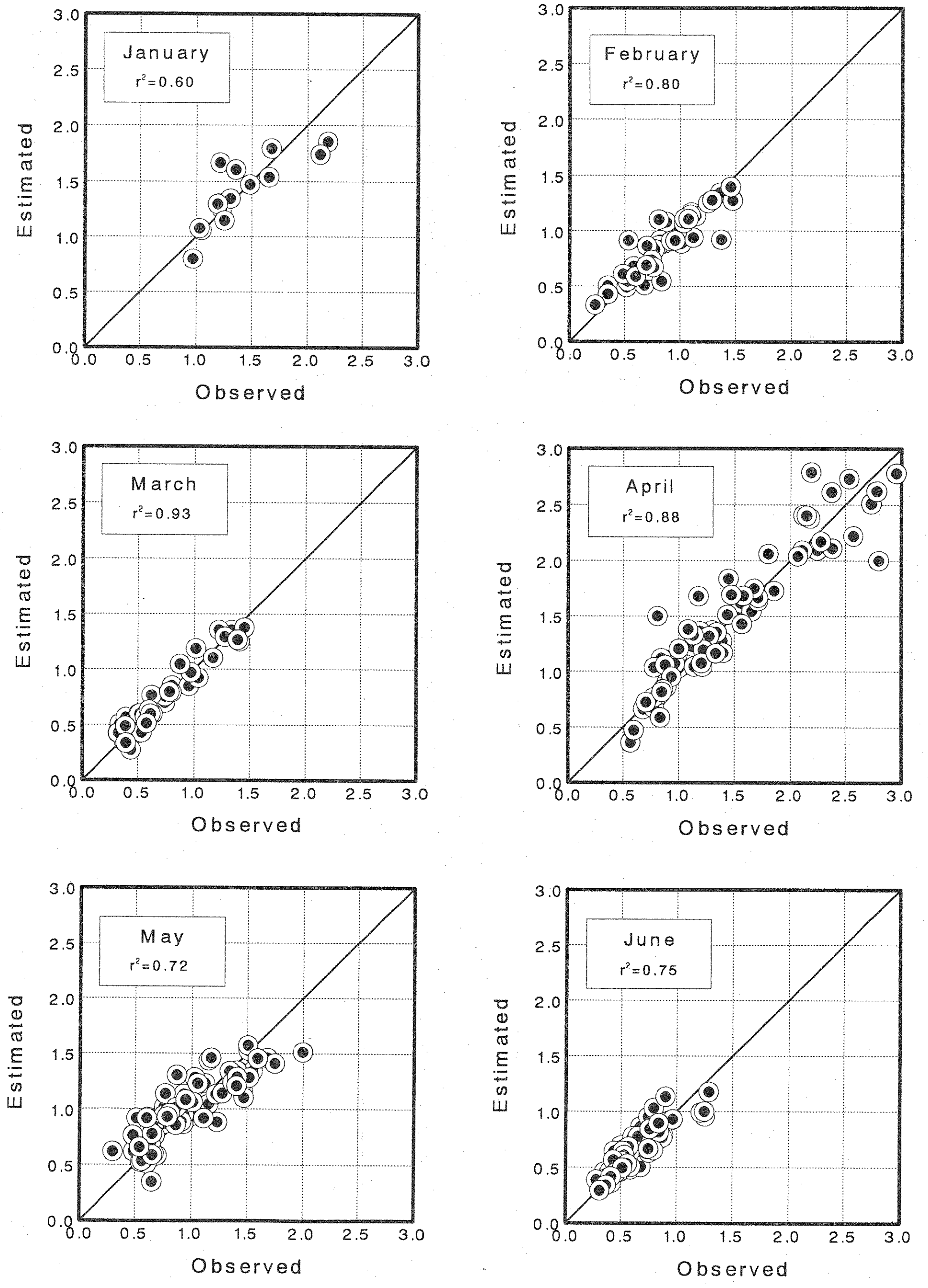

Fig. 7(a) Comparison between estimated and observed transpiration factor from January to June

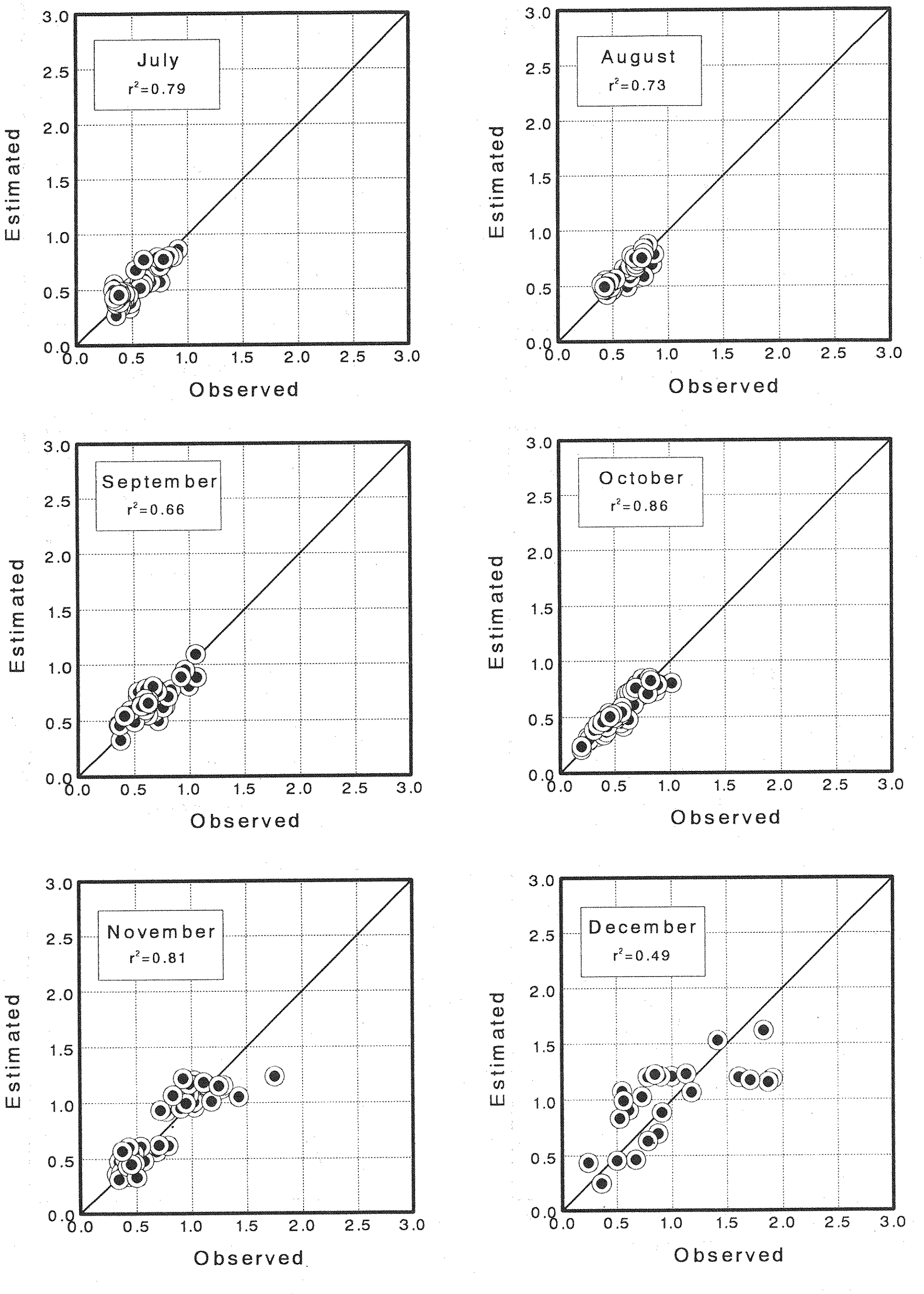

Fig. 7(b) Comparison between estimated and observed transpiration factor from July to December represent the daily transpiration factor. Subsequently, cloudy conditions are not described by solar radiation and, as a result, monthly rainfall is an index of the cloudy atmosphere.

CONCLUSION

In this study, mathematical models, in particular for developing countries, enable us to separately evaluate daily evaporation and transpiration with precision for cases in which hydro-meteorological data are difficult to obtain. A daily evaporation model was developed combining the daily GMS rainfall and the linear regression rainfall interception models. Daily duration of sunshine providing daily solar radiation was evaluated with the application of the GMS-VIS image data. A daily transpiration model was developed using the transpiration factor provided by the HPTM. The afore-mentioned models were applied to data from Shirakawatani Experimental Forested Basin. The validity of the models was verified. On the presumption that GMS WE-FAX data and daily air temperature are obtained, separately evaluating daily evaporation and transpiration will be the result. If daily air temperature is evaluated without measuring instruments on the ground, it may lead to a method for separately evaluating daily evaporation and transpiration without routine data from meteorological observatories. However, field measures of rainfall interception loss and transpiration ground truth data are required for tuning model parameters. The quantitative validity of the models should be verified by the water balance method in the basin.

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APPENDIX – NOTATION

The following symbols are used in this study :

a,b	= regression coefficients for daily evaporation model (Eq. 3);
CL	= difference between upper and lower cloud amount data;
e	= evaporation rate in Eq. 4;
E_H	= Hamon's potential evapotranspiration;
E_{Td}	= daily transpiration;
Fc	= cool spot rate;
I	= rainfall interception loss;
IR	= GMS WE-FAX infrared image data
k_{ij}	= regression coefficients for GMS daily rainfall model (Eq. 2);
K	= coefficient corresponding to leaf area in Eq. 4;
l_{ij}	= regression coefficients for daily transpiration model;
LL	= cloud amount data in lower layer;
n	= daily duration of sunshine;
N	= potential daily duration of sunshine;
Qa	= daily solar radiation on the top of atmosphere;
Qg	= daily solar radiation on the ground surface;

r	= rainfall intensity;
R	= daily rainfall;
R_m	= monthly rainfall;
r^2	= determination coefficient;
T	= daily air temperature;
T_R	= rainfall duration;
UL	= cloud amount data in upper layer;
V	= rainfall interception loss after rain ceases in Eq. 4;
VIS	= GMS WE-FAX visible image data;
WL	= cloud amount data in whole layer;
α, β	= regression coefficients for the model evaluating daily duration of sunshine; and
Φ_d	= daily transpiration factor.

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