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Estimation of Evapotranspiration in Itoshima Area Japan by the FAO56-PM Method

by

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Abstract

This paper represents an application of Penman-Monteith equation standardized by the Food and Agriculture Organization (FAO56-PM) simultaneously with crop coefficient approach (single crop coefficient) for the estimation values of reference evapotranspiration (ET_o) and crop evapotranspiration under standard conditions (ET_c) from forest and rice field. Seven year daily meteorological data (Jan 1996 – Dec 2002) were used in Itoshima peninsula, western region of Fukuoka City, Japan. The reference crop that used for calculating ET_o was considered as a hypothetical crop with an assumed height of 0.12 m having a surface resistance of 70 s m^{-1} and an albedo of 0.23. The standard conditions refer to crops grown in large fields under excellent agronomic and soil water conditions. The aim is to introduce an effective water resources management for Itoshima area regarding that it will have a future change in land use due to the construction of the new campus (Ito campus) of Kyushu University.

Keywords: Crop coefficient, Crop evapotranspiration, Food and Agriculture Organization, Reference evapotranspiration, Water budget estimation

1. Introduction

The combination of two separate processes whereby water is lost on the one hand from the soil surface by evaporation and on the other hand from the crop by transpiration is referred to as evapotranspiration (*ET*). The evapotranspiration rate from a reference surface, is called the reference evapotranspiration and is denoted as ET_o. The crop evapotranspiration under standard conditions, denoted as ET_c, is the evapotranspiration from disease-free, well-fertilized crops, grown in large fields, under optimum soil water conditions, and achieving full production under the given climatic conditions [1)].

Estimation of evapotranspiration is one of the major hydrological components and it is very important for determining crop water use, scheduling irrigation at a regional level, besides water

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budget is becoming indispensable for the calculation of a reliable recharge and evapotranspiration rate for the groundwater flow analysis. Therefore, reliable and consistent estimate of evapotranspiration is of great importance for the efficient management of water resources. Evapotranspiration (*ET*) plays an important role in the hydrology of a catchment, together with other processes such as precipitation, runoff and infiltration.

Although numerous empirical and semi-empirical equations have been developed to assess *ET*, the FAO56-PM method is recommended and is now widely used as the standard method for the computation of reference evapotranspiration (ET_o) from meteorological data. In the FAO56-PM method, ET_c is estimated by multiplying ET_o by a crop coefficient factor (K_c). Although the FAO56-PM method suggests K_c for specific crops and locations, locally determined K_c values are necessary to estimate actual evapotranspiration more accurately [1), 2)].

Regional Water resources management in Itoshima Peninsula area, the western region of Fukuoka City, Japan, where a new campus (Ito campus) of the Kyushu University is under construction requires the appropriate method for estimating *ET*. The construction of the new Kyushu University campus may cause the reduction in the groundwater flow toward the residential area unless proper countermeasures are considered. Besides, the urbanization in the surrounding area may also induce the potential effect on the local hydrologic cycle in the future. Thus, the water budget analysis is indispensable for the surface runoff and groundwater flow analyses. In this regard the reliable and consistent estimates of evapotranspiration have to be investigated in order to understand the characteristics of the water movement in the new campus as well as the surrounding area [2), 3)].

This paper demonstrates how the reference evapotranspiration (ET_o) is determined from meteorological data in the study area. The estimation of ET_o with daily time step for seven years from 1996 until 2002 was obtained by means of FAO56-PM. This paper also presents the calculation procedures and the result of crop evapotranspiration under standard conditions (ET_c) from forest and rice fields by means of the K_c - ET_o approach.

2. Materials and Methods

2.1 Study area and climatic characteristics

The area which has been selected for this study as shown in **Fig. 1** is Itoshima peninsula area including the new campus (Ito campus) of Kyushu University, located in western region of Fukuoka City, northern part of Kyushu Island, Japan. The total area of Itoshima peninsula is about 112 km^2. The climate in the area is characterized as having high humidity, and heavy precipitation. The average annual precipitation during 7 years (1996-2002) is 1646 mm $year^{-1}$ and more than 50% of which occurs in June to August. Air temperature ranges from 19.2°C – 31.1°C in summer and 1.7°C – 15.4°C in winter months. Daily mean temperature in summer is 23.3°C and 9.6°C in winter. On the other hand, daily mean minimum and maximum relative humidity are 35% and 95% with annual average of 67% respectively. The daily average of wind speed is 2.1 m s^{-1}. The elevation of the ground surface ranges from 0.2 m at the lowest point to about 400 m. The lowland area is used for agriculture such as greenhouse farming and paddy fields [2)].

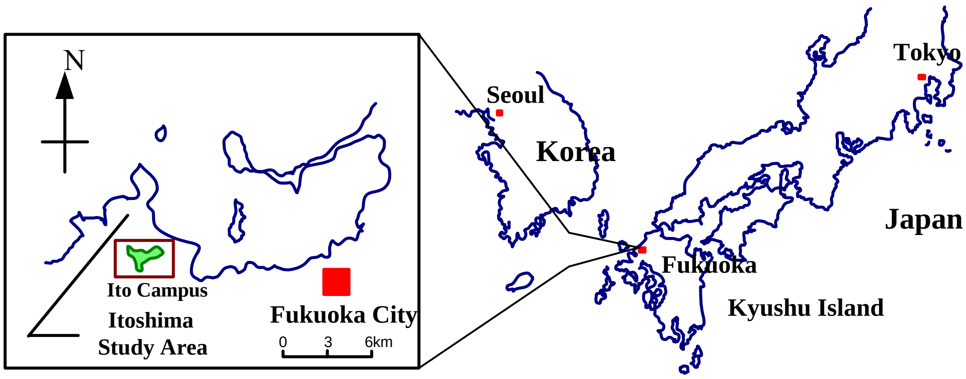


Fig. 1 Study area (Itoshima peninsula).

2.2 Methods

Evapotranspiration is not easy to measure. Specific devices and accurate measurements of various physical parameters or the soil water balance in lysimeters are required to determine *ET*. The methods are often expensive, demanding in terms of accuracy of measurement and can only be fully exploited by well-trained research personnel. Owing to the difficulty of obtaining accurate field measurements, *ET* is commonly computed from weather data. A large number of empirical or semi-empirical equations have been developed for assessing *ET* from meteorological data [1).

The FAO56-PM model is a reliable, physically based method, and it is now recommended as the standard method for the definition and computation of reference evapotranspiration (ET_o).

The ET_c from crop surfaces under standard conditions is determined by single crop coefficients (K_c) that relate ET_c to ET_o. The FAO56-PM method is recommended as the sole method for determining *ET* [1), 4)].

In the present study the FAO56-PM method was applied to compute the daily ET_o values from daily meteorological data and then to estimate the ET_c values for forest and rice fields from their crop coefficients.

2.2.1 FAO56-PM equation

The FAO56-PM equation to predict ET_o for 24-hour calculation time steps has the form:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \dfrac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{1}$$

where ET_o is reference evapotranspiration [mm day^{-1}], R_n is net radiation at the crop surface [MJ m^{-2} day^{-1}], G is soil heat flux density [MJ m^{-2} day^{-1}], T is mean daily air temperature at 2 m height [°C], u_2 is wind speed at 2 m height [m s^{-1}], e_s is saturation vapor pressure [kPa], e_a is actual vapor pressure [kPa], e_s-e_a is saturation vapor pressure deficit [kPa], Δ is slope vapor pressure curve [kPa °C^{-1}], and γ is psychrometric constant [kPa °C^{-1}]. In application having 24-hour calculation time steps, G is presumed to be 0 and e_s is computed as

$$e_s = \frac{e^0(T_{\max}) + e^0(T_{\min})}{2} \tag{2}$$

where $e^0(\ )$ is the saturation vapor and $T_{\max}$ and $T_{\min}$ are the daily maximum and minimum air temperature. The FAO56-PM equation predicts the evapotranspiration from a hypothetical grass reference surface that is 0.12 m in height having a surface resistance of 70 s m^{-1} and albedo of 0.23. The equation provides a standard to which evapotranspiration in different periods of the year or in other regions can be computed and to which the evapotranspiration from other crops can be related. Standardized equations for computing all parameters in **Eq. (1)** are given in Allen et al. 1998 [5].

2.2.2 Crop coefficient approach

In the crop coefficient approach the crop evapotranspiration under standard conditions (ET_c) is calculated by multiplying the reference evapotranspiration (ET_o) by a crop coefficient (K_c):

$$ET_c = K_c \times ET_o \tag{3}$$

where ET_c is crop evapotranspiration under standard condition, K_c is crop coefficient, ET_o is reference evapotranspiration.

The ET_o is calculated using the FAO56-PM equation. The crop coefficient (K_c) is basically the ratio of the ET_c to the ET_o, and it represents an integration of the effects of four primary characteristics that distinguish the crop from reference grass. These characteristics are:
Crop height, Albedo (reflectance) of the crop-soil surface, Canopy resistance, Evaporation from soil, especially exposed soil.

3. Results and Discussion

3.1 Reference evepotranspiration (ET_o) [mm day^{-1}]

3.1.1 Input meteorological data

Calculation of ET_o with the Penman-Monteith equation on 24-hour time scales will generally provide accurate results as mentioned in the previous section.

The meteorological data of 7 years at the Maebaru AMeDAS station covering the period of January 1996 - December 2002 were analyzed for calculating ET_o.

The daily maximum (T_{max}) and minimum (T_{min}) temperature, wind speed (u_2), relative humidity (RH), sunshine hour (n) , and vapor pressure used for ET_o estimations are shown in **Fig. 2**.

The statistics of the daily climatic data are listed in **Table 1**.

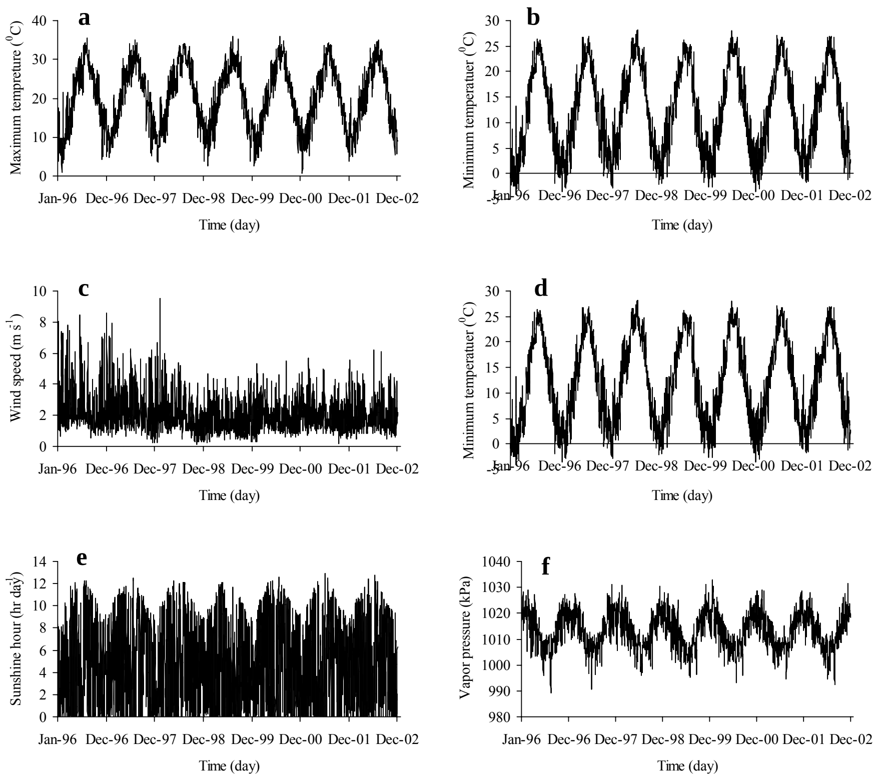


Fig. 2 Input parameters used in the estimation of ET_o by FAO56-PM method (a) maximum temperature [^oC]; (b) minimum temperature [^oC]; (c) wind speed [m s^{-1}]; (d) relative humidity [%]; (e) sunshine hour [hr day^{-1}]; (f) vapor pressure [kPa].

Table 1 Statistics of the daily climatic data.

	1996	1997	1998	1999	2000	2001	2002	Average
Daily average(T_{max}) [°C]	19.7	20.2	21.1	20.3	20.2	20.1	20.3	20.27
Daily average(T_{min}) [°C]	11.5	12.2	13.3	12.2	12.4	12.4	12.8	12.4
Daily average(U_2) [m s^{-1}]	2.6	2.5	2.1	1.7	1.8	1.9	2.1	2.1
Daily average(RH) [%]	68	66.9	64.5	67.9	65.7	66	66	66.43
Daily average(n) [h day^{-1}]	4.6	4.9	4.4	4.1	5.2	4.9	4.7	4.7

3.1.2 Calculation procedures

Several procedures have been developed to assess the evapotranspiration rate from required parameters. ET_o expresses the evaporating power of the atmosphere at a specific location and time of the year and does not consider the crop characteristics (factors data) and soil types.

ET_o can be estimated by means of the calculation sheet or a computer. In this study all the ET_o calculations were done by means of a computer. The calculation procedure consists of the following steps:

Derivation of some climatic parameters from the daily maximum (T_{max}) and minimum (T_{min}) air temperature and mean wind speed (u_2).

Calculation of the vapor pressure deficit (e_s - e_a). The saturation vapor pressure (e_s) is derived from T_{max} and T_{min}, while the actual vapor pressure (e_a) is derived from the mean relative humidity (RH_{mean}).

Determination of the net radiation (R_n) as the difference between the net shortwave radiation (R_{ns}) and the net longwave radiation (R_{nl}). The effect of soil heat flux (G) is ignored for daily calculations as the magnitude of the flux in this case is relatively small. The net radiation, expressed in [MJ m^{-2} day^{-1}], is converted to [mm day^{-1}] (equivalent evaporation) in the FAO56-PM equation by using 0.408 as the conversion factor in the **Eq. (1)**.

ET_o is obtained by combining the results of the previous steps.

Daily variations of the calculated variables are shown in **Fig. 3**.

The daily average values of the calculated parameters are listed in **Table 2**.

Table 2 Average values of the calculated parameters by FAO56-PM.

	1996	1997	1998	1999	2000	2001	2002	Average
(Δ) [kPa°C^{-1}]	0.124	0.126	0.13	0.12	0.128	0.128	0.129	0.128
(e_s) [kPa]	2.06	2.10	2.24	2.11	2.13	2.12	2.14	2.13
(e_a) [kPa]	1.45	1.445	1.61	1.49	1.44	1.43	1.45	1.47
(e_s-e_a) [kPa]	0.61	0.65	0.63	0.62	0.69	0.68	0.70	0.66
(R_a) [MJ m^{-2} day^{-1}]	30.29	30.29	30.29	30.29	30.29	30.29	30.29	30.29
(R_s) [MJ m^{-2} day^{-1}]	13.34	13.70	13.09	12.62	14.12	13.77	13.51	13.45
(R_{so}) [MJ m^{-2} day^{-1}]	22.73	22.73	22.73	22.73	22.73	22.73	22.73	22.73
(R_{ns}) [MJ m^{-2} day^{-1}]	10.27	10.54	10.08	9.72	10.87	10.61	10.40	10.36
(R_{nl}) [MJ m^{-2} day^{-1}]	2.68	2.85	2.53	2.55	3.00	2.87	2.77	2.75
(R_n) [MJ m^{-2} day^{-1}]	7.60	7.69	7.55	7.17	7.87	7.73	7.63	7.61

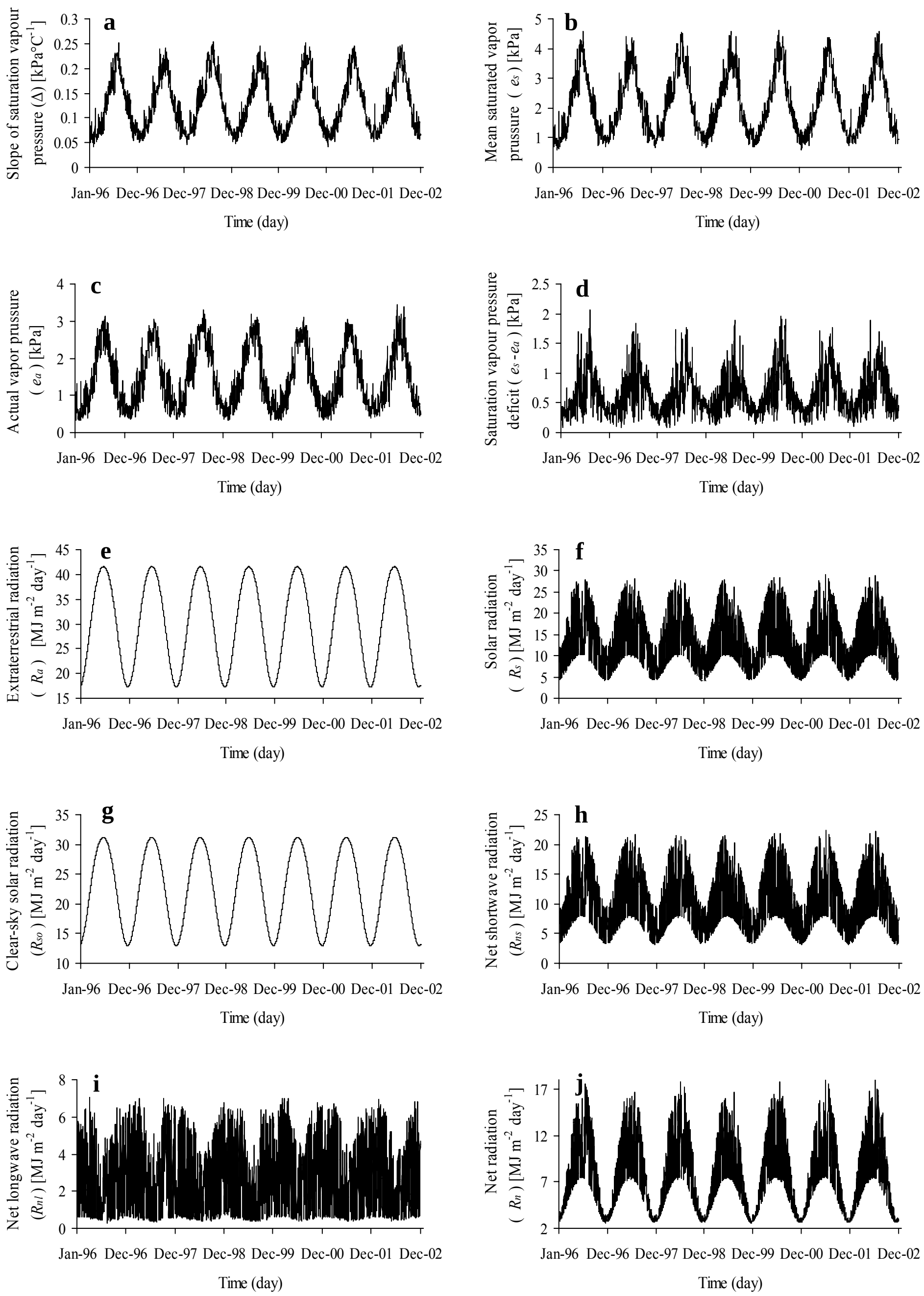


Fig. 3 Daily variation of the calculated variables; (a) slope of saturation vapor pressure; (b) mean saturation vapor pressure; (c) actual vapor pressure; (d) saturation vapor pressure deficit; (e) extraterrestrial radiation; (f) solar radiation; (g) clear-sky solar radiation; (h) net shortwave radiation; (i) net longwave radiation; (j) net radiation.

3.1.3 Estimating daily reference evepotranspiration (ET_o)

Values of ET_o [mm day^{-1}] as shown in **Fig. 4** were computed on daily basis using the procedures which were already outlined earlier. The daily average value of ET_o for 7 years is 2.79 [mm day^{-1}], the maximum value is 7.97 [mm day^{-1}], and the minimum value is 0.62 [mm day^{-1}].

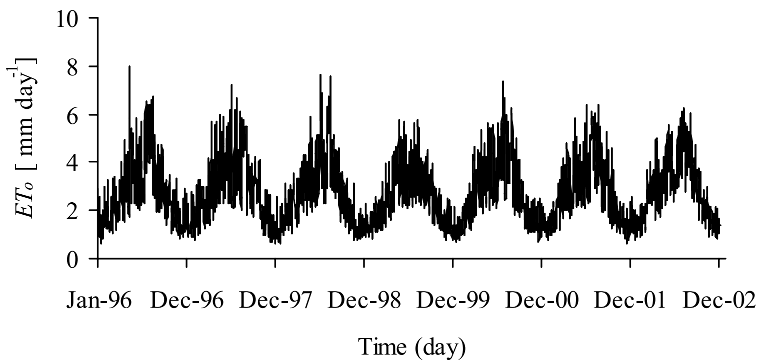


Fig. 4 Daily values of reference evapotranspiration (ET_o) [mm d^{-1}].

3.2 Crop evapotranspiration under standard conditions (ET_c) [1)]

The standard conditions refer to crops grown in large fields under excellent agronomic and soil water conditions. The ET_c differs distinctly from the reference evapotranspiration (ET_o) as the ground cover, canopy properties and aerodynamic resistance of the crop are different from grass.

The effects of characteristics that distinguish field crops from grass are integrated into the crop coefficient (K_c). In the crop coefficient approach, crop evapotranspiration under standard conditions is calculated by multiplying ET_o by K_c.

3.2.1 Factors determining the crop coefficient

Different crops will have different K_c coefficients. The changing characteristics of the crop over the growing season also affect the K_c coefficient. The conditions affecting soil evaporation also have an effect on K_c.

Crop type, climate, soil evaporation, crop growth stage (initial stage, crop development stage, mid-season stage, late season stage) are the main factors affect the crop coefficient, more details about these factors and how determining crop coefficient are founded in paper of FAO 56- PM.

3.2.2 General procedures

ET_c is calculated by multiplying ET_o by K_c, a coefficient expressing the difference in evapotranspiration between the cropped and reference grass surface. The difference can be combined into one single coefficient, or it can be split into two factors describing separately the differences in evaporation and transpiration between both surfaces.

For normal irrigation planning and management purposes, and for hydrologic water balance studies, average crop coefficients are relevant and more convenient than the K_c computed on a daily time step using a separate crop and soil coefficient.

In the present study, a single time-averaged crop coefficient is used to calculate ET_c on monthly basis.

The calculation procedure for ET_c consists of:

1. Identifying the crop growth stages and selecting the corresponding K_c coefficients.

2. Adjusting the selected K_c coefficients for frequency of wetting or climatic conditions during the stage.
3. Constructing the crop coefficient curve and
4. Calculating ET_c as the product of ET_o and K_c.

3.2.3 Estimating monthly average ET_c from rice field.

Table 3 lists the typical values of K_c for rice crop according to recommendations of FAO 56-PM method, under standard climatic conditions, which are defined as a sub-humid climate with average daytime minimum relative humidity (RH_{min}) of about 45% and having calm to moderate wind speeds averaging 2 m s^{-1} [1), 6)]. Since the climate conditions in the study area are similar to the standard conditions given by FAO56-PM, the presented crop coefficient in **Table 3** is applicable.

Figure 5 shows the monthly average values of K_c of rice in the study area.

The monthly average values of reference evapotranspiration (ET_o) are listed in **Table 4**.

Table 3 Monthly crop coefficient (K_c) values for rice.

	May	Jun	Jul	Aug	Sep
K_c of rice	1.05	1.125	1.20	1.20	0.9

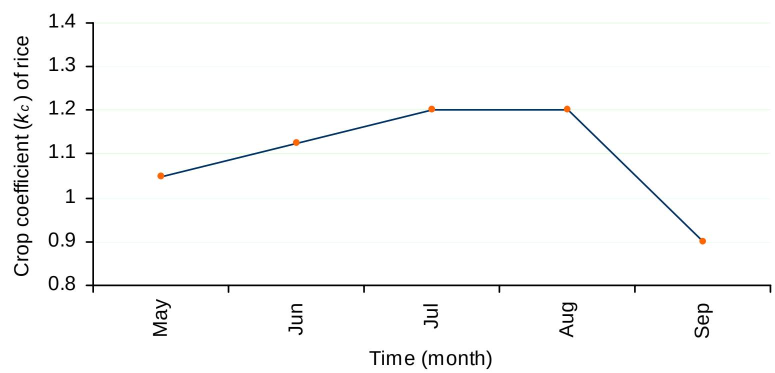


Fig. 5 Monthly average values of K_c of rice.

Table 4 Monthly average ET_o [mm $month^{-1}$].

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1996	48	50	73	92	124	105	134	136	102	74	55	44	1036
1997	50	55	71	96	120	118	132	136	99	95	52	42	1065
1998	42	51	72	84	107	98	135	150	103	69	50	41	1001
1999	43	46	62	80	116	104	102	108	91	76	49	45	922
2000	37	51	81	101	115	104	149	141	101	69	49	44	1042
2001	43	44	79	94	109	108	139	144	104	78	50	40	1032
2002	49	46	85	96	105	112	127	141	108	78	53	42	1040
Average	45	49	75	92	114	107	131	317	101	77	51	43	1020

3.2.3 (1) Monthly average ET_c from rice

The results of the monthly average values of ET_c from rice are listed in **Table 5**.

Table 5 Monthly average ET_c [mm month^{-1}] from rice.

	May	Jun	Jul	Aug	Sep	Total
1996	130	118	161	163	92	664
1997	126	132	158	163	89	668
1998	112	111	162	180	93	658
1999	121	118	122	130	82	573
2000	121	118	179	167	91	676
2001	115	122	167	172	94	670
2002	110	126	152	169	97	654
Average	119	121	157	163	91	652

3.2.3 (2) Crop coefficient (k_c) of forest

Kondo, J., *et al*. (1992) presented ET_c particularly in the forestry area of Japan which covered by trees of 15 m height and a leaf area index (*LAI*) equal to 6 in summer and 3 in winter. In their study, data from 66 regional meteorological stations in Japan were used for determining interception. The heat balance-bulk method was applied to calculate transpiration and direct evaporation of intercepted rainfall. As a result, the annual average ET_c from the forest in Fukuoka area accounted for 860 [mm yr^{-1}] in 1992 [2), 3), 7)]. The result as the monthly average values of ET_c [mm month^{-1}] is listed in **Table 6**.

Table 6 Monthly average ET_c [mm month^{-1}] from forest by Kondo, J., *et al*. (1992).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
ET_c in 1992	32	31	47	64	90	102	119	127	96	71	45	36	860

As mentioned before K_c can be calculated from **Eq. (3)** by dividing ET_c over ETo.

In the present study the average monthly values of Kc of forest was calculated from the average values of monthly ET_c which are listed in **Table 6** and the average values of monthly ET_o in **Table 4**. The result of K_c is listed in **Table 7** and shown in **Fig. 6**.

Table 7 Monthly average values of crop coefficient (K_c) of forest.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Des
K_c of forest	0.73	0.64	0.64	0.70	0.79	0.95	0.92	0.94	0.95	0.93	0.89	0.85

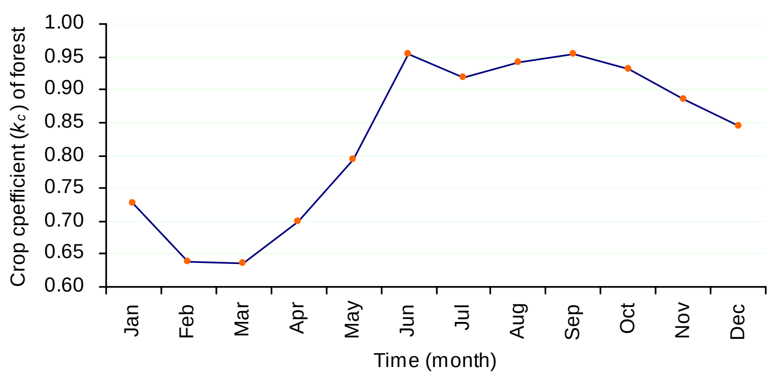


Fig. 6 Monthly average values of K_c of forest.

3.2.3 (3) Monthly average ET_c from forest

Once K_c for forest is obtained, the monthly average ET_c corresponding to ET_o in **Table 4** can be calculate as shown in **Table 8**.

Table 8 Monthly average ET_c [mm month^{-1}] from forest.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1996	35	32	46	64	99	100	123	127	97	69	48	37	878
1997	37	35	45	67	96	112	121	128	94	89	46	36	905
1998	31	32	46	59	85	94	124	141	98	64	44	35	852
1999	31	29	40	56	92	100	93	102	86	71	43	38	782
2000	27	32	52	71	91	100	137	132	96	64	44	36	883
2001	31	28	50	66	87	103	128	135	99	73	44	34	878
2002	36	29	54	67	83	107	117	132	103	73	47	36	882
Average	33	31	48	64	90	102	120	128	96	72	45	36	866

3.3 Result discussion

In order to support an effective water resources management in the study area, the FAO56-PM equation with the single coefficient approach was applied for calculating ET_o and ET_c from forest and rice fields.

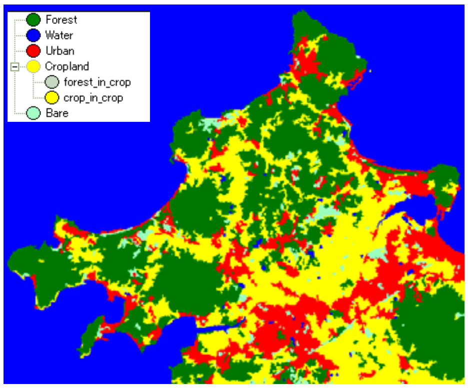
Tsutsumi et al. (2004) applied the Thornthwaite method in order to estimate the monthly crop evapotranspiration (ET_c) in the new campus area of Kyushu University, which is included in the present study area.

Based on the Thorthwaite method, they proposed a scheme to estimates the spatial distribution of the ET_c by coupling the conventional rainwater infiltration model with the groundwater flow analysis in the study area. They found that the mean special ET_c over the study area was 831 [mm yr^{-1}] in 1999 [2), 3)].

In the present study the annual average ET_c from forest calculated by FAO56-PM equation using crop coefficient approach, was estimated to be 866 [mm yr^{-1}]. This can be compared with the 831 [mm yr^{-1}] estimated by Tsutsumi et al. (2004). This means that the calculated values of K_c for forest by FAO56-PM single crop approach are appropriate and applicable.

The results of crop evapotranspiration of both forest and rice field which were obtained from the present study may be considered as basic elements of managing water resources efficiently, and also as important factors in computing water balance, irrigation system design and management, crop yield simulation, and hydrologic studies.

Figure 7 shows the land use map in the study area with the typical seasonal values of ET_c from forest and ET_c from crop and rice field.



Land use map

Month	ET_c from forest (mm/month)	ET_c from crop and rice (mm/month)
Jan	33	45
Feb	31	49
Mar	48	75
Apr	64	92
May	90	119
Jun	102	121
Jul	120	157
Aug	128	163
Sep	96	91
Oct	72	77
Nov	45	51
Dec	36	43

Fig. 7 Land use distribution with typical seasonal values of ET_c from forest and rice.

4. Conclusions

Seven year of daily meteorological data from 1996 to 2002 derived from Maebaru AMeDAS station and Fukuoka local meteorological station located in Fukuoka Japan, was used as input parameters for estimating daily reference crop evapotranspiration, and monthly crop evapotranspiration under stsndard conditions in Itoshima peninsula area by applying Food and Agriculture Organization (FAO) Penman-Monteith equation method.

The FAO Penman-Monteith method uses standard climatic data that can be easily measured or derived from commonly measured data. All calculation procedures have been standardized according to the available weather data and daily time scale of computation. The single crop coefficient method was used to derive crop evapotranspiration from ET_o. It is the approach that integrates the relationships between evapotranspiration of the crop and the reference surface into a single K_c. The selection of the K_c approach dependeds on the purpose of the study and the required interval time step.

Since the conditions encountered in the field differ from the standard conditions, the local calibration of K_c under given climatic conditions is required. K_c should be adjusted to the field conditions under the environmental effects.

In conclusion, it can be emphasized that the use of the FAO56-PM as a standard method remains the most desirable method for estimating ET_o if accuracy of data collection is considered to be the main consideration.

Acknowledgment

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