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Alkaeed, Othoman
Department of Urban and Environmental Engineering : Graduate Student

Flores, Clariza
Department of Urban and Environmental Engineering : Postdoctoral

Jinno, Kenji
Institute of Environmental Systems : Professor

Tsutsumi, Atsushi
GEOSCO

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Comparison of Several Reference Evapotranspiration Methods for Itoshima Peninsula Area, Fukuoka, Japan

by

Othoman ALKAEED *, Clariza FLORES **, Kenji JINNO*** and Atsushi TSUTSUMI****

Abstract

Six reference evapotranspiration (ET_o) methods are compared, based on their daily performances under the given climatic condition in the western region of Fukuoka City. The Penman-Monteith equation standardized by the Food and Agriculture Organization (FAO56-PM) is used to compare with the Thornthwaite, Hargreaves, and Hamon methods. The FAO56-PM method has also been used as an index for two equations: the solar radiation (R_s) based and net radiation (R_n) based equations, which are the simplified versions of FAO56-PM. Performance analysis for the calculated values using meteorological data for 7 years (Jan 1996 – Dec 2002) was made. The standard error of estimates (*SEE*) was calculated on monthly basis. The estimated values by the Thornthwaite, Hargreaves, Hamon, and the R_s-based and R_n-based radiation methods were all correlated with FAO56-PM having correlation (r^2) values calculated by Pearson's correlation of 0.80, 0.69, 0.48, 0.71 and 0.45 and their standard error estimates were 0.25, 0.25, 0.25, 0.28 and 0.24 mm mon^{-1}, respectively. Proximity in ET_o estimates by the Hargreaves and the R_s-based methods showed that the solar radiation as input variable was important as the FAO56-PM method. Also, the Thornthwaite method, which uses only temperature as input variable, has been found to have highly correlated with the FAO56-PM method. Thus, when considering the availability and reliability of the input data, the use of all these methods are suggested as practical methods for estimating ET_o if the standard FAO56-PM equation is not applicable due to the complexity of its input parameters.

Keywords: Reference evapotranspiration by FAO56-PM, Crop evapotranspiration, Water budget estimation, Crop coefficient, Automated Meteorological Data Acquisition System (AMeDAS)

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* Graduate Student, Department of Urban and Environmental Engineering
** Postdoctoral, Department of Urban and Environmental Engineering
*** Professor, Institute of Environmental Systems
**** GEOSCO

1. Introduction

Efficient consumption of groundwater as agricultural irrigation, drinking water and wineries is an important issue in Itoshima Peninsula, the western region of Fukuoka City, Japan, where a new campus of the Kyushu University is under construction. It is anticipated that the construction of the new campus could reduce the groundwater flow toward the residential area, unless appropriate countermeasures are taken.

Evapotranspiration (*ET*) is the loss of water to the atmosphere by the combined processes of evaporation from the soil and plant surface and transpiration from plants [1)]. Estimation of evapotranspiration is one of the major hydrological components for determining the water budget and is becoming indispensable for the calculation of a reliable recharge and evaporation rate for the groundwater flow analysis. It is therefore, reliable and consistent estimate of evapotranspiration is of great importance for the management of water resources efficiently.

Quantification of referable reference evapotranspiration (ET_o) for short grass is necessary in the context of many issues, for example, crop production, management of water resources, scheduling of irrigation, evaluation of the effects of changing land use on water yields, and environmental assessment [2)]. In the neighboring area including the new Kyushu University campus, groundwater is consumed for greenhouse by 700 m^3d^{-1}, for houses by 400 $m^3d^{-1,}$ and a few 10 m^3 d^{-1} for wineries. However, with the construction of the new Kyushu University campus, it is anticipated that this may cause the reduction in the groundwater flow toward the residential area unless proper groundwater management measures 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. It is in this regard that 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.

Tsutsumi et al. (2004) applied the Thornthwaite method in order to estimate the monthly crop evapotranspiration (ET_c) in the study area based on the measured mean monthly temperature. However, uncertain estimate with this method in winter gave relatively small values. Therefore, it is worthwhile to examine the other methods to compare with the obtained values by the Thornthwaite method in this area.

Kondo et al. (1992) presented ET_c particularly in the forestry area of Japan using the heat balance-bulk method. They showed the method which includes the effect of transpiration and direct evaporation of the intercepted rainfall of the forest canopy. As a result, the crop evapotranspiration from the forest in Fukuoka area accounted for 860 mm yr^{-1} in 1992. It should be notified that the method developed by Kondo et al. (1992) is useful because the rainfall interception can be evaluated in their approach and applicable for the subsequent estimation of the rainwater infiltration and surface runoff components [3), 4)]. It is obvious that the estimation of rainfall interception is important for the assessment of the possible effect of deforestation on the regional hydrologic cycle.

Based on the Thorthwaite's method, Tsutsumi et al. (2004) 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. However, the ET_c calculated by the Thorthwaite method gave remarkable inconsistent vales in winter.

Since direct measurement of referable ET_o for short grass is difficult, time consuming and costly, the most practical approach would be to estimate ET_o from climatic variables, such as solar radiation, air temperature, wind speed, and relative humidity. In connection with, various methods are available for estimating ET_o, involving equations ranging from the most complex energy balance method requiring detailed climatological data (Allen, 1989) to simpler method requiring less data (Hargreaves, 1982; Samani, 1985). Among them, the FAO-56 based on the Penman-Monteith (PM) method (Allen et al., 1998) is currently used and is considered to be a standard method [8)]. However, the major drawback of FAO56-PM method is that this method requires air temperature, relative humidity, wind speed, and solar radiation which could not be easily available in many meteorological stations particularly in a given location where quality of data and difficulties in gathering all of the necessary weather parameters can present serious limitations [9)]. Additionally, it also uses the complicated unit conversions and lengthy calculations [10)]. On the other hand, the Thornthwaite method is considered to be a popular method since it only requires monthly average air temperature. Mintz and Walker (1993) stated that the Thornthwaite method was developed for temperature measured under potential conditions and it only represents the potential evaporation when there is no soil moisture stress. Hence, this method tends to overestimate the potential evaporation in arid regions if air surface temperature is applied. The Hargreaves method is also quite simpler that requires only two climatic parameters: the temperature and incident radiation. This method has been tested using some high quality lysimeter data and broad range in climatological conditions (Hargreaves, 1994) whose results revealed as nearly accurate as PM in estimating ET_o. Therefore, the use of the Hargreaves method is recommended in cases where reliable data are lacking. The Hamon method is also considered as one of the simplest estimates of ET_o [13)], and applicable to estimate seasonal (monthly) or annual values. Haith and Shoemaker (1987) stated that the Hamon method is applicable easily since it requires only average number of daylight hours per day and saturated vapor pressure. Irmak et al. (2003) simplified the FAO56-PM method by expressing a multi-linear regression function which requires less input parameters and computation. This uses only the solar radiation (R_s), net radiation (R_n) and mean daily temperature (T_m) as input parameters to estimate the ET_o.

Although, many approaches have been developed and adapted for various applications based on available input data, there is still a remarkable range of uncertainty related to which method is to be adopted specifically in the calculation of reference evapotranspiration for short grass at a given area. Thus, for the purposes of establishing a common method which can provide a more accurate ET_o estimation, these estimation methods were researched on the basis of their variability in input variables. The performances of these methods were evaluated and compared with the FAO56-PM for estimating the ET_o particularly at the new Kyushu University Campus area whose meteorological properties are characterized as having high humidity and heavy precipitation.

Besides, the crop coefficient for the forest canopy was discussed through the comparisons of the presented values for the forest in the Fukuoka areas with the reference values calculated by the above six methods.

2. Methodology

2.1 Study area and climatic characteristics

Figure 1 shows the study area (Itoshima peninsula) including new campus of Kyushu University, located in the northern part of Kyushu Island, western region of Fukuoka City, Japan, latitude 33^o 25' to 33^o 40' N, longitude 130^o 07' 30" to 130^o 16' E.

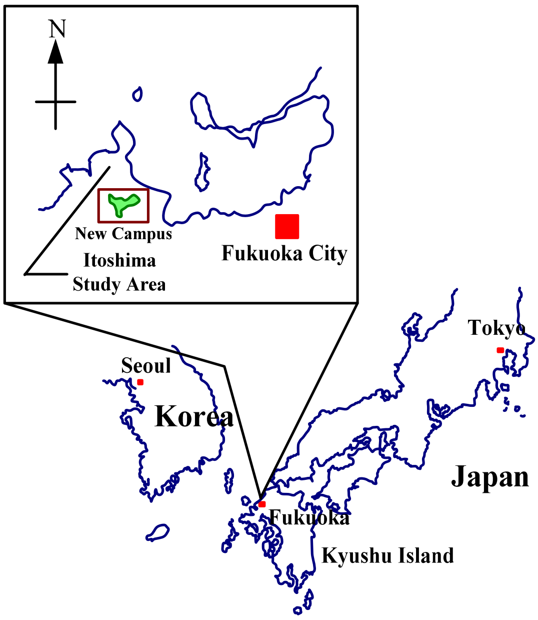

Fig. 1 Study area (Itoshima).

The total area of Itoshima is about 111.61 km^2. The climate in the area is characterized as having high humidity, high wind speed, and heavy precipitation. The meteorological data in the present study were obtained from the Maebaru Automated Meteorological Data Acquisition System (AMeDAS) station in Maebaru City, Fukuoka, Japan, which is close to the new Kyushu University Campus, (latitude 33^o 33' 36" N, longitude 130^o 11' 30" N) within an agricultural area. The average annual precipitation is 1646 mm yr^{-1}(1996-2002), approximately more than 50% of which occurs in June-August. Air temperature ranges from 19.2^{o}C and 31.1^{o}C in summer and 1.7^{o}C and 15.4^{o}C in winter months. Daily mean temperature in summer is 23.3^{o}C and 9.6^{o}C in winter. On the other hand, daily mean minimum and maximum relative humidity are 37% and 92% with annual average of 67%, respectively. The observed maximum and average daily wind speed in this period were 4.5 m s^{-1} and 2.8 m s^{-1} [3].

2.2 Equations

2.2.1 The (FAO56) Penman-Monteith equation

The (FAO56) Penman-Monteith equation for predicting ET_o where applied on 24-h 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 vapour pressure [kPa], e_a is actual vapour pressure [kPa], e_s-e_a is saturation vapour pressure deficit [kPa], Δ is slope vapour pressure curve [kPa °C^{-1}], and γ is psychrometric constant [kPa °C^{-1}]. In application having 24-h 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 function and $T_{\max}$ and $T_{\min}$ are the daily maximum and minimum air temperature. The FAO Penman-Monteith 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. (1994ab, 1998) or Smith et al. (1991), [15].

2.2.2 Thornthwaite equation

The Thornthwaite equation given by (Thornthwaite, W. 1948) is

$$ET_0 = 16 \times \left(\frac{10T_i}{I}\right)^a \left(\frac{N}{12}\right)\left(\frac{1}{30}\right) \tag{3}$$

$$I = \sum_{i=1}^{12} \left(\frac{T_i}{5}\right)^{1.514} \tag{4}$$

$$a = \left(492390 + 17920I - 771I^2 + 0.675I^3\right) \times 10^{-6} \tag{5}$$

where, T_i is the mean monthly temperature [°C], N is the mean monthly sunshine hour. The main advantage of this method is that only the temperature information is needed besides the sunshine hours. Generally, it is known that the Thornthwaite method gives the underestimate in the arid area while the overestimate in the humid area, respectively.

2.2.3 Hargreaves equation

The Hargreaves et al. (1985) equation is expressed as

$$ET_o = 0.0023(T_m + 17.8)\left(\sqrt{T_{\max} - T_{\min}}\right)R_a \tag{6}$$

where T_m is daily mean air temperature [°C], $T_{\max}$ is daily maximum air temperature [°C], $T_{\min}$ is daily minimum air temperature [°C], and R_a is extraterrestrial radiation [MJ m^{-2} day^{-1}]. The mean air temperature in the Hargreaves equation is calculated as an average of $T_{\max}$ and $T_{\min}$ and R_a is computed from information on location of the site and time of the year. Therefore air temperature is the only parameter that needs to be measured continuously in order to use Eq. (6) [17].

2.2.4 Hamon equation

The Hamon equation given by (Haith, D. A. and Shoemaker, L. L., 1987) is expressed as

$$ET_o = \frac{2.1 \times H_t^{\,2} e_s}{\left(T_{mean} + 273.2\right)} \tag{7}$$

where H_t [day] is average number of daylight hours per day.

2.2.5 Solar radiation (R_s) based method (Irmak et al., 2003)

$$ET_o = -0.611 + 0.149 R_s + 0.079 T_{mean} \tag{8}$$

where R_s [MJ m^{-2} day^{-1}] is solar shortwave radiation.

2.2.6 Net radiation (R_n) based method (Irmak et al., 2003)

$$ET_o = 0.489 + 0.289 R_n + 0.023 T_{mean} \tag{9}$$

where R_n [MJ m^{-2} day^{-1}] is net radiation.

2.3 Climatic parameters required by each equation

One of the important considerations in establishing a simple method other than the standard method such as the FAO56-PM is the high possibility of unavailability and unreliable weather data measurement and collections. In general, a setup of the devices for the meteorological measurement at the remote areas and at a given location is difficult. With this given scenario, accuracy of data, specifically the data of advanced input variables such as humidity and radiation would be low. **Table 1** shows the data requirements for the FAO56-PM, Thornthwaite, Hargreaves, Hamon, and R_s-based and R_n-based equations, respectively.

Table 1 Comparison of each method in terms of the number of parameters required.

method	FAO56-PM	Thorthwaite	Hargreaves	Hamon	R_s-based radiation	R_n-based radiation
variables						
temperature	necessary	necessary	necessary	necessary	necessary	necessary
humidity	necessary	-	-	-	necessary	necessary
wind speed	necessary	-	-	-	-	-
radiation	necessary	-	necessary	-	necessary	necessary
no. of daylight hours	-	necessary	-	necessary	necessary	necessary
saturated vapour pressure	necessary	-	-	-	-	-

3. Results and Discussions

3.1 Climatic data

The meteorological data of 7 years at the Maebaru AMeDAS station covering the period of January 1996 - December 2002 were analyzed for purposes of calculating evapotranspiration by the different methods. **Figure 2** shows the daily precipitation, temperature, wind speed, relative humidity, solar radiation and net radiation data used for ET_o estimations. The daily solar radiation and net solar radiation were plotted in **Fig 2(e)** and **Fig. 2(f)**. They were calculated by the procedures which are presented in the FAO56-PM estimation [1)]. These variables are important for the calculation of ET_o as required in the FAO56-PM estimation. The relationship between solar radiation and net solar radiation depicts the same trend in all years wherein the total solar radiation is doubled of that in the net radiation.

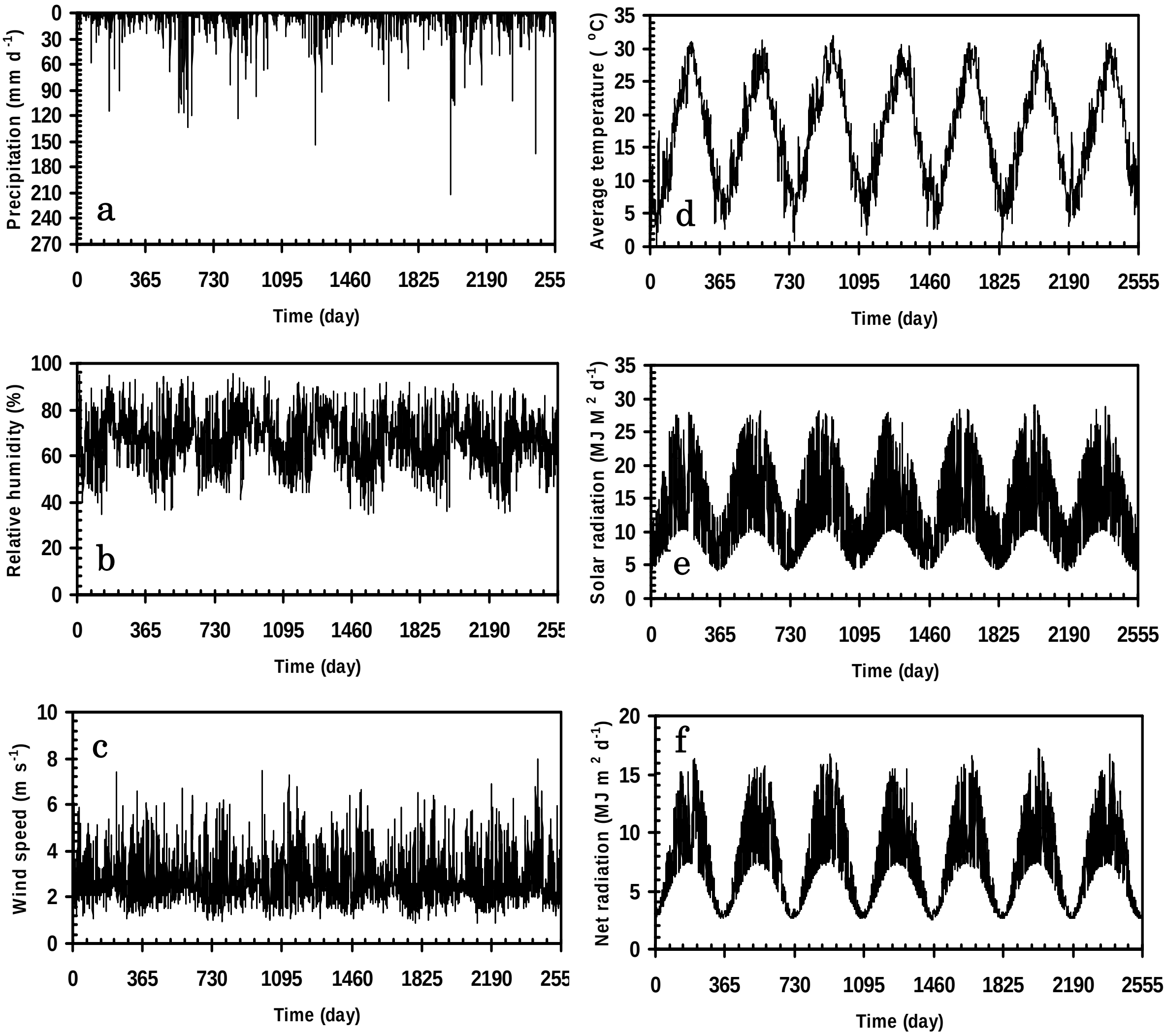

Fig. 2 Input parameters used in the calculation of ET_o by different ET_o estimation methods (a) precipitation [mm day^{-1}]; (b) relative humidity [%]; (c) wind speed [m s^{-1}]; (d) average temperature [^{o}C]; (e) solar radiation [MJ m^{-2} day^{-1}]; and, (f) net solar radiation [MJ m^{-2} day^{-1}], respectively.

The 7 year-daily weather data were used to validate the performances of the commonly used ET_o estimation methods.

Comparison of monthly ET_o values specifically for the Thornthwaite, Hargreaves, Hamon, R_s-based and R_n-based equations and are presented in **Fig. 3**.

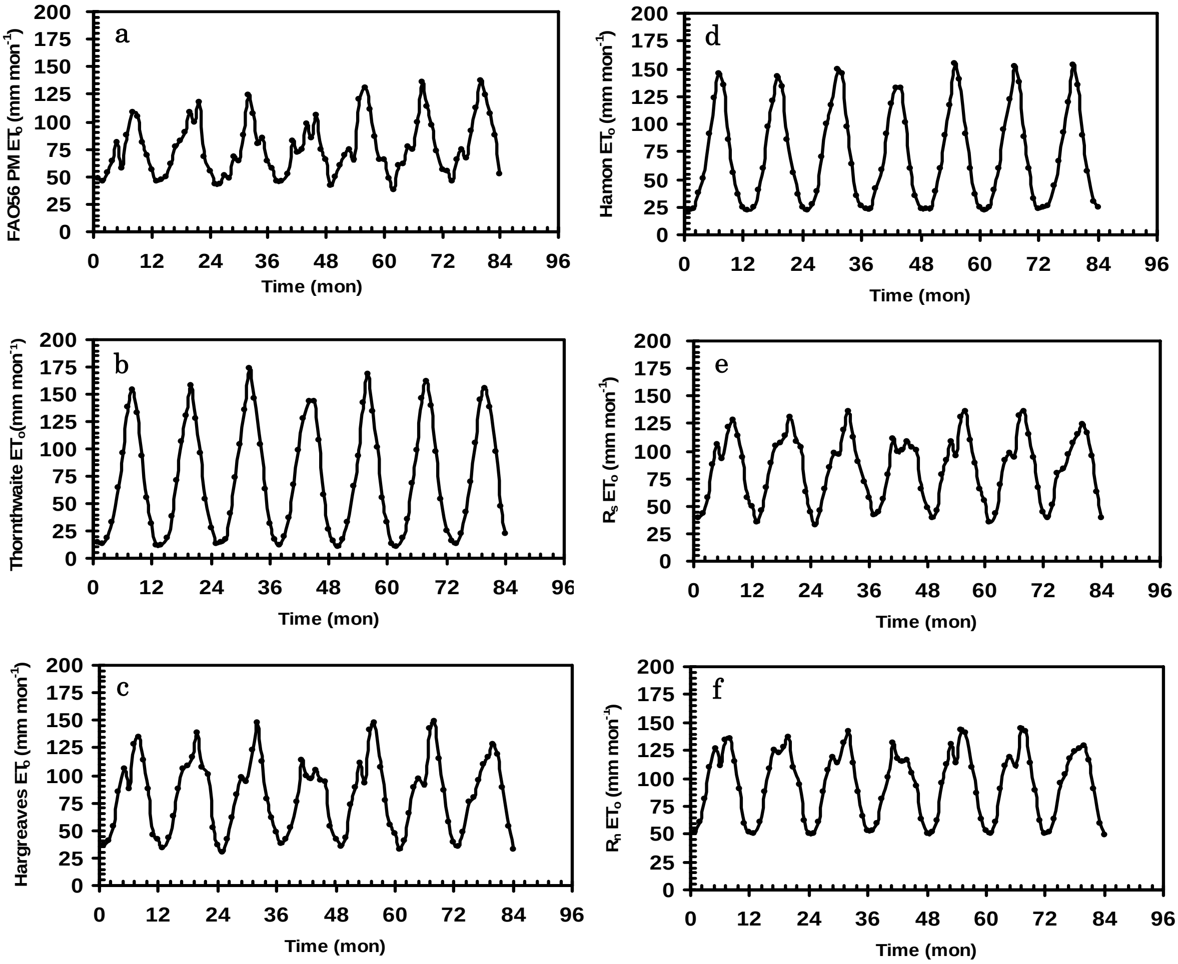

Fig. 3 Estimated ET_o derived from different methods: (a) FAO56-PM (b) Thornthwaite (c) Hargreaves (d) Hamon (e) R_s-based method (f) R_n-based method. Unit is [mm mon^{-1}].

Although the trends of the estimated ET_o are in proximity among the applied methods, it is surprising that none of the methods show the same results. Seasonal variations in the ET_o estimation reflect the differences in the variables applied in each method. **Figure 4** shows the comparisons of annual ET_o estimations.

In the present calculations, the annual sum of ET_o estimations based on the solar radiation as input variable showed the highest value among the tested methods having the values ranged from 957 mm yr^{-1} in 1999 – 1042 mm yr^{-1} in 2000 in R_s-based method, while 1084 mm yr^{-1} in 1999 – 1143 mm yr^{-1} in 2001 for R_n-based method, respectively. The ET_o estimations by the Hamon method has the lowest values ranged from 831 mm yr^{-1} in 1996 – 895 mm yr^{-1} in 1998 whereas the Thorntwaite method is very close with the FAO56-PM having the values ranged from 845 mm yr^{-1} in 1996 – 916 mm yr^{-1} in 1998, respectively. The low ET_o values obtained by the Hamon and Thornthwaite methods having 831 mm yr^{-1} and 845 mm yr^{-1} both in 1996 were found to be close with the ET_o estimations reported by Kondo (1992) et al. and Tsutsumi et al. (2004) of 860 mm in 1992 and 831 mm in 1996 for Fukuoka area.

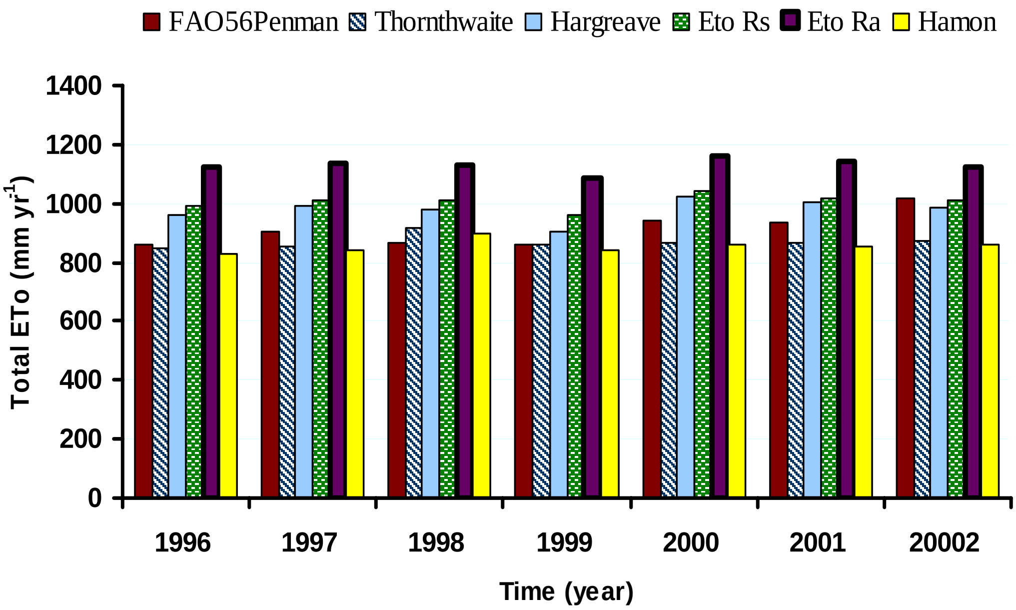

Fig. 4 Total annual evapotranspiration estimates given by the different methods covering the 7 year meteorological data obtained from the Maebaru AMeDAS station, Fukuoka, Japan.

Comparisons of the Thornthwaite, Hargreaves, Hamon, and the R_s- and R_n- based methods were all correlated with FAO56-PM having r^2 values, which can be calculated using Pearson's correlation (STATSOFT, Statistica, 1999 Edition), of 0.80, 0.69, 0.48, 0.71 and 0.45 as shown in **Fig. 5**, respectively. Results of the ET_o estimations by the Hargreaves and R_s-based methods, which use the solar radiation, and the Thornthwaite method by temperature as input variable, were found to be significantly correlated with the ET_o estimation by the FAO56-PM. This fact implies that these input variables are significant for obtaining the proximate values in the ET_o estimations. When considering the availability and reliability of the input data, the use of these methods are suggested as practical methods for estimating ET_o, if the standard FAO56-PM equation can not be used due to the complexity of its input parameters.

3.2 Comparison of the performance of different methods relative to FAO56-PM

The performances of the tested methods were analyzed by computing the standard error of estimate *SEE* of the monthly ET_o between the FAO56-PM and other methods. The *SEE* is computed following the equation presented by Irmak et al. (2003) as:

$$SEE = \sqrt{\left[1 \Big/ \{n(n-2)\} \right] \left[n\sum_{i=1}^{n} y_i^2 - \left(\sum_{i=1}^{n} y_i \right)^2 - \frac{\left[n\sum_{i=1}^{n} x_i y_i - (\sum_{i=1}^{n} x_i) \times (\sum_{i=1}^{n} y_i) \right]^2}{n\sum_{i=1}^{n} x_i^2 - \left(\sum_{i=1}^{n} x_i \right)^2} \right]} \tag{10}$$

where

x_i ; ET_o estimated using the FAO56-PM (mm mon^{-1})

y_i ; ET_o estimated using other equations (mm mon^{-1})

$n_{i;}$ sample size

The lower *SEE* implies the better performance of the applied method. **Table 2** and **Fig. 5** show the calculated average *SEE* on the monthly basis for all the methods indicating the low values such as 0.25, 0.25, 0.25, 0.28 and 0.24 mm d^{-1} for the Thornthwaite, Hargreaves, Hamon, R_s and R_n-based methods, respectively. The calculated *SEE* for all the methods shows almost the same values reflecting good performances as manifested for all the calculation years. The average ratio above and below 1.0 for different methods indicates over- and underestimation of ET_o relative to FAO56-PM method. As shown in **Table 2**, the average ratio defined as the ratio of ET_o method to ET_o FAO56-PM gave the values of 0.89, 1.10, 1.13 and 1.32 and 0.94 for the Thornthwaite, Hargreaves, Hamon, R_s and R_n-based methods, respectively. Among the methods, the Hargreaves, Hamon, and R_s-based methods resulted in the overestimation of ET_o relative to the FAO56-PM method.

The high correlation of ET_o by the Hargreaves and R_s-based methods with FAO56-PM method clearly reflects the importance of the incident solar radiation as they are calculated by using the temperature and solar radiation. This fact is also supported by many studies which reveal that the Hargreaves method is nearly as accurate as the FAO56-PM method in estimating ET_o. Therefore, it could be recommended to use the Hargreaves method in the case of which other reliable data are lacking [1)]. However, it should be notified, as Temesgen et al. (1999) have indicated, that high humidity conditions may result in an overestimation of ET_o by the Hargreaves method whereas the conditions with high wind speed may result in the underestimation of ET_o. Moreover, the performance of the RB_s-based method developed with the aim of simplifying the calculation and input variables for the FAO56-PM method performed well and its estimations of daily, monthly and annual ET_o are close to the estimates obtained by the FAO56-PM method. Additionally, the comparisons made for all the methods signifies that all these methods can be successfully used to estimate the ET_o specifically in areas having the same climatic conditions as the one presented in this study.

Table 2 Standard Error of Estimates (*SEE*) in mm mon^{-1} of *ET*, Average Ratio of *ET* method / ET_o FAO56-PM of the commonly used methods for estimating *ET* covering the years 1996-2002.

year	Performance indicator	Thornthwaite	Hargreaves	Hamon	R_s	R_n
1996	*SEE* of monthly estimate	0.24	0.25	0.25	0.28	0.23
	Average ratio	0.92	1.12	1.16	1.36	0.97
1997	*SEE* of monthly estimate	0.24	0.26	0.26	0.29	0.24
	Average ratio	0.87	1.12	1.14	1.32	0.93
1998	*SEE* of monthly estimate	0.26	0.25	0.26	0.28	0.25
	Average ratio	0.99	1.17	1.21	1.42	1.06
1999	*SEE* of monthly estimate	0.25	0.23	0.24	0.27	0.23
	Average ratio	0.96	1.09	1.15	1.35	1.00
2000	*SEE* of monthly estimate	0.25	0.26	0.26	0.29	0.24
	Average ratio	0.84	1.10	1.14	1.31	0.90
2001	*SEE* of monthly estimate	0.25	0.26	0.26	0.29	0.24
	Average ratio	0.84	1.09	1.11	1.29	0.91
2002	*SEE* of monthly estimate	0.25	0.25	0.24	0.26	0.24
	Average ratio	0.79	1.00	1.03	1.17	0.84
Average	*SEE* of monthly estimate	0.25	0.25	0.25	0.28	0.24
	Average ratio	0.89	1.10	1.13	1.32	0.94

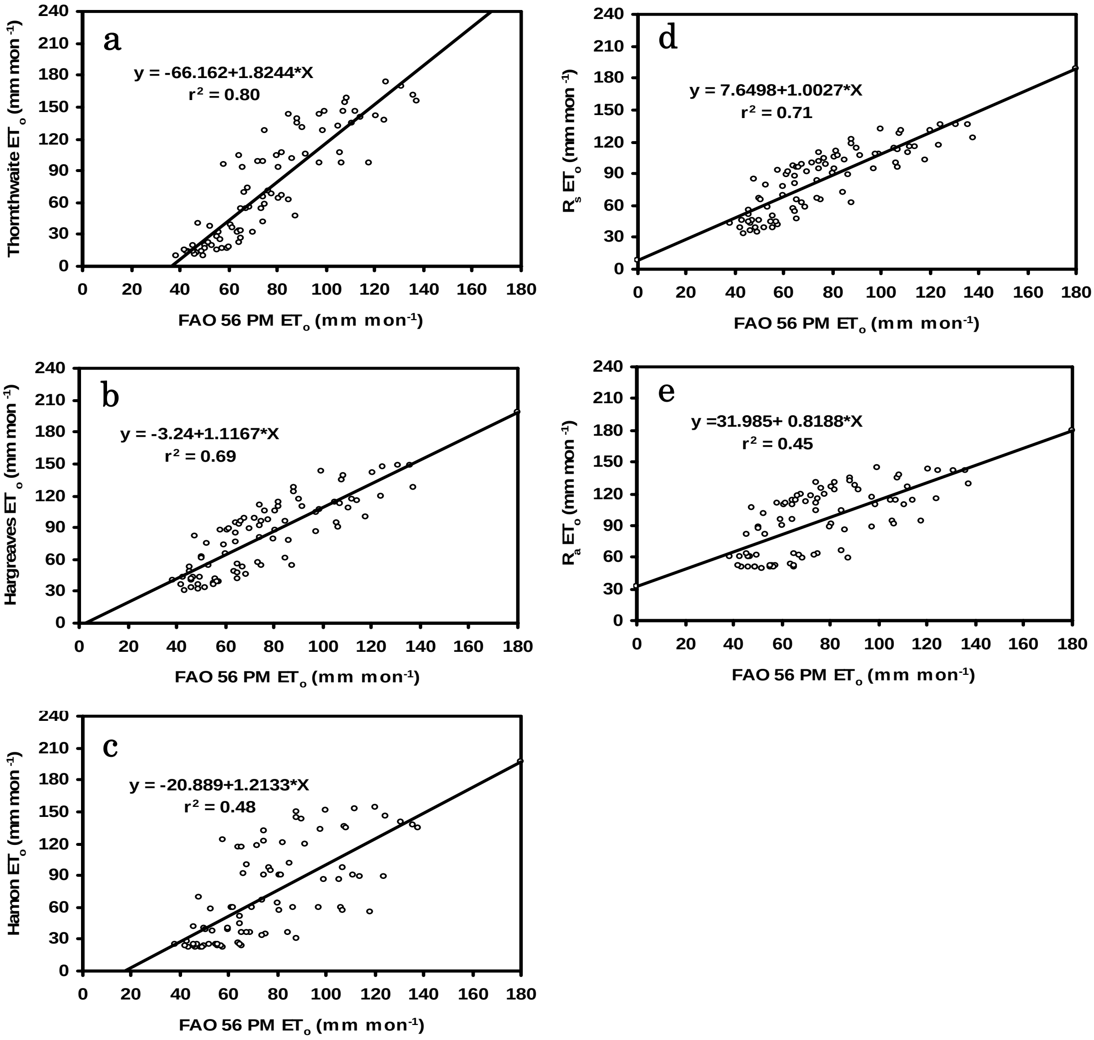

Fig. 5 Regression analysis for the ET_o estimates of (a) Thornthwaite (b) Hargreaves (c) Hamon (d) R_s-based method (e) R_n-based method with FAO56-PM for evaluation years of 1996-2002 at Maebaru, Fukuoka, Japan. Unit in (mm mon^{-1}) and n = 84.

4. Conclusions

The 7-year meteorological data derived from Maebaru AMeDAS station and Fukuoka local meteorological station located in Fukuoka Japan was applied as input parameters for comparing different methods to estimate ET_o under existing climatic conditions in Fukuoka, Japan. The major drawback is that the "real" ET_o is unknown however, numerous studies have been performed wherein the FAO56 PM method have shown to be the best method for estimating ET_o in which the calculated ET_o values correspond to lysimeters and other precise devices where real ET_o can best obtained. The performances of the Thorthwaite, Hargreaves, Hamon, R_s-based and R_n-based equations for monthly ET_o estimates and are significantly correlated with the ET_o estimates in FAO56-PM method although the Thorthwaite method was found to have highly significant estimates. Among the methods used, only the Thorthwaite method requires temperature as the only input parameter whereas other methods used radiation input to estimate the ET_o. These approaches require only few parameter inputs thus making it more dynamic for the application in the area when the accuracy in weather measurement is less expected as compared with complex data input required by FAO56-PM approach. Thus, these methods could be used as a potential method to estimate ET_o.

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. But in many cases especially in areas where accurate data collection is difficult, the application Hargreaves and R_s-based equation could be utilized for accurate and consistent estimates of daily ET_o relative to the FAO56-PM method especially in humid climate like in Japan is to be considered. Alternatively, reliable ET_o estimates derived from Thornthwaite method can be used to calculate the ET_o when temperature is the only input parameter available. However, the differences in the ET_o estimates using these methods have provided a significant range of uncertainty. It is therefore important to compare and validate these methods based on the precise evaluation considering the land coverage and topographical condition.

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