EVALUATION OF TECHNIQUES FOR ESTIMATING REFERENCE EVAPOTRANSPIRATION FOR JAWA - INDONESIA

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EVALUATION OF TECHNIQUES FOR ESTIMATING REFERENCE EVAPOTRANSPIRATION FOR JAWA - INDONESIA

by

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To

My children:

Nina,

Irfan,

Riska,

and

My wife:

DAIMATUL HASANAH,

Bandung, Indonesia.

ABSTRACT

Due to the shortage of measured consumptive use of water for crops (i.e., evapotranspiration, ET_c) in Indonesia, estimation of reference evapotranspiration (ET_o) using climatological data is necessary in order to determine crop water requirements for irrigation planning and operation.

The objectives of this study are to compare 24 methods of estimating ET_o, and to adjust selected methods to the standard method recommended by the Food and Agricultural Organization (FAO) of the United Nations and to derive new empirical equations using regression analysis of published climatological data. This study uses 4156 monthly data values from 50 stations on Jawa.

In this study, the methods are classified into 4 categories according to the number of climatic variables (i.e., from one to four) used in the equation. From each category, the most promising method is selected and the possibility of adjusting the method to give results closer to that of the standard method is investigated. In addition, simpler empirical equations for each category are derived using regression analysis.

The methods which use a greater number of variables and where solar radiation is the dominant factor in estimating reference evapotranspiration gave the best results. All the non-standard methods required adjusting to give results that are, on average, equal to the standard method. The new empirical equations derived by regression analysis gave excellent results and are easy to use when compared to both the standard and non-standard methods.

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Contents

List of Tables

List of Figures

List of Symbols

Symbols	Descriptions
a_{TH}	- constant as a function of sum of monthly heat index
a and b	- intercept and slope of the regression line
a_{BC} and b_{BC}	- FAO Blaney-Criddle correction factor
a_1, a_2, .. a_n	- regression coefficients
a_{re} and b_{re}	- correlation coefficients for emissivity equation
a_s and b_s	- a fraction of extraterrestrial radiation on overcast days
AET	- actual evapotranspiration
AFCV	- adjusted four-climatic-variable method
Alt	- altitude, m
AOCV	- adjusted one-climatic-variable method
ATOV	- adjusted two-climatic-variable method
ATHCV	- adjusted three-climatic-variable method
BCR	- Blaney-Criddle's method
BMX	- Behnke-Maxey's method
c_{FPN}	- correction factor for FAO-Penman, dimensionless
c_p	- specific heat of moist air = 1.013 kJ kg^{-1} $°C^{-1}$
cv	- coefficient of variation
C	- the available of soil moisture capacity, mm $month^{-1}$

C_{HMN}	-	Hamon's coefficient
d_r	-	relative distance between earth and sun
DVD	-	David's Method
e_s	-	saturation vapour pressure, kPa or mb Conversion: 1 mb = 0.1 kPa
e_d	-	vapour pressure at dew point temperature, kPa or mb
e_w	-	vapour pressure at wet bulb temperature, mb
ET_c	-	evapotranspiration of a particular crop, mm equivalent water evaporation day^{-1} or mm equivalent water evaporation month^{-1}
ET_o	-	reference evapotranspiration, mm equivalent water evaporation day^{-1} or mm equivalent water evaporation month^{-1}
$ET_{o\text{-}STD}$	-	standard reference evapotranspiration, mm equivalent water evaporation month^{-1}
$ET_{o\text{-}Adjs1}$	-	ET_o calculated using adjusted one-climatic-variable method, mm equivalent water evaporation month^{-1}
$ET_{o\text{-}Adjs2}$	-	ET_o calculated using adjusted two-climatic-variable method, mm equivalent water evaporation month^{-1}
$ET_{o\text{-}Adjs3}$	-	ET_o calculated using adjusted three-climatic-variable method, mm equivalent water evaporation month^{-1}
$ET_{o\text{-}Adjs4}$	-	ET_o calculated using adjusted four-climatic-variable method, mm equivalent water evaporation month^{-1}

ET_{oRgr}	-	ET_o calculated using regression method, mm equivalent water evaporation month^{-1}
ET_{oRgv1}	-	ET_o calculated using one-climatic-variable regression method, mm equivalent water evaporation month^{-1}
ET_{oRgv2}	-	ET_o calculated using two-climatic-variable regression method, mm equivalent water evaporation month^{-1}
ET_{oRgv3}	-	ET_o calculated using three-climatic-variable regression method, mm equivalent water evaporation month^{-1}
ET_{oRgv4}	-	ET_o calculated using four-climatic-variable regression method, mm equivalent water evaporation month^{-1}
FAO	-	Food and Agricultural Organization
FAO-BCR	-	FAO Blaney-Criddle's Method
FAO-PNM	-	FAO Penman Corrected Method
FAO-PNM c=1	-	FAO Penman Uncorrected or using correction factor c=1 Method
FAO-PPP-PNM	-	FAO Penman Plant Production and Protection Method
FAO-RAD	-	FAO Radiation Corrected Method
FAO-RAD c=1	-	FAO Radiation Uncorrected or using the correction factor c=1 Method
FCVR	-	four-climatic-variable regression method
g	-	gravitational acceleration = 9.8 m s^{-2}
G	-	soil heat flux, MJ m^{-2} day^{-1}

HGF'74	-	Hargreaves' 1974 Method
HGF-Rs	-	Hargreaves' method using incoming solar radiation (Rs)
HGF-Rn	-	Hargreaves' method net radiation (Rn)
HMN	-	Hamon's Method
i	-	monthly heat index, dimensionless
I	-	sum of monthly heat index (i), dimensionless
IVN	-	Ivanov's Method
JD	-	Julian day or number of the day in the year
k_c	-	crop coefficient, dimensionless
kPa	-	kiloPascal
Lats	-	Latitudes, °South
m	-	percentage of non-vegetated land
	-	meter
mb	-	millibar
M	-	available soil moisture, mm month^{-1}
MF	-	Hargreaves' coefficient
MKK	-	Makkink's Method
MSL	-	mean sea level, m
n_R	-	number of rainy day
n	-	bright sunshine hours per day, hours
n/N	-	relative sunshine fraction, %
N	-	maximum day light hours, hours

OLV	-	Olivier's Method
OST	-	Ostromecki's Method
OCVR	-	One-Climatic-Variable Regression method
p	-	Thornthwaite's or Hamon's coefficient
p_{BC}	-	Blaney-Criddle's coefficient
P, P_o	-	atmospheric pressure at a particular elevation and sea level, kPa or mb
PNM	-	Penman's Method
PRS	-	Prescott's Method
P_t	-	saturated water-vapour density (absolute humidity), g m^{-3} x 0.01
PTL	-	Priestly-Taylor's Method
PWJ'72	-	Penman-Wright-Jensen's 1972 Method
r^2	-	coefficient of determination
r_a	-	external resistance of the air to molecular diffusion
rh ; RH	-	relative humidity, %
r_s	-	effective stomatal resistance
R	-	specific gas constant = 287 J kg^{-1} $°K^{-1}$
R_a	-	extraterrestrial radiation, MJ m^{-2} day^{-1} or cal cm^{-2} day^{-1} or mm equivalent water evaporation $month^{-1}$
RHmax	-	maximum relative humidity, %
RHmin	-	minimum relative humidity, %

$R_l \uparrow$	-	out going radiation emitted by vegetation and soil into atmosphere (up ward flux), MJ m^{-2} day^{-1}
$R_l \downarrow$	-	incoming radiation emitted by atmosphere and cloud cover to the earth surface (down ward flux), MJ m^{-2} day^{-1}
R_n	-	net radiation at crop surface, MJ m^{-2} day^{-1} or cal cm^{-2} day^{-1} or mm equivalent water evaporation day^{-1}
R_{nl}	-	net outgoing long wave radiation at crop surface, MJ m^{-2} day^{-1} or cal cm^{-2} day^{-1} or mm equivalent water evaporation day^{-1}
R_{nlo}	-	net long wave radiation for clear skies, MJ m^{-2} day^{-1} or cal cm^{-2} day^{-1} or mm equivalent water evaporation day^{-1}
R_{ns}	-	net incoming short wave radiation at crop surface, MJ m^{-2} day^{-1} or cal cm^{-2} day^{-1} or mm equivalent water evaporation day^{-1}
R_s	-	incoming solar radiation at crop surface, MJ m^{-2} day^{-1} or cal cm^{-2} day^{-1} or mm equivalent water evaporation day^{-1}

Conversion: 1 MJ m^{-2} day^{-1} = 0.408 mm equivalent water evaporation day^{-1}

1 cal cm^{-2} day^{-1} = 1/58.6 mm equivalent water evaporation day^{-1}

1 MJ m^{-2} day^{-1} = 23.884 cal cm^{-2} day-1

s	-	standard deviation
ss	-	sunshine duration or relative sunshine fraction (n/N), %
Std-Error	-	standard error

STD	-	Standard Method
STP	-	Stephens' Method
T ; Temp	-	mean monthly temperature, °C
T_t	-	mean monthly temperature, °C
T_k	-	mean monthly temperature, °K
T_{ko}	-	reference temperature at sea level, °K
THR	-	Thornthwaite's Method
THCVR	-	three-climatic-variable regression method
TCVR	-	two-climatic-variable regression method
TRC	-	Turc's Method
U_2	-	windspeed measured at 2 m height, m s^{-1} or km day^{-1}
U_{24}	-	average windspeed over 24 hours measured at 2 m height, m s^{-1} or km day^{-1}
U_d	-	windspeed during day time, m s^{-1} or km day^{-1}
U_n	-	windspeed during night time, m s^{-1} or km day^{-1}
U_z	-	windspeed measured at z m height, m s^{-1} or km day^{-1}
$X_1, X_2, \ldots X_n$	-	variable 1,..... variable n
y	-	ET_o computed based on standard method. mm $month^{-1}$
y_{est}	-	ET_o computed based on non-standard method, mm $month^{-1}$
$\bar{y}$	-	mean ET_o computed based on standard method. mm $month^{-1}$
$W\phi$	-	Olivier's constant, dimensionless

z - the hight or elevation measured from ground surface, m (windspeed) or sea level (atmospheric pressure), m

z_o - elevation at reference level, m

α - canopy radiation reflection or albedo, dimensionless

α_{lap} - constant lapse rate saturated air = 0.0065 °K m^{-1}

β_H - Ostromecki's constant = 0.50

γ - psychrometric constant, kPa °C^{-1}

Δ - slope vapour pressure curve, kPa °C^{-1}

δ - solar declination, radians

f - a factor to adjust for cloud cover, dimensionless

ϵ - ratio of molecular weight of water vapour/dry air = 0.622

λ - latent heat of vaporization, MJ kg^{-1}

σ - Stefan-Boltzmann constant=4.90x10^{-9} MJ m^{-2} °K^{-4} day^{-1}

ε_a - effective emissivity of the temperature, dimensionless

ε_{vs} - emissivity by vegetation and soil, dimensionless

ε' - net emissivity, dimensionless

φ - latitude, radians

ω_s - sunset hour angle, radians

CHAPTER 1

INTRODUCTION

1.1 Background

The estimation of consumptive use or potential evapotranspiration of a crop (ET_c) is required in water resources planning and operation in order to devise optimal management systems for the use of water. ET_c can be estimated from direct and empirical formulas based on climatic data.

In Indonesia, direct measurement data are limited. Therefore, empirical formulae, which require climatic data for estimating potential evapotranspiration, are preferred. Estimations of potential evapotranspiration of a given crop can be calculated as follows:

$$ET_c = k_c \times ET_o \tag{1.1}$$

where ET_c = potential evapotranspiration, mm equivalent water evaporation $month^{-1}$

ET_o = reference evapotranspiration, mm equivalent water evaporation $month^{-1}$

k_c = crop coefficient.

The reference crop evapotranspiration is equal to the potential evapotranspiration from a reference crop: the definition of potential and reference evapotranspiration is given in Chapter 3. The crop coefficient depends on the type and stage of growth of a particular crop and irrigation scheduling.

A number of methods for estimating ET_o based on climatic data have been developed. However, climatic data required for some methods are difficult to obtain in Indonesia. The data available are usually mean monthly values.

Recently, a standard method for estimating ET_o has been published by the Food and Agricultural Organization (FAO) of the United Nations (Smith, 1991). The FAO recommends that other methods be calibrated in accordance with this standard method.

Most irrigation projects have been designed and implemented by using non-standard methods which may not be suitable in Indonesia. Thus, evaluation of the existing methods is urgently required so that efficient use of water resources may be made. In addition, it should be noted that the Department of Public Works of the Government of Indonesia is presently encouraging the establishment of guidelines for hydrology, which include the estimation of reference evapotranspiration based on available climatic data. The result of this study therefore, will be a useful tool for helping the Indonesian Government to meet its objectives for the Jawa area, and may possibly be applied to other islands in Indonesia as well as other tropical regions.

1.2 Objectives

The objectives of this study are as follows:

(i). To calculate ET_o using the standard and commonly used non-standard methods based on the available climatic data in Jawa.

(ii). To compare and select the best methods within each set of methods to suit the conditions in Jawa.

(iii). To adjust the best selected methods to obtain results that are on average closer to the standard method.

(iv). To derive new empirical equations which are applicable to Jawa using regression analysis.

1.3 Available Data

The climatic data which are available include: mean monthly air temperature and relative humidity, mean monthly sunshine duration, and wind speed. These data have been collected from 50 stations distributed over Jawa island. The data were published by the Meteorological and Geophysical Agency from 1971 to 1989. The stations are located mainly at altitudes lower than 250 meter above mean sea level (MSL). Forty one stations are located within this altitude range. The highest station is situated at 1399 meters above MSL. The number of observations-years varies from 1 to 17 years. Table 1.1 lists the meteorological stations used in this study and Figure 1.1 shows the location of the stations. The total number of data available for analysis are 4156 monthly data values.

Table 1.1 List of Meteorological Stations

No.	Station Name	Latitude South	Longitude East	Altitude Meter	Years of observation
1	Serang	6°07′	106°08′	25	14
2	Curug	6°14′	106°39′	46	13
3	Atang Senjaya	6°33′	106°46′	164	8
4	Darmaga	6°30′	106°46′	250	11
5	Jatiwangi	6°45′	108°16′	50	9
6	Tasikmalaya	7°29′	108°35′	350	8
7	Ciledug	6°16′	106°40′	26	10
8	Geofisika-Bdg	6°55′	107°36′	791	3
9	Husein S.	6°54′	107°35′	743	9
10	Pusakanegara	6°15′	107°45′	7	1
11	Kalijati	6°33′	107°41′	110	6
12	Tanjung Priok	6°06′	106°52′	2	17
13	Jakarta Obs.	6°10′	106°49′	7	17
14	Halim PK.	6°16′	106°51′	26	16
15	Kemayoran	6°09′	106°51′	6	14
16	Cilacap	7°44′	109°01′	6	17
17	Tegal	6°51′	109°09′	3	7
18	A.Yani-Smg	6°58′	110°22′	3	16
19	Maritim-Smg	6°57′	110°25′	1	9
20	Adi Sumarno	7°32′	110°55′	104	4
21	Colo	6°40′	110°05′	700	8
22	Beji	6°26′	110°48′	20	2
23	Bojongsari	7°25′	109°24′	68	5
24	Borobudur	7°07′	110°01′	270	4
25	Kledung	7°23′	110°01′	1399	10
26	Rendole	6°43′	111°01′	17	6
27	MPB-Semarang	6°59′	109°23′	3	7

Table 1.1 (continued)

No.	Station Name	Latitude South	Longitude East	Altitude Meter	Years of observation
28	Sempor	7°29′	109°19′	114	6
29	Wadaslintang	7°37′	110°55′	224	1
30	Iswahyudi	7°37′	111°31′	110	13
31	Selorejo	7°53′	112°21′	637	7
32	Surabaya-Perak	7°13′	112°45′	7	17
33	Pasuruan	7°38′	112°49′	4	7
34	UNBRA-Malang	7°57′	112°37′	505	12
35	Abd. R. Saleh	7°58′	112°42′	526	4
36	Banyuwangi	8°13′	114°23′	2	7
37	Kalianget	7°03′	113°58′	3	16
38	Sangkapura	5°51′	112°38′	3	12
39	Jatiroto	8°10′	112°20′	29	6
40	Maritim-Surabaya	7°13′	112°43′	3	6
41	PG. Wonolangun	8°14′	113°12′	100	3
42	Bulakmojo	7°36′	111°55′	50	3
43	Kening	7°00′	110°00′	42	6
44	AURI-Surabaya	7°13′	112°43′	3	3
45	Wlingi	8°05′	112°19′	174	3
46	Genteng	8°37′	114°23′	168	1
47	Adi Sucipto	7°47′	110°26′	122	16
48	UGM-Yogyakarta	7°46′	110°23′	137	3
49	Wonosari	7°56′	110°33′	179	2
50	Sukamandi	6°20′	110°30′	16	1

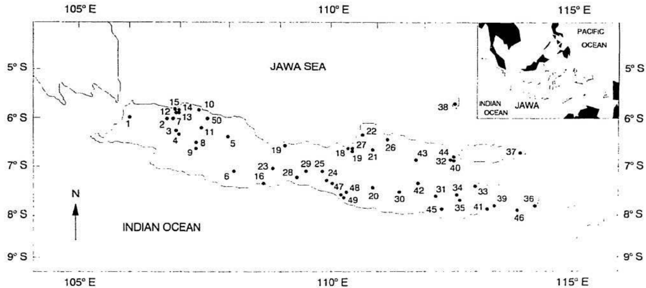

Figure 1.1 Location of Meteorological Stations

1.4 Outline of the thesis

Chapter 1 presents the outline of the study. Chapter 2 discusses the characteristics of the study area, Jawa, Indonesia. The theory of evaporation and evapotranspiration is described in Chapter 3. In chapter 4 the methods for estimating reference evapotranspiration are presented. The results of the comparison between the various methods are detailed in Chapter 5. Chapter 6 presents the discussion of the results. The conclusions and recommendations arising from this study are presented in Chapter 7.

CHAPTER 2

DESCRIPTION OF STUDY AREA

2.1 Location, Land use and Population

The area of study is Jawa island, one of the principal islands of Indonesia, which includes Madura and Bawean. This area consists of 5 provinces: West, Central, East Jawa, Jakarta Metropolitan District Area, and Yogyakarta Special District Area. Jawa is located in the southern part of Indonesia, which lies between 5°37.2′ and 8°49.2′ south latitude and between 105°06′ and 114°36′ east longitude. The location of the study area is shown in Figure 2.1.

This area is the most developed island in Indonesia. The land use patterns show considerable diversity, and include various types of land use: agricultural land with irrigated and non-irrigated areas, forest, human settlements and bare lands. Inhabitants grow rice, maize, cassava, sweet potatoes, soya beans, groundnuts, sugarcane, tea, tobacco, garlic and onions. Some of these products are intended for export, such as tobacco and tea. The rice growing area is about 55% of the total rice growing area in Indonesia. The forested lands makes up 22% of the total land area (Oldeman and Frere,

Figure 2.1 Map of Indonesia

1982). In order to increase the food production in Indonesia, so that the country can meet the demands of a growing population, various measures such as the intensified cultivation of arable lands have been tried. One alternative to this method is the expansion of the irrigated area by claiming more of the wetland.

The area of Jawa is about 127000 km^2. This island is the most densely populated island, with about 60 percent of the population occupying only 7% of the land area of Indonesia. The population of Indonesia is about 185 million. The population density is about 800 inhabitants per square kilometre, and the population growth is about 2 percent per year. Most of the population are employed in the agricultural sector and live in rural areas.

2.2. Topography

A range of volcanoes dissects the length of Jawa. The highest peaks are Mt. Cikuray (2821 m) in West Jawa, Mt. Sumbing (3371 m) and Mt. Merbabu (3142 m) in Central Jawa, Mt. Lawu (3638 m) and Mt. Mahameru (3678 m) in East Jawa. Some volcanoes are still active, such as Mt. Merapi in Central Java and Mt. Mahameru and Kelud in East Jawa. Some regions of this island are comprised of karst formation. The agricultural areas are concentrated in the volcanic slopes and alluvial plains where the soils are favourable for growing seasonal crops. Rivers flowing from volcanic slopes pass through volcanic plains before reaching the oceans. Hydraulic works like reservoirs, weirs, diversions, dikes and flood ways have been built to supply irrigation water and to protect settlements, industrial and agricultural areas which produce crops year-round.

2.3. Climate

The climate of this area is classified as humid tropic with uniformly high temperature, high humidity and heavy rainfall. There are two seasons in Jawa, a dry season from April to October and a wet or rainy season from November to March. The air circulation is affected by the mountains and this results in orographic rainfall types. High rainfall is found in the mountainous areas. Mean annual rainfall is about 2250 mm, mean annual temperature is about 26°C and mean annual relative humidity is about 70%.

The agroclimate of Jawa is suitable for multiple cropping practices, however, the water surplus during the wet season should be stored in order to adequately supply irrigation areas during the dry season.

2.4. Source of Data

In Indonesia, the Meteorological and Geophysical Agency, a branch of the Department of Communications, is responsible for meterological data management. The climatic data presented in this study have been obtained from this agency. Other institutions, such as the Department of Agriculture, Public Works, Mines and Energy and Forestry, also maintain meteorological stations but they send their data to the above mentioned agency for publication. For the purposes of this study, four types of data expressed in mean monthly values have been collected: air temperature, relative humidity, sunshine duration, and windspeed.

CHAPTER 3

EVAPORATION AND EVAPOTRANSPIRATION

3.1 Evaporation

This chapter describes the concepts, factors and measurement of evaporation and evapotranspiration.

3.1.1 Definition and the process of evaporation

Evaporation is the change of water from a liquid phase to a gaseous state and its diffusion into the air.

The molecules of water are in constant motion. Raising the temperature of water stimulates the molecules to become increasingly energized and to move more quickly, the result being an increase in distance between liquid molecules and an associated weakening of the forces between them. At high temperatures, more molecules near the water surface will tend to jump into the lower layer of the overlying air. At the same time, water vapour molecules in these lower air layers are also in continuous motion, and some of these will penetrate into the underlying mass of water. The rate of evaporation at any given time will, therefore, depend on the difference between the number of molecules leaving the water surface and the number of returning molecules (Ward, 1975). Approximately 2.5 million joules are required to evaporate one kilogram of water (Shuttleworth, 1993) or 586 calories per gram is required to evaporate water. For evaporation to occur continuously, there should be a supply of energy to provide this latent heat of evaporation and some mechanism to remove the water vapour (Singh, 1989; Ward, 1975).

3.1.2 Factors affecting evaporation

Evaporation depends on the supply of heat energy and the vapour pressure gradient, which, in turn, depend on meteorological factors such as water and air temperature, wind, atmospheric pressure, solar radiation, quality of water, and the nature and shape of the evaporating surface (Morton 1968 in Singh 1989; Ward 1975). These factors affect evapotranspiration as well.

Solar radiation is the principal energy source for evaporation (Jensen et al., 1990; Chang, 1971; Barry, 1971; Ward, 1975; Bruce and Clark, 1966). Since air and water temperature are largely dependent upon solar radiation, one would expect a fairly close correlation between the temperature at the interface of water and air and the rate of evaporation (Ward, 1975).

The rate of evaporation is proportional to the difference between the actual humidity and the saturated humidity at a given temperature. In general, the actual vapour pressure varies only slightly throughout the day. In contrast, relative humidity is a much more variable characteristic. As the relative humidity of the air over the evaporating surface area rises, proportionally fewer of the water vapour molecules leaving the evaporating surface can be retained in the air, so that the rate of evaporation is gradually reduced, although even at 100% relative humidity some evaporation normally takes place. Since relative humidity increases as the air temperature falls, even though the water vapour content of the air remains constant, it is easy to see why, if other conditions remain constant, a decrease in temperature will result in a decrease in the rate of evaporation. In cold weather, the rate of evaporation may be lower than in warm weather because the overlying air is able to hold only a small amount of water vapour below saturation level.

The rate of evaporation is almost always influenced by air movement. Turbulent movement is more important than the strength of the wind although in fact the degree of turbulence is closely related to wind velocity and to surface roughness - the latter factors being more important in relation to evaporation from a land surface. Wind does not actually *cause* evaporation but, by removing water vapour above the interface of water and air, allows a given rate of evaporation to be maintained (Ward, 1975).

The rate of evaporation may vary according to the water quality. When a solute is dissolved in water, it reduces the vapour pressure of the solution. This reduction in turn reduces the rate of evaporation, which is less than that of the fresh water. The rate of evaporation decreases with increases in specific gravity. There is about a 1% reduction in evaporation rate due to a 1% increase in specific gravity until crusting occurs, usually at a specific gravity of 1.3. The evaporation from sea water with an average salinity of 3.5% is some 2 to 3% less than the evaporation from fresh water. This difference is negligible for the purpose of estimation of reservoir evaporation (Singh, 1989). The turbidity of water probably has little effect upon evaporation although, by affecting the albedo (or reflectivity) of the water, and consequently its heat budgets and temperature, it may have an indirect effect (Ward, 1975). Monomolecular films such as, kerosene, benzene, petroleum ether, etc. over water surface may reduce reservoir or lake evaporation rate about 60% (Jones, 1992).

The effect of water depth and the size of water surface upon the rate of evaporation may be quite considerable. Large, deep lakes not only have a much higher capacity for heat storage than small water bodies, but in the middle and higher latitudes they normally experience a marked thermal stratification which also affects evaporation from their surface. The seasonal evaporation rate from shallow and deep lakes, therefore, varies very markedly (Ward, 1975).

Evaporation from soils is affected by the moisture content of the soil, soil capillary characteristics, water table depth, soil colour and the presence of vegetation. In the present study, the effects of the presence of vegetation on evaporation (evapotranspiration) is the main concern.

3.1.3 Measurement of Evaporation

Many devices have been developed to measure evaporation. Direct measurement is possible with the use of a Piche evaporimeter, Wild evaporimeter, Livingston atmometer, or evaporation pan. Indirect measurements can be determined from the eddy correlation and water budget technique (Brutsaert, 1982).

The Piche evaporimeter comprises of a glass tube closed at the top. It is 23 to 30 cm long and has an inside diameter of 1 cm. The tube is filled with water and a disk of blotting paper with an exposed area of 8 cm is held in place at the bottom. Scales on the tube indicate the amount of water evaporated through the paper. This device is placed in a meteorological shelter. Since the instrument is sheltered from solar radiation, measurements are affected by the vapour pressure deficit and have been shown to be empirically related to the aerodynamic portion of the Penman equation (Brutsaert, 1982).

The Wild evaporimeter is composed of a dish filled with water that is placed on a balance scale. The evaporation rate is indicated by the scale. The applicability of the data obtained in this way as a measure of natural evaporation is questionable (Brutsaert, 1982).

The Livingston Atmometer consists of a thin walled, porous porcelain ball, 5 cm in diameter with a narrow glazed tube connected to a supply of water. The capillary action of the porous material provides a uniform evaporating surface. Data from this instrument is difficult to analyze (Brutsaert, 1982).

The evaporation pan is the simplest and the most common instrument used to measure direct evaporation from a free water surface. The 'Class A' pan of the United States Weather Bureau, approved by the World Meteorological Organization, is 122 cm in diameter and 25.4 cm deep. Possible errors may be caused by overflowing, splashing, heating of the pan walls, and interference from birds or animals. The installation position (floating, sunken or mounted on or above the surface) is particularly critical. Unfortunately, pan evaporation is not correlated to lake evaporation in any simple or constant manner. Lake evaporation, however, can be estimated from a pan evaporation times pan coefficient. The pan coefficient, is generally between 0.6 to 0.8 for United States (Ward, 1975; Barry, 1971).

The 'evapotron', developed in Australia, is used to measured the magnitude and direction of vertical eddies which transfer water vapour upward. This complicated method is likely to be limited to research applications (Barry, 1971).

Evaporation can also be indirectly measured from a reservoir or lake by calculating the water balance of the lake. This technique is based on a principle of continuity which holds that the sum of water inflow equals the sum of outflow plus storage. Because of many possible errors such as the stage-area data relationship and inflow and outflow measurements, the accuracy of this method is not generally considered reliable (Brutsaert, 1982).

3.2 Evapotranspiration

3.2.1 Definition and Process of Evapotranspiration

Evapotranspiration (ET) is the combined evaporation from all surfaces and the transpiration of plants. Transpiration has been defined as '... the process by which water vapour escapes from living plants, principally the leaves, and enters the atmosphere' (Ward, 1975). The terms consumptive use and evapotranspiration are considered synonymous because the amount of water contained within plant tissue is extremely small compared to that evaporated from soil and plant surface. Internationally, the term evapotranspiration is more common than consumptive use (Jensen et al., 1990).

Potential evapotranspiration (ET_p) is the rate at which water, if available, would be removed from wet soil and plant surfaces. It is expressed as the rate of latent heat transfer per unit area or as a depth of water per unit of time. The potential evapotranspiration for a particular crop (ET_c) depends on the height and the leaf type of the crop and is independent of the available soil moisture.

Reference evapotranspiration (ET_o) is defined as the rate of evapotranspiration from a hypothetical crop with an assumed crop height (12 cm) and a fixed canopy resistance (70 s m^{-1}) and albedo (0.23). This crop closely resemble evapotranspiration from an extensive surface of green grass cover of uniform height, actively growing, completely shading the ground, and having no shortage of water (Smith, 1991). In fact, the reference evapotranspiration is the same as potential evapotranspiration for the reference crop.

Transpiration or water loss from plants takes place when the vapour pressure in the air is less than that in the leaf cells. The water loss occurs mainly in the daytime, because water vapour is transpired through small pores, or stomata, in the leaves, which open in response to stimulation by light. Transfer of water vapour to the atmosphere is the initiating process in the movement of water from the soil via the plant. This process is vital in the internal transport of nutrients and in cooling leaf surfaces. The amount of water used in transpiration is much greater than the direct water needs of the plants.

Resistances to water movement in the soil and in plant tissues include soil-water tension, the resistance of cell walls in the roots and leaves to water transport, and the resistance of stomata to vapour transfer. The internal (stomata) resistance of a single leaf to diffusion represents an important controlling factor in the transpiration process. It is dependent on the size and distribution of the stomata. For a crop or vegetation cover with several leaf layers, the effective stomatal resistance (r_s) is reduced to approximately 30% of that of an individual leaf, owing to the decreased ventilation within the cover. Seasonal variations associated with changes in the leaf area affect r_s, as do diurnal variations. The latter result partly from the opening and closing of the stomata when water uptake lags behind transpiration. A separate external resistance of the air to molecular diffusion (r_a) arises through frictional drag of air over the leaf (larger leaves have lower transpiration rates) and the interference between diffusing molecules of water vapour. A decrease in r_a may be due to higher wind speeds or greater 'roughness' of the vegetation surface, which causes increased turbulence in the air flow. Generally the stomatal resistance r_s is larger than r_a, although, the interaction of r_s and r_a is an important determinant of evaporation rates (Barry, 1971).

3.2.2 Factors affecting evapotranspiration

The rate of evapotranspiration depends on the evaporative power of the air as determined by temperature, wind, humidity and radiation (Chang, 1968). Chang (1968) also reports that Mukammal and Bruce (1960) found that the relative importance of radiation, humidity and wind in determining pan evaporation are in the ratio 80:6:14 respectively. Thus, radiation is the dominant factor for potential evapotranspiration (Jensen et al., 1990; Chang 1968). Climatic factors affecting free-water surface evaporation such as radiation, temperature, humidity and wind velocity obviously also affect evapotranspiration. Other factors controlling evapotranspiration are soil and vegetation (Singh, 1989). Evapotranspiration tends to increase as the temperature, solar radiation, and windspeed increase and as humidity decreases (Ward, 1975).

Soil factors, soil moisture in particular, restrict the rate of evapotranspiration. Evapotranspiration decreases with the soil moisture.

The effect of vegetation type on evapotranspiration is due to the reflectivity or albedo of the vegetation surface which materially influences the energy balance at the evaporating surface. The evapotranspiration rate will vary with the main stages of plant development, for example during ripening stage the evapotranspiration rate may decrease significantly below the potential rate (Ward, 1975). The consumptive use of water of a crop also varies with the height of the crop. Evapotranspiration rate of a tall crop is more than twice that of a short crop (Chang, 1968).

3.2.3 Measurement of Potential Evapotranspiration

Various methods for measuring evapotranspiration include tanks and lysimeters, field plots, and inflow-outflow measurements.

Lysimeters are tanks filled with soil in which crops are grown under natural conditions and the amount of water lost by evaporation and transpiration is measured. There are several types of lysimeters and tanks. These are equipped to record precipitation, runoff, gravity flow, and changes in soil moisture, thus providing information from which evapotranspiration can be directly evaluated. Lysimetry is the only method which provides direct measurement of evapotranspiration. Lysimetres are frequently used to investigate climatic effects and to evaluate other methods of estimation of ET_p. Errors can occur due to the differences between the lysimeter and natural condition in soil profile, soil moisture regime, plant root characteristics, methods of application, and net energy exchange. If their installations satisfy certain minimum standards, however, lysimeters provide the most reasonably reliable measurement of ET_p for short time periods (Singh, 1989).

Field plots must be selected in places where the water table is deep so that plants do not extract ground water. Crops are grown under natural conditions. An inventory of water added by precipitation and irrigation, surface runoff, and change in soil moisture is prepared. Since water is added to plots in small quantities, deep percolation is minimized and not measured. ET_p is the residual in the water balance. The primary advantage of using field plots is that ET_p is measured under field conditions (Singh, 1989).

For large catchments, where lysimeters can not be used, evapotranspiration can be determined under natural conditions by observing differences between inflow and outflow and adjusting for changes in ground water storage. These differences are considered as ET_p values. This method provides only gross estimates of ET_p for extended time intervals (seasonal, annual) and should not be used for short-term rates within a season (Singh, 1989).

Evapotranspiration can also be estimated under natural conditions by observing changes in soil moisture over a period of time. The soil is usually sampled at several representative sites, where the water table is deeper than the plant root zone, especially during periods of light rainfall in order to minimize drainage. The same sites are measured each time to minimize error due to soil variability. The major source of error with this method is drainage from the zone sampled or upward movement from a saturated zone (Singh, 1989).

3.3 Actual evapotranspiration

The rate of actual evapotranspiration (AET) is maintained at the potential rate (ET_p), when the water supply is unlimited. As the soil dries out, the actual evapotranspiration will fall below the potential rate.

One view is that the potential evapotranspiration rate is maintained until soil-moisture content drops below some critical value, after which there is a sharp decrease in evapotranspiration. An alternative explanation is that the rate decreases progressively with diminishing soil moisture. At field capacity (maximum soil moisture content under free drainage), $AET/ET_p = 1$. That is, evaporation proceeds at the maximum potential rate. Chang (1968) reported that Veihmeiyer and Hendrickson in 1955 consider that no change takes place in this ratio until the plant is near the wilting point. Chang (1968) reported that Thornthwaite and Mather (1955) assume the decrease below field capacity to be a logarithmic function of soil suction. But more recent work suggests that $AET/ET_p \approx 1$ as long as the moisture content is at least 75% of field capacity (Chang, 1968). The soil type and climatic conditions are important factors in the actual evapotranspiration process. Soil moisture capacity depends on the soil type, and ranges from 25 mm in shallow sandy soil to 550 mm in deep clay-loams (Chang, 1968). Veihmeyer and

Hendrickson's results may be applied to a heavy soil with vegetation cover in humid, cloudy regions, whereas in sandy soils with vegetation cover under arid conditions a rapid decline in AET/ET_p is likely (Barry, 1971). The relation between actual and potential evapotranspiration can be expressed as (Thornthwaite and Mather, 1955):

$$AET = ET_p \, (M/C) \tag{3.1}$$

where AET = actual evapotranspiration, mm equivalent water evaporation month^{-1}

ET_p = potential evapotranspiration, mm equivalent water evaporation month^{-1}

M = the available soil moisture, mm month^{-1}

C = the available of soil moisture capacity, mm month^{-1}.

In Indonesia, an equation for estimating monthly actual evapotranspiration has been presented by Mock in 1973. Based on a study using data from Indonesia, Mock (1973) suggested that the monthly actual evapotranspiration (AET) for water balance analysis can be computed from:

$$AET = ET_p - ET_p \, (m/20)(18-n_R) \tag{3.2}$$

where AET = actual evapotranspiration, mm equivalent water evaporation month^{-1}

ET_p = potential evapotranspiration, mm equivalent water evaporation month^{-1}

m = percentage of non vegetated land, %

n_R = number of rainy days.

In contrast to potential evapotranspiration, actual evapotranspiration is a more complex process because it depends on the availability of soil moisture. In a catchment area the actual evapotranspiration from a river basin ma_ be estimated by using a rainfall-runoff soil moisture accounting model. The soil moisture and evapotranspiration, the two unmeasurable factors are estimated from the measurable factors: rainfall as data input and runoff as data output.

CHAPTER 4

METHODS OF ESTIMATING EVAPOTRANSPIRATION

This chapter describes the methods of estimating evapotranspiration used in this study.

4.1 General

In this study, methods for estimation of ET_o have been selected based on the availability of meteorological data such as mean monthly air temperature, relative humidity, sunshine duration, and windspeed. These methods are classified into four groups depending on the number of climatic variables used, which range from one to four. The FAO standard (STD) method requires these four types of data. In this study, the other methods are referred to as non-standard methods.

Methods that require temperature data only are referred to here as one-climatic-variable methods, and they include:

- Thornthwaite's (THR) method,
- Hamon's (HMN) method, and
- Blaney-Criddle's (BCR) method.

Methods that require temperature and relative humidity data are referred to here as two-climatic-variable methods, and they include:

- Olivier's (OLV) method,
- Hargreaves' 1974 (HGF-74) method,
- Ostromecki's (OST) method,
- David's (DVD) method,
- Prescott's (PRS) method,
- Ivanov's (IVN) method,
- Behnke-Maxey's (BMX) method,
- Hargreaves' Rs (HGF-RS) method and
- Stephens's (STP) method.

Methods that require temperature, relative humidity and sunshine duration as data input are referred to here as three-climatic-variable methods, and they include:

- Hargreaves' Rn (HGF-RN) method,
- FAO Radiation Uncorrected (FAO-RAD c=1) method,
- Priestly-Taylor's (PTL) method,
- Makkink's (MKK) method, and
- Turc's (TRC) method.

The methods which employ all four climatic variables (temperature, relative humidity, sunshine duration, and windspeed) include:

- Penman's (PNM) method,
- Penman-Wright-Jensen's 1972 (PWJ-72) method,
- FAO Penman Corrected (FAO-PNM) method,

- FAO Penman Uncorrected (FAO-PNM c=1) method,
- FAO Radiation Corrected (FAO-RAD) method,
- FAO Plant Production and Protection Penman (FAO-PPP-PNM) method, and
- FAO Blaney-Criddle Corrected (FAO-BCR) method.

The data requirements and the references for the methods are shown in Table 4.1. The details of each method such as the equation, estimated parameters and empirical constants will be described in the next section.

In the calculation, monthly ET_o estimates are obtained by multiplying daily ET_o estimates by the number of days of the month.

4.2 FAO's Standard Method

The FAO standard method estimates reference crop evapotranspiration (ET_o) from the dry surface canopy. It is based on energy and aerodynamic principles. This method requires observations of temperature, humidity, radiation (which may be derived from cloud cover or sunshine duration), and wind speed. The FAO standard has been successfully tested using measured ET_o data from USA, Europe, Australia, and Africa. It has now replaced the FAO 1977 equation as the standard. Smith (1991) reported that the equation for the FAO standard method for calculating the reference evapotranspiration is based on the Penman-Monteith equation (Monteith, 1965) and is given by:

Table 4.1 Classif.cation, Data requirement and Reference of methods for estimating ET_o

Method	Data requirement				Reference
	T	rh	ss	U_2	
Standard	*	*	*	*	Smith, 1991; Jensen at. al 1990
1-Climatic Variable					
Thornthwaite	*				Thornthwaite, 1948
Hamon	*				Hamon, 1961
Blaney-Criddle	*				Bonier,1979; Jensen et al., 1990
2-Climatic-Variables					
Olivier	*	*			Olivier, 1964
Hargreaves 1974	*	*			Hargreaves, 1974
Ostromecki	*	*			Jensen, 1974
David	*	*			Jensen, 1974
Prescott	*	*			Jensen, 1974
Ivanov	*	*			Jensen, 1974
Behnke-Maxey	*	*			Jensen, 1974
Hargreaves Rs	*		*		Hargreaves et al., 1985; Jensen et al., 1990
Stephens	*		*		Jensen, 1974
3-Climatic Variables					
Hargreaves Rn	*	*	*		Hargreaves et al., 1985
FAO Radiation Uncorrected	*	*	*		Jensen et al., 1990
Priestly-Taylor	*	*	*		Jensen et al., 1990
Makkink	*	*	*		Jensen et al., 1990
Turc	*	*	*		Turc, 1954
4-Climatic Variables					
Penman	*	*	*	*	Penman, 1948, 1963; Olivier, 1964
Penman-Wright-Jensen 1972	*	*	*	*	Jensen, 1974
FAO Penman Corrected	*	*	*	*	Jensen et al., 1990
FAO Penman Uncorrected	*	*	*	*	Jensen et al., 1990
FAO Radiation Corrected	*	*	*	*	Jensen et al., 1990
FAO PPP Penman	*	*	*	*	Frere and Popov, 1979
FAO Blaney-Criddle	*	*	*	*	Jensen et al., 1990

$$ET_o = \frac{\frac{\Delta R_n}{\lambda} + \gamma \frac{900}{T + 273.15} U_2 (e_a - e_d)}{\Delta + \gamma (1 + 0.34 U_2)} \quad (4.1)$$

where ET_o = reference crop evapotranspiration, (mm equivalent water evaporation day^{-1})

R_n = net radiation at crop surface, ($MJ\ m^{-2}\ day^{-1}$)

λ = latent heat of vaporization, ($MJ\ kg^{-1}$)

T = mean monthly air temperature, (°C)

U_2 = windspeed measured at 2 m height, ($m\ s^{-1}$)

e_a = saturation vapour pressure, (kPa)

e_d = vapour pressure at dew point, (kPa)

Δ = the slope of the vapour pressure curve, ($kPa\ °C^{-1}$)

γ = a psychrometric constant, ($kPa\ °C^{-1}$)

900 = a constant, ($kJ^{-1}\ kg\ °K$)

and R_n is estimated from:

$$R_n = R_{ns} - R_{nl} \quad (4.2)$$

where R_{ns} = net incoming short wave radiation, ($MJ\ m^{-2}\ day^{-1}$)

R_{nl} = net outgoing long wave radiation, ($MJ\ m^{-2}\ day^{-1}$)

and R_{ns} is calculated using:

$$R_{ns} = (1 - \alpha)\ R_s \qquad (4.3)$$

where α = canopy radiation reflection or albedo = 0.23 for grass (Smith, 1991; Jensen et.al., 1990)

R_s = incoming solar radiation, (MJ m^{-2} day^{-1})

and R_s is estimated by:

$$R_s = (a_s + b_s \frac{n}{N})\ R_a \qquad (4.4)$$

where a_s = a fraction of extra terrestrial radiation (Ra) on overcast days ≈ 0.25 (Smith, 1991)

b_s ≈ 0.50 (Smith, 1991)

a_s+b_s = a fraction of radiation on clear days ≈ 0.75

n/N = relative sunshine fraction expressed as percentage

n = bright sunshine hours per day, (hours)

N = maximum day light hours, (hours)

R_a = extra terrestrial radiation, (MJ m^{-2} day^{-1})

and R_a is calculated from:

$$R_a = 37.60\ d_r\ (\omega_s \sin\varphi \sin\delta + \cos\varphi \cos\delta \sin\omega_s) \qquad (4.5)$$

where d_r = the relative distance between earth and sun

δ = the solar declination, (radians)

φ = latitude, (radians)

ω_s = sunset hour angle, (radians)

and ω_s is estimated using:

$$\omega_s = arcos(-\tan\varphi \tan\delta) \tag{4.6}$$

or as defined by Jensen et. al., (1990)

$$\omega_s = \frac{\pi}{2} - \arctan\frac{[-\tan\varphi\tan\delta]}{\sqrt{1 - \tan^2\varphi\tan^2\delta}} \tag{4.7}$$

where δ = solar declination, (radians)

φ = latitude, (radians)

and d_r is estimated from:

$$d_r = 1 + 0.033 \cos(\frac{2\pi}{365} JD) = 1 + 0.033 \cos (0.0172 JD) \tag{4.8}$$

and δ is calculated from:

$$\delta = 0.409 \sin(\frac{2\pi}{365} JD - 1.39) = 0.409 \sin (0.0172 JD - 1.39)$$

where JD = the Julian day (see Table 4.2)

Table 4.2 Julian days of the year representing the middle of the month (Duffie and Beckman, 1980)

Year	Month											
	J	F	M	A	M	J	J	A	S	O	N	D
Normal	17	47	75	105	135	162	198	228	258	288	318	334
Leap	17	47	76	106	136	163	199	229	259	289	319	335

The maximum day light hours (N) is estimated using:

$$N = \frac{24}{\pi}\,\omega_s \tag{4.10}$$

and R_{nl} is calculated using:

$$R_{nl} = -R_{ld}\downarrow + R_{lu}\uparrow = f(\varepsilon_a - \varepsilon_{vs})\,\sigma\,T_k^4 \tag{4.11}$$

where $R_{lu}\uparrow$ = outgoing thermal radiation emitted by vegetation and soil into the atmosphere (upward flux), (MJ m^{-2} day^{-1})

$R_{ld}\downarrow$ = incoming long wave (thermal) radiation emitted by the atmosphere and cloud cover to the earth surface (downward flux), (MJ m^{-2} day^{-1})

f = a factor to adjust for cloud cover, dimensionless

ε_a = effective emissivity of the atmosphere

ε_{vs} = emissivity by vegetation and soil $\approx$ 0.98 (Jensen et. al. , 1990)

σ = Stefan-Boltzmann constant = 4.90×10^{-9} MJ m^{-2} K^{4} day^{-1}

T_k = mean monthly air temperature, (°K)

The factor to adjust for cloud cover (f) is calculated using:

$$f = 0.9\ n/N + 0.1 \tag{4.12}$$

The net emissivity (ε') is estimated using:

$$\varepsilon' = (\varepsilon_a - \varepsilon_{vs}) = \left(a_{re} + b_{re}\sqrt{e_d}\right) \approx \left(0.34 - 0.14\sqrt{e_d}\right) \tag{4.13}$$

where ε_a = effective emissivity by atmosphere

ε_{vs} = emissivity by vegetation and soil = 0.98

a_{re} = an empirical coefficients ≈ 0.34 - 0.44

b_{re} = an empirical coefficients ≈ -0.14 - -0.25

The windspeed at 2 m height is calculated using:

$$U_2 = U_z\left(\frac{4.87}{\ln(67.8\ z - 5.42)}\right) \tag{4.14}$$

where U_2 = the windspeed measured at 2 m height, (m s^{-1})

U_z = the windspeed measured at z m height, (m s^{-1})

z = the height of windspeed measurement, (m)

The z value for the available data is 4 m.

The saturation vapour pressure (e_a) is estimated using:

$$e_a = 0.611\ \exp\left(\frac{17.27\ T}{T+237.3}\right) \tag{4.15}$$

The actual vapour pressure (e_d) is calculated from:

$$e_d = e_a \times rh \tag{4.16}$$

where rh = mean monthly relative humidity, (%)

The slope of the vapour pressure curve (Δ) is calculated using:

$$\Delta = \frac{4098\ e_a}{(T+237.3)^2} \tag{4.17}$$

where Δ = the slope of the vapour pressure curve, (kPa°C^{-1})

T = mean monthly air temperature, (°C)

e_a = saturation vapour pressure at temperature T, (kPa)

The psychrometric constant, γ is estimated from:

$$\gamma = \frac{c_p P}{\epsilon \lambda} \times 10^{-3} = 0.00163\ \frac{P}{\lambda} \tag{4.18}$$

where γ = a psychrometric constant, (kPa °C^{-1})

c_p = specific heat of moist air = 1.013, (kJ kg^{-1} °C^{-1})

P = atmospheric pressure (kPa)

ϵ = ratio of molecular weight water vapour/dry air = 0.622

λ = latent heat of vaporization, (MJ kg^{-1})

The atmospheric pressure (P) is calculated from:

$$P = P_o \left(\frac{T_{ko} - \alpha_{lap}(z - z_o)}{T_{ko}} \right)^{\frac{g}{\alpha_{lap} R}} \tag{4.19}$$

where P = atmospheric pressure at elevation z, (kPa)

P_o = atmospheric pressure at sea level, (kPa)

z = elevation, (m)

z_o = elevation at reference level (0) , (m)

g = gravitational acceleration = 9.8 m s^{-2}

R = specific gas constant = 287 J kg^{-1} $°K^{-1}$

T_{ko} = reference temperature, °K at elevation z_o $\simeq 273.15 + T(°C)$

α_{lap} = constant lapse rate of saturated air = 0.0065 °K m^{-1}

The latent heat of vaporization (λ) is estimated using:

$$\lambda = 2.501 - (2.361 \times 10^{-3})\ T \tag{4.20}$$

where λ = latent heat of vaporization, (MJ kg^{-1})

T = mean monthly air temperature, (°C)

4.3. One-Climatic-Variable Methods

The one-climatic-variable methods require temperature data only. The Thornthwaite, Hamon and Blaney-Criddle methods are examples of this type of method. Because they use temperature data only, they are often referred to as temperature methods.

4.3.1. Thornthwaite's Method

The Thornthwaite method is the earliest and one of the most widely used of the one climatic variable methods. This method is based on an annual temperature efficiency index, I, which is defined as the sum of 12 monthly values of heat index, i. Each index is a function of the mean monthly air temperature T, in degrees Celsius. The Thornthwaite formula (Thornthwaite 1948) is:

$$ET_o = 1.6\ p\ (10\frac{T}{I})^{a_{TH}} \tag{4.21}$$

where ET_o = reference evapotranspiration, (cm equivalent water evaporation $month^{-1}$)

I = sum of monthly heat index (i)

i = monthly heat index = $(T/5)^{1.514}$ (4.22)

a_{TH} = $0.000000675I^3 - 0.0000771I^2 + 0.01792I + 0.49239$ (4.23)

p = daytime hours in units of 12 hours, as a function of latitude and month (see Table 4.3).

This formula does not apply for high temperatures. For T > 26.5 °C, which occurs frequently in a tropical or hot climate, Thornthwaite provided a table for estimating ET_0 (see Table 4.4). Many text books on hydrology, e.g, Gray et. al., (1970), Jensen (1974), and Ponce (1989) do not present this table, which may account for different estimates of ET_0. In Indonesia the Thornthwaite method is a popular method, particularly because temperature values are the only data required as input and often the only reliable data available, but it may not be the best temperature based method due to the fact that it was developed for use in temperate regions (east-central USA).

Table 4.3 Daytime hours of units of 12 hours (Thornthwaite, 1948)

Latitude South	Month											
	J	F	M	A	M	J	J	A	S	O	N	D
5°	1.06	0.95	1.04	1.00	1.02	0.99	1.02	1.03	1.00	1.05	1.03	1.06
6°	1.06	0.95	1.04	1.00	1.02	0.99	1.02	1.03	1.00	1.05	1.03	1.07
7°	1.07	0.96	1.04	1.00	1.02	0.98	1.01	1.02	1.00	1.05	1.04	1.07
8°	1.07	0.96	1.05	1.00	1.02	0.98	1.01	1.02	1.00	1.06	1.04	1.08
9°	1.08	0.97	1.05	0.99	1.01	0.97	1.00	1.02	1.00	1.06	1.05	1.09
10°	1.08	0.97	1.05	0.99	1.01	0.96	1.00	1.01	1.00	1.06	1.05	1.10

Table 4.4 Reference evapotranspiration for temperatures above 26.5°C (Thornthwaite, 1948)

Temperature, (°C)	ET_o, (cm equivalent water evaporation)
26.5	13.5
27.0	13.95
27.5	14.37
28.0	14.78
28.5	17.17
29.0	15.54
29.5	15.89
30.0	16.21
30.5	16.52
31.0	16.80
31.5	17.07
32.0	17.31
32.5	17.53
33.0	17.72
33.5	17.90
34.0	18.05
34.5	18.18
35.0	18.29
35.5	18.37
36.0	18.43
36.5	18.47
37.0	18.49
37.5	18.50
38.0	18.50

4.3.2 Hamon's Method

Hamon (1961) designed an equation to estimate evapotranspiration based on saturated vapour density as a function of absolute humidity at saturation. This value can be calculated based on air temperature and possible hours of sunshine duration. This method has been evaluated using lysimeter data from USA and is sometimes used in Indonesia. His equation is as follows:

$$ET_o = C_{HMN}\, p^2 P_t \tag{4.24}$$

where ET_o = reference evapotranspiration, (inches equivalent water evaporation day^{-1})

P_t = saturated water-vapour density (absolute humidity at saturation) at the mean monthly air temperature, ($g\ m^{-3} \times 10^{-2}$) (Table 4.5)

C_{HMN} = a coefficient. The value of 0.55 has been empirically determined by Hamon for estimating reference evapotranspiration (Hamon, 1961)

p = same p as in Thornthwaite's equation.

Table 4.5 Saturated water-vapour density (Bonier, 1979; Jensen et al., 1990)

Temperature °C	Water-vapour density $g\ m^{-3} \times 10^{-2}$
10	9.3
15	12.3
20	17.1
25	22.8
30	30.4
35	39.6

4.3.3 Blaney-Criddle's Method

The Blaney-Criddle formula developed in semi arid lands of the western USA is typical of the one climatic variable models for estimating evapotranspiration which requires temperature data as the only input. Reference evapotranspiration is calculated from potential evapotranspiration using as the crop coefficient for grass. It is a simple method, therefore is used frequently in Indonesia. The Blaney-Criddle formula in SI units is:

$$ET_o = k_c\ p_{BC}(0.4572T + 8.128) \qquad (4.25)$$

where ET_o = reference crop evapotranspiration, (mm equivalent water evaporation day^{-1})

k_c = reference crop coefficient (0.75) (Veihmeyer, 1964; Ward, 1975)

p_{BC} = Coefficient for Blaney-Criddle's Equation (Table 4.6).

Table 4.6 Coefficient for Blaney-Criddle equation (Doorborens and Pruits, 1977)

Lats South	Month											
	J	F	M	A	M	J	J	A	S	O	N	D
5°	0.28	0.28	0.28	0.27	0.27	0.27	0.27	0.27	0.27	0.28	0.28	0.28
10°	0.29	[illegible]	0.28	0.27	0.26	0.26	0.26	0.27	0.27	0.28	0.28	0.28

4.4 Two-Climatic-Variable Methods

The two-climatic-variable methods require temperature and humidity or sunshine duration. These methods include Olivier's, Hargreaves' '74, Ostromecki's, David's, Prescott's, Ivanov's, Behnke-Maxey's, Hargreaves' Rs, and Stephens' methods. The value of e_a, e_d and γ are calculated using the same way as in the standard method and the units are converted accordingly.

4.4.1 Olivier's Method

Olivier (1964) developed an equation for estimating ET_o based on the average depression of the wet bulb temperature and a constant which depends on latitude and month. This method has been tested successfully using data from USA. The equation is:

$$ET_o = (T - T_w)\ W_\phi \qquad (4.26)$$

where ET_o = reference crop evapotranspiration, (mm equivalent water evaporation day^{-1})

T_w = the wet-bulb temperature, (°C)

W_ϕ = Coefficient for Olivier Equation (Table 4.7)

The value of $T-T_w$ is calculated by trial and error from the equation:

$$(e_a - e_w) = \gamma\ (T - T_w) \qquad (4.27)$$

where e_a = mean monthly saturation vapour pressure, (mb)

e_w = mean monthly vapour pressure at wet bulb temperature, (mb)

4.4.2 Hargreaves' '74 Method

Hargreaves (1974) proposed the following equation to estimate ET_o which requires both temperature and relative humidity data. This method has been tested using measured ET_o data from USA, Denmark, Australia, Lebanon, Congo, and coastal Ecuador. It has also been used in Malaysia. The Hargreaves '74 formula is:

$$ET_o = 3.96 + 0.966\ MF\ (1.8T + 32) \times 0.166\ \sqrt{(100 - rh)} \qquad (4.28)$$

where ET_o = reference crop evapotranspiration, (mm equivalent water evaporation month^{-1})

MF = a monthly factor depending upon latitude, see Table 4.8

rh = mean monthly relative humidity, (%)

T = mean monthly air temperature, (°C)

4.4.3 Ostromecki's Method

Jensen, 1974 reported that Ostromecki (1965) suggested a formula for estimating ET_o based on vapour pressure deficit data. This method was developed in eastern Europe. The formula is:

$$ET_o = \beta_H (e_a - e_d) \tag{4.29}$$

(Jensen, 1974)

where β_H = a "hygrometric" coefficient = 0.56 (Jensen, 1974)

e_a = saturation vapour pressure, (mb)

e_d = vapour pressure at dew point, (mb)

Table 4.7 Coefficient Wϕ for Olivier Equation (Olivier, 1964)

Latitudes South	Month											
	J	F	M	A	M	J	J	A	S	O	N	D
5°	0.67	0.71	0.73	0.69	0.61	0.57	0.61	0.66	0.73	0.74	0.69	0.65
6°	0.68	0.71	0.73	0.68	0.61	0.57	0.60	0.66	0.73	0.74	0.70	0.66
7°	0.68	0.71	0.73	0.68	0.61	0.56	0.59	0.65	0.72	0.74	0.71	0.67
8°	0.69	0.72	0.74	0.67	0.59	0.55	0.58	0.65	0.72	0.74	0.72	0.68
9°	0.69	0.72	0.74	0.67	0.58	0.54	0.57	0.64	0.71	0.74	0.73	0.69
10°	0.70	0.72	0.74	0.66	0.58	0.53	0.56	0.64	0.71	0.74	0.73	0.70

Table 4.8 Coefficient MF for Hargreaves Equation (Hargreaves, 1974)

Lats South	Month											
	J	F	M	A	M	J	J	A	S	O	N	D
5°	2.418	2.189	2.363	2.134	2.020	1.854	1.968	2.126	2.234	2.411	2.345	2.407
6°	2.447	2.205	2.363	2.117	1.980	1.820	1.926	2.101	2.228	2.422	2.371	2.442
7°	2.478	2.221	2.363	2.099	1.959	1.785	1.893	2.078	2.218	2.433	2.397	2.470
8°	2.508	2.237	2.362	2.081	1.927	1.750	1.854	2.054	2.210	2.443	2.423	2.510
9°	2.538	2.251	2.360	2.062	1.896	1.715	1.824	2.026	2.201	2.453	2.448	2.544
10°	2.567	2.266	2.357	2.043	1.864	1.679	1.789	2.003	2.191	2.462	2.473	2.577

4.4.4 David's Method

Jensen (1974) reported that, in 1936, David proposed an equation for estimating ET_o requiring temperature and humidity data. The equation is as follows:

$$ET_o = 0.50(e_a - e_d) \tag{4.30}$$

4.4.5 Prescott's Method

Similar to David (1936), it has been reported by Jensen (1974) that Prescott (1949) suggested a formula to estimate ET_o, which is expressed as:

$$ET_o = (e_a - e_d)^{0.75} \tag{4.31}$$

(Jensen, 1974)

4.4.6 Ivanov's Method

Jensen (1974) reported that Ivanov (1954) developed an equation for estimating ET_o. This is a two climatic variable method which requires temperature and relative humidity as data input. The equation is expressed as follows:

$$ET_o = 0.0018\ (25 + T)^2(100 - rh) \tag{4.32}$$

(Jensen, 1974)

where ET_o = reference evapotranspiration, (mm equivalent water evaporation month^{-1})

T = mean monthly air temperature, (°C)

rh = mean monthly relative humidity, (%)

4.4.7 Behnke-Maxey's Method

Behnke-Maxey (1969) proposed an equation which requires temperature and humidity data (Jensen, 1974). This method is similar to the Olivier method. The formula for this method is:

$$ET_o = \frac{T}{1.9} W_\phi \tag{4.33}$$

(Jensen, 1974)

where ET_0 = reference evapotranspiration, (mm equivalent water evaporation day^{-1})

W_ϕ = Coefficient for Olivier's equation (Table 4.7)

T = mean monthly air temperature, (°C)

4.4.8 Hargreaves Rs Method

Hargreaves et al. (1985) developed an equation to estimate ET_o that required temperature and solar radiation data which can be computed using sunshine data. The Hargreaves Rs equation is:

$$ET_o = 0.0075\ R_s\ T_m \tag{4.34}$$

where ET_0 = reference evapotranspiration, (mm equivalent water evaporation day^{-1})

R_s = solar radiation, (mm of equivalent water evaporation day^{-1})

T_m = mean monthly temperature, (°F)

To convert the units of Rs from MJ m^{-2} day^{-1} to mm of equivalent water evaporation day^{-1}, the earlier unit is divided by the latent heat of vaporization (λ), or multiplying by 0.408 (Smith, 1991).

4.4.9 Stephens's method.

Stephens developed his equation in 1965 and it is also a two climatic variable method (Jensen, 1974). His method was developed using data from Florida. The formula for Stephen's method is:

$$ET_o = (0.014\ T_m - 0.37)\ \frac{R_s}{1500} \tag{4.35}$$

(Jensen, 1974)

where ET_0 = reference evapotranspiration, (inches equivalent water evaporation day^{-1})

R_s = solar radiation, (cal cm^{-2} day^{-1})

T_m = mean monthly temperature, (°F)

To convert the unit of Rs from cal cm^{-2} day^{-1} to mm of equivalent water evaporation day^{-1}, the earlier unit is divided by the latent heat of vaporization (λ), or 58.6 (Smith, 1991).

4.5 Three-Climatic-Variable Methods

The three-climatic-variable methods considered include Hargreaves' Rn, FAO Uncorrected Radiation, Priestly-Taylor's, Makkink's, and Turc's methods. These methods require temperature, humidity, and radiation data. The values for R_s, R_n, Δ, γ are calculated using the same procedure as in the standard method and the units are converted accordingly.

4.5.1 Hargreaves' Rn Method

Hargreaves et al. (1985) proposed a formula for estimating ET_o which uses three kinds of data: temperature, relative humidity and radiation or sunshine duration. In this equation the net radiation is used in conjunction with the solar radiation.

$$ET_o = 0.0075\ Rn\ T_m \tag{4.36}$$

(Hargreaves et al., 1985)

where ET_0 = reference evapotranspiration, (mm equivalent water evaporation day^{-1})

Rn = net solar radiation, (mm equivalent water evaporation day^{-1})

T_m = mean monthly temperature, (°F)

4.5.2 FAO Radiation Uncorrected Method

The FAO Radiation formula is similar to Makkink's formula and contains some adjustments which are based on studies by Doorborens and Pruitts (1977) using lysimeter data from various international locations. The formula is:

$$ET_o = \frac{\Delta}{\Delta + \gamma} R_s - 0.3 \tag{4.37}$$

(Doorborens and Pruitts, 1977)

where ET_0 = reference evapotranspiration, (mm equivalent water evaporation day^{-1})

R_s = solar radiation, (mm equivalent water evaporation day^{-1})

Δ = the slope of the saturation pressure-temperature curve, (mb °C^{-1})

γ = a psychrometric constant, (mb °C^{-1})

4.5.3 Priestly-Taylor's Method

Priestly-Taylor (1972) suggested that potential evapotranspiration can be estimated from the radiation part of the Penman equation. He introduced an empirical constant to fit the Penman formula which requires air temperature, humidity, and radiation or sunshine duration data. His study was based on measured data from Australia and USA. The Priestly-Taylor's equation is:

$$ET_o = 1.26 \frac{\Delta}{\Delta + \gamma} R_n \tag{4.38}$$

(Priestly and Taylor, 1972)

where ET_0 = reference evapotranspiration, (mm equivalent water evaporation day^{-1})

Δ = the slope of the saturation pressure-temperature curve, (mb °C^{-1})

γ = a psychrometric constant, (mb °C^{-1})

R_n = net solar radiation, (mm equivalent water evaporation day^{-1})

4.5.4 Makkink's Method

This method, developed in 1957 under the cool climatic condition of the Netherlands, estimates evapotranspiration based on temperature, humidity and radiation or sunshine duration data. It is similar to the Priestly-Taylor method but uses a different coefficient. Makkink's method is the basic formula of the FAO Radiation method and is given by:

$$ET_o = 0.61 \frac{\Delta}{\Delta + \gamma} R_s - 0.12 \tag{4.39}$$

(Makkink, 1957)

where ET_o = reference evapotranspiration, (mm equivalent water evaporation day^{-1})

Δ = the slope of the saturation pressure-temperature curve, (mb °C^{-1})

γ = a psychrometric constant, (mb °C^{-1})

R_s = solar radiation, (mm equivalent water evaporation day^{-1})

4.5.5 Turc's Method

The method of estimating reference evapotranspiration developed by Turc in 1961 under the general climatic conditions of western Europe, is based on the use of the most frequently observed climatological factors: temperature, humidity, and sunshine duration or radiation. This method can be classified as a three climatic variable method.

For relative humidity < 50% the formula is:

$$ET_o = 0.013 \frac{T}{T + 15} (R_s + 50) (1 + \frac{50 - rh}{70}) \tag{4.40}$$

For relative humidity > 50% the formula is:

$$ET_o = 0.013 \frac{T}{T + 15} (R_s + 50) \tag{4.41}$$

where ET_o = reference evapotranspiration, (mm equivalent water evaporation day^{-1})

T = mean monthly air temperature, (°C)

R_s = solar radiation, (cal cm^{-1} day^{-1})

rh = mean monthly relative humidity, (%)

4.6 Four-Climatic-Variable Methods

The four-climatic-variable methods use temperature, humidity, sunshine and windspeed as inputs. Some of these are the so called combination formula methods which include energy budget and aerodynamic principles. These methods include FAO Corrected Blaney-Cridlle, FAO Radiation Corrected, FAO Penman Corrected, Penman 1963, FAO Penman Uncorrected, FAO PPP Penman methods. R_n, Δ, γ, e_a, e_d and U_2 are calculated using the same procedure as in the standard method. The units, if necessary, are transformed accordingly.

4.6.1 Penman's Method

Penman's method which was developed in southern England is still widely used in Indonesia without any adjustments to the constants. Penman (1948) derived an equation to estimate ET_o, (sometimes called a semi-empirical formula) which is based on a combination of energy balance and vapour transfer approaches. In 1963 he refined his formula by using albedo of grass surface instead of water surface. The equation is as follows:

$$ET_o = \frac{\Delta}{\Delta+\gamma} R_n + \frac{\gamma}{\Delta+\gamma} 0.35(1.0 + 0.0098U_2)(e_a - e_d) \quad (4.42)$$

(Penman, 1948 and 1963; Olivier, 1964)

where ET_o = reference evapotranspiration, (mm equivalent water evaporation day^{-1})

Δ = the slope of the saturation pressure-temperature curve, (mb $°C^{-1}$)

γ = a psychrometric constant, (mb $°C^{-1}$)

R_n = net radiation at crop surface, (mm equivalent water evaporation day^{-1})

u_2 = windspeed, (miles day^{-1})

e_d = vapour pressure at dew point, (mb)

e_s = saturation vapour pressure, (mb)

and

$$\begin{aligned} R_n = {} & R_a(1-r)(0.18 + 0.55\, n/N) \\ & - \sigma T_a^4(0.56 - 0.092\sqrt{e_d})(0.10 + 0.90\, n/N) \end{aligned} \quad (4.43)$$

(Olivier, 1964)

where ET_o = reference evapotranspiration, (mm equivalent water evaporation day^{-1})

R_a = mean monthly extra terrestrial radiation, (mm equivalent water evaporation day^{-1})

n = bright sunshine hours per day, (hours)

N = maximum day light hours, (hours)

r = radiation reflection (0.23) (Jensen, 1990)

σ = Stevan-Boltzmann constant, (2.01 X 10^{-9} mm equivalent water evaporation day^{-1})

T_k = mean monthly temperature, (°K)

and U_2 is calculated from the following equation:

$$U_2 = U_z \times \frac{\log 6.6}{\log z} \tag{4.44}$$

(Olivier, 1964)

where z = the height of wind measurement, (feet)

4.6.2 Penman-Wright-Jensen's 1972 Method

Similar to Penman's method, Penman-Wright-Jensen's 1972 method requires four kinds of data: temperature, relative humidity, sunshine duration, and windspeed. In this formula the wind function is modified based on his study using lysimeter data from Idaho, USA. The formula is given by:

$$ET_o = \frac{1}{1.15}\left(\frac{\Delta}{\Delta+\gamma} R_n + \frac{\gamma}{\Delta+\gamma} 0.2625(0.75 + 0.0115U_2)(e_a - e_d)\right)$$

(Jensen et al., 1990) (4.45)

where ET_o = reference evapotranspiration, (mm equivalent water evaporation day^{-1})

Δ = slope of the saturation pressure-temperature curve, (mb $°C^{-1}$)

γ = psychrometric constant, (mb °C^{-1})

R_n = net radiation at crop surface, (mm equivalent water evaporation day^{-1})

u_2 = windspeed, (km day^{-1})

e_d = vapour pressure at dew point, (mb)

e_a = saturation vapour pressure, (mb)

4.6.3 FAO Penman Corrected Method

Doorborens and Pruitts (1977) proposed a modified Penman's formula by introducing a correction factor as a function of relative humidity, sunshine duration, windspeed and ratio of day to night windspeed based on their study using measured ET_o data from various international locations. This method is widely used in Indonesia and was the FAO standard method in the past. The formula is:

$$ET_o = c_{FPN}\left[\frac{\Delta}{\Delta + \gamma} R_n + \frac{\gamma}{\Delta + \gamma} 2.7(1 + 0.01\ u_2)(e_a - e_d)\right]$$

(Jensen et al., 1990) (4.16)

where ET_o = reference evapotranspiration, (mm equivalent water evaporation day^{-1})

Δ = the slope of the saturation pressure-temperature curve, (mb °C^{-1})

γ = psychrometric constant, (mb °C^{-1})

R_n = net radiation at crop surface, (mm equivalent water evaporation day^{-1})

u_2 = windspeed, (km day^{-1})

e_d = vapour pressure at dew point, (kPa)

e_s = saturation vapour pressure, (kPa)

and c_{FPN} = 0.892 - 0.0781 U_d + 0.00219 $U_d R_s$ + 0.000402 $RH_{max} R_s$ + 0.000196 $U_d/U_n\ U_d\ RH_{max}$ + 0.0000198 $U_d/U_n\ U_d\ RH_{max}\ R_s$ + 0.00000236 $U_d^2\ RH_{max}\ R_s$ - 0.0000086 $(U_d/U_n)^2\ U_d\ RH_{max}$ - 0.0000000292 $U_d/U_n\ \ U_d^2\ (RH_{max})^2\ R_s$ - 0.0000161 $RH_{max}\ R_s^2$ (Allen and Pruitts, 1991) (4.47)

where RH_{max} = maximum mean monthly relative humidity, (%)

R_s = solar radiation, (mm equivalent water evaporation day^{-1})

U_d = windspeed during day time(07.00 - 19.00), (m s^{-1})

U_n = windspeed during night time(19.00 - 07.00), (m s^{-1}).

4.6.4 FAO Penman Uncorrected Method

Doorborens and Pruitts (1977) modified Penman's formula by introducing a correction factor as a function of relative humidity, sunshine duration, windspeed and day to night windspeed. In the FAO Penman Uncorrected Method, the correction factor is represented by the value of one instead of the original value and is referred to here as as the FAO Penman c=1 method. The formula is given by:

$$ET_o = c\left[\frac{\Delta}{\Delta + \gamma} R_n + \frac{\gamma}{\Delta + \gamma} 2.7(1 + 0.01\ u_2)(e_a - e_d)\right]$$

(Jensen et al., 1990) (4.48)

where ET_o = reference evapotranspiration, (mm equivalent water evaporation day^{-1})

Δ = the slope of the saturation pressure-temperature curve, (mb °C^{-1})

γ = a psychrometric constant, (mb °C^{-1})

R_n = net radiation at crop surface, (mm equivalent water evaporation day^{-1})

u_2 = windspeed, (km day^{-1})

e_d = vapour pressure at dew point, (kPa)

e_a = saturation vapour pressure, (kPa)

c = 1

4.6.5 FAO Radiation Corrected Method

Doorborens and Pruitts (1977) modified Makkink's method by introducing a correction factor as a function of relative humidity, sunshine duration, and windspeed based on their study from lysimeter data from various international locations. The formula is given by:

$$ET_o = b \frac{\Delta}{\Delta + \gamma} R_n - 0.3 \qquad (4.49)$$

(Doorborens and Pruitts, 1977)

where ET_o = reference evapotranspiration, (mm equivalent water evaporation day^{-1})

Δ = slope of the saturation pressure-temperature curve, (mb °C^{-1})

γ = psychrometric constant, (mb °C^{-1})

R_n = net solar radiation, (mm equivalent water evaporation day^{-1})

and b = $1.066 - 0.0013 \times rh + 0.045 \times U_d - 0.00020 \times rh \times U_d - 0.0000315\ rh^2 - 0.0011 \times U_d^2$ (Frevert et al., 1983; Allen and Pruitts, 1991) (4.50) where rh = relative humidity, (%)

U_d = daytime windspeed, (m s^{-1})

4.6.6 FAO PPP Penman Method

Frere and Popov (1979) modified a method for estimating ET_o based on the Penman formula (based on more than a decade of FAO research) which is referred to as FAO Plant Production and Protection Penman (FAO PPP Penman method). The formula is given by:

$$ET_o = \frac{\frac{P_o}{P}.\frac{\Delta}{\gamma}\left[0.77R_a(a+b\frac{n}{N}) - \sigma T_k^4(0.56-0.079\sqrt{e_d})(0.10+0.90\frac{n}{N})\right]}{\frac{P_o}{P}.\frac{\Delta}{\gamma} + 1.00}$$

$$\times \frac{0.26(e_a - e_d)(1.0 + 0.54u_2)}{\frac{P_o}{P}.\frac{\Delta}{\gamma} + 1.00} \qquad (4.51)$$

(Frere and Popov, 1979)

where ET_o = reference evapotranspiration, (mm equivalent water evaporation day^{-1})

P_o = mean atmospheric pressure at sea level, (mb)

P = mean atmospheric pressure as a function of altitude, (mb)

0.77 = factor expressing the reduction in the incoming short wave radiation on the canopy surface and corresponding to an albedo of 0.23

Δ = the slope of the saturation pressure-temperature curve, (mb °C^{-1})

γ = a psychrometric constant, (mb °C^{-1})

R_a = short wave radiation received at the atmosphere, (mm of evaporable water). One mm = 58.6 calories and taking the solar constant the value of 2.00 cal. cm^{-2} .min^{-1}

a = 0.29 (for humid tropical zones)

b = 0.42 (for humid tropical zones)

u_2 = windspeed at 2 m height, (km day^{-1})

n = bright sunshine hours ··r day, (hours)

N = maximum daylength, (hours)

σT_k^4 = blackbody radiation for the prevailing air temperature, (mm)

e_a = saturation vapour pressure, (mb)

e_d = vapour pressure at dew point, in mb

T_k^o = mean monthly air temperature, in °K

4.6.7 FAO Blaney-Criddle Corrected Method

Doorborer·· and Pruitts (1977) proposed a modified Blaney-Criddle formula by introducing a correction factor as function of relative humidity, sunshine duration, windspeed and the ratio of day to night windspeed. The correction factor was obtained based on measured ET_o from various international locations. The formula is:

$$ET_o = a_{BC} + b_{BC}\, p_{BC}(0.4572T + 8.128) \tag{4.52}$$

where ET_o = reference evapotranspiration, (mm equivalent water evaporation day^{-1})

k_c = reference crop coefficient (0.75) (Ward, 1975)

p_{BC} = a day length variable, the ratio of the total daytime hours for a given month to the total day time hours in the year, a function of latitude (Table 4.3)

T = mean monthly air temperature, (°C)

and a_{BC} = 0.0043 RH_{min}-(n/N)-1.41 (Doorborens and Pruitts, 1977) (4.53)

RH_{min} = minimum relative humidity, (%)

n = bright sunshine hours per day, (hours)

N = maximum day light hours, (hours)

and b_{BC} = $0.908 - 0.00483\ RH_{min} + 0.7949\ n/N + 0.0768\ [\ln(U_d + 1)]^2 - 0.0038\ RH_{min}\ n/N - 0.000443\ RH_{min}\ U_d + 0.281\ [\ln(U_d + 1)]\ [\ln(n/N + 1)] - 0.00975\ [\ln(U_d + 1)]\ [\ln(RH_{min} + 1)]^2\ [\ln(n/N + 1)]$ (Allen and Pruitts, 1989) (4.54)

$$U_d = \frac{2\ U_{24}(U_d/U_n)}{1 + (U_d/U_n)} \tag{4.55}$$

(Jensen et al., 1990)

where U_d = windspeed during day time(07.00 - 19.00), (m s^{-1})

U_n = windspeed during night time(19.00 - 07.00), (m s^{-1})

U_{24} = average windspeed over 24 hours, (m s^{-1})

In this study, the value of U_d/U_n is equal to 1.2 based on Hyeman, (1990).

CHAPTER 5

METHOD OF COMPARISON AND RESULTS

This chapter describes the method of comparison and subsequent results between monthly ET_o calculated using the standard and the non-standard methods which are listed in Table 4.1. In addition, adjustments to the best non-standard methods so that they can give unbiased estimates are also considered.

5.1 Method of Comparison

The performance of each method for estimating reference evapotranspiration was tested by comparing the results from each method with the standard method, using regression analysis. The regression equation is of the form

$$ET_{oSTD_i} = a + b\ ET_{oEst_i} + e_i \tag{5.1}$$

where ET_{oSTDi} = monthly ET_o computed based on standard method

ET_{oEsti} = monthly ET_o computed based on non-standard method

a = constant term or intercept

b = regression coefficient or slope

e_i = random error

The parameters of the regression are estimated using the standard ordinary least square method. If there is perfect agreement between ET_{oStd} and ET_{oEst} then it is obvious that for $ET_{oStd} = ET_{oEst}$, $a=0$, $b=1$, and $e_i=0$ for all data points. If ET_{oStd} is plotted against ET_{oEst} on the same scale, then the plotted points will fall along the line of perfect agreement 45° to the horizontal axis. In general, however, $a \neq 0$, $b \neq 1$, and there is scatter about the regression line.

The goodness of-fit of the regression line is measured by the coefficient of determination (r^2) between the calculated values of a particular method and the standard method. The r^2 is computed by using:

$$r^2 = \frac{\text{Explained variation}}{\text{Total variation}} = \frac{\sum_{i=1}^{n} (y_{iest} - \bar{y})^2}{\sum_{i=1}^{n} (y_i - \bar{y})^2} \tag{5.2}$$

where y_{iest} = estimated y values (ET_o values estimated based on non-standard method)

y_i = y values (ET_o computed based on standard method)

$\bar{y}$ = mean of y (mean ET_o computed based on standard method)

The r^2 is a measure of the percentage of variance in the dependent variable explained by the independent variable and its square root (r) is a measure of linear association between the dependent and independent variable. If $r^2 = 1$, then all variation in the dependent variable is explained by the independent variable and there will be no scatter about the regression line. In this study, the best methods were selected based on the r^2 value. However, the other statistical parameters, the intercept, and the slope are just as important because they are indicators of the bias in estimation of each of the methods of estimating ET_o. For example, for a particular method, with $r^2 = 1$ but $a \neq 0$ and $b \neq 1$, the agreement between ET_{oStd} and ET_{oEst} is still not perfect. The values of a and b were used to adjust the best methods, as described in Section 5.2.

5.2 Adjustment to the Non-standard Methods

The non-standard methods were classified into four categories, based on the number of climatic variables. Within each of the groups, the best method was selected based on the r^2 value. The adjusted method adjust the best selected methods to give closer results to the standard method. The regression line between the standard and the adjusted methods should have intercept and slope equal to zero and one, respectively. The r^2 would remain the same however.

The general formula for adjusting the estimated ET_o for the selected methods is:

$$ET_{oAdj} = a + b\, ET_{oSel} \tag{5.3}$$

where ET_{oAdj} = ET_o adjusted from the best selected method, (mm equivalent water evaporation month^{-1})

ET_{oSel} = ET_o estimated based on the best selected method, (mm equivalent water evaporation $month^{-1}$)

a = the intercept of the regression line of the best selected method

b = the slope of the regression line of the best selected method.

The results of the comparison of the estimated ET_o using the non-standard methods with the standard method were grouped into several cases, according to the values of the slope and intercept of the regression lines. For example the case where the slope > 1 and intercept > 0, the estimated ET_o based on the selected method were lower than the standard method as can be seen in the hypothetical example in Figure 5.1. To adjust these results the estimated ET_o based on the selected method were multiplied by the slope, b, and the intercept, a, was added. That is :

$$ET_{oAdj} = a + b\ ET_{oSel} \tag{5.4}$$

After the adjustment, the regression line between ET_{oStd} and ET_{oAdj} should now have an intercept of zero and a slope of 1. The r^2, however would be equal to the unadjusted case. Three other common cases are:

slope, $b < 1$, intercept, $a > 0$. (See Figure 5.2)

slope, $b > 1$, intercept, $a < 0$. (See Figure 5.3), and

slope, $b < 1$, intercept, $a < 0$. (See Figure 5.4).

Other cases: $b=1$ and $a=0$, $b<1$ or $b>1$ and $a=0$, and $b=1$ and >1 or $a<0$, are less important because they rarely occur.

The method of adjustment for all the above cases are similar to the first except for the values and signs of b and a.

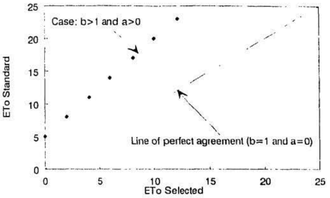

Figure 5.1 Typical case for a slope greater than 1 and a positive intercept

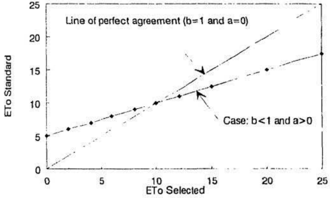

Figure 5.2 Typical case for a slope smaller than 1 and a positive intercept

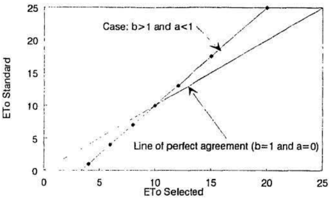

Figure 5.3 Typical case for a slope greater than 1 and a negative intercept

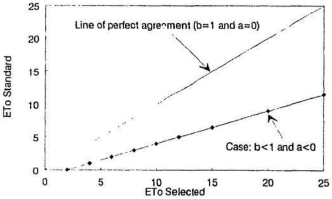

Figure 5.4 Typical case for a slope smaller than 1 and a negative intercept

5.3 Comparison between one-climatic-variable methods and the standard method

Table 5.1 and Fig. 5.5-5.7 show the results of the regression analysis between the monthly standard ET_o and the estimated ET_o based on one-climatic-variable methods. Figures 5.5 - 5.7 show the scatter diagram for the ET_o estimated based on the Thornthwaite, Hamon, and Blaney-Criddle methods versus the standard method. The highest r^2 is obtained using the Hamon (r^2=0.299) method. The Hamon method was therefore selected as the one-climatic-variable method for adjustment.

Table 5.1 Results of regression analysis between the one climatic variable methods and the standard method.

Method	r^2	a	b	Std.Error
Thornthwaite	0.272	51.42	0.550	15.98
* Hamon	0.299	48.59	0.698	16.17
Blaney-Criddle	0.238	-49.14	1.374	16.86

a and b are the intercept and slope of the regression line, respectively

* Method with highest r^2

The one-climatic-variable method derived from the Hamon results is adjusted as follows to remove the bias is:

$$ET_{oAdj1} = 48.59 + 0.698\ (C_{HMN}\, p^2\, P_t) \qquad (5.8)$$

where ET_{oAdj1} = ET_o calculated by the Adjusted One-climatic-variable method

C_{HMN} = 0.55

p = the same as p for Thornthwaite's method

P_t = saturated water-vapour density at the mean monthly temperature (g m^{-3} x 10^{-2}) (see Table 4.5)

Figure 5.8 shows the ET_o estimated based on the adjusted one-climatic-variable and standard methods. Table 5.2 shows the mean, standard deviation, coefficient of determination (r^2), and the intercept and slope of the regression lines estimated based on the standard, best one-climatic-variable, and adjusted methods. From Table 5.2, it is clear that the mean ET_o values of the adjusted and the standard methods are equal. However, there is a reduction in the standard deviation after the adjustment. The r^2 remains unchanged after the adjustment. Therefore, if the adjusted one-climatic-variable method is used to estimate ET_o, on average it will give the same results as that given by the standard method but will smaller variability.

Table 5.2 Comparison results for one-climatic-variable methods

Method	Mean	s.dev	r^2	a	b
Standard	124.5	19.31	1.000	0.00	1.000
* Hamon	108.7	15.14	0.299	48.59	0.698
Adjusted one-climatic-variable	124.5	10.57	0.299	0.00	1.000

* The best one-climatic-variable method

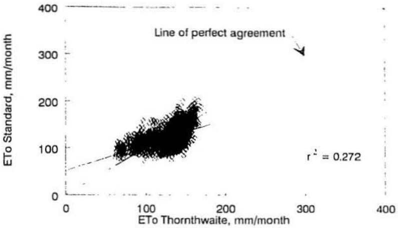

Figure 5.5 Comparison between ETo estimated based on FAO's Standard and Thornthwaite's Methods

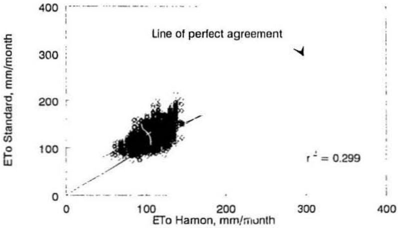

Figure 5.6 Comparison between ETo estimated based on FAO's Standard and Hamon's Methods

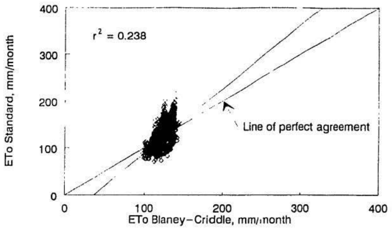

Figure 5.7 Comparison between ETo estimated based on FAO's Standard and Blaney–Criddles's Methods

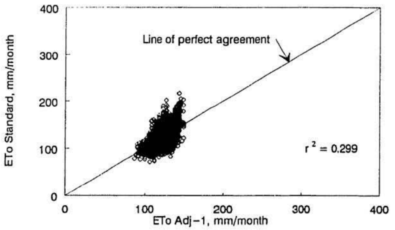

Figure 5.8 Comparison between ETo estimated based on FAO's Standard and Adjusted One–Climatic–Variable Methods

5.4 Comparison between two-climatic-variable methods and standard method

The regression constants and the coefficients of determination (r^2) between the monthly standard ET_o and ET_o as estimated by the two-climatic-variable methods are summarized in Table 5.3. Table 5.3 shows that the majority of the methods have r^2 less than 0.6 with the exception of the Hargreaves' Rs and Stephens's methods. The scatter diagrams for the ET_o estimated based on two-climatic-variable methods and the standard method are shown in Figures 5.9 - 5.17. The Hargreaves Rs method shows the highest r^2 (0.924), the smallest intercept (1.878) and a slope close to 1 (0.921). This method was therefore chosen for adjustment.

Table 5.3 Results of regression analysis between the two climatic variable methods and the standard method

Method	r^2	a	b	Std.Error
Olivier	0.588	82.76	0.739	12.40
Hargreaves '74	0.583	44.17	0.628	12.47
Ostromecki	0.554	83.65	0.338	12.89
David	0.554	83.65	0.379	12.89
Prescott	0.551	70.25	0.415	12.93
Ivanov	0.525	82.34	0.433	13.30
Behnke-Maxey	0.328	28.15	0.341	15.83
* Hargreaves Rs	0.924	1.878	0.921	5.34
Stephens	0.914	11.69	0.687	5.66

a and b are the intercept and slope of the regression line, respectively

* Method with highest r^2

The adjustment is as follows.

$$ET_{oAdj2} = 1.19 + 0.92\ (0.0075\ T_m\ R_s) \qquad (5.9)$$

where ET_{oAdj2} = ET_o calculated by the Adjusted two-climatic-variable method, (mm month^{-1})

T_m = mean monthly temperature (°F)

Rs = solar radiation (mm of equivalent water evaporation day^{-1} x number of days of the months)

Figure 5.18 shows the scatter diagram of ET_o estimated based on the adjusted two-climatic-variable and standard methods. Table 5.4 shows the mean, standard deviation, coefficient of determination (r^2), and the intercept and slope of regression lines of ET_o estimated based on the standard, best two-climatic-variable and adjusted 2-climatic-variable methods. From Table 5.4, it can be seen that the mean ET_o values of the adjusted and the standard methods are equal. Also, after adjustment the standard deviation of the ET_o values closer to that of the standard method in this case. Thus, the adjusted method gives mean and standard deviation closer to the standard method.

Table 5.4 Comparison results for two-climatic-variable methods

Method	Mean	s.dev	r^2	a	b
Standard	124.5	19.31	1.000	0.0	1.000
* Hargreaves Rs	133.1	20.15	0.924	1.878	0.921
Adjusted two-climatic-variable	124.5	18.56	0.924	0.0	1.000

* The best two-climatic-variable method

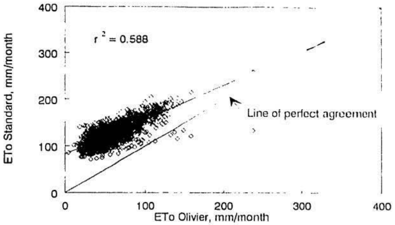

Figure 5.9 Comparison between ETo estimated based on FAO's Standard and Olivier's Methods

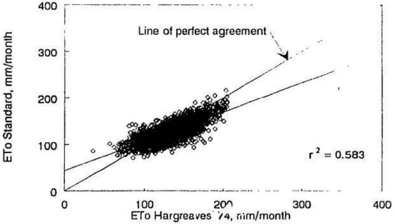

Figure 5.10 Comparison between ETo estimated based on FAO's Standard and Hargreaves' 1974 Methods

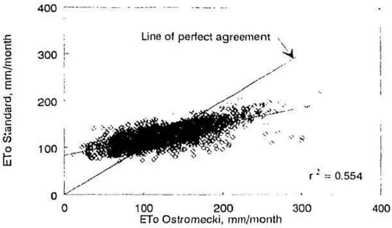

Figure 5.11 Comparison between ETo estimated based on FAO's Standard and Ostromecki's Methods

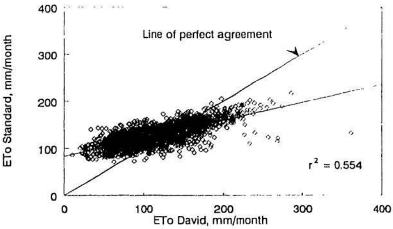

Figure 5.12 Comparison between ETo estimated based on FAO's Standard and David's Methods

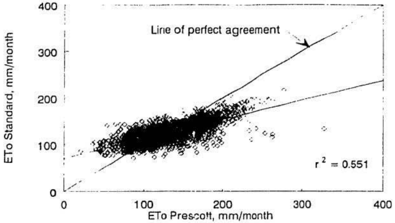

Figure 5.13 Comparison between ETo estimated based on FAO's Standard and Prescott's Methods

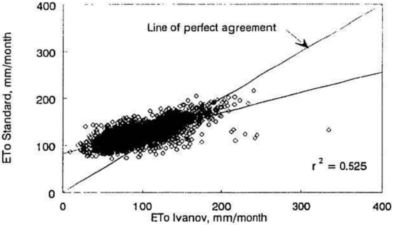

Figure 5.14 Comparison between ETo estimated based on FAO's Standard and Ivanov's Methods

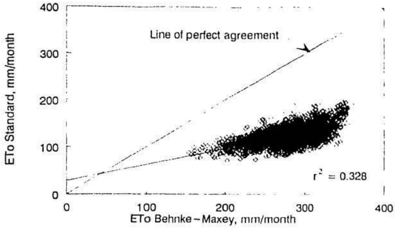

Figure 5.15 Comparison between ETo estimated based on FAO's Standard and Behnke – Maxey's Methods

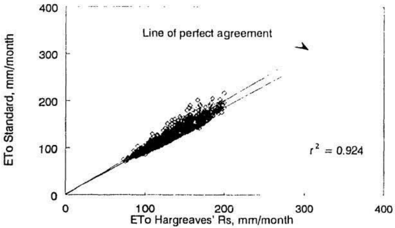

Figure 5.16 Comparison between ETo estimated based on FAO's Standard and Hargreaves' Rs Methods

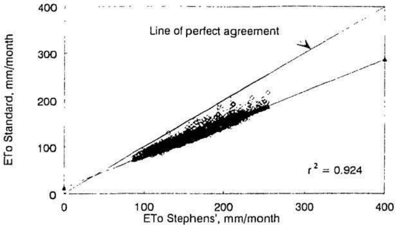

Figure 5.17 Comparison between ETo estimated based on FAO's Standard and Stephens' Methods

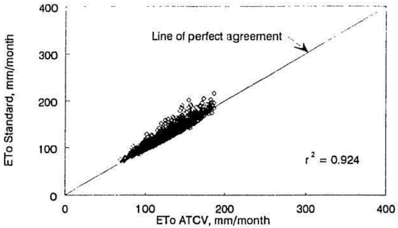

Figure 5.18 Comparison between ETo estimated based on FAO's Standard and Adjusted Two–Climatic–Variable Methods

5.5 Comparison between three-climatic-variable methods and standard method

The regression constants and the coefficients of determination (r^2) between the monthly standard ET_o and the ET_o estimated based on the three-climatic-variable methods are summarized in Table 5.5. It can be observed from this table that all methods have high coefficient of determination (more than 0.80). The scatter diagram estimated based on the selected three-climatic-variable methods and standard method are presented in Figure 5.19 - 5.23.

The highest r^2 value is obtained by using the FAO Radiation C=1 (FAO RAD C=1) method (r^2=0.906). Therefore the FAO RAD C=1 method is selected for adjustment.

Table 5.5 Results of regression analysis between the three climatic variable methods and the standard method

Method	r^2	a	b	Std.Error
Hargreaves Rn	0.896	0.137	1.330	6.24
* FAO Radiation c=1	0.906	0.100	0.782	5.92
Priestly-Taylor	0.888	-10.458	0.906	6.48
Makkink	0.887	-3.820	1.876	6.49
Turc	0.832	-27.188	1.518	7.92

a and b are the intercept and slope of the regression line, respectively

* Method with highest r^2

The adjustment is as follows:

$$ET_{oAdj3} = 17.11 + 0.70\ (\frac{\Delta}{\Delta + \gamma}\ R_s - 0.3) \qquad (5.10)$$

where ET_{oAdj3} = ET_o calculated by the Adjusted Three climatic variable method

Rs = solar radiation (mm of equivalent water evaporation day^{-1} x number of days of the months)

The value of Δ and γ are calculated using equations 4.17 and 4.18.

Figure 5.24 shows the scatter diagram ET_o estimated based on adjusted three-climatic-variable methods and standard method. Table 5.6 shows the mean, standard deviation, coefficient of determination (r^2), and the intercept and slope of regression lines estimated based on the standard, best three-climatic-variable and adjusted methods. From Table 5.6, it can be seen that the mean ET_o values of the adjusted and the standard methods are equal as expected, and is much closer to that of the standard method.

Table 5.6 Comparison results for three-climatic-variable methods

Method	Mean	s.dev	r^2	a	b
Standard	124.5	19.31	1.000	0.0	1.000
* FAO Radiation c=1	158.9	23.49	0.906	0.10	0.782
Adjusted three-climatic-variable	124.5	18.37	0.906	0.0	1.000

* The best three-climatic-variable method

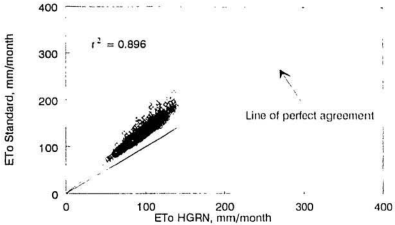

Figure 5.19 Comparison between ETo estimated based on FAO's Standard and Hargreaves' Rn (HGRN) Methods

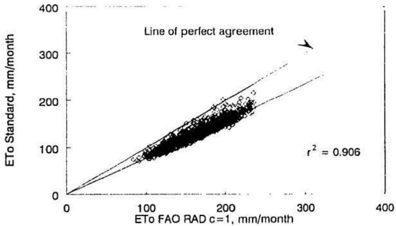

Figure 5.20 Comparison between ETo estimated based on FAO's Standard and FAO Radiation Uncorrected (FAO RAD c=1) Methods

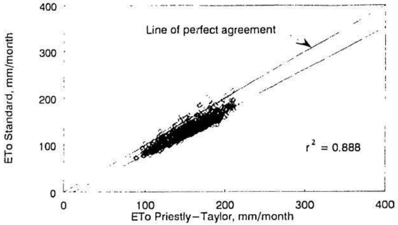

Figure 5.21 Comparison between ETo estimated based on FAO's Standard and Priesly–Taylor's (PT) Methods

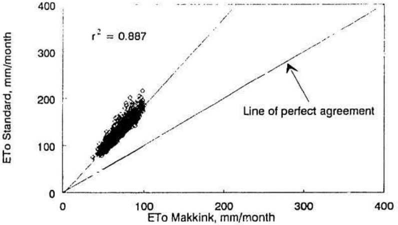

Figure 5.22 Comparison between ETo estimated based on FAO's Standard and Makkink's (MKK) Methods

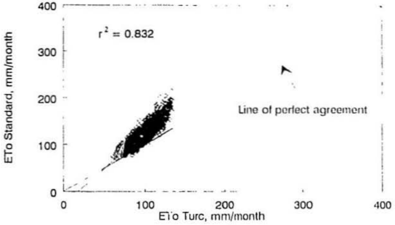

Figure 5.23 Comparison between ETo estimated based on FAO's Standard and Turc's Methods

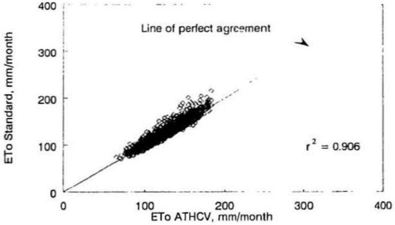

Figure 5.24 Comparison between ETo estimated based on FAO's Standard and Adjusted Three–Climatic–Variable (ATHCV) Methods

5.6 Comparison between four-climatic-variable methods and standard method

The regressions constant and the coefficients of determination (r^2) between ET_o estimated based on the standard and the four-climatic-variable methods are provided in Table 5.7. All methods in Table 5.7 have high r^2 (greater than 0.85). The FAO Penman Corrected method has the highest r^2 value (0.990). Therefore, this method is selected for adjustment. The scatter diagram of ET_o estimated based on the selected four-climatic-variable methods and the standard method are shown in Figures 5.25 - 5.31.

Table 5.7 Results of regression analysis between the four climatic variable methods and the standard method

Method	r^2	a	b	Std.Error
Penman	0.976	14.93	1.009	2.96
Penman-Wright-Jensen 1972	0.894	34.79	1.013	6.15
* FAO Penman Corrected	0.990	17.11	0.702	1.91
FAO Penman Uncorrected	0.964	14.46	0.752	3.65
FAO Radiation Corrected	0.964	26.31	0.786	3.64
FAO PPP Penman	0.879	-5.07	1.072	6.72
FAO Blaney-Criddle	0.818	-3.11	1.033	8.25

a and b are the intercept and slope of the regression line, respectively

* Method with highest r^2

The adjustment is as follows:

$$ET_{oAdj4} = 17.11 + 0.70\ ET_{o\text{-}FAO\text{-}PNM} \tag{5.11}$$

where ET_{oAdj4} = ET_o calculated by the adjusted four-climatic-variable method.

The $ET_{o\text{-}FAO\text{-}PNM}$ is calculated from equation 4.46. Figure 5.32 shows the scatter diagram of ET_o estimated based on the adjusted four-climatic-variable methods and the standard method. Table 5.8 shows the mean, standard deviation, coefficient of determination (r^2), and the intercept and slope of the regression lines estimated based on the standard, best four-climatic-variable and adjusted methods. It can be seen that the mean ET_o values of the adjusted and the standard methods are equal and the standard deviation is much closer to that of the standard method. In this case, the mean and standard deviation of the adjusted 4-climatic-variable method is practically the same as those of the standard method. It is of interest to note that the FAO Penman Corrected method was the previous standard method recommended by FAO.

Table 5.8 Comparison results for four-climatic-variable methods

Method	Mean	s.dev	r^2	a	b
Standard	124.5	19.31	1.000	0.0	1.000
* FAO Penman Corrected	153.0	27.38	0.990	17.11	0.702
Adjusted four-climatic-variable	124.5	19.21	0.990	0.0	1.000

* The best four-climatic-variable method

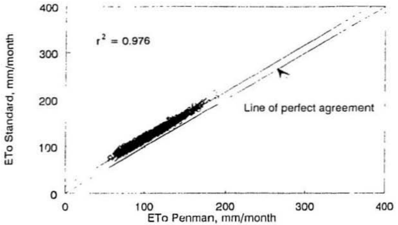

Figure 5.25 Comparison between ETo estimated based on FAO's Standard and Penman's Methods

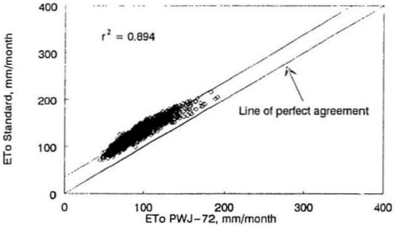

Figure 5.26 Comparison between ETo estimated based on FAO's Standard and Penman-Wright-Jensen 1972 (PWJ-72) Methods

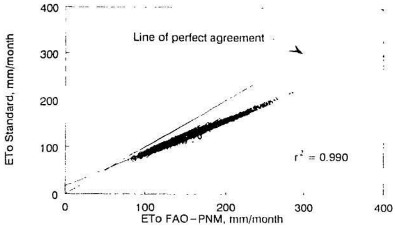

Figure 5.27 Comparison between ETo estimated based on FAO's Standard and FAO Penman Corrected (FAO-PNM) Methods

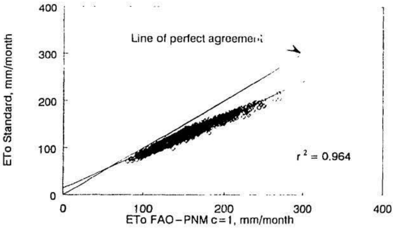

Figure 5.28 Comparison between ETo estimated based on FAO's Standard and FAO Penman Uncorrected (FAO PNM c= ,) Methods

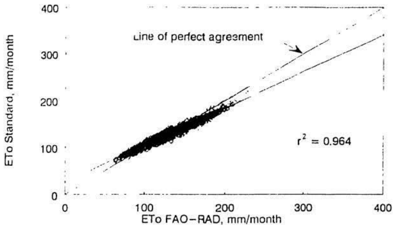

Figure 5.29 Comparison between ETo estimated based on FAO's Standard and FAO Radiation Corrected (FAO-RAD) Methods

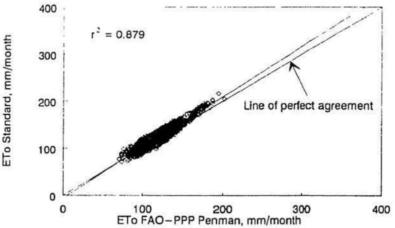

Figure 5.30 Comparison between ETo estimated based on FAO's Standard and FAO Plant Production and Protection Penman (FAO-PPP Penman) Methods

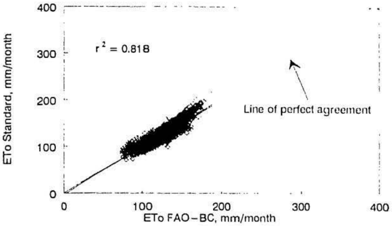

Figure 5.31 Comparison between ETo estimated based on FAO's Standard and FAO Blaney–Criddle (FAO–BC) Methods

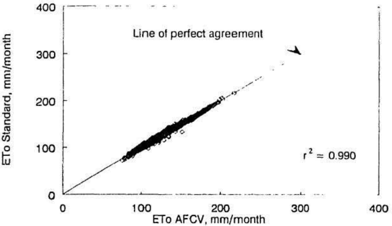

Figure 5.32 Comparison between ETo estimated based on FAO's Standard and Adjusted Four–Climatic–Variable (AFCV) Methods

Chapter 6

REGRESSION METHOD

In the previous chapter, ET_o was estimated by some one, two, three, or four climatic-variable methods and then was adjusted using the results of a regression analysis. A simpler alternative is to develop a regression equation directly between the desired climatic variables and the ET_o based on the standard method. This chapter discusses the procedure used to estimate ET_o using linear regression techniques by using one, two, three, or four climatic- variables as independent variables. The general for the regression equation is:

$$ET_{o\text{-}Reg} = a_o + a_1\, X_1 + a_2\, X_2 + \ldots\ldots a_n\, X_n + e_i \qquad (6.1)$$

where $ET_{o\text{-}Reg}$ = ET_o estimated based on regression method

$a_0, a_1, \ldots a_n$ = regression coefficients

$X_1, X_2, \ldots X_n$ = climatic variables 1, 2,...n

e_i = random error

The following sections describe the development of the regression equations using one to four climatic-variables. The parameters of the regression equations were estimated using ordinary least squares.

6.1 Regression using one climatic variable

The estimates of ET_o using the standard method were regressed with one climatic variable as the independent variable from a list of possible variables. The variables include temperature, relative humidity, sunshine duration, windspeed, elevation, and solar radiation. The best equation is selected based on the largest r^2 value.

Table 6.1 shows that the variable R_s gave the highest r^2 (0.832). Therefore, it is selected as the variable to be used in the one-climatic-variable regression model (OCVR). In this study R_s is not directly measured, it was calculated using the sunshine duration data. The regression equation is:

$$ET_{Rgs1} = -11.45 + 18.49\ R_g \tag{6.2}$$

where ET_{Rgs1} = ET_o estimated using the one-climatic-variable regression method (mm equivalent water evaporation month^{-1})

R_s = solar radiation, (mm equivalent water evaporation day^{-1})

Figure 6.1 is the plot of the ET_o values estimated based on the one-climatic-variable regression and standard methods. The mean, standard deviation and coefficient variation of ET_o estimated based on one climatic variable regression method are 124.4, 17.62 and 0.142, respectively. The regression method automatically gives unbiased estimates of the mean. The standard deviation, however, is slightly lower than that of the standard method (19.31).

Table 6.1 Coefficient of determination (r^2) for regression using one climatic variable method

Variable	r^2
Temperature (T)	0.266
Relative humidity (rh)	0.453
Sunshine duration (ss)	0.543
Windspeed (U_2)	0.122
Altitude (Alt)	0.103
* Solar radiation (Rs)	0.832

* The variable with highest r^2

6.2 Regression using two climatic variables

The regression using two-climatic-variables (TCVR) is obtained by correlating the standard method with two climatic variables as independent variables. By trying several combinations of two variables (temperature, relative humidity, sunshine duration, windspeed, elevation, solar radiation) the best equation was selected based on the highest r^2 value.

It can be seen in Table 6.2 that the combination of relative humidity and solar radiation (R_s) has the highest coefficient of determination (r^2=0.894), therefore it was selected as the two-climatic-variable-regression model. The regression equation is:

$$ET_{Rgs2} = 81.76 - 90.04\ rh + 15.56\ R_s \qquad (6.3)$$

where ET_{Rgs2} = ET_o estimated based on two climatic variable regression method (mm month^{-1})

rh = relative humidity, (%)

R_s = solar radiation, (mm equivalent water evaporation day^{-1})

Table 6.2 Coefficient of determination (r^2) for regression using two climatic variables method

Variable	r^2
Temperature (T), and relative humidity (rh)	0.542
Temperature (T), and sunshine (ss)	0.662
Temperature (T), and windspeed (U_2)	0.342
Temperature (T), and solar radiation (Rs)	0.889
* Relative humidity (rh), and solar radiation (Rs)	0.894

* The combination of variables with highest r^2

Figure 6.2 shows the scatter diagram of ET_o estimated based on the two-climatic-variable regression and standard methods. The mean, standard deviation and coefficient variation of ET_o estimated based on the two-climatic-variable regression method are 124.8, 18.29 and 0.147, respectively. These results shows good agreement with those of the standard method.

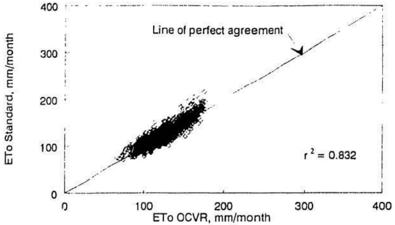

Figure 6.1 Comparison between ETo estimated based on FAO's Standard and One-Climatic-Variable-Regression Methods

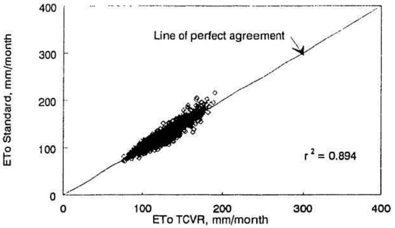

Figure 6.2 Comparison between ETo estimated based on FAO's Standard and Two-Climatic-Variable-Regression (FCVR) Methods

6.3 Regression using three climatic variables

The regression based on using three climatic variables (THCVR) regress the standard method with a combination of three climatic variables as independent variables.

From in Table 6.3, it can be seen that a combination of temperature, relative humidity, and R_s produced the highest r^2 (0.928). The regression equation is:

$$ET_{Rgs3} = 18.99 + 2.12\ T - 74.01\ rh + 14.79\ R_s \qquad (6.4)$$

where ET_{Rgs3} = ET_o estimated based on three climatic variable regression method (mm month^{-1})

T = mean monthly temperature, (°C)

rh = relative humidity, (percent)

R_s = solar radiation, (mm equivalent water evaporation month^{-1})

Table 6.3 Coefficient of determination (r^2) for regression using three climatic variables method

	Variables	r^2
	Temperature, relative humidity, and sunshine duration	0.716
	Temperature, windspeed (U_2), and sunshine duration	0.706
*	Temperature, relative humidity, and solar radiation	0.928
	Temperature, windspeed (U_2), and solar radiation	0.925

* Combination of variables with highest r^2

Figure 6.3 shows the scatter diagram of ET_o estimated based on the three-climatic-variable regression and standard methods. The mean, standard deviation and coefficient variation of ET_o estimated based on three-climatic-variable regression method are 124.4, 18.37 and 0.149, respectively which are close to those of the standard method.

6.4 Regression using four climatic variables

The regression based on using four climatic variables (FCVR) regress the standard method with a combination of four climatic variables as independent variables.

Table 6.4 shows that the combination of four variables (temperature, relative humidity, windspeed at 2 m height (U_2), and solar radiation (R_s) gave a r^2=0.952. The regression equation is:

$$ET_{Rgs4} = 7.3 + 2.02\,T - 62.6\,rh + 5.37\,U_2 + 14.7\,R_s \quad (6.5)$$

where ET_{Rgs4} = ET_o estimated based on four climatic variable regression method (mm equivalent water evaporation month^{-1})

T = mean monthly temperature, (°C)

rh = relative humidity, (percent)

R_s = solar radiation, (mm equivalent water evaporation month^{-1})

U_2 = windspeed measured at 2 m, m sec^{-1}

Figure 6.4 shows the scatter diagram of ET_o estimated based on the four-climatic-variable regression and standard methods. The mean, standard deviation and coefficient variation of ET_o estimated based on four-climatic-variable regression method are 124.2, 18.81 and 0.151, respectively. These values are almost equal to the values based on standard method.

Regression analysis using other combinations such as rh x Rs, T x Rs, U_2 x Rs, Altitude x Rs, etc. and the logarithmic transformation have been tried but they did not give better results.

Table 6.4 Coefficient of determination (r^2) for regression using four climatic variables method

Variables	r^2
Temperature, relative humidity, sunshine duration, and windspeed (U_2)	0.745
Temperature, windspeed (U_2), altitude, and sunshine duration	0.736
Temperature, relative humidity, sunshine duration, and solar radiation	0.930
Relative humidity, windspeed (U_2), altitude, and solar radiation	0.939
* Temperature, relative humidity, windspeed (U_2), and solar radiation	0.955

* Combination of variables with highest r^2

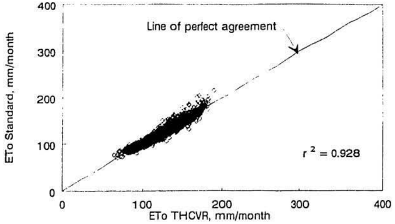

Figure 6.3 Comparison between ETo estimated based on FAO's Standard and Three–Climatic–Variable–Regression Methods

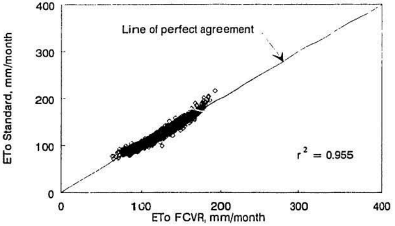

Figure 6.4 Comparison between ETo estimated based on FAO's Standard and Four–Climatic–Variable–Regression (FCVR) Methods

CHAPTER 7

DISCUSSION AND SUMMARY OF RESULTS

This chapter discusses the results of the comparison between estimates of ET_o using the standard method and the various non-standard methods. A summary of the results obtained is also presented.

7.1 One-Climatic-Variable Methods

The single climatic variable methods which require temperature as the sole data input include the Thornthwaite, Hamon and Blaney-Criddle methods. In Indonesia, the Thornthwaite method is still widely used when temperature is the only data available. The low r^2 value for the Thornthwaite method (r^2=0.272) indicates that it is weakly correlated to the standard method. The reason may be that the constants used in the Thornthwaite method are not suitable for this area. On the other hand, the Hamon method shows the best results compared to the other two methods. This method is also weakly correlated to the standard method, as indicated by the small r^2 value. The reason may be because temperature alone is not the best predictor of evapotranspiration.

The ET_o estimated based on Hamon method on average gave lower estimates that from the standard method as indicated by a mean which is 23% lower than the mean of the standard method. In addition, the standard deviation is 22% lower than the standard deviation of the standard method. The Adjusted Hamon method yielded a mean equal to the standard method but the standard deviation is 45% lower compared to the standard method. This means the bias in the mean has been corrected but the variance has been reduced.

The only method which has a high r^2 value (0.828) is the single climatic variable regression approach which requires solar radiation (estimated from sunshine duration) as input data. This agrees with the basic principle that radiation is the major factor in the evapotranspiration processes. It is also in agreements with the FAO recommendation suggesting the use of radiation rather than temperature based formulas.

7.2 Two-Climatic-Variable Methods

The two climatic variable methods yielded better results compared to the single climatic variable model. This is because of the presence of the sunshine duration variable which is expressed in terms of solar radiation. The increase in the r^2 is about 20 percent from the one-climatic-variable methods. The Hargreaves Rs method shows the best performance, because it uses solar radiation. The adjusted two climatic variable method was developed from the Hargreaves Rs method. The reason that the Hargreaves Rs method approximated the standard method quite well may be because it was developed under similar climatic conditions as those found in the study area.

The ET_o calculated based on Hargreaves Rs method is higher on average when compared to the standard method. This was indicated by the mean being 7% higher than the mean of the standard method. In addition, the standard deviation is 4% higher than the standard deviation of the standard method. The Adjusted Hargreaves Rs method gave mean and standard deviation much closer to the standard method. This means the bias has been corrected quite successfully by the adjustment.

The r^2 produced by the two climatic variable regression method was found to be close to the Hargreaves Rs value of 0.894. One possible reason for this is that the regression formula also employs solar radiation (the dominant factor in evapotranspiration as noted above).

7.3 Three-Climatic-Variable Methods

The three climatic variable methods require temperature, relative humidity, and sunshine data. They all performed close to the standard method which yielded r^2 values ranging from 0.832 for Turc's method to 0.914 for FAO Radiation Uncorrected method. The best performance is achieved by the FAO Radiation Uncorrected method which yields a r^2 value of 0.906. Consequently, it was selected for the adjusted three climatic variable method.

The ET_o estimated based on FAO Radiation Uncorrected method over estimated on average as indicated by the mean which is 22% higher than the mean of the standard method. In addition, the standard deviation is 23% higher than the standard deviation of the standard method. The Adjusted FAO Radiation Uncorrected method produced a mean equal to the standard method and the standard deviation is much closer to the standard method (0.05% lower). This means the bias has been successfully corrected.

The regression method, with temperature, solar radiation, and humidity as independent variables yielded a r^2 value of 0.928, which is higher than the above three-climatic-variable methods.

In general, three-climatic-variable methods yielded higher r^2 values as expected in comparison with the single and two climatic variable methods.

7.4 Four-Climatic-Variable Methods

The majority of the four-climatic-variable methods gave fairly good results. They have r^2 values greater than 0.9. These methods require four variables, temperature, relative humidity, sunshine duration, and windspeed. The highest r^2 is given by the FAO Penman Corrected method (the past FAO Standard method) in the order of $r^2=0.990$. The ET_o results based on FAO Penman Corrected method however over estimated on average which is indicated by a mean which is 23% higher than the mean of the standard method. In addition, the standard deviation is 42% higher than the standard deviation of the standard method. The Adjusted FAO Penman Corrected method produced a mean and standard deviation practically equal to those of the standard method.

The four climatic variable methods, with the exception of the FAO Blaney-Criddle and the FAO Radiation Methods, are combination methods which include energy balance and aerodynamic functions. The high value of the r^2 implies that the modified combination methods are not significantly different from the original Penman method in predicting ET_o for Jawa conditions. However, these methods are complicated. The four climatic variable regression method is much simpler to apply. It displays considerable predictive accuracy and approximates the standard method very well as indicated by a r^2 value of 0.952, and the mean and standard deviation are almost unbiased.

7.5 Summary of results of the best selected, adjusted, and regression methods

This study has evaluated techniques in estimating reference evapotranspiration which are based on one to four climatic-variables. Table 7.1. and Figure 7.1 - 7.4 summarizes the results of the comparison between the standard, best selected, adjusted and regression methods in terms of the coefficient of determination, mean, standard deviation, and coefficient of variation, and boxplots. In general, the adjusted and regression methods yielded results closer to the standard method and the r^2 values of these methods are more than 0.8 except for best the one-climatic-variable method which gave the lowest r^2 value.

Table 7.1 Summary results

Methods	Coefficient of determination			Standard deviation			Mean			Coeff. of variation		
Standard	1.000			19.31			124.50			0.155		
	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)
One Variable	0.299	0.299	0.832	15.14	10.57	17.62	108.7	124.5	124.4	0.139	0.085	0.142
Two Variables	0.924	0.924	0.894	20.15	18.56	18.29	133.1	124.5	124.8	0.151	0.149	0.147
Three Variables	0.906	0.906	0.928	23.49	18.37	18.37	158.9	124.5	124.4	0.148	0.148	0.149
Four Variables	0.990	0.990	0.952	27.38	19.21	18.81	153.0	124.5	124.2	0.179	0.154	0.151

(1) Selected the best method
(2) Adjusted method
(3) Regression method

```
                     --------
      *****-----------I  +  I-----------***                ET_o-Regr1
                     --------

                      ------
             ***-------I + I------                         ET_o-Adj1
                      ------

                 --------
 ****-----------I  +  I---------                           ET_o-Hamon
                 --------

                     ---------
        **-----------I   +   I-----------********* **    O ET_o-Standard
                     ---------

----+---------+---------+---------+---------+---------+--  ET_o mm month-1

    60        90       120       150       180       210
```

Figure 7.1 Box-plots for 1-climatic variable methods

```
                   ---------
       *-----------I   +   I-------------***** *            ET_o-Regr2
                   ---------

                   ---------
     ***-----------I   +   I-------------*****              ET_o-Adj2
                   ---------

                       ----------
       ***-------------I   +   I-----------******           ET_o-HgRs
                       ----------

                   ---------
      **-----------I   +   I-----------********* **   O     ET_o-Standard
                   ---------

--+---------+---------+---------+---------+---------+----  ET_o mm month-1
 60        90       120       150       180       210
```

Figure 7.2 Box-plots for 2-climatic variable methods

```
                    --------
* **----------I  +   I---------**** *                 ETo-Regr3
                    --------

                    --------
** ----------I  +   I---------****                    ETo-Adj3
                    --------

                              ----------
     *** -------------I   +   I------------*****      ETo-FAO-Rad
                              ----------

                    --------
 **----------I  +   I---------******** *    O         ETo-Standard
                    --------

------+---------+---------+---------+---------+---------  ETo mm month-1

     70       105       140       175       210       245
```

Figure 7.3 Box-plots for 3-climatic variable methods

```
              -------
****---------I  +  I-------******                     ETo-Regr4
              -------

              -------
  *---------I  +  I--------*********  O               ETo-Adj4
              -------

                    ---------
   *------------I   +   I------------************  O  ETo-FAO-PNM
                    ---------

              -------
 **---------I  +  I--------*********  O               ETo-Standard
              -------

----+---------+---------+---------+---------+---------+--  ETo mm month-1

   80       120       160       200       240       280
```

Figure 7.4 Box-plots for 4-climatic variable methods

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS

This chapter presents the conclusions which can be drawn from the study and some recommendations for further study and applicability of the results.

8.1 CONCLUSION

The conclusions which can be drawn from this study are:

1. As expected, in general, the greater number of climatic variables used in a method to calculate reference evapotranspiration yields better results.

2. Solar radiation is the dominant factor in predicting reference evapotranspiration.

3. The one to four regression equations are simple to apply and are results that were reasonably close to the standard method.

4. Where data are limited, the single climatic variable regression method, which requires sunshine data only, appears to be well suited for Jawa, Indonesia.

8.2 RECOMMENDATIONS

From the results of this study, the following actions are recommended:

1. In this study the standard method was treated as observed data. It is recommended that for verification of the obtained results, observed reference evapotranspiration in the study area should be used. Therefore lysimeters have to be installed over a range of latitudes and elevations.

2. One important factor in estimating reference evapotranspiration is solar radiation. The existing radiation constants were obtained from research conducted in different locations. For the purpose of irrigation scheduling in particular, which uses ET_o estimated based on solar radiation, it is recommended that the solar radiation constants in the incoming shortwave radiation equation in the area of study, Jawa, Indonesia be further verified.

3. The climatic conditions in other islands of Indonesia are similar to the area of study. The findings of the study may be applicable to these islands. For this purpose, it is recommended that the applicability of the adjusted and regression methods be tested for other islands of Indonesia and other humid tropical areas.

4. Other climatic data such as, pan evaporation, maximum and minimum temperature data which may be available at some meteorological stations, have not been used in this study to estimate reference evapotranspiration. It is recommended that a similar study using these data be conducted in future.

5. Estimates of reference evapotranspiration that are currently in use by water resources planners should be evaluated or adjusted using the results of this study.

REFERENCES

Allen, R.G., and Pruitt, W.O. (1991). "FAO-24 Reference Evapotranspiration Factors," *Journal of Irrigation and Drainage Engineering*, ASCE, Vol. 117, no. 5, pp. 758-773.

Barry, R.G. (1971). "Evaporation and Transpiration," *Introduction to Physical Hydrology*, ed. R.J. Chorley, Methuen & Co Ltd., London, pp. 82-97

Bonier, A. (1979). *Estimating Potential Evapotranspiration and Evaporation. Part I: Review of Existing Methods*, Directorate General of Water Resources Development, Ministry of Public Works, Government of the Republic of Indonesia, 32 p.

Bonier, A. (1979). *Estimating Potential Evapotranspiration and Evaporation. Part II: Use of Existing Methods and Catchment Area Water Balance*, Directorate General of Water Resources Development, Ministry of Public Works, Government of the Republic of Indonesia, 32 p.

Brutsaert, W.H. (1982). *Evaporation into the Atmosphere*, D.Reidel Publishing Company, Dordercht, Holland, Boston-USA and London, England, 299 p.

Calder, I.R., (1990). *Evaporation in the Uplands*, John Wiley & Sons Ltd., Chichester, England, 148 p.

Chang, J.H., (1968). *Climate and Agriculture. An Ecological Survey*, Aldinne Publishing Company, Chichago, Illinois 60606, 304 p.

Department of Communications, Agency for Meteorology and Geophysics. (1971-1989). *Climate Data in Indonesia*, Jakarta, Indonesia.

Doorborens, J. and Pruitts, W.O., (1977). *Guidelines for Predicting Crop Water Requirements*, Food and Agricultural Organization of the United Nations, Rome, Italy, 144 p.

Duffie, J.A. and Backman, W.A., (1980). *Solar Engineering of Thermal Processes*, John Wiley & Sons, New York, USA, 762 p.

Feddes, R.A. (1987). "Crop factors in relation to Makkink Reference-Crop Evapotranspiration," *Evaporation and Weather*, ed. Hooghart, TNO Committee on Hydrological Research, Proceeding and Information no. 39, The Hague, The Netherlands, pp. 33-45.

Frere, M. and Popov, G.F. (1979). *Agrometeorological Crop Monitoring and Forecasting*, FAO Plant Production and Protection Paper No. 17, FAO, Rome, Italy, 43 p.

Frevert, D.K., Hill, R.W. and Braaten, B.C. (1983). Estimation of FAO Evapotranspiration Coefficients. *Journal of Irrigation and Drainage Engineering*, ASCE, Vol. 109, no. 2, pp. 265-271.

Gray, D.M., McKay, G. A., Wigham, J. M., (1970). "Energy, Evaporation and Evapotranspiration," *Handbook on the Principles of Hydrology*, ed. D.M. Gray, Canadian National Committee for Hydrological Decade, Ottawa, Canada pp. 3.1-3.66

Hamon, W.R. (1961). "Estimating Potential Evapotranspiration," *Journal of Hydraulic Division*, Proceeding of the American Society of Civil Engineers, Vol. 87, no. HY 3, pp. 107-120

Hargreaves, G.H. (1974). "Estimation of potential crop evapotranspiration," *Trans. Am. Soc. Agr. Engrs.*, pp. 701-704.

Hargreaves, G.L., Hargreaves, G.H. and Riley, J.P. (1985). "Irrigation Water Requirement for Senegal River Basin," *Journal of Irrigation and Drainage Engineering*, ASCE, Vol. 111, No. 3, pp. 265-275.

Hyemans, J. (1991). *Calculation Reference Evapotranspiration in Bengawan Solo River Basin*, Memo No. 0013/KTA-BTA155/13-1991, 15 p.

Jensen, M.E. (ed.) (1974). *Consumptive Use of Water and Irrigation Water Requirements*, Report of Technical Committee on Irrigation Water Requirements, Irrigation and Drainage Division, ASCE, 215 p.

Jensen, M.E., Burman, R.D. and Allen, R.G. (ed.) (1990). *Evapotranspiration and Irrigation Water Requirements*, American Society of Civil Engineers, New York, 332 p.

Jones, F.E., (1992). *Evaporation of Water. With Emphasis on Applications and Measurements*, Lewis Publishers, Inc., Chelsea, Michigan 48118, 188p.

Makkink, G.F. (1957). "Testing the Penman formula by means of Lysimeters," *Journal Institution of Water Engineering*, Vol. 11, no. 3, pp 277-288.

Mock, F.J. (1973). *Water availability appraisal*, Report prepared for the Land Capability Appraisal Project, Indonesia, Institute of Soil Survey, Bogor, Indonesia, 64 p.

Monteith, J.L. (1965). "Evaporation and the Environment," *The State and Movement of Water in Living Organism*, XIXth Symposia of the Society for Experimental Biology, Swansea, Cambridge University Press, pp 205-234.

Oldeman, L.R. and Frere, M. (1982). *A Study of the Agroclimatology of the Humid Tropics of South-East Asia*, Technical Note No. 179. World Meteorological Organization, Geneva, Switzerland, 229 p.

Olivier, H. (1964). *Irrigation and Climate*, Edward Arnold Limited, London, 250 p.

Penman, H.L. (1948). "Natural Evaporation from open water, bare soil and grass," *Proceeding of the Royal Meteorological Society of London*, Series A.Vol. 193. pp. 120-146.

Penman, H.L. (1963). *Vegetation and Hydrology*, Technical Communication No. 53. Commonwealth Bureau of Soils, Harperden, Agricultural Bureaux, Farnham Royal, Bucks, England, 124 p.

Ponce, V.M. (1989). *Engineering Hydrology*, Prentice Hall, Inc. Englewood Cliffs, New Jersey 07632, 640 p.

Priestly, C.H.B. and Taylor R.J. (1972). "On the assessment of surface heat flux and evaporation using large scale parameters," *Monthly Weather Review*, Vol. 100, pp. 81-92.

Singh, V.P. (1989). "*Hydrologic System. Watershed Modelling*," Volume II, Prentice-Hall, Inc., Englewood Cliffs, New Jersey 07632, 320 p.

Smith, M. (1991). "*Report on the Expert Consultation on Procedures for Revision of FAO Guidelines for Prediction of Crop Water Requirements*," Land and Water Development Division, Food and Agricultural Organization of the United Nations, Rome, Italy, 54 p.

Shuttleworth, W.J. (1993). "Evapotranspiration," *Handbook of Applied Hydrology*. ed. Maidment D.R., McGrawHill Inc., USA, pp. 4.1-4.53.

Thornthwaite, C.W. (1948). "An approach toward a Rational Classification of Climate," *The Geographical Review*, The American Geophysical Society , Vol. XXXVIII, pp 55-94.

Thornthwaite, C.W. and Mather, J.R. (1955). " The water balance", Drexel Institute of Technology, Laboratory of Climatology, Centerton, New Jersey. Vol. 8, No. 1, 56 p.

Turc, L. (1961). "Evaluation de besoins en eau d'irrigation, evapotranspiration potentiale, formule climatique simplifice et mise a jour" (Estimation of irrigation water requirements, potential evapotranspiration. A Simple climatic formula evolved up to date)," *Ann. Agronomique*, Vol. 12. pp 13-49.

Veihmeyer, F.J. (1964). "Evapotranspiration," *Handbook of Applied Hydrology. A Compendium of Water-Resources Technology*, ed. Ven Te Chow, McGrawHill Book Company, pp. 11.1-11.38

Ward, R.C. (1975). *Principles of Hydrology*, Second Edition. McGraw-Hill Book Company (UK) Limited, Maidenhead, Berkshire, England, 367 p.