AN ABSTRACT OF THE THESIS OF

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The major objectives of this project were to evaluate the performance of the Bowen ratio energy balance (BREB) method and to compare the performance of the BREB, CIMIS Penman, and hydrologic balance (HBM) methods for estimating evapotranspiration. Meteorological and soil parameters were measured in an Alta fescue field in October 1989 and from July to October 1990.

An hourly analysis of the Bowen ratio variation for clear and cloudy sky conditions was made to evaluate the performance of the BREB method. Hourly and daily comparisons were performed for clear, cloudy, and combined data sets to check agreement between the BREB method and CIMIS Penman. Comparisons were also performed to evaluate the agreement between the BREB method and the HBM. The first test consisted of an evaluation of the error and goodness of fit of evapotranspiration estimated by the Bowen ratio energy balance method (ETB) versus evapotranspiration estimated by the CIMIS Penman (ETP) and by the hydrologic balance method (ETH). The second test consisted of linear regression analysis to test the agreement and variation between ETB versus ETP and ETH.

The study indicated that the performance of the BREB method was very good for clear and cloudy sky conditions. Hourly values of the Bowen ratio (B) indicated that the Bowen ratio system produced errors in calculation of latent heat flux less than approximately 5 percent from sunrise to sunset. However, hourly values of B were less -0.5 at night indicating that considerable errors in calculation of latent heat flux were produced, especially following clear days.

The error and regression analysis indicated that the agreement between the BREB and CIMIS Penman methods was excellent under clear and cloudy sky conditions. However, ETP was greater than ETB at midday when the conditions to obtain reference evapotranspiration at the experimental site were not maintained. The comparison between the BREB method and the HBM indicated that cumulative ETH was about 13 percent less than that obtained using the BREB method. This underprediction was probably produced by spatial variability of soil properties, neutron probe emission variation, and inaccurate measurement of water applied and drainage.

Analysis of Evapotranspiration by the Bowen Ratio, Penman, and Hydrologic Balance Methods

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ANALYSIS OF EVAPOTRANSPIRATION BY THE BOWEN RATIO, PENMAN, AND HYDROLOGIC BALANCE METHODS

1 INTRODUCTION

1.1 Statement of the Problem

The interest of many scientists in quantifying the rate of water loss from the Earth's surface has been increased in the last decade. The quantification of water loss is essential for irrigation planning and scheduling, water resources and hydrologic studies, and global climatic models. Depending on the objectives, the spatial scale of evapotranspiration estimates can range from a square meter to a square kilometer with a temporal scale from minutes to years. There are various methods for measuring or estimating evapotranspiration for different kinds of soil-plant surfaces. The choice of methods depends primarily on the type of soil-vegetation surface and the objectives for which the information is required.

On a regional scale, the estimation of the evapotranspiration has been used in the application of complex numerical and global climatic models to predict both short-term weather conditions and long-term climatic changes. Regional evapotranspiration estimates have been used for water resources planning and management in agriculture and urban areas. For water resource planning, the spatial scale of regional evapotranspiration can range from 1 to 500 km^2 with a temporal scale from weeks to years (Cuenca and Amegee, 1987; Sharma, 1985).

At the local or field scale, an accurate and consistent estimate of evapotranspiration is necessary to improve irrigation planning and scheduling. This is central to irrigation system design and operation, increase irrigation efficiency, reduced irrigation cost and maximization of crop production (Pescara et al., 1988). The spatial scale of local evapotranspiration for such purposes can be less than 1 km^2 with a temporal scale from hours to weeks (Sharma, 1985).

Several empirical or semiempirical methods based on concepts of meteorology, hydrology, and plant physiology have been developed to estimate evapotranspiration. Most applied methods are based on meteorological and hydrological approaches. In general, the accuracy of these approaches improves in proportion to the number of physically significant parameters used, but this requires expensive and sophisticated data collection systems (Sharma, 1985).

Methods based on concepts of meteorology use as input temperature, relative humidity, wind velocity, and radiation measured at a reference level. The Penman equation and Bowen ratio approaches, according to Garratt (1984) and Sharma (1985) may be recommended for the estimation of evapotranspiration because they have more physically significant parameters.

The Penman model is the most widely used method based on meteorological information for estimating local evapotranspiration (Weiss, 1982). This method includes both aerodynamic and energy balance terms. However, severe problems have been noted in the Penman equation when daily or longer-period mean weather data are used to estimate daily evapotranspiration. Several factors are believed to contribute significantly to the problem. Interaction between several input parameters, mainly the day-night distribution of wind, saturation deficit and level of radiation, can produce considerable errors in the computation of daily evapotranspiration (Pruitt and Doorenbos, 1977). Another important factor that could reduce significantly the feasibility of the method is the empirical wind function. The Penman model requires specific calibration and evaluation when it is introduced to a particular region.

To increase the accuracy of the Penman method, many improvements and advances have been made. More physically significant parameters such as stomatal resistance and atmospheric stability terms have been added. However, these improvements have been not enough to increase the accuracy of the method, and apparently the accuracy of the Penman approach could be increased significantly when hourly weather data is used as an input. Several researchers have suggested that accurate reliable estimates of daily reference evapotranspiration could be obtained from hourly weather data (Pruitt and Doorenbos, 1977; Weiss, 1982; Snyder, 1984).

Advances in computer technology and instrumentation have permitted estimation of daily evapotranspiration from hourly weather data. The Penman model developed by Pruitt and Doorenbos (1977) has been modified for use on an hourly basis and is being used in a computerized information network which provides growers with daily reference evapotranspiration (Snyder, 1987). This hourly Penman model has been successfully applied in California, but still has certain problems due to its empirical aerodynamic term.

The Bowen ratio approach computes evaporanspiration based on the energy balance. Net radiation, soil heat flux, and sensible heat flux are measured or estimated, and evapotranspiration is obtained as a residual. This approach requires no detailed specification of surface properties, but involves relatively complex instrumentation to measure vertical differences of air temperature and vapor pressure (Pruitt et al. 1987b). With the exclusion of eddy correlation, it is potentially the most accurate method using micrometeorological data and should be applicable for crops and forests over a wide range of evapotranspiration conditions (Garrant, 1984). However, under very dry conditions or with considerable advection the method may not be nearly so accurate (Angus and Watt 1984).

Like the Bowen ratio approach, methods based on the hydrologic balance compute evapotranspiration as a residual term. In general, hydrologic models use as input precipitation, irrigation, runoff, drainage and change in soil moisture storage. The accuracy of this approach in estimating evapotranspiration depends on the accuracy with which all input parameters are measured. Precipitation and irrigation can be measured by installation of raingages in sufficient number to give acceptable accuracy to the measurement (Sharma, 1985; Hill 1990). The amount of run-off generally is small in agriculture fields and particularly in irrigated fields, so that, it can sometimes be regarded as negligible in comparison with major components of the water balance (Hill 1990). The change in the soil water moisture status can be measured effectively using the neutron moderation technique (Allen and Segura, 1990). However, there are not reliable, practical methods available for measuring the deep percolation or drainage directly in typical agricultural fields. These missing data could produce important errors in the estimation of evapotranspiration.

The hydrologic balance and energy balance approaches are intimately connected since they involve processes that require energy. The soil water content affects the way the energy flux reaching the field is partitioned and utilized. Likewise, the energy flux affects the state and movement of water. A physical description of the soil-plant atmospheric system must be based on understanding both balances together. In particular, the evapotranspiration process is often the principal consumer of both water and energy in the field.

1.2 Objectives and Scope

The objective of this study is to compare the performance of the Bowen ratio energy balance (BREB), CIMIS Penman equation, and hydrologic balance methods for estimating evapotranspiration. The specific objective of this thesis are:

- To evaluate the performance of the BREB method on an hourly basis under clear and cloudy sky conditions.

- To compare the performance of the BREB method and CIMIS Penman model on an hourly basis and daily basis under clear and cloudy sky conditions.

- To compare the performance of BREB method and hydrologic balance method for estimating actual evapotranspiration.

Data for project was collected at the OSU Schmidt Farm, 15 km north of Corvallis, Oregon. To compute hourly and daily evapotranspiration, the Corvallis site was equipped with a Bowen ratio station, manual and automatic meteorological station, a radiation station, and access tubes for soil moisture evaluation by neutron probe. The data set was collected in October 1989 and from July to October 1990. 67 complete days of hourly data from this period were available for this study.

2 LITERATURE REVIEW

2.1 Energy Balance Theory for Estimation of Evapotranspiration

2.1.1 Introduction

The energy balance of a crop environment is based on the physical principle of energy and matter conservation which is the first law of thermodynamics. This principle states that energy cannot be created nor destroyed, but only changed from one form to another. In other words, the net flux of radiation entering the cropped surface area is equal to energy leaving the soil-plant-system plus energy stored by the system. This can be summarized by expression [1].

$$E_i = E_o + E_s \qquad [1]$$

where

E_i = *energy into the crop system, W* m^{-2}

E_o = *energy leaving the crop system, W* m^{-2}

E_s = *energy stored by the crop system, W* m^{-2}

The E_i is made up of absorbed solar radiation and absorbed infrared radiation from surroundings; E_o is made up of emitted infrared radiation, heat convection, heat conduction and heat loss accompanying water evaporation; E_s is made up of metabolic processes (photosynthesis, respiration, etc), dry matter production, and leaf temperature changes. The heat conducted and convected from the crop environment is referred to as sensible heat flux, while that associated with the evaporation or the condensation of water is known as latent heat flux. These phenomena are described in expression [2].

$$R_n = G + H + LE + PS + M \qquad [2]$$

where

R_n = *net radiation, W m*$^{-2}$

G = *soil heat flux, W m*$^{-2}$

H = *sensible heat flux, W m*$^{-2}$

LE = *latent heat flux, W m*$^{-2}$

PS = *energy used in metabolic processes, W m*$^{-2}$

M = *energy stored in dry matter, W m*$^{-2}$

The various terms in equation [2] differ greatly in magnitude. For example, the energy storage terms are generally relatively small. Photosynthesis by leaves may require only about 1 percent of the rate of absorption of daily solar radiation. Other storage components and leaf temperature changes are usually less important on an energy basis than photosynthesis, so that they too can be generally ignored (Tanner, 1988; William, 1989; Nobel, 1983).

When the energy storage terms in equation [2] are ignored, the remaining contributors to the energy balance of the crop environment system are either radiation or heat terms. The energy balance for crop water requirement studies can be expressed by equation [3].

$$R_n \approx G + H + LE \qquad [3]$$

This equation states that the net flux of radiation entering the crop environment is dissipated through the soil heat flux (G), sensible heat flux(H), and latent heat flux (LE). A positive net flux of radiation indicates a net energy input into the crop environment whereas a negative value indicates a net energy loss. A positive value of G indicates a net flux of energy into the soil which warms the soil. A positive value for H indicates that the atmosphere is warming. A positive value for LE indicates water vapor is transported by evaporation from the soil plant system to the atmosphere.

There are several techniques to estimate the energy balance components. The Bowen ratio energy balance (BREB) method seem to be the most satisfactory technique due to its reduced costs and complexity (Tanner, 1988). In this method, the quantity of energy dissipated through evapotranspiration is indirectly determined through the calculation of the Bowen ratio (B). The Bowen ratio is the ratio of sensible heat flux to latent heat flux (H/LE) and is proportional to the ratio of the air temperature gradient to the vapor pressure gradient as measured over some vertical distance above the surface.

2.1.2 Definition of Energy Balance Components

Net radiation, R_n, is the primary climatic factor controlling evapotranspiration when water is not limited (Jensen et al., 1990). Net radiation for crop water requirement estimates is defined as the net energy flux of longwave and shortwave radiation available for the crop environment. This parameter can be measured directly using a hemispherical net radiometer, or estimated from net shortwave and longwave components. The net radiation is described by equation [4].

$$R_n = (1-\alpha)R_s + I\downarrow - I\uparrow \qquad [4]$$

where

α = *albedo (reflectance)*

R_s = *incoming solar radiation (shortwave) at surface of the Earth,* $W\ m^{-2}$

$I\downarrow$ = *infrared energy (longwave) reflected from atmosphere to surface of the Earth,* $W\ m^{-2}$

$I\uparrow$ = *infrared energy from surface of the Earth to the atmosphere,* $W\ m^{-2}$

Positive net radiation occurs during daylight hours and results in a net positive input into the crop environment. This is the net input that dissipated through G, H, and LE.

Soil heat flux is defined as energy absorbed by the soil to warm the soil surface. This absorbed energy is dissipated by conduction to the surrounding air and into the soil profile. A positive value of G occurs during daylight hours with increasing soil temperature.

Sensible heat flux is the flux of energy leaving the crop and soil surface which warms the atmosphere. This energy transfer involves conduction and convection processes that transport sensible heat away from the soil and plant surfaces. During daylight hours, the solar radiation that reaches soil and plants increases their surface temperature and ultimately warms the adjacent air through conduction. This air is lifted out of the crop environment through convection. The sensible heat flux is positive when the atmosphere is warming through the conduction and convection processes.

Latent heat flux is an energy transfer associated with water vapor movement. Energy is used to transform water from a liquid to a vapor state. An positive value of LE indicates that the energy is used to change the phase of water from liquid to gas state. A negative value of LE indicate that water vapor is changed to liquid state.

2.1.3 Estimation of Soil Heat Flux in the Bowen Ratio Energy Balance Method.

Soil heat flux is estimated with a soil heat flux plate or a combination of a soil flux plate and thermocouples. The plate measures the average heat flux and thermocouples measure the average heat stored in the surface layer. In the BREB method, the soil heat flux is computed by adding the average heat flux to the average heat stored on the surface layer. The mathematical relationship relating these two terms is given by equation [5].

$$G = HF + HS \qquad [5]$$

where

HF = *average heat flux in the surface layer, W* m^{-2}

HS = *average heat stored in the surface layer, W* m^{-2}

The storage term is calculated by multiplying the change in soil temperature over an averaging period by the soil heat capacity. This is described by equation [6].

$$HS = \frac{(C_p \Delta T D)}{\Delta t} \qquad [6]$$

where

C_p = *specific heat of the soil,* $J m^{-3}$ $°C^{-1}$

ΔT = *change in soil temperature,* $°C$

D = *fixed depth at which the soil temperature is measured, m*

Δt = *change in time, s*

The specific heat of the soil depends on soil texture, bulk density, and soil moisture content. These parameters can be combined using equation [7].

$$C_p = BD\{CS + \Theta_m(CW)\} \quad [7]$$

where

BD = *bulk density of the surface layer, kg* m^{-3}

CS = *specific heat of dry soil, J kg* m^{-1} $°C^{-1}$

Θ_m = *soil moisture content on a mass basis, fraction*

CW = *specific heat of water, J kg* m^{-1} $°C^{-1}$

2.1.4 The Bowen Ratio Energy-Balance Method for Estimation of Sensible and Latent Heat Fluxes

The Bowen ratio is an indirect method used to estimate evapotranspiration. This ratio was mathematically defined by Bowen as the ratio between the sensible heat flux and latent heat flux. The Bowen ratio is expressed by equation [8].

$$B = \frac{H}{LE} \quad [8]$$

Applying the universal gas law to the Bowen ratio and assuming one dimensional vertical transport of a scalar within the free air above the surface, fluxes of sensible heat and vapor may be expressed by equations [9] and [10] respectively.

$$H = \rho_a C_p K_h \frac{\partial T}{\partial Z} \quad [9]$$

$$LE = \frac{\lambda \rho_a \epsilon K_u}{P} \left(\frac{\partial e}{\partial Z} \right) \quad [10]$$

where

ρ_a = *air density, kg m^{-3}*

C_p = *specific heat at constant pressure, J kg*$^{-1}$ $°K^{-1}$

K_h = *eddy diffusivity of heat,* m^2 s^{-1}

T = *time averaged air temperature,* $°C$

K_u = *eddy diffusivity of vapor,* m^2 s^{-1}

e = *time averaged air vapor density, mb*

Z = *height above the surface*

λ = *latent heat of vaporization, J kg*$^{-1}$

ϵ = *ratio of the molecular weight of water to the molecular weight of dry air*

P = *atmospheric pressure, mb*

The Bowen ratio can be formulated by dividing the previous two equations. This is described by equation [11].

$$B = \frac{PC_p}{\lambda\epsilon}\left(\frac{K_H}{K_w}\right)\left(\frac{\frac{\partial T}{\partial Z}}{\frac{\partial e}{\partial Z}}\right) \qquad [11]$$

In practice, this relationship is generally simplified by assuming K_u equal to K_h and approximating the partial derivatives by discrete differences. This is described by equation [12].

$$B \approx \left(\frac{PC_p}{\lambda\epsilon}\right)\left(\frac{T_1 - T_2}{e_1 - e_2}\right) \approx \gamma\left(\frac{T_1 - T_2}{e_1 - e_2}\right) \qquad [12]$$

where

γ = *psychrometric constant, mb* $°C^{-1}$

T_1 = *air temperature at low level,* $°C^{-1}$

T_2 = *air temperature at high level,* $°C^{-1}$

e_1 = *vapor pressure at low level, mb*

e_2 = *vapor pressure at high level, mb*

The ratio of the molecular weights of water vapor to air is assumed to be 0.622. The vapor pressure of air can vary slightly with atmospheric pressure and humidity with extreme values from 1004 for dry air to 1089 J kg^{-1} $°C^{-1}$ for moist air (Jensen et al., 1990). The latent heat of vaporization (J kg^{-1}) and atmospheric pressure (mb) can be estimated by equations [13] and [14], respectively.

$$\lambda = 2500.78 - 2.3601(T_{air}) \qquad [13]$$

$$P = 1013 - 0.1055(E) \qquad [14]$$

where

T_{air} = *air temperature,* $°C^{-1}$

E = *site elevation, m*

The psychrometric constant (γ) represents a balance between the sensible heat gained from air flowing past a wet bulb thermometer and sensible heat transformed into latent heat. The psychrometric constant varies directly with air pressure, which decreases with altitude, and latent heat of vaporization. From equation 12, γ can be expressed by the following relationship.

$$\gamma = \frac{PC_p}{0.622\lambda} \quad [15]$$

In the BREB method, measurements of R_n and G are made and the value of B is determined from measured gradients of air temperature and vapor pressure. From the energy balance equation (equation [3]), LE and H can be expressed by equations [16] and [17], respectively.

$$LE = \frac{(Rn - G)}{(1 + \mathrm{B})} \quad [16]$$

$$H = \mathrm{B}\frac{(Rn - G)}{(1 + \mathrm{B})} \quad [17]$$

2.1.5 Advantages and Disavantages of the Bowen Ratio Energy Balance Method

The Bowen ratio energy balance method has certain advantages for determining evapotranspiration in crop environments because it is relatively simple and does not require complex formulation. Perhaps one of the most important advantages as compared to empirical methods or even the Penman model is that the gradients of temperature and humidity measured are directly related to the actual balance at the surface. No empirically-based wind function nor estimate of aerodynamic roughness and canopy resistance are required for the method (Pruitt et al., 1987b).

Under moist conditions with irrigated pastures or crops, the BREB method can give very good results (Angus and Watts, 1984). With the exclusion of eddy correlation, the BREB method is potentially the most accurate method and should be applicable for crops and forests over a wide range of evapotranspiration conditions (Garrantt, 1984).

Pruitt et al. (1987) observed excellent agreement between lysimeter determined grass ET and hourly estimated ET by the BREB method. Also, Pruitt et al. (1987) found that in the same conditions hourly estimated ET by the BREB method was 20-25 % higher than reference crop ET (8-15 cm tall grass) determined by Penman equation which had been calibrated for hourly use.

However the BREB method has several disadvantages. This method involves relatively complex instrumentation to measure small vertical differences of temperature and humidity in the air (Garratt, 1984). The BREB method requires continuous checks of sensors that measure air temperature and vapor pressure gradients which are usually quite small (Rosenberg, 1983). Another problem is when the Bowen ratio is close to -1, predicted LE becomes erroneously high and indeed equal to infinity when B equals zero. This situation often occurs around sunrise and sunset when air temperature differences approaches zero and $R_n - G$ is small. Fortunately, this usually happens for a brief period each day, and the error introduced in daily totals of LE is small (Pruitt, 1989). In practice, when B is close to -1 (e.g, $-1.25 < B < -0.75$), LE and H are assumed to be negligible and are not calculated (Campbell Scientific, 1988; Tanner, 1988).

The basic assumption of the BREB method, which states that K_h is equal to K_u, should be kept in mind when site for a Bowen ratio station is under investigation (Katul, 1990). The method may not be nearly so accurate under very dry conditions, or with considerable advection because the relative error in LE due to the error in B becomes large (Angus and Watts, 1984). The Bowen ratio approach could be improved by using the actual K_h/K_u ratio rather than the basic assumption that $K_h/K_u = 1$ (Rosenberg et. al., 1983).

2.1.6 Error Analysis for the Bowen Ratio Energy Balance Method

The accuracy of the computed value of LE is strongly dependent the accuracy of the Bowen ratio. Angus and Watts

(1984) reported that a errors of 20 percent in the Bowen ratio (B) produce error less than 5 percent in *LE* when the B ranges from -0.2 to 0.2. In addition, they indicated that a errors of 30 percent in the Bowen ratio (B) also produce error less than 5 percent in *LE* when the B ranges from -0.45 to 0.45. Angus and Watts (1984) demonstrated that the potential error in calculation of *LE* increase exponentially as B drops below the lower limit of the range (-0.2 or -0.4). However, when the B is greater than the upper limit of range (0.2 or 0.4), the relative error in *LE* increase linearly. For example, Angus and Watts showed that when B was equal to -0.95, the relative error introduced in *LE* was very large (over 100 percent), but when it was equal to 0.95 the relative error was only about 10 percent.

Comparisons between the lysimeter and Bowen ratio approaches by Pruitt et al. (1987b) indicated that the departure from correct values commenced by the time the Bowen ratio dropped to -0.55. Pruitt et al. (1987b) observed that when the B decreased from a value of -0.55 to -0.85, the average value of *LE* estimated by the Bowen ratio method was about 125 W m^2 while *LE* estimated by lysimeter was about -19 W m^2 (a difference of 115 %.).

2.2 Combination Penman Equation for Estimation of Hourly Reference Evapotranspiration

The combination-type equation computes crop evapotranspiration using both energy balance and aerodynamic terms. The best known combination method is that developed by Penman (Jensen et al., 1990; Cuenca, 1989). The original Penman equation has been subject to several variations and improvements by changing the wind function coefficients and adding other terms such as the aerodynamic resistance to sensible heat and vapor transfer (Jensen et al., 1990).

Several researchers have observed that the Penman equation has serious accuracy problems in estimating reference evapotranspiration (ETo) using daily weather data (Snyder, 1984; Weiss, 1982). Interaction between several input parameters, mainly the day-night distribution of wind, saturation deficit and level of radiation can produce a 20-40 percent underprediction and as much as 200-300 percent overprediction (Pruitt and Doorenbos, 1977). These problems could be avoided using hourly weather data.

Technological advances in electronic data logging have greatly enhanced the ability to obtain accurate and reliable estimates of real-time values of ETo from hourly weather data. The California Irrigation Management Information System (CIMIS) is a computerized system which provides daily ETo estimates based on hourly computations using a combination Penmam equation.

2.2.1 California Irrigation Management Information System

The California Irrigation Management Information System (CIMIS) is a computerized meteorological data gathering and information network that is being used to provide daily reference evapotranspiration (ETo) information for the purpose of scheduling irrigations. In the CIMIS network, daily ETo is computed from a modified version of the Penman equation which uses hourly weather data (Snyder, 1987; Snyder et al., 1984). The calculation of daily ETo from hourly data using the Penman model is described by equation [18].

$$ETo = W R_n + (1 - W)(VPD) f(u) \qquad [18]$$

where

ETo = *reference evapotranspiration, mm* h^{-1}

R_n = *net radiation, mm* h^{-1}

W = *dimensionless weighting function for elevation and temperature*

VPD = *vapor pressure deficit, kPa*

$f(u)$ = *aerodynamic wind function, mm* kPa^{-1}

The weighting function is a function of the slope of saturation vapor pressure curve as a fuction of temperature and the psychrometric constant. This relationship can be expressed by equation [19].

$$W = \frac{\Delta}{\gamma + \Delta} \quad [19]$$

where

Δ = *slope of saturation vapor pressure versus temperature curve at* T_{mean}

γ = *psychrometric constant*

The psychrometric constant can be calculated using equation [2] (Section 2.1). The slope of saturation vapor pressure is determined from each hourly average air temperature (T_{mean}) using equation [20].

$$\Delta = 2(0.00738T_{mean} + 0.8072)^7 - 0.00116 \quad [20]$$

where

T_{mean} = hourly average air temperature, $°C$

The hourly vapor pressure deficit is calculated as the difference between saturation vapor pressure and actual vapor pressure. The saturation vapor pressure at the hourly average temperature and actual vapor pressure on an hourly average air relative humidity are calculated using equations [21] and [22], respectively.

$$e_s = 0.6108\exp\left(\frac{\{17.27T_{mean}\}}{\{237.3 + T_{mean}\}}\right) \quad [21]$$

where

$$e_a = e_s\left(\frac{RH}{100}\right) \qquad [22]$$

e_s = *saturation vapor pressure, kPa*

e_a = *actual vapor pressure, kPa*

T = *hourly average air temperature,* $°K$

RH = *hourly average air relative humidity, %*

CIMIS has incorporated two empirical wind functions presented by Snyder (1987). When net radiation is less than or equal to zero, the wind function is given by equation [23]l; when it is greater than zero, the aerodynamic wind function is estimated by equation [24].

$$f(u) = 0.125 + 0.0439(u) \qquad [23]$$

$$f(u) = 0.03 + 0.0576(u) \qquad [24]$$

where

u = *average hourly wind speed at 2 m height, m* s^{-1}

If wind speed is measured at a height other than 2 m , it can be modified to the equivalent 2 m wind speed by application of the log-wind law (Cuenca, 1989). The modification can be made using equation [25].

$$U_{2m} = U_z\left(\frac{2.0}{z}\right)^{0.2} \qquad [25]$$

where

U_{2m} = *equivalent wind speed at 2 m height, m* s^{-1}

U_z = *wind speed measured at height z, m* s^{-1}

z = *height of measurement, m*

2.2.2 Advantages and Disavantages of the Hourly Penman Equation

The advantages of using hourly data to estimate daily *ETo* has been recognized by many researchers. Pruitt and Doorenbos (1977) recommended that daily *ETo* for irrigation management services be predicted from the summation of hourly values. This could largely overcome the deficiencies of the Penmam type of equation as usually employed on a daily basis. In spite a wide range of weather conditions, Pruitt and Doorenbos (1977) found an excellent prediction of daily *ETo* using a wind function developed from hourly grass *ETo* and weather data. Pruitt et al. (1987) found good agreement between lysimeter-determined grass *ETo* and hourly estimated *ETo* using an hourly Penman model.

An hourly Penman model can provide precise and reliable *ETo* information to growers for the purpose of scheduling irrigation. However, this model requires large amounts of data and sophisticated data collection systems (Sharma, 1985). Data collection systems such as CIMIS need continuous quality control of the data, expensive maintenance and technical expertise to give useful *ETo* information to growers for the purpose of scheduling irrigation (Craddock, 1991).

The hourly Penman equation is still an empirical model for estimating *ETo*. It requires local calibration of the aerodynamic wind function (Hatfield and Fuchs, 1991). Furthermore, the model does not account the effect of the physical roughness of the vegetation on the transfer of energy and mass from the surface to atmosphere (Sharma, 1985).

2.3 Theory of the Hydrologic Balance Model

2.3.1 Introduction

The hydrologic balance model is an account of all quantities of water added to, subtracted from, and stored within a given volume of soil during a given period of time. In its simplest form, the water balance model merely states that the differences between the amount of water added and the amount of water withdrawn during a certain period is equal to the change in water content during the same period. Soil water content changes finally depend on various soil water flow processes such as infiltration, drainage, redistribution, evaporation, and water uptake by plants. These processes are strongly interdependent and occur sequentially or simultaneously (Hill and Allen, 1990).

As for the energy balance, the hydrologic balance is based on the first law of thermodynamics. The soil water content of a profile of finite volume cannot increase without addition from the outside by precipitation, irrigation, infiltration or capillary rise nor can it diminish unless transported to the atmosphere by evapotranspiration or to deeper zones by drainage.

In practice, the hydrologic balance model is used to estimate actual evapotranspiration ($ETac$)(Cuenca, 1988; Boman and Higging, 1990; André et al., 1986). Conceptually $ETac$ is estimated as a residual term in the water balance in which precipitation and irrigation are balanced by streamflow, and changes in ground water and soil water content. The water balance is applicable to small plots (10 m^2) or to large catchments (> 10^6 m^2); it may cover periods ranging from a week to a year (Rose and Sharma, 1984). On a yearly basis, changes in storage are usually negligible and $ETac$ is calculated using water applied to the control volume and streamflow.

To estimate $ETac$ using the hydrologic balance model, it is necessary either to measure or calculate changes in soil water storage and the amount of applied water. The neutron moderation technique provides the most appropriate method to measure the soil water content at various depths in the soil profile (Cuenca, 1988; Sharma, 1985; Rose and Sharma, 1984). The amount of applied water from precipitation and irrigation can be measured by installation of rain gages in numbers required to give acceptable accuracy.

2.3.2 Hydrologic Balance Components

The water balance approach for a given volume of soil states that changes in water content during a certain period equals the difference between the amount of water added and the amount of water withdrawn during the same period. This approach for the root zone may be expressed in an integral form by equation [26].

$$\Delta S + \Delta V = (P + I + U) - (R - D + E + T) \qquad [26]$$

where

ΔS = *change in root zone soil moisture storage, mm*

ΔW = *increment of water incorporated in the plant, mm*

P = *precipitation, mm*

I = *irrigation, mm*

U = *upward capillary flow into the root zone, mm*

R = *runoff, mm*

D = *drainage out of the root zone, mm*

E = *evaporation, mm*

T = *transpiration by plants, mm*

Equation [26] can be simplified by neglecting capillary rise and the increment of water incorporated in the plant, and computing the effect of evaporation and transpiration as one term, actual evapotranspiration ($ETac$). This can be described by equation [27].

$$P + I = ETac + R + \Delta S + D \qquad [27]$$

Mathematically, the change in root zone soil moisture storage (ΔS) can be obtained by integrating the change in soil moisture over depth and time. This relationship can be expressed by equation [28].

$$\Delta S = \int_0^{z_s} \int_{t_0}^{t_1} \left(\frac{\partial \theta}{\partial t} \right) d z_s dt \qquad [28]$$

where

θ = *volumetric soil moisture, fraction*

z_s = *soil depth, m*

t_0 = *initial time*

t_1 = *final time*

Equation [28] can be applied to any scale, ranging from continental land masses and hydrologic catchments to small fields. In most water balance studies, all elements in equation [27] other than $ETac$ are measured or otherwise estimated and $ETac$ is calculated as residual. The accuracy of this model to calculate $ETac$ depends on the accuracy with which rainfall, irrigation, runoff, drainage and ΔS are measured. The errors in measurement of these parameters are sometimes significant (Rosenberg et al., 1983).

2.3.3 Advantages and Disavantages of the Hydrologic Balance Method

The advantages of the soil water balance approach, especially over long periods (> 1 year) compared to above-ground measurements of water vapor flux, are the ease of data processing and the integration of the effect of various soil and vegetation units, which may exhibit large spatial heterogeneity (Sharma, 1985). The disadvantages are the low level of measurement accuracy of hydrologic balance components (precipitation, irrigation, runoff and drainage) and difficulties of assessing $ETac$ during rainy period. Even with careful measurement it is difficult to detect soil water change with an accuracy better than ± 2 mm of water (Rosenberg et al., 1983).

Errors associated in the measurements of water balance components invalidate this method for estimating $ETac$ on a daily basis (Rosenberg et al). Carrijo (1988) observed that the hydrologic balance model used on daily basis produced a very large variation in estimated $ETac$ both within individual access tube and from day to day using the neutron scattering technique to determinate soil moisture content. This variation was associated with inaccuracy in the calibration equation, spatial variation and variation in the probe reading. Carrijo (1988), also, reported that five day data gave the highest coefficient of determination (r^2) between the Penman-Monteith model and hydrologic balance method. However, the coefficient of determination was only about 70 percent. Rosenberg et al. (1983) observed that the hydrologic balance method should be acceptable for 2- or 3-day intervals if water balance components, especially drainage, were accurately measured.

2.3.4 Neutron Probe Theory

The neutron probe is a fast and nondestructive instrument for measuring soil moisture content which has become widely used in agricultural management and research (Allen and Segura, 1990). This method requires specific field calibration to determinate soil moisture content because neutron probe readings are affected by several factors such as soil chemical and physical properties, access tube material, and air gaps between access tube and profile (Stone, 1990a; Stone, 1990b; Gylan, 1990). The neutron probe calibration is developed by relating neutron probe readings to soil moisture content determined by gravimetric sampling for several levels of soil moisture. Using proper calibration procedures, probe errors are usually less than 1 percent of soil water content determined by the gravimetric sampling technique (Gylan, 1990b).

The neutron probe consists of two main components: a) a probe lowered into an access tube inserted vertically into the soil which contains a source of fast neutrons and a detector of slow neutrons; and b) a scaler or ratemeter to monitor the flux of slow neutrons scattered by the soil. The probe contains a radioisotope neutron source which constantly emits energized neutrons. The low level radioactive source is generally a mixture of Beryllium powder (a potential neutron emitter) and Americium (an alpha particle emitter) in a tightly compressed pellet. Energized neutrons are emitted when the alpha particles strike the Beryllium atoms (CPN corporation, 1984).

The fast emitted neutrons have a mass similar to hydrogen ions and are deflected upon striking a hydrogen ion. In the course of the collision, energy is absorbed and the energized neutrons are slowed down or reduced to a thermal energy level. The probe detector is sensitive to thermal or slow neutrons and so the number of slow neutrons detected is proportional to hydrogen ion content in the soil, most of which is bound up in water molecules.

The number of thermal neutrons detected by the probe can be related to soil moisture content using a calibration curve. By simultaneously making neutron probe readings and taking gravimetric samples for soil moisture content and bulk density, a regression equation can be developed correlating the gravimetric soil moisture content and the ratio of the neutron detector count to the probe standard count. The ratio of the neutron detector count is calculated using equation [29].

$$CR = \frac{NMR}{STD} \qquad [29]$$

where

CR = *count ratio*

NMR = *neutron meter reading*

STD = *standard count for specific neutron probe*

The count ratio generally is used instead of direct count because count times can be changed without affecting the calibration curve. The count ratio also automatically corrects for electronic drift and source decay (Gylan, 1990).

2.3.5 Neutron Probe Calibration

The neutron probe calibration consists of two steps: a) estimation of the soil moisture content using gravimetric sampling technique; b) division of the soil profile into layers according to its soil physical and chemical properties, and establishment of neutron probe calibration constants for each layer.

The gravimetric technique is the original and most basic method to accurately measure soil moisture content. This method consists of removing a sample from the soil and determining its moist and dry weights. The moist weight is taken by at the time of sampling. The dry weight is obtained after drying the sample to a constant weight in an oven. The standard method of drying is to place the sample in an oven at 105 $^{\circ}C$ for 24 h. The gravimetric water content is calculated by equation [30].

$$\Theta_m = \frac{M_w}{M_s} \qquad [30]$$

where

Θ_m = *water content on a mass basis, fraction*

M_w = *mass of water, g*

M_s = *mass of dry soil, g*

The gravimetric moisture content can be converted to a volume basis using the bulk density of each layer. This relationship can be expressed by equation [31].

$$\Theta_v = \Theta_m \left(\frac{\Gamma_b}{\Gamma_w} \right) \quad [31]$$

where

Θ_v = *volumetric water content, fraction*

Γ_b = *soil bulk density, g cm^{-3}*

Γ_w = *density of water, g cm^{-3}*

The second step in the calibration process is to divide the soil profile into layers of distinct bulk densities and to separate out the surface layer down to a depth of approximately 15 cm. The surface layer is separated from the soil profile because neutrons are lost to the atmosphere and there is a great variation in physical and chemical properties in this layer. For these conditions and the increased accuracy of the method it is necessary to develop a separate calibration for the surface layer. In addition to the surface layer, the soil profile should be divided into those layers for which soil bulk density or soil organic matter content changes appreciably. A separate calibration curve is required for each layer. The calibration equation for each layer correlating detector count with volumetric moisture content is described by equation [32].

$$\Theta_v = A\{CR\} + B \qquad [32]$$

where

Θ_v = *volumetric moisture content, %*

A *and* B = *statistical coefficient fron linear regression analysis*

This relationship is affected by several factors such as soil properties, access tube design, and the air gap between the access tube and soil profile. The soil properties include capture elements, organic matter, and bulk density. The access tube design includes material type, thickness, and size of access tube.

The capture elements in the soil essentially decrease the neutron probe reading for a given soil water content as compared to no capture conditions. The effect is to change the slope of calibration curve. Iron, potassium, chlorine and boron have a high affinity for neutrons and have the greatest effect on the calibration (Gylan, 1990; Stone, 1990).

A high concentration of organic matter in the soil increases the thermal neutron count and changes the intercept of the calibration curve. This occurs because organic matter has a high amount of bound hydrogen not in the form of water which increases the number of slow neutrons and neutron probe reading.

Not everyone agrees that bulk density has an effect on the calibration curve and that a change in bulk density requires a change in the calibration. Stone (1990) suggested that bulk density is not important and an integrated average of gravimetric moisture measurements should be considered during calibration for soils with significant moisture variation. Allen and Segura (1990) suggested that the change of bulk density on the probe calibration is not necessary and might well be ignored except for the most stringent precision. On the other hand, Gylan (1990) suggested that increasing the soil density increases the concentration of capture elements in a given soil which changes the slope of the calibration function.

Allen and Segura (1990) found that as access tube diameter, thickness, and air gaps increase the meter counts decrease. Allen and Segura (1990) also found that the effect of thickness of tube access was much higher for polyvinylchloride (PVC) tubes than for an aluminum tubes due to an increase in neutron capture by chloride ions in the PVC. Air gaps between the access tube and the soil profile decrease the neutron probe reading due to displacement of the zone of thermalization farther away from the detector causing a reduction in thermalized neutrons returning to detector. The effect of an air gap on neutron counts is similar to the effect of an increased tube diameter.

2.3.6 ETMASTER Hydrologic Balance Model

ETMASTER is a hydrologic balance model program developed to compute soil moisture status and hydrologic water components such as actual evapotranspiration and drainage. ETMASTER has three main programs which create and update several data files, calculate the status of water content in the soil profile and estimate periodic evapotranspiration. This computer model employs neutron probe readings for soil moisture content coupled with measured amounts of precipitation and irrigation.

The application of ETMASTER requires a selection of evapotranspiration periods. An evapotranspiration period is defined as the time interval between two neutron probe readings. Ideally, an evapotranspiration period begins on the day after a set of neutron probe readings have been taken. Ideally such readings are made preceding application of water to the field. The final condition of soil moisture content for the previous period is assumed to be the starting condition for the subsequent period.

ETMASTER calculates the soil moisture deficit and the depth of applied water retained in the soil profile at the start of an evapotranspiration period. At the end of an evapotranspiration period, the change in the soil moisture content and maximum cumulative evapotranspiration is estimated for the period. The soil moisture deficit is defined as the difference between field capacity and soil moisture content measured by the neutron probe. This variable is calculated using equation [33].

$$SMD = \sum_{i=1}^{n} (FC_i - \Theta_i) \qquad [33]$$

where

SMD = *soil moisture deficit, mm*

n = *number of depth layers*

FC_i = *field capacity of layer i, mm*

Θ_i = *soil moisture content at start of period for layer i, mm*

ETMASTER offers three methods to estimate field capacity for each depth layer; a) first value of soil moisture content in the soil moisture history table; b) maximum soil water content from the soil moisture history table and c) user specified field capacity for each depth layer.

To estimate the applied water retained in the soil profile, the amount of applied water at the start of the evapotranspiration period is considered. Applied water is distributed to an individual depth layer up to the limit of field capacity. If the depth of applied water is greater than the capacity of the surface layer to store water, the excess water is added to the profile. This distribution is described by equations [34] and [35].

$$DR_s = CP_s \qquad [34]$$

and

$$AW_p = AW_t - DR_s \qquad [35]$$

where

DR_s = *depth of water retained in surface layer, mm*

CP_s = *capacity of surface layer to store water, mm*

AW_t = *total depth of applied water, mm*

AW_p = *depth of water applied to remainder of soil profile, mm*

If the depth applied water is less than the capacity of surface layer to store water, $AW_P = 0$ and $DR_s = AW_t$. On the other hand, if the amount of water applied to the remainder of the profile is greater than the capacity of the profile, the excess of water is considered to be lost to deep percolation. This can be described by equations [36] and [37].

$$DR_p = CP_p \qquad [36]$$

and

$$D_p = AW_p - DR_p \qquad [37]$$

where

DR_p = *depth of water retained in remainder of soil profile, mm*

CP_p = *capacity of remainder of soil profile to store water, mm*

D_p = *deep percolation beyond active root zone, mm*

If the ΔW_p is less than the capacity of the profile to store water, $DP = 0$ and $DR_p = \Delta W_p$.

The end of ET period is determined by a set of neutron probe readings which shows the final status of water content in the soil profile. The change in the soil moisture content over the ET period is calculated by equation [38].

$$\Delta\Theta = \sum_{i=1}^{n} (\Theta_{Ei} - \Theta_{Si}) \qquad [38]$$

where

$\Delta\Theta$ = *change in water content, mm*

Θ_{Ei} = *water content at the end of the evapotranspiration period for depth layer i, mm*

Θ_{Si} = *water content at start of period for depth layer i, mm*

The actual evapotranspiration for a period is calculated by summation of applied water stored in the surface layer and profile plus the change in water content in the soil profile. This is described by equation [39].

$$ETac = DR_s + DR_p + \Delta\Theta \qquad [39]$$

where

$ETac$ = *actual evapotranspiration over the ET period, mm*

If the calculated depth of $ETac$ is greater than a maximum upper limit, the excess may be indicated as drainage of the profile. The maximum value is generally computed using a meteorological-based model. Application of an estimated maximum evapotranspiration rate to calculate drainage is activated at the option of the user.

ETMASTER can be used to study soil moisture status, evapotranspiration, and irrigation scheduling. Goutorbe et al. (1989) applied this computer model to study soil moisture variation on regional and local scales. Cuenca and Noilhan (1991) used ETMASTER as a ground-based measured model for estimation and verification of HAPEX-MOBILHY regional evapotranspiration. In irrigation scheduling, Nichols et al. (1988) found that the use of the model resulted in a reduction of water requirement over the traditional fixed irrigation time used previously. However, this model computes deep percolation as a function of the field capacity of each layer which in certain conditions is difficult to calculate. This could produce significant errors in the estimation of evapotranspiration.

3 MATERIALS AND METHODS

3.1 Evapotranspiration Investigation Plot

The Oregon Evapotranspiration Investigation Plot (ETIP) is located at the OSU Schmidt Farm, 15 km north of Corvallis at a latitude of 44° 37′46′′ N, logitude 123° 13′ 8′′ W, and an elevation of 70 m above sea level. The climate is modified maritime. Average annual precipitation is 1080 mm, occurring mainly from October to April. The soils found at the ETIP site are classified as Amity silt loam and Woodburn silt loam. These soils are deep and well drained through most of the profile.

The ETIP site is rectangular with an area of 2.11 ha (136 m X 155 m) covered by a well established stand of Alta fescue (*Festuca elatior*). The Alta fescue was maintained to a height between 8-20 cm, well irrigated, and free from weeds. However the fungus disease called rusts (*Puccinia brachypodii var. nemoralis*) was observed early and late in the summer. The irrigation system used was a hand moved sprinkler system with a sprinkler spacing of 9 meters and an irrigation frequency of 7 days.

The ETIP site is used to study land surface processes which include the hydrologic balance, energy balance, remote sensing, and soil moisture studies. The plot has a manual meteorological station, an automatic meteorological station, a Bowen ratio station, radiation station, and access tubes for neutron probe readings.

3.1.1 Manual Meteorological Station

The purpose of the manual station is to do a station performance diagnosis. Measurements are made of daily maximum air temperature (T_{max}), minimum air temperature (T_{mim}), air relative humidity (RH), soil temperature (T_s), piche evaporation (P_{et}), precipitation (P), and wind speed (U). The T_a, RH and T_s data from this station were directly compared to the Bowen ratio station and automatic meteorological station. P, and U were compared to automatic meteorological station during the data proccesing. Only ± 5 percent differences were permitted between stations. Over this limit, the Bowen ratio and automatic meteorologic stations require a careful check. The manual meteorological station data were collected manually 3 times per week during the spring, 6 times per week during the summer, and 3 times per week during the autumn. This was done one time per day early in the morning. Details of instrumentation and meteorological variables are summarized in Table 1.

3.1.2 Automatic Meteorological Station

Data from the automatic meteorological station is used to compute reference evapotranspiration on an hourly and daily basis. This station records air temperature (T_a), air relative humidity (RH), soil temperature (T_s), incoming shortwave

Table 1. Summary of variables and instrumentation characteristics of the manual meteorological station.

Variable	Units	Height above surface	Instrument	Accuracy
T_{max}	$°C$	1 m	Thermometer, model 4421	0.2 C above freezing
T_{min}	$°C$	1 cm	Thermometer, model 4421	
RH	%	0.5 m	Sling psychrometer, model 5210	0.5 %
T_s^*	$°F$	0.2 m	Thermometer, model 2261	0.5%
P_{ev}	ml	1 m	Piche evaporemeter, model 68052-A	0.1 ml
P	in.	surface	Raing gage, model 6310	0.01 in.
U	mi.	3 m	Anemometer, model 2510	0.1 mi.

* measured below the soil surface

solar radiation (R_s) and reflected shortwave solar radiation (R_r), wind speed (U), wind direction (U_d), and precipitation (P) at 15 minute intervals. The maximum values, minimum values, average values and cumulative precipitation during 15 minute were collected using a Campbell Scientific CR 21 Micrologger which transfer the collected data onto an external tape recorder. The tape recorder was read 1 time per week during spring, 2 times per week during summer, and 1 time per week during the autumn. Details of sensors and meteorological variables are summarized in Table 2.

3.1.3 Bowen Ratio Station

The Campbell Scientific Bowen ratio station is used to the study the energy balance of the crop canopy. This system uses a Campbell Scientific CR 21x Micrologger to control station operation and for data logging. Data were averaged every 20 minutes and transfered by the micrologger onto a tape recorder daily. Net radiation (R_n), air temperature (T_a), dew point temperature (T_{dw}), soil temperature (T_s), and the soil heat flux (HF_s) were measured directly by the system sensors. The vapor pressure (e) was indirectly estimated by the micrologger using a dew point hygrometer. The estimation of sensible heat flux, latent heat flux, and soil heat flux were externally computed (Section 2.1.4). To measure the air temperature gradient (Δt) and estimate air the vapor pressure gradient (Δp) in the Bowen ratio energy balance method, the air temperature and dew point temperature are measured at two levels. Each level has a chromel-constantan thermocouple to measure air temperature and an air intake open to the atmosphere. To prevent contamination of the dewpoint hygrometer, the air intakes have a 25 mm Teflon filter with a 1 um pore diameter.

Table 2. Summary of variables and sensor characteristics of automatic meteorological station.

Variable	Units	Height above surface	Instrument	Accuracy
T_a	$°C$	2 m	PCRC-11	±0.1%
RH	%	2 m	PCRC humidity transducer PCRC-11	±0.1%
T_s^*	$°C$	0.1 m and 0.3 m	Temperture probe, model 107 B	±0.5%
R_s	$W m^{-2}$	3 m	Pyrometer, model Py 3721	±3%
R_r	$W m^{-2}$	3 m	Pyrometer, model Py 6698	±2%
P	mm	surface	Tipping bucket raingage, model 6011-B	±5%
U	$km h^{-1}$	3 m	Anemometer, model 014 A	±5%
U_d	°	3 m	Anemometer, model 024 A	±5%

* measured below the soil surface

To measure the air temperature gradient (Δt) and estimate the air vapor pressure gradient (Δp) in the Bowen ratio energy balance method, the air temperature and dew point temperature are measured at two levels. Each level has a chromel-constantan thermocouple to measure air temperature and an air intake open to the atmosphere. To prevent contamination of the dewpoint hygrometer, the air intakes have a 25 mm Teflon filter with a 1 um pore diameter.

The dewpoint temperature is measured by a dewpoint hygrometer (DEW-10). The DEW-10 consists of a small mirror in which a platinum resistance thermometer is imbedded. The mirror temperature is adjusted to the dewpoint temperature using the mirror reflection. The reflection of the mirror's surface is reduced as the mirror temperature is decreased. This temperature is decreased to a level below the dewpoint by an attached thermoelectric cooler. Upon reaching the dewpoint temperature, a servo controller reduces the current supplied to the thermoelectric cooler and then the mirror temperature is slightly increased above the dewpoint temperature. Approximately 1.5 cooling and warming cycles are required before the mirror temperature approaches the dewpoint temperature for a properly adjusted DEW-10. This operation requires air samples from two heights be routed to the cooled mirror. Every 2 minutes the air being drawn through the cooled mirror is switched from one height to the other. Forty seconds is allowed for the mirrow to stabilize on the new point, and 1 minute and 20 seconds worth of measurements for an individual level are obtained for each 2 mimute cycle. The dewpoint temperature is measured every second and the vapor pressure is calculated using the datalogger. The average vapor pressure at each height is calculated every 20 minutes. Datails of sensors and meteorological variables are summarized in Table 3.

Table 3. Summary of variables and sensor characteristics of the Bowen ration station.

Variable	Units	Heigth above surface	Instrument	Accuracy
T_a	$°C$	0.3 and 1.3 m	Type E fine wire thermocouple	±0.006 $°C$
T_{dw}	$°C$	0.3 and 1.3 m	Dewpoint hygrometer model DEW-10	±0.003 $°C$
e^{**}	kPa	0.3 and 1.3 m	Dewpoint hygrometer, model DEW-10	$\pm 0.01 kPa$
T_s^*	$°C$	0.02 m and 0.06 m	Averaging soil thermocouple probe, Model TCAU	$\pm 0.5\%$
R_n	$W m^{-2}$	1.2 m	REBS net radiometer (Fritschen), model Q-5	$\pm 10 W m^{-2}$
HF_s^*	$W m^{-2}$	0.08 m	REBS soil heat flux plate, model HFT-1	$5-10\%$

** computed using the 21x micrologger

* below the soil surface

3.1.4 Radiation Station

The radiation station is used to study the radiation balance at the Earth's surface. This station records incoming and outgoing solar radiation on 15 minutes interval. The data were collected by the Campbell Scientific CR21 Micrologger and stored on a tape recorder. The tape recorder was read 1 time per week during the spring, summer, and autumn seasons.

The solar radiation components are measured by a albedometer, Model 3023 which has a sensitivity of 15 microvolts per W m^{-2}. This sensor is an combination of a upward and downward facing pyramometer. The upward and downward facing pyramometers measure total incoming solar radiation and total reflected solar radiation, respectively. Due to the albedometer spectral response of 0.3 to 3 microns, no longwave radiation can be measured.

3.2 Data Collection

3.2.1 Meteorological and Radiation Data

The data set was collected in October 1989 and from July to October, 1990. Only 67 days from the data set were available for this analysis due to sensor problems and difficulties in reading the tapes. The biggest problems were found in the Bowen ratio station. In this station, technical errors were found in the dewpoint hygrometer and air intakes producing erroneous estimates of the vapor pressure difference. These problems mainly occurred following rainfall and irrigation. In the automatic meteorological station, technical errors were not important and only few days had erroneous measurements of air temperature and air relative humidity.

The duration and frequency of errors during the day were used as criteria to eliminate days. Days that had errors with a duration more than 1 hour were eliminated from the data set. Errors that occurred during a short period of time (< 1 hour) were corrected by estimating a value using linear interpolation. Days that had more than 3 short periods with error daylight were eliminated from the analysis. Using these criteria errors observed in the Bowen ratio station were about 49 percent of the collected data in 1990. On the other hand, problems in the reading tape occurred 9.2 percent of the collected data in 1990.

The evapotranspiration estimating method assumed to be correct for this was that computed using the Bowen ratio energy balance system. Evapotranspiration obtained from the Bowen ratio method was compared to that obtained from the hourly Penman model and the hydrologic balance method. These comparisons were done for cloudy and clear sky conditions.

To study the performance of the Bowen ratio approach and CIMIS model during clear days and cloudy, the data set was divided into a clear data set, a cloudy data set, and a combined data set. The ratio between total incoming solar radiation, R_s, and clear sky solar radiation, R_{so}, was used to define the percentage of clear sky. When the solar radiation was less than 90 percent of maximum cumulative total, the day was considered cloudy. R_s was computed as the integration of incoming solar radiation measured in the radiation station during the day and R_{so} was calculated by equation [40] (Jensen et al., 1990).

$$R_{so} = 0.75 Ra \qquad [40]$$

Values of extraterrestrial radiation, Ra, were calculated using the following set of equations where all angles are expressed as radians (Jensen et al., 1990):

$$Ra = 458.4 G_{sc} dr \{\omega_s \sin(\Phi)\sin(\delta) + \cos(\Phi)\cos(\delta)\sin(\omega_s)\} \qquad [41]$$

$$dr = 1 + 0.033\cos\left(\frac{2\pi J}{365}\right) \qquad [42]$$

$$h'_s = arccos\{-\tan(\Phi)\tan(\delta)\} \quad [43]$$

$$\delta = 0.4093 \sin\left(\frac{(284 + J)}{365}\right) \quad [44]$$

where

Ra = *daily extraterrestral radiation, MJ* m^{-2} d^{-1}

G_{sc} = *solar constant equivalent to 0.082 MJ* m^{-2} min^{-1}

dr = *relative distance of the Earth from the Sun*

h'_s = *sunset hour angle, radians*

Φ = *latitude of the station, radians (negative for southern latitudes)*

δ = *declination angle, radians*

J = *Julian day*

To evaluate the cumulative daytime and nighttime evapotranspiration a sunrise/sunset calculation was made. The sunrise (t_1) and sunset (t_2) times were estimated by equations [45] and [46], respectively.

$$t_1 = \frac{12}{\pi} \cos^{-1}\left(\tan(\delta) * \tan(\Phi) + \frac{0.0145}{\cos(\delta) * \cos(\Phi)} \right) \quad [45]$$

$$t_2 = 24 - t_1 \quad [46]$$

where

t_1 = *sunrise, h*

t_2 = *sunset, h*

3.2.2 Soil Water Content Data

Soil water content data were obtained using the neutron moderation technique. The neutron probe used in this study was a model 503 Hydroprobe nuclear moisture gauge with a neutron source of 50 mCi Americium-241/Beryllium (CPN, 1984).

The soil moisture data were collected three times per week during the growing season. The neutron probe readings were made in five access tubes at 5, 15, 25, 35, 45, 55, 65, 75, 85, 95, and 105 cm depths. Two readings per depth and a 32 second count time per readings were made. Applied water was measured using an automatic raingage connected to the meteorological station as well as a manual raingage in the vicinity of the access tubes.

3.2.3 Neutron Probe Calibration

Neutron probe calibration was performed by relating volumetric water content measured gravimetrically (Section

3.3.4) with probe readings. The soil profile at the ETIP site was divided into four distinct depth layers from 10-20 cm, 20-30 cm, 30-40 cm, and 40-200 cm. A different calibration curve was determined for each layer. An independent calibration curve was developed for the surface layer from 0-10 cm.

An outlier detection technique based on the laverage value and studentized residual applied. To identify the influence of outliers, an analysis of influence on the fitted values (DFFITS) was performed. The outliers that had significant influence on the fitted line were eliminated (Nester, Wasserman, and Kutner, 1989).

Linear regression was performed with the revised data set to estimate calibration coefficients. The results of this analysis for each soil layer are shown in Table 4.

Table 4. Summary of regression analysis for the neutron probe.

Depth (cm)	Intercept	Slope	Coefficient of determination
0-10	10.095	17.209	0.74
10-20	5.486	16.744	0.60
20-30	21.715	10.303	0.88
30-40	2.552	22.755	0.76
40-200	15.583	32.865	0.95

3.3 Reference Evapotranspiration Computations

3.3.1 Data Proccesing

Several programs developed by the Water Resource Engineering Team were used in data processing to obtain hourly evapotranspiration from the Bowen ratio and automatic meteorological stations. The name, size and use of each program are presented in Table 5. Data processing required the following steps.

1. Collected data from the tape or neutron probe was transferred to an ASCII file.

2. Tape errors and useless information from the ASCII file were eliminated. This permitted creation of useful files on 15-minute intervals for the automatic meteorological and radiation stations and a 20-minute interval for the Bowen ratio station.

3. Files from the automatic meteorological station and Bowen ratio station were combined to compute the hourly evapotranspiration.

Table 5. Programs used to estimate hourly evapotranspiration.

Name	Size (kb)	Used to
Tape program*	20	transfer collected data from the tape to an ASCII file
MTSWIZ	89.07	read raw data from the automatic meteorological station and eliminate errors and useless information
BOWWIZ	81.53	read raw data from the Bowen ratio station and eliminate errors and useless information
RADWIZ	67.12	read raw data from the radiation station and eliminate errors and useless information
SPLITWIZ	113.22	compute energy balance components on a 20 minute interval
COMWIZ	59.79	combine MTSWIZ and BOWWIZ data files on hourly data file
CIMISWIZ	57.27	compute hourly and daily evapotranspiration
CP-NP	60.88	transfer collected data from the neutron probe to an ASCII file
ETMASTER**	401.53	compute $ETac$ and hydrologic balance

* Developed by Campbel Scientific to read the PC 201 card.

** Originally developed by Cuenca (1988).

3.3.2 Bowen Ratio Approach

To calculate hourly reference evapotranspiration from the Bowen ratio energy balance method, the SPLITWIZ and CIMISWIZ programs were used. The SPLITWIZ programs uses 20-minute averaged data to estimate sensible heat flux, latent heat flux, and soil heat flux. This program estimates latent heat flux using the following steps:

1. Compute the Bowen ratio from equation [12] using vapor and air temperature differences between two levels. The psychrometric constant was calculated using equation [15]. Specific heat of the air and ratio of mass of water vapor to dry air were assumed to be 1.0035 kJ kg^{-1} $°C^{-1}$ and 0.62198, respectively. Constant atmospheric pressure was calculated by equation [14] using an elevation of 70 m. Latent heat of vaporization was calculated from equation [13] using the average temperature between the two levels.

2. Compute of soil heat flux from equation [5] using average heat flux (HF) and heat stored flux (HS) in the first 20 cm of the soil profile. HF was measured by heat flux plates which were buried in the soil at a fixed depth of 8 cm. HS was computed by equations [6] and [7] using the variable soil temperature, specific heat of dry soil of 840 J kg^{-1} $°C^{-1}$, bulk density of 1410 kg m^{-2}, and specific heat of water of 4190 J kg^{-1} $°C^{-1}$. To measure the soil temperature four parallel thermocouples were buried at 2 and 6 cm below the soil surface. Bulk density was measured at 8 cm below the soil surface.

3. Compute 20-minute averaged LE from equation [16] using the calculated soil heat flux, Bowen ratio, and net radiation measured from the Bowen ratio station.

4. Compute the hourly ET using CIMISWIZ program.

3.3.3 Hourly Penman Equation Approach

To compute hourly *ETo* from the Penman model, the data set from the automatic meteorological station and Bowen ratio station were used. The data set was combined on an hourly basis using the COMWIZ program. CIMISWIZ computes *ETo* from the Penman equation by the following steps:

1. Estimate the weighting function from equation [19]. The slope of saturation vapor pressure and psychrometer constant were calculated from equations [20] and [15], respectively.

2. Estimate the vapor pressure deficit using equations [21] and [22]. The air temperature and relative humidity used were taken as the average between both stations.

3. Estimate the aerodynamic wind function using equations [23] and [24]. Wind speed from the automatic meteorological station at 3.0 m was modified to the 2.0 m wind speed using equation [25].

4. Estimate hourly *ETo* from equation [18] using wind functions, vapor pressure deficit, the weighting function and net radiation. Net radiation was measured at the Bowen ratio station.

3.3.4 Hydrologic Balance Method

ETMASTER was used to compute daily *ETac* using the hydrologic balance approach. This program has as input neutron probe readings, standard acounts, field capacity, calibration coefficients, precipitation, and irrigation. ETMASTER computes daily *ETac* in the following steps:

1. Estimate the soil moisture deficit from equation [33] using field capacity and neutron probe readings at the start of the *ETac* period for each layer. The neutron probe reading are converted to soil moisture content using equation [32]. The statistical coefficients for equation [32] are shown in Table 4.

2. Estimate the applied water retained in the soil profile from equations [33], [35], [36], and [37]. The maximum water retained is assumed to be the field capacity of each layer. If the amount of water applied is greater than field capacity of the profile, the excess of water is computed by ETMASTER as deep percolation or drainage.

3. Estimate the change in the soil water content for each layer from equation [38]. The model considers the neutron probe readings the start and at the end of the ET period.

4. Estimate *ETac* from equation [39]. *ETac* is a fuction of changes in soil water content, and applied water retained in the soil profile.

4 RESULTS AND DISCUSSION

This section presents results obtained using the Bowen ratio energy balance (BREB) method, CIMIS Penman, and hydrologic balance method (HBM) for estimating evapotranspiration. An hourly analysis of the Bowen ratio variation for clear and cloudy sky conditions was done to evaluate the performance of the BREB method at ETIP. Hourly and daily comparisons were performed for the clear data set, the cloudy data set, and the combined data set to check agreement between the BREB method and the CIMIS Penman. Comparisons were also performed to evaluate the agreement between the BREB method and the HBM. Each comparison included two statistical analyses. The first test consisted of an evaluation of the error to check the goodness of fit of evapotranspiration (ET) estimated by the Bowen ratio energy balance method (ETB) versus evapotranspiration estimated by the hourly Penman equation (ETP) and by the hydrologic balance method (ETH) without any adjustment or calibration. The second test consisted of a linear regression analysis to test agreement and variation between ETB versus ETP and ETH.

In order to minimize the high variation in daily evapotranspiration estimates, a simple moving average for various time imtervals was computed. Analysis was made of the standard error of the estimate (SEE) and the coefficient of determination using the moving average data set.

4.1 Description of the Statistical Analyses

Analysis of the Bowen ratio variation was done using a t-confidence interval for the hourly average Bowen ratio. Upper and lower limits of were defined using a confidence level 95 percent. Upper and lower limits were obtained using expression [47].

$$\bar{x} \pm \frac{s t_c}{\sqrt{n}} \qquad [47]$$

where

$\bar{x}$ = *hourly average of Bowen ratio*

s = *standard deviation*

n = *number of observations*

t_c = *t-critical value which is based on* $n-1$ *degrees of freedom*

The error analysis included a sample hypothesis test and an evaluation of the standard error of the estimate (SEE). The sample hypothesis test was used to check whether the difference or error between the average of ETB versus ETP and ETB versus ETH were significantly different from zero. The SEE was used to evaluate the variation of the error in the data set and the performance of the BREB method with respect to the other methods without any adjustment.

The standard error of the estimate was calculated for evapotranspiration derived from the BREB method, CIMIS Penman, and HBM. This parameter is different from the standard error of the estimate obtained from the regression fit. This statistical parameter was obtained using equation [48].

$$SEE = \sqrt{\sum_{i=0}^{n} \frac{(ETB_i - ETe_{(i)})^2}{n-1}} \qquad [48]$$

where

ETB_i = *estimated ET from BREB method, mm* h^{-1} *or mm* d^{-1}

ETe_i = *estimated ET from CIMIS Penman or HBM, mm* h^{-1} *or mm* d^{-1}

n = *total number of observations*

To check whether the error was statistically different from zero, a sample hypothesis test was used. The statistical test used in this study can be defined in the following steps:

1. Null hypothesis: $H_o: \mu_1 - \mu_2 = 0$ or $Error = 0$

2. Alternative hypothesis: $H_1: \mu_1 - \mu_2 \neq 0$ or $Error \neq 0$

3. Test statistic: The z-test was used when the data set was greater than 120 observations and the t-test when data

set was less than 120 observations (Devore and Peck, 1986). The z-test and t-test are described by equations [49] and [50] respectively.

$$z = \frac{\bar{x}_1 - \bar{x}_2 - (\mu_1 - \mu_2)}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}} \qquad [49]$$

$$t = \frac{\bar{x}_1 - \bar{x}_2 - (\mu_1 - \mu_2)}{\sqrt{\frac{s_p^2}{n_1} + \frac{s_p^2}{n_2}}} \qquad [50]$$

where

μ_1 = *average of ETB, mm* h^{-1} *or mm* d^{-1}

μ_2 = *average of ETP or ETH, mm* h^{-1} *or mm* d^{-1}

$\bar{x}_1$ = *sample mean of ETB, mm* h^{-1} *or mm* d^{-1}

$\bar{x}_2$ = *sample mean of ETP or ETH, mm* h^{-1} *or mm* d^{-1}

s_1 = *standard deviation of ETB, mm* h^{-1} *or mm* d^{-1}

s_2 = *standard deviation of ETP or ETH, mm* h^{-1} *or mm* d^{-1}

n_1 = *number of observations for ETB*

n_2 = *number of observations for ETP or ETH*

s_p = *pooled standard deviation between ETB and ETP or ETH, mm* h^{-1} *or mm* d^{-1}

The computed t was compared to a critical t. The significance level employed in this study was 0.05 to achieve a 95 % confidence level. If the critical t was greater than the computed t, the null hypothesis was not rejected, and the sample means were not statistically different from zero. The same analysis was done using the z-test.

The performance and goodness of fit between the BREB method versus CIMIS Penman and HBM were tested using a simple linear regression with the ETB as the independent variable and ETP or ETH as the dependent variable. Two linear models were developed. The regression through the origin and regression with a nonzero offset along the ordinate axis are represented by equations [51] and [52], respectively.

$$ETF = \beta_1 ETB + \epsilon_i \qquad [51]$$

$$ETF = B_o + \beta_1 ETB + \epsilon_i \qquad [52]$$

where

ETF = *fitted evapotranspiration, mm* h^{-1} *or mm* day^{-1}

ETB = *estimated evapotranpiration from BREB method, mm* h^{-1} *or mm* day^{-1}

B_o = *intercept of regression line, mm* h^{-1} *or mm* day^{-1}

B_1 = *slope of the regression which represents the average change in* ETP *or* ETH *associated with a unit increase in* ETB

ϵ_i = *random error term*

These models assume that the error term ϵ_i is normally distributed and has a constant variance. This assumption could be checked by a normal probability plot or frequency histograms.

To check the consistency and ability of the method to estimate evapotranspiration, the F-test and the coefficient of determination, r^2, were used. The F-test evaluates whether there is a linear relationship between independent and dependent variables. The coefficient of determination indicates what proportion of the variation of the parameter of interest is explained by the linear regression model. The linear association between independent and dependent variables using the F-test is described by the following steps:

1. Null hypothesis: $H_o: B_1 = 0$ or there is not a linear association between ETB and ETP or ETH.

2. Alternative hypothesis: $H_1: B_1 \neq 0$ or there is linear association between ETB and ETP or ETH.

3. Test statistic:

$$F = \frac{\sum_{i=0}^{n}(ETF_i - \overline{ETB})^2}{\sum_{i=0}^{n}(ETB_i - ETF_i)^2} = \frac{MSR}{MSE} \qquad [53]$$

where

MSR = *regression mean square, mm h^{-1} or mm day^{-1}*

MSE = *error mean square, mm h^{-1} or mm day^{-1}*

The computed F-ratio was compared to a critical F value. If the calculated F-ratio was less than the critical F, the null hypothesis was not rejected, i.e. there was not a linear association between variables. A 0.05 % significance level was used to attain a 95 % confidence level.

The final test was to check if the slope and intercept of the regression equation were significantly different from unity or zero, respectively. The t-test and z-test were performed using as the null hypothesis: H_o:$B_1 = 1$ or $B_o = 0$ against: H_o:$B_1 \neq 1$ or $B_o \neq 0$. The test statistic was defined as

$$t = \frac{B_o - 0}{s_{b\,o}} \qquad [54]$$

$$t = \frac{B_1 - 1}{s_{b\,1}} \qquad [55]$$

where

$s_{b\,o}$ = standard deviation of the intercept

$s_{b\,1}$ = standard deviation of the slope

If the calculated t-test was less than the critical t-value, the null hypothesis is not rejected. This meant that the slope and intercept were significantly equal to unity and zero, respectively.

4.2 Statistical Analysis for the Bowen Ratio Energy Balance Method and CIMIS Penman

An hourly analysis of the Bowen ratio variation for BREB method, and comparisons between the BREB method and CIMIS Penman are presented in this section. Hourly and daily comparisons are presented for the clear sky data set, cloudy sky data set, and combined data set. For each data set, a moving average is presented using 1, 3, 5, 7, 9, 11, and 15-day time averaging intervals.

4.2.1 Hourly Analysis of the Bowen Ratio Variation

This analysis was performed based on studies by Angus and Watts (1984) and Pruitt et al.(1987). Angus and Watts reported that an error of 30 percent in the B produces errors of less than 5 percent in *LE* when B ranges from -0.45 to 0.45. Angus and Watts showed that the potential for error in calculation of *LE* increases very rapidly as B drops below -0.45. However, when B is greater than 0.4, the relative error in LE increases slowly. Comparisons between lysimeter measured evapotranspiration and that estimated using the Bowen ratio approach made by Pruitt et al. (1987) indicated that the departure from reality commenced by the time the Bowen ratio dropped to -0.55.

In this study, the range from -0.5 to 0.85 was used to evaluate the performance of BREB method at ETIP. According to Angus and Watts, these lower and upper limits of B could produce errors in LE less than 5 % and 7 %, respectively.

Included in Table 6 are the hourly average Bowen ratio and the confidence intervals (lower and upper limit) for clear and cloudy days. The t-confidence interval was obtained using equation [41] with a 95 % confidence level.

Figures 1 and 2 indicate the Bowen ratio variation for clear and cloudy days, respectively. Included in these figures are hourly averages of B and confidence intervals. The lower and upper solid lines represent the range from -0.5 to 0.85.

Under clear sky conditions, the hourly averages of B were between -0.5 and 0.9 from 600 h to 1800 h (Table 6). However, Figure 1 shows that B had an important variation from 600 h to 1300 h. The largest variations were observed at 600 h and 700 h for which the errors introduced in daily totals of LE were quite small. According to these results, the performance of the BREB method was within acceptable performance criteria from sunrise to sunset. During the nighttime, the hourly averages of B were less than -0.4 indicating that considerable errors in calculation of latent heat flux were produced. During this period, a large confidence interval were observed (Figure 1) indicating a large variation of the data and an inconsistent performance of the BREB method. Studies by Angus and Watt (1984) and Pruitt et al. (1987b) shown similar results. Angus and Watts observed that around sunrise and sunset when air teperature difference approached zero and $R_n - G$ was very small, high errors in

Table 6. Variation of the Bowen ratio for clear and cloudy days.

Time (h)	Bowen ratio for clear days			Bowen ratio for cloudy days		
	Lower limit	Mean	Upper limit	Lower limit	Mean	Upper limit
100	-2.089	-0.670	0.749	-1.386	-0.964	-0.769
200	-4.042	-2.062	-0.083	-1.289	-0.483	0.323
300	-3.124	-1.484	0.156	-1.144	-0.264	0.616
400	-4.043	-2.050	-0.057	-0.605	0.210	1.025
500	-3.315	-1.720	-0.126	-0.759	0.336	1.431
600	-2.369	-0.411	1.548	-0.710	0.081	0.871
700	-1.144	-0.177	0.790	-0.593	-0.119	0.354
800	-0.459	-0.028	0.403	-0.451	-0.045	0.361
900	-0.178	0.278	0.735	0.280	0.554	0.830
1000	0.371	0.896	1.420	0.395	0.561	0.726
1100	-0.068	0.423	0.914	0.546	0.686	0.827
1200	0.348	0.771	1.193	0.425	0.590	0.754
1300	0.310	0.481	0.651	0.400	0.520	0.648
1400	0.051	0.286	0.520	0.194	0.376	0.558
1500	-0.003	0.175	0.353	-0.001	0.109	0.218
1600	-0.636	-0.344	-0.053	-0.322	-0.075	0.173
1700	-1.132	-0.214	0.704	-0.592	-0.335	-0.077
1800	-1.487	-0.598	0.292	-1.287	-0.844	-0.402
1900	-2.856	-0.851	1.154	-1.742	-1.056	-0.370
2000	-4.434	-2.312	-0.190	-2.728	-2.256	-1.784
2100	-5.039	-2.766	-0.493	-2.429	-1.860	-1.291
2200	-5.023	-3.202	-1.382	-2.260	-1.665	-1.069
2300	-4.402	-1.949	0.505	-0.185	0.617	2.412
2400	-5.702	-3.331	-0.961	-1.904	-1.248	-0.592

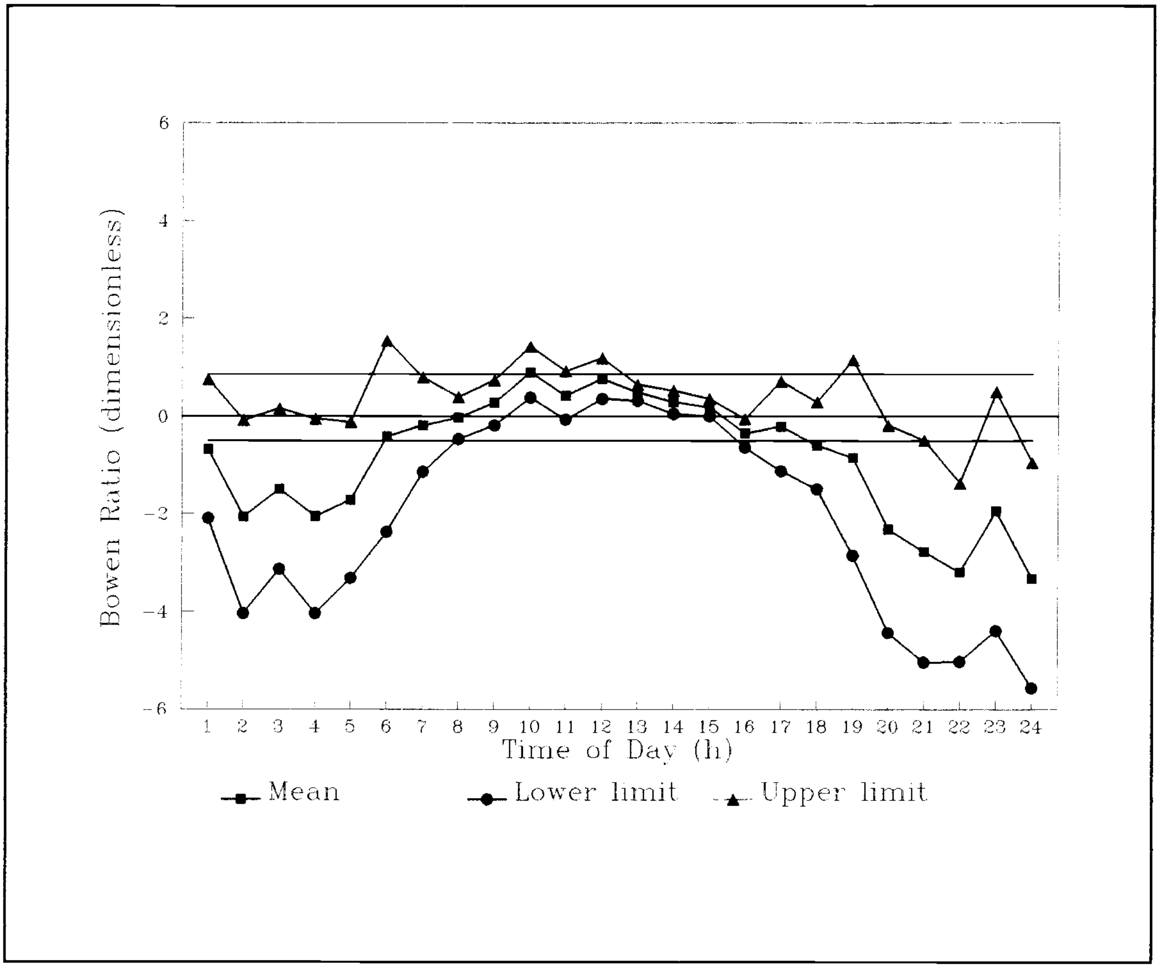

Figure 1. Clear day Bowen ratio variation.

LE were produced. They indicated that the accuracy requirement becomes increasingly more demanding as B drops below -0.3 or so. Pruitt et al. (1987) observed the same problems when $R_n - G$ became very small or negative. They observed that B decreased from a value of -0.55 at 1900 h to -0.84 at 2000 h, producing a average LE of 125 W m^{-2} while LE estimated by the lysimeter was -19 W m^{-2}.

Under cloudy sky conditions, Table 6 shows that hourly averages of B were between -0.48 and 0.69 from 200 h to 1700 h hours indicating that the BREB method was within acceptable performance criteria during the daylight and most of the nighttime. However, important variations in values of B were observed from sunset to sunrise specially from 2000 h to 500 h (Figure 2).

In general, *t*-confidence intervals or hourly values of the Bowen ratio variation for clear days were greater than those for cloudy days. This indicates that the performance of the BREB method under cloudy sky conditions was more consistent than the performance under clear condition.

To evaluate the contribution of LE produced from sunset to sunrise, cumulative ET for daylight and nighttime periods was computed. The cumulative ET for day period was computed from sunrise to sunset and the cumulative ET for night period was computed from sunset to sunrise. The sunrise and sunset time were estimated using equations [45] and [46], respectively. In Table 7 are the cumulative ET produced during the night (ET_{night}), cumulative ET produced during the day (ET_{day}), and the absolute values of ET_{night} as a percentage of daily cumulative ET.

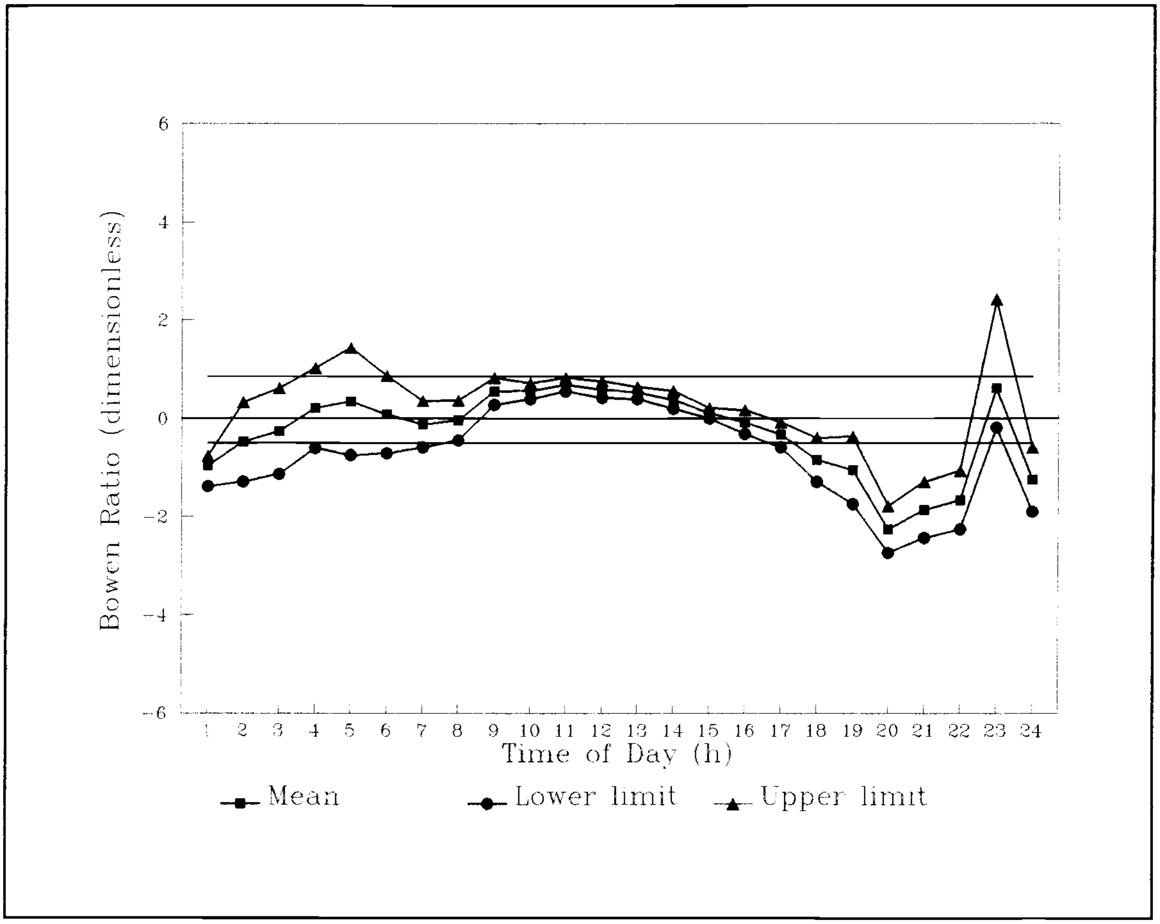

Figure 2. Cloudy day Bowen ratio variation.

Table 7. Cumulative ET produced during the day and night periods.

Data Set	ET_{night} (mm)	ET_{day} (mm)	$\frac{\lvert ET_{night} \rvert}{ET_{day}}$ (%)
Clear	1.965	99.74	1.93
Cloudy	-2.463	51.08	5.03
Combined	-0.498	150.82	0.33

Table 7 indicates that LE produced at night represented 1.93 %, 4.82 %, and 2.94 % of daily cumulative LE for the clear, cloudy, and combined data sets, respectively. These results indicate that the cumulative LE produced at night did not have a considerable effect on the daily ET and could be considered negligible. The BREB method can therefore be considered a very good method to estimate daily LE, in spite of the poor performance observed at night under clear conditions.

4.2.2 Statistical Analysis for the Clear, Cloudy, and Combined Data Sets on an Hourly Basis

The hourly error analysis between the BREB method and CIMIS Penman is presented in Tables 8, 9, and 10 for clear, cloudy, and combined data sets, respectively. The error was computed as the difference between the average of ETB and ETP. The *t*-test was employed to check whether the error or difference between the average of ETB and ETP was significantly different from zero. A *t*-critical equal to 2.03 at the 5 percent confidence level was used to reject or confirm the null hypothesis. Included in Tables 8, 9 and 10 are the average of ETP and ETB, error, standard error of the estimate (SEE), and computed *t*.

Table 8 shows that under clear sky conditions, the null hypothesis was not confirmed during the night. The data strongly suggest that the average of ETB exceeded significantly the average of ETP at the 95% confidence level. However, under cloudy days (Table 9), the null hypothesis was not rejected and the average error was not different from zero from sunset to sunrise. These results indicate that the agreement of the BREB method and CIMIS Penman at night was strongly affected by the weather conditions during the day.

The disagreement observed at night under clear conditions could be explained by problems either in the BREB method or CIMIS Penman. Angus and Watt (1984) indicated that the potential error in calculation of LE increased rapidly when the Bowen ratio droped below -0.4. Figure 1 (Section 1.2.1) shows that the hourly averages of the Bowen ratio were below -0.4 from sunset to sunrise indicating that

Table 8. Summary of hourly error analysis for clear days.

Time (h)	Mean of ETP $(mm h^{-1})$	Mean of ETB $(mm h^{-1})$	Error $(mm h^{-1})$	t-test	SEE $(mm h^{-1})$
100	-0.018	-0.007	0.026	3.44	0.051
200	-0.019	0.007	0.025	4.02	0.048
300	-0.019	-0.006	0.026	3.78	0.049
400	-0.02	-0.012	0.032	3.99	0.058
500	-0.019	-0.004	0.016	2.92	0.037
600	-0.016	-0.003	0.013	2.86	0.022
700	0.003	0.001	0.007	1.16	0.024
800	0.063	0.061	- 0.003	-0.23	0.033
900	0.161	0.119	- 0.042	-2.10	0.082
1000	0.278	0.193	- 0.086	-3.50	0.106
1100	0.407	0.276	- 0.131	-4.30	0.166
1200	0.495	0.364	- 0.130	-4.30	0.150
1300	0.544	0.416	- 0.130	-3.70	0.148
1400	0.539	0.429	- 0.110	-2.90	0.134
1500	0.500	0.430	- 0.073	-1.90	0.100
1600	0.400	0.380	- 0.017	-0.43	0.077
1700	0.264	0.278	- 0.001	-0.01	0.079
1800	0.155	0.178	0.023	0.62	0.069
1900	0.057	0.071	0.015	0.54	0.074
2000	0.003	0.011	0.008	1.12	0.034
2100	-0.011	0.005	0.016	2.40	0.039
2200	-0.015	0.010	0.025	5.80	0.036
2300	-0.019	-0.001	0.021	2.90	0.041
2400	-0.022	-0.003	0.018	2.90	0.051

Table 9. Summary of hourly error analysis for cloudy days.

Time (h)	Mean of ETP (mmh^{-1})	Mean of ETB (mmh^{-1})	Error (mmh^{-1})	t-test	SEE (mmh^{-1})
100	-0.018	-0.012	0.006	0.96	0.037
200	-0.018	-0.015	0.003	0.60	0.027
300	-0.016	-0.011	0.005	1.06	0.026
400	-0.015	-0.012	0.002	0.51	0.025
500	-0.013	-0.012	0.002	0.47	0.021
600	-0.012	-0.012	0.000	0.00	0.023
700	-0.005	-0.003	0.002	0.55	0.021
800	0.020	0.017	-0.004	-0.49	0.019
900	0.065	0.066	-0.000	-0.00	0.033
1000	0.134	0.105	-0.029	-1.34	0.051
1100	0.190	0.140	-0.051	-1.77	0.084
1200	0.237	0.172	-0.065	-1.96	0.097
1300	0.292	0.212	-0.080	-2.19	0.122
1400	0.286	0.220	-0.066	-1.98	0.114
1500	0.224	0.224	-0.000	-0.00	0.092
1600	0.181	0.160	-0.021	-0.62	0.072
1700	0.118	0.108	-0.876	-0.32	0.061
1800	0.046	0.059	0.013	0.65	0.046
1900	0.007	0.010	0.003	0.39	0.036
2000	-0.014	-0.014	0.000	0.00	0.041
2100	-0.017	-0.017	0.000	0.00	0.040
2200	-0.018	-0.018	0.000	0.00	0.055
2300	-0.017	-0.017	0.000	0.00	0.042
2400	-0.017	-0.002	0.016	2.64	0.042

Table 10. Summary of hourly error analysis for the combined data set.

Time (h)	Mean of ETP ($mm h^{-1}$)	Mean of ETB ($mm h^{-1}$)	Error ($mm h^{-1}$)	t-test	SEE ($mm h^{-1}$)
100	-0.018	-0.003	0.016	2.89	0.044
200	-0.018	-0.005	0.014	3.20	0.039
300	-0.018	-0.002	0.005	3.56	0.039
400	-0.017	-0.000	0.016	3.41	0.044
500	-0.016	-0.008	0.009	2.58	0.030
600	-0.015	-0.009	0.006	1.86	0.026
700	-0.001	-0.004	0.005	1.35	0.022
800	0.040	0.039	-0.002	-0.21	0.025
900	0.109	0.084	-0.026	-1.85	0.056
1000	0.202	0.149	-0.053	-2.68	0.077
1100	0.290	0.206	-0.084	-3.18	0.123
1200	0.356	0.262	-0.093	-3.07	0.120
1300	0.408	0.307	-0.101	-3.12	0.132
1400	0.402	0.316	-0.086	-2.65	0.122
1500	0.351	0.297	-0.054	-1.57	0.095
1600	0.281	0.262	-0.019	-0.59	0.074
1700	0.194	0.187	-0.006	-0.21	0.070
1800	0.097	0.114	0.018	0.76	0.051
1900	0.030	0.040	0.010	0.71	0.044
2000	-0.006	-0.007	0.013	2.67	0.046
2100	-0.014	0.003	0.017	3.80	0.030
2200	-0.016	-0.003	0.019	5.45	0.031
2300	-0.018	-0.002	0.016	3.51	0.032
2400	-0.019	-0.003	0.017	3.03	0.047

important errors were made in the computation of LE. In the CIMIS Penman, problems on the empirical wind function could have produced erroneous estimates of hourly ET during the night.

During the day the performance of the methods varied with the increase or decrease of net radiation. Under clear conditions (Table 8), the error was not significantly different from zero between 700 h and 800 h. After that, the difference between the average of ETB and ETP was markedly different than zero from 900 h to 1400 h. Maximum errors were at midday when ETP was 1.35 times greater than ETB. In the afternoon, between 1500 h and 2000 h, the null hypothesis was not rejected. The errors decreased as net radiation decreased, in any case, the errors were not statistically different from zero between 1500 h and 2000 h. According to these results, the poorest performance between the methods was found with very high net radiation and dry conditions.

The CIMIS Penman for clear days tended to overestimate the hourly evapotranspiration during midday and early afternoon conditions. During this time, the grass was under high water stress and dry atmospheric conditions, high air temperature and low air relative humidity. Under these conditions an important fraction of $R_n - G$ is dissipated into the sensible heat flux. This process is not considered by the hourly Penman model and $R_n - G$ available energy is computed as evapotranspiration. On the other hand, the BREB method accounts for the dissipation of $R_n - G$ into LE and H. Therefore as water become less available, the Bowen ratio increases reducing LE and increasing H. Another important aspect is that the BREB method can integrate the effect of canopy resistance (Pruitt et al., 1987b). The canopy resistance is increased by dry conditions and/or soil moisture deficit. Under these conditions, plant evapotranspiration is reduced and increases canopy temperature which finally augments H.

Under cloudy sky conditions (Table 9), the null hypothesis was only rejected at 1300 h during the day. At this point the average of ETP was 1.37 times greater than the average of ETB, but the error was only about 0.079 mm/h. The results indicate a very good agreement between the Bowen ratio and CIMIS Penman to estimate ET under low levels of net radiation. Under this conditions, the grass was not under water stress and conditions defined for obtaining the potential evapotranspiration were maintained (Jensen at al., 1990). Consequently the potential evapotranspiration computed by the hourly Penman model corresponded to evapotranspiration computed by the BREB method.

The hourly error analysis for the combined data set (Table 10) shows that the error between the average of ETB and ETP was different from zero from sunset to sunrise. Early in the morning from 600 h to 900 h and in the afternoon from 1500 h to 1900 h, the null hypothesis was not rejected and the hourly errors were not different from zero. At midday from 1000 h to 1400 h, the error was statistically different from zero indicating an important difference between the methods.

The distribution of hourly errors followed an approximately normal distribution for the clear, cloudy, and combined data sets. Similar to the hourly error, the SEE values depended on the level of net radiation. The SEE was maximum when the net radiation was maximum and SEE decreased as net radiation decreased. The maximum values of SEE observed at midday were 0.17 mm h^{-1}, 0.12 mm h^{-1}, and 0.13

mm h^{-1} for the clear, cloudy, and combined data sets, respectively. The standard error of the estimate for the cloudy days was ,in general, less than clear days throughout the day. These results indicate that the goodness of fit between the Bowen ratio and CIMIS Penman model without any adjustment or calibration was better under low net radiation conditions.

Figures 3, 4, and 5 present the performance of the BREB method and CIMIS Penman for the clear, cloudy, and combined data sets, respectively. Net radiation, ETB, and ETP are expressed as energy flux in W m^{-2}. These figures show the agreement of the methods with a maximum departure at midday. After midday, the hourly errors and SEE decreased as net radiation decreased. When the net radiation became negative, the agreement of methods decresed abruptly after sunset.

Figures 3 and 4 show that the maximum net radiation for clear sky conditions was almost twice the maximum net radiation for cloudy conditions. The hourly average net radiation for clear and cloudy conditions was 443 W m^{-2} and 252 W m^{-2}, respectively. This could explain the disagreement observed between the BREB method and CIMIS Penman at midday especially under clear sky conditions. Under high net radiation, the grass was under a large water stress due to soil moisture deficit and/or high atmospheric water demand. This could produce an increase in stomatal resistance, a reduction in LE and an increase in H. Theoretically, all these phenomena are considered by BREB method, but they are not accounted for by the CIMIS Penman since it is used to compute a reference ET.

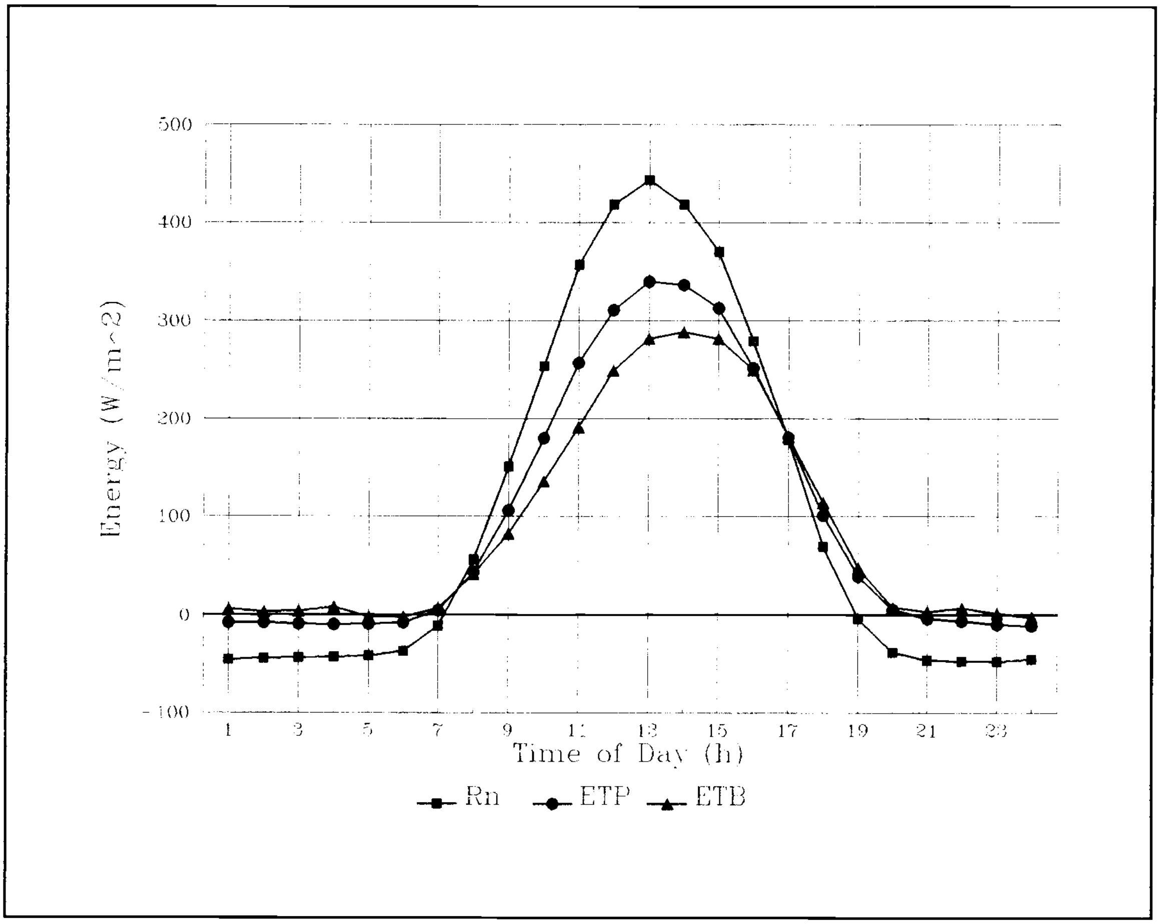

Figure 3. Performance of the BREB method (ETB) and CIMIS Penman (ETP) for clear days.

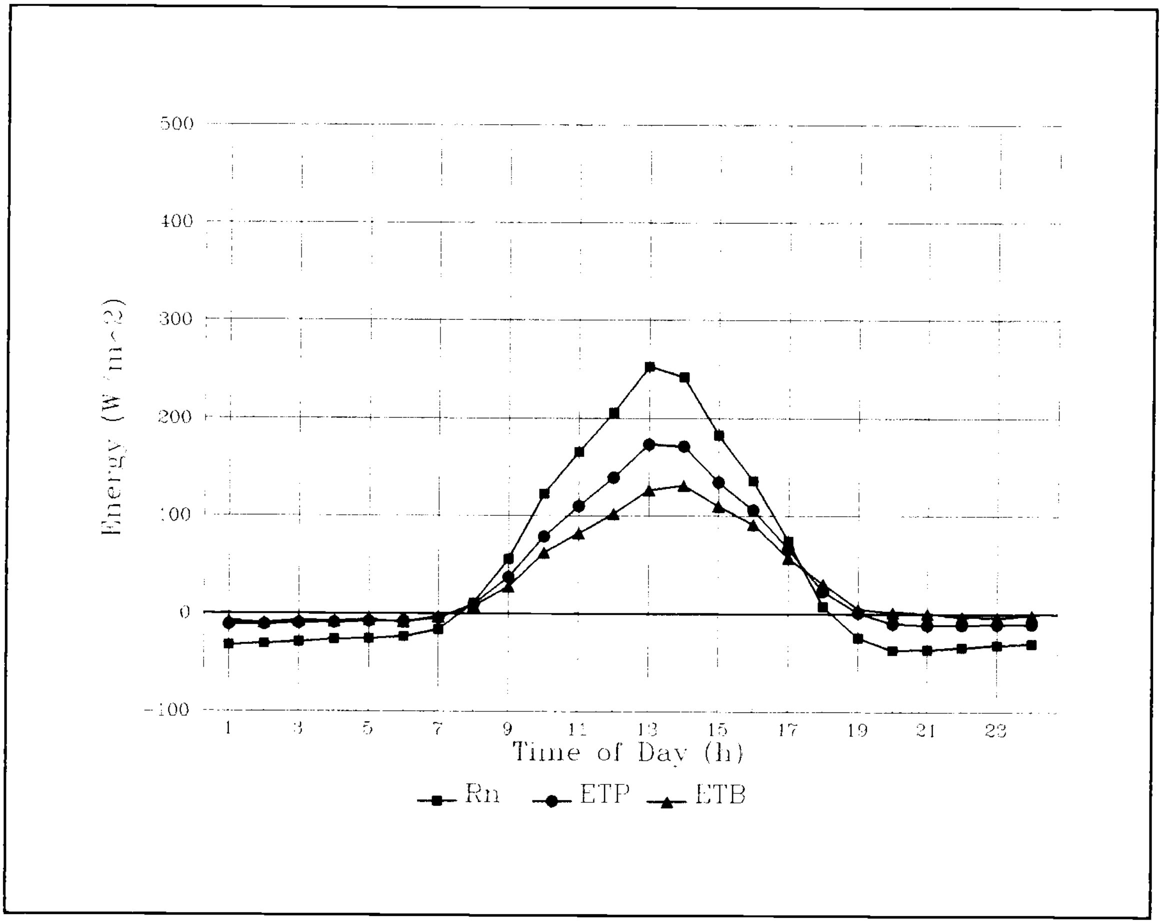

Figure 4. Performance of the BREB method (ETB) and CIMIS Penman (ETP) for coudy days.

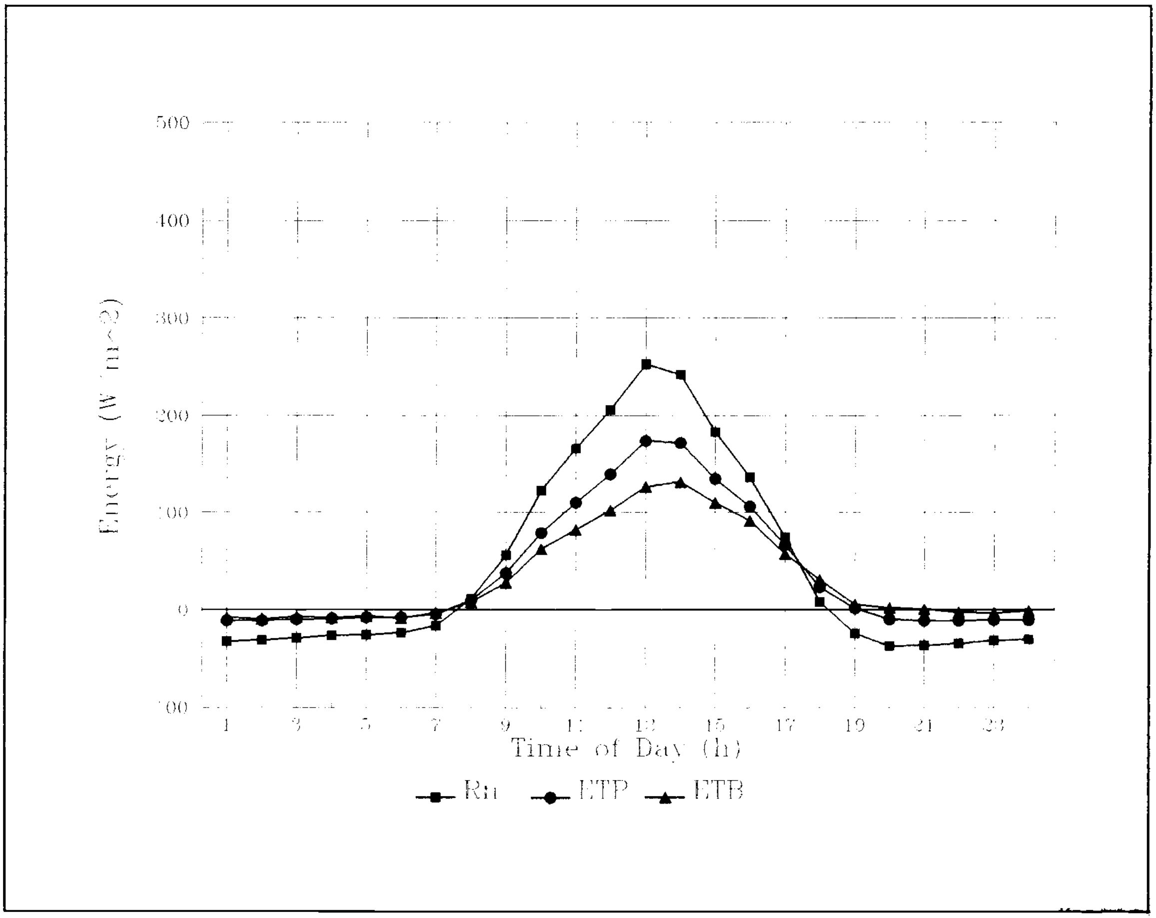

Figure 4. Performance of the BREB method (ETB) and CIMIS Penman (ETP) for cloudy days.

Regression analysis was on hourly data performed to check the consistency of the correlation and goodness of fit between ET estimated by the BREB method and ET estimated by the CIMIS Penman for the clear, cloudy and combined data sets. The F-test was employed to check whether there was a linear association between ETB and ETP. A F-test equal to 4.17 at the 5 percent confidence level was utilized to reject or confirm the null hypothesis which states that the slope is equal to zero or there is no linear association between ETB and ETP. A *t*-test equal to 2.04 was utilized to check whether the slope and intercept of the regression equation were significantly different from unity and zero, respectively. Tables 11, 12, and 13 present the coefficient of determination (r^2), intercept (B_0), slope (B_1), standard error of the regression fit (SEER), and F-test for the clear, cloudy, and combined data sets, respectively.

From 700 h to 1900 h, the null hypothesis was rejected and the data suggest that there was a strong linear relationship between ETB and ETP under clear sky conditions (Table 11). In the morning from 700 h to 1100 h, the relationship between the two methods was statistically significant, but the coefficients of determinations were not very strong because the linear regression could only explain between 48 and 77 percent of observed variations. Adequate and consistent correlations were observed later between 1200 h and 1900 h. In this period between 80 and 92 percent of total variation in estimated ET was successfully explained by the linear regression. From sunset to sunrise, the analysis of variance suggests that there was no

Table 11. Hourly regression analysis for clear days.

Time (h)	r^2	B_0 ($mm h^{-1}$)	B_1 ($mm h^{-1}$)	SEER ($mm h^{-1}$)	F-test
100	0.11	-0.018	0.012	0.044	0.03
200	11.10	-0.018	-0.161	0.044	3.85
300	2.24	-0.018	-0.075	0.055	0.70
400	5.51	-0.019	-0.078	0.044	1.81
500	1.80	-0.019	-0.080	0.044	0.56
600	2.06	-0.016	0.077	0.044	0.65
700	48.91	-0.002	0.399	0.044	19.07
800	64.00	0.0148	0.7600	0.028	42.30
900	57.67	0.0795	0.7377	0.052	20.73
1000	76.87	0.1323	0.7600	0.044	62.39
1100	56.40	0.2700	0.4900	0.063	40.16
1200	80.48	0.2391	0.6900	0.048	96.01
1300	86.32	0.2240	0.7500	0.045	126.29
1400	84.31	0.2100	0.7580	0.077	129.52
1500	90.25	0.1400	0.8460	0.048	147.75
1600	92.59	0.0334	0.9671	0.044	119.06
1700	87.84	0.0338	0.8500	0.057	135.67
1800	89.60	0.0300	0.7000	0.044	267.12
1900	85.27	0.0130	0.5300	0.032	105.11
2000	7.44	-2.8400	0.3300	0.032	2.49
2100	1.74	-0.0110	0.0880	0.022	0.55
2200	1.86	-0.0140	-0.1200	0.014	0.59
2300	11.45	-0.0200	0.0500	0.040	4.00
2400	14.86	-0.0210	0.0960	0.012	2.30

Table 12. Hourly regression analysis for cloudy days.

Time (h)	r^2	B_0 (mmh^{-1})	B_1 (mmh^{-1})	SEER (mmh^{-1})	F-test
100	18.58	-0.017	0.122	0.010	7.76
200	11.90	-0.016	-0.112	0.010	4.59
300	2.09	-0.015	-0.057	0.010	0.73
400	7.07	-0.013	-0.097	0.010	2.59
500	0.32	-0.013	-0.029	0.010	0.11
600	1.51	-0.011	0.054	0.010	0.52
700	9.52	-0.0048	0.0018	0.035	3.58
800	74.23	0.0041	0.8850	0.017	71.71
900	77.97	0.0106	1.1253	0.028	120.31
1000	81.93	0.0285	1.0060	0.042	154.13
1100	90.01	0.0254	1.0900	0.040	109.39
1200	89.31	0.0498	1.009	0.046	122.78
1300	83.94	0.0484	1.0719	0.065	88.60
1400	76.49	0.0500	1.009	0.071	69.80
1500	79.21	0.0342	0.9459	0.063	83.17
1600	86.28	0.0243	0.9065	0.050	137.07
1700	84.07	0.02348	0.7916	0.046	130.07
1800	81.24	0.0050	0.6906	0.032	147.24
1900	18.33	0.0018	0.5218	0.033	7.63
2000	0.76	-0.0145	0.0292	0.010	0.26
2100	0.05	-0.0170	0.0084	0.010	0.02
2200	13.48	-0.0178	-0.1340	0.010	10.91
2300	20.60	-0.0176	-0.1256	0.010	8.82
2400	17.82	-0.0174	-0.1063	0.010	7.37

Table 13. Hourly regression analysis for the combined data set.

Time (h)	r_2	B_0 (mmh^{-1})	B_1 (mmh^{-1})	SEER (mmh^{-1})	F-test
100	4.03	-0.001	0.064	0.013	2.04
200	0.66	-0.001	-0.033	0.013	0.42
300	0.85	-0.001	-0.042	0.014	0.56
400	2.30	-0.017	-0.051	0.012	1.53
500	2.21	-0.017	-0.085	0.013	1.47
600	0.64	-0.014	0.039	0.012	0.42
700	50.65	-0.000	0.3695	0.013	30.24
800	77.65	0.0058	0.8358	0.021	172.49
900	86.95	0.0144	1.1065	0.031	129.46
1000	89.97	0.032	1.1167	0.039	253.24
1100	87.53	0.0478	1.1035	0.058	149.51
1200	88.22	0.0757	1.0340	0.064	337.82
1300	87.83	0.0832	1.0241	0.069	296.80
1400	86.13	0.0800	0.9876	0.073	280.93
1500	90.44	0.0424	1.025	0.064	390.59
1600	93.95	0.0204	0.9796	0.047	410.20
1700	90.27	0.0241	0.8607	0.051	362.73
1800	92.37	0.0128	0.7418	0.033	537.93
1900	80.37	0.0031	0.5547	0.028	164.58
2000	2.90	-0.006	0.155	0.026	1.94
2100	0.59	-0.0140	0.041	0.017	0.38
2200	4.47	-0.016	-0.113	0.013	3.04
2300	0.00	-0.018	-0.000	0.012	0.00
2400	1.35	-0.019	-0.029	0.011	0.89

linear relationship between the two models. The total variation in ETP was not successfully explained by the linear regression model. These results indicate that there was adequate agreement between methods to estimate hourly ET using the CIMIS Penman when the net radiation was greater than zero. This agreement was stronger in the afternoon than in the morning. Also it is important to observe that the F-test and the r^2 decreased drastically at sunset when the net radiation became negative. Conversely, at sunrise, these statistical parameters increased rapidly when the net radiation became positive.

The *t*-test strongly suggests that the intercepts and slopes were different from zero and unity, respectively. These results indicate that an important percent of the error was added to the intercept and a unit change in ETB did not correspond to unit change in ETP.

The analysis performed under cloudy conditions (Table 12) shows that the agreement between the BREB method and CIMIS Penman to estimate hourly ET was good from sunrise to sunset. The linear association between ETB and ETP was statistically important between 800 h to 1800 h. Coefficients of determination were between 18 and 90 percent. The poorest coefficients of determination were found at 800 h, 1500 h, and 1900 h when a 74, 76, and 18 percent, repectively, of observed variations were explained by the linear model. However, during the night the variance analysis and r^2 indicate that there was not agreement between the methods. Similar to clear days, under cloudy conditions the agreement of the BREB method and CIMIS Penman decreased after sunset and increased abruptly after sunrise.

Contrary to clear days, intercepts were not significantly different from zero during the daytime. Also, from 1000 h to 1600 h, slopes were not significantly different from unity indicating that a unit change in ETB corresponded to a unit change in ETP. But, early in the morning from 800 h to 900 h and late in the afternoon from 1700 h to 1900 h, the slopes were statistically less than unity. This indicates that the CIMIS Penman tended to underestimate hourly ET. Similar to the hourly error analysis, these results indicate that the agreement and goodness of fit of the models were excellent from 1000 h to 1600 h. In the afternoon, the agreement was good, but the CIMIS Penman tended to underestimate hourly ET.

An hourly regression analysis for the combined data set is presented in Table 13. The variance analysis strongly suggests that there was a linear association between the two models from 800 h to 1800 h. Similar to the F-test, the coefficients of determination between 77 and 94 percent indicated an adequate and consistent correlation during this period. However, from sunrise and sunset, the relationship between the BREB method and CIMIS Penman was not significant. These results indicate that the distribution and magnitude of net radiation had a considerable impact in the agreement of the methods.

Similar to clear days, an important departure from the regression through the origin was observed. Intercepts were statistically different from zero most of the daylight hours. They were only equal to zero at 800 h, 1000 h, 1600 h, and 1900 h. However, the slopes during all daylight hours were statistically different from unity. These results indicate that the CIMIS Penman tended to overpredict ET for the period ranging from 900 h to 1200 h and underpredict it for the period between 1600 h and 1900 h.

4.2.3 Statistical Analysis for the Clear, Cloudy, and Combined Data Sets on a Daily Basis

Error analysis was performed for the daily clear, cloudy, and combined data sets to evaluate the agreement between the ETB and ETP computed using hourly weather data. A *t*-critical equal to 2.03 at the 5 % confidence interval was used to check whether the error between daily ETB and ETP was significantly different from zero. Included in Table 11 are ETP, ETB, error, and SEE on a daily basis. This Table also includes the computed *t*.

Table 14. Daily error analysis for the BREB method and CIMIS Penman.

Data Set	Mean of ETP (mmd^{-1})	Mean of ETB (mmd^{-1})	Error (mmd^{-1})	t-test	SEE (mmd^{-1})
Clear	3.69	3.28	0.407	1.13	0.73
Cloudy	1.62	1.35	0.266	0.98	0.46
Combined	2.58	2.24	0.331	1.19	0.68

Table 14 shows that the null hypothesis was not rejected for the clear, cloudy, and combined data sets. The data strongly indicate that the average daily error between ETB and ETP was not different from zero. However, the values of the SEE for all data sets indicate that the data had considerable variation.

The decrease in the standard error with increase in the days averaged is presented graphically in Figures 6 and 7. These figures indicate that the values of SEE did not decrease appreciably when the moving average was used. Similar to hourly values of SEE, Figures 6 shows that values of SEE for cloudy sky conditions were less than values of SEE for clear sky conditions. These results indicate that the hourly variation observed at midday could have an important effect in the daily ET, especially under clear conditions (Section 1.2.2).

A regression analysis on a daily basis was developed to test the goodness of fit between ETB and ETP for clear, cloudy, and combined data sets. An F-test equal to 4.0 at 5 % confidence level was used to evaluate the linear relationship between ETB and ETP. A t-test equal to 2.0 was used to reject or comfirm whether the slope and intercept of regression curve were statistically different from unity and zero, respectively. Table 11 includes coefficients of variation, slope, intercept, standard deviation of regression (SEEr), and F-test results.

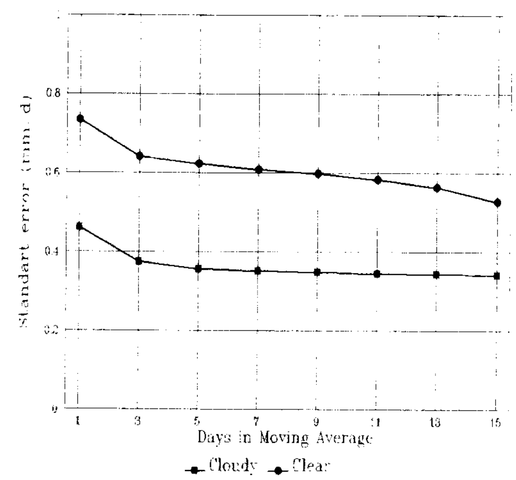

Figure 6. SEE using moving average for Bowen ratio system and CIMIS Penman (clear and cloudy days).

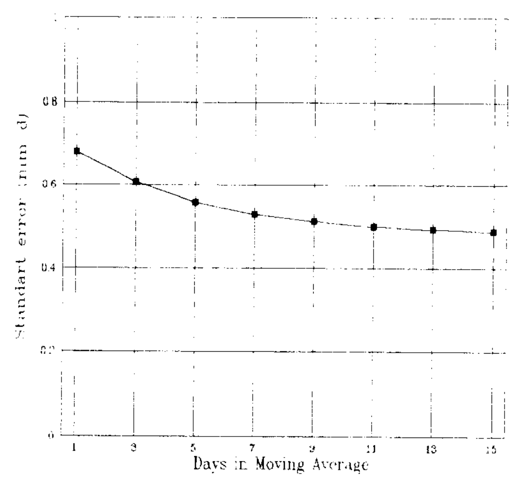

Figure 7. SEE using moving average for Bowen ratio system and CIMIS Penman(combined data set).

An adequate agreement between the Bowen ratio method and CIMIS Penman model was observed. The analysis of variance indicates that there was a strong association between the two methods. The coefficients of determination were between 79.24 and 87.16 percent. The weakest correlations was noted for the cloudy days and the strongest for the combined data set.

Table 15. Daily regression analysis for the BREB method and CIMIS Penman

Data set	r^2	B_0	B_1	SEER	F-test
Clear	84.74	1.13	0.780	0.51	161.02
Cloudy	79.24	0.38	0.92	0.57	110.47
Combined	87.16	0.52	0.92	0.65	441.12

According to the *t*-test, intercepts of the regression line were statistically different from zero for the three data sets. Slopes were also statistically different from unity for all data sets.

A daily regression analysis using a moving average is presented in Figures 8 and 9. The coefficients of determination were computed for the case of forcing the regression through the origin. Similar to daily values of SEE, Figures 8 and 9 show that coefficients of determination did not increase very much when the moving average was used.

Figure 9 indicates that after a 3-day averaging interval, the combined data set had a coefficient of determination higher than 0.88. Figure 8 indicates that the cloudy data set had a coefficient of determination higher than 0.85 after 7-day interval and the clear data set reached the same value after a 15-day interval.

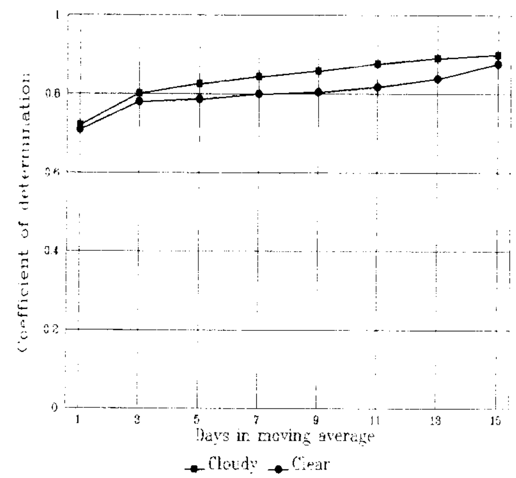

Figure 8. Regression analysis using moving average for BREB method and CIMIS Penman(clear and cloudy days).

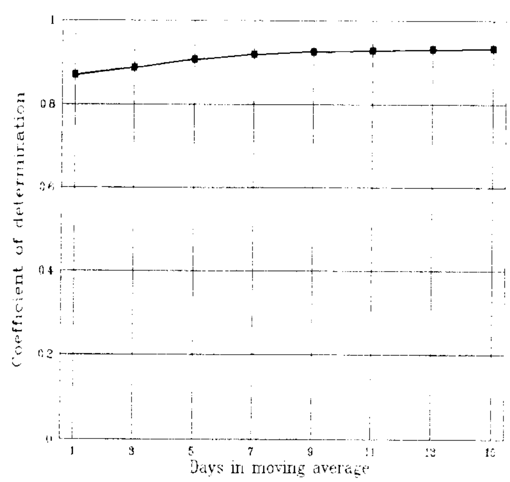

Figure 9. Regression analysis using moving average for BREB method and CIMIS Penman(combined data set).

4.2.4 Regression Analysis for the Clear, Cloudy, and Combined Data Sets Using All Hourly Data

A regression using all hourly data was developed to test goodness of fit and variation between ETB and ETP for the clear, cloudy, and combined data sets. An F-test equal to 3.84 at the 5 percent confidence level was utilized to check whether there was linear association between ETB and ETP. A z-test equal to 1.96 was used to test whether the slope and intercept of the regression equation were statistically different from unity and zero, respectively. Table 15 includes the regression with a nonzero offset along the ordinate axis. This table also includes the r^2, intercept, slope, and F-test results.

Table 16. Regression analysis for the clear, cloudy, and combined data set using all hourly data.

Data set	r^2	B_0	B_1	SEER	F-test
Clear	92.60	-0.036	1.14	0.004	6141.46
Cloudy	90.56	0.002	1.08	0.001	4551.26
Combined	93.10	0.000	1.11	0.008	11954.00

A very strong linear association between ETB and ETP was found for the clear, cloudy, and combined data sets using a 95 percent confidence level. Table 16 indictes that the coefficients of variation were excellent. 92.6, 90.5, and 93.5 percent of observed variations were successfully explained by the linear regression for the clear, cloudy, and combined data sets, respectively.

The z-test suggests that intercepts for the three data sets were statistically different from zero. Analysis of the regression through the origin suggests that the slopes were significantly different from unity indicating a unit change in ETB did not correspond to a unit change in ETP. When ETB increased one unit the change of ETP was greater than 1 for the clear, cloudy, and combined data sets (Figures 10, 11, 12). This effect was more important under clear conditions in which the CIMIS Penman overpredicted ET by about 14 percent. This overprediction occurred at midday when a considerable departure between the models was observed (Figure 3 in Section 4.2.1). Under cloudy conditions, the CIMIS Penman overpredicted ET by about 8 percent, however, the hourly error analysis did not show any significant departure during the daylight period.

This analysis show an excellent agreement and goodness of fit between models. This closeness is remarkable because the ETP values came from an equation with an empirically-determined wind function based on Davis, California studies conducted for the most part under clear sky conditions. Comparisons of ET measured with the BREB method and CIMIS Penman realized by Pruitt et al. (1987) shown similar results. Pruitt et al. (1987) found that ETB values averaged 20-25 % higher most of the day under clear-sky and moderate to low relative humidity conditions. According to Pruitt et al. (1987), these results were remarkable because the ETP values came from an equation with empirically-deternined wind function based on Davis, California studies.

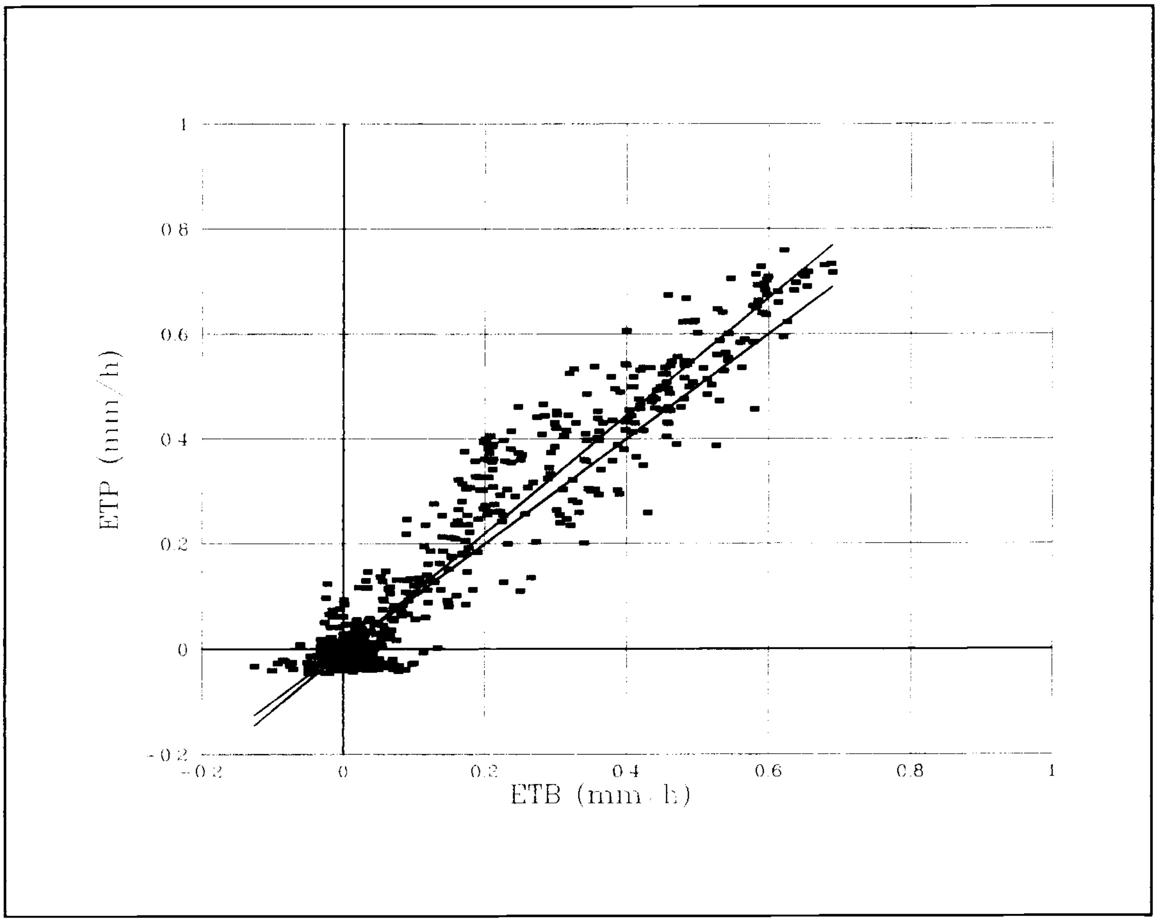

Figure 10. BREB method(ETB) versus CIMIS Penman(ETP) for clear days.

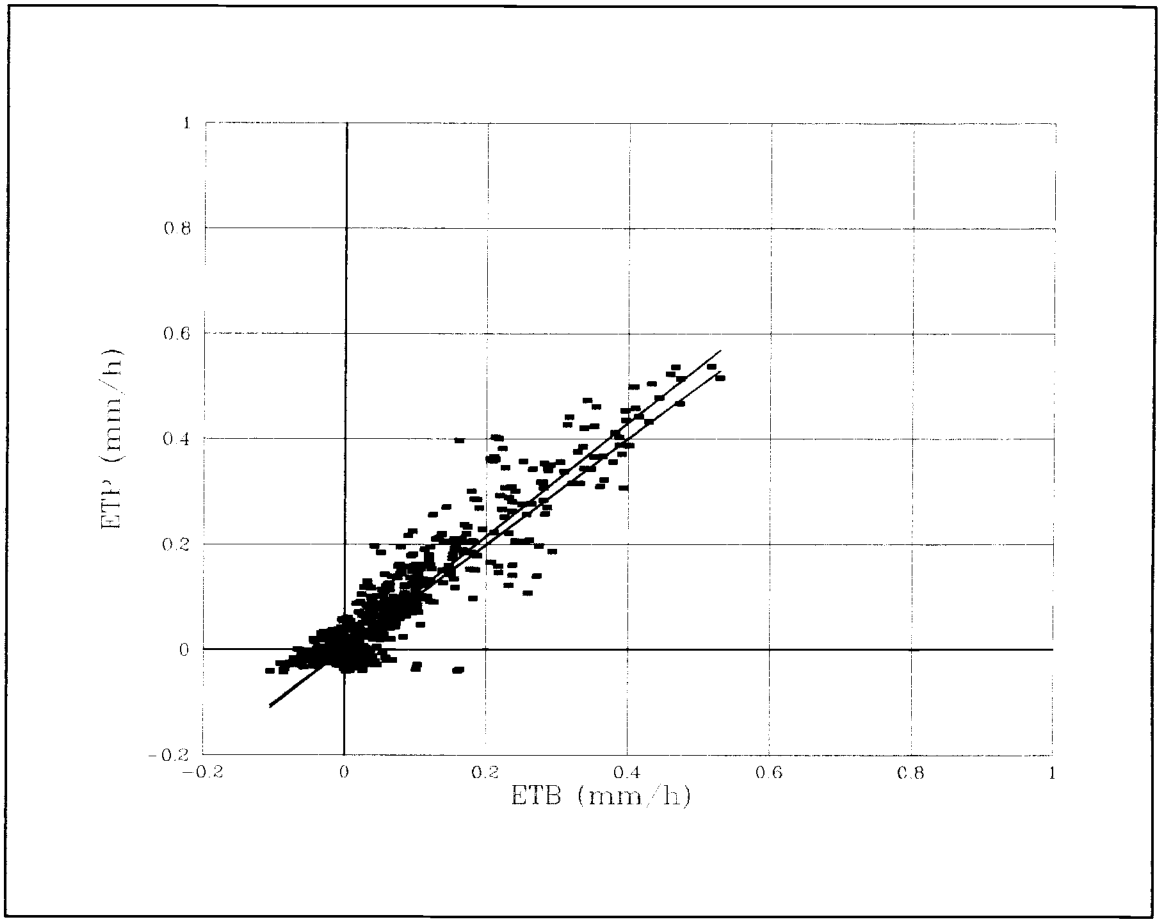

Figure 11. BREB method(ETB) and CIMIS Penman(ETP) for cloudy days.

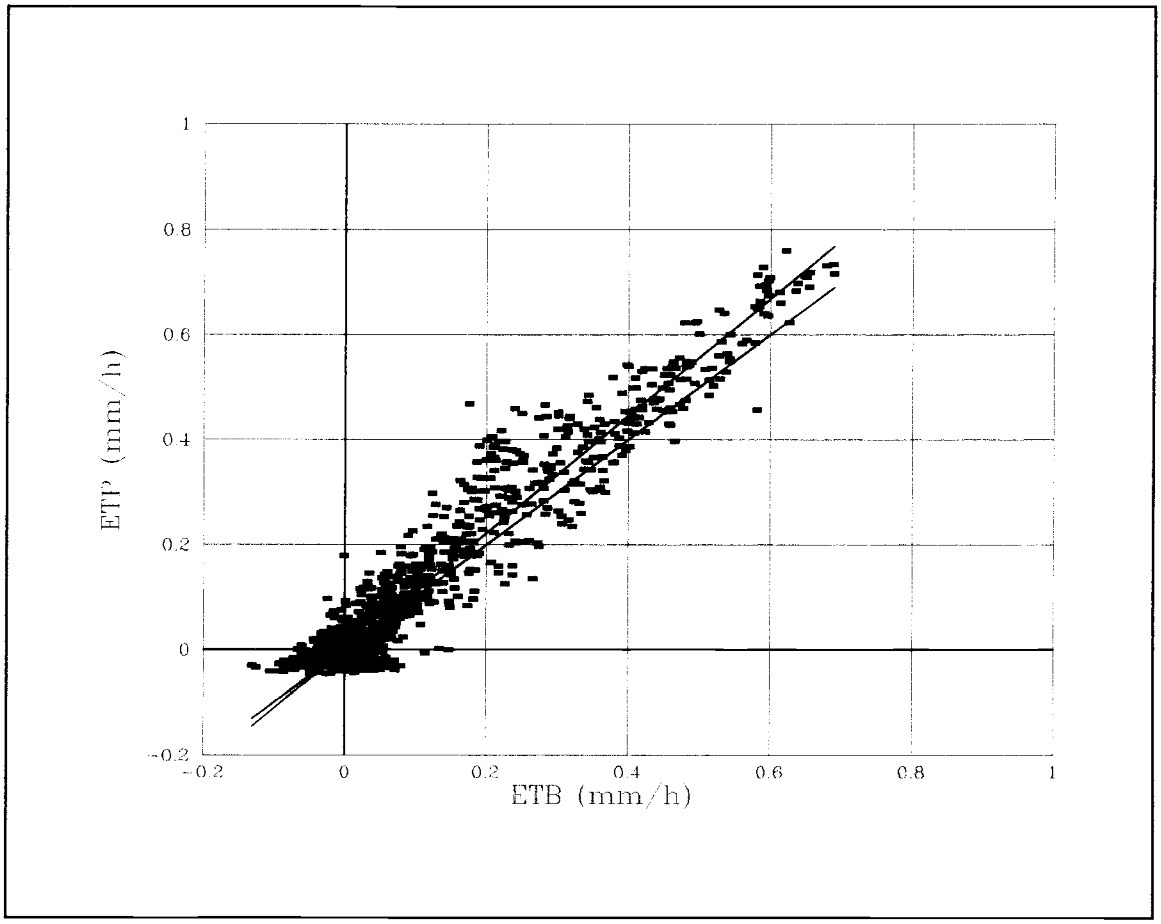

Figure 12. BREB method(ETB) and CIMIS Penman(ETP) for the combined data set.

4.3 Statistical Analysis for Bowen Ratio Energy Balance Method and Hydrologic Balance Method

This section presents comparisons between BREB method and the hydrologic balance method (HBM). Included in the comparisons are error analysis and linear regression analysis. This analysis was made using evapotranspiration periods which were defined by the neutron probe readings.

To check whether the error between the average of ET periods estimated by BREB method (ETB) and the average of ET periods estimated by the hydrologic balance method (ETH)was statistically different from zero, a *t*-critical equal to 2.02 was used to reject or confirm the null hypothesis (Section 2.1.1). A 0.05 significant level was used to reach 95 percent confidence level. Included in Table 17 are ETB periods, ETH periods, error, *t*-test and SEE results.

Table 17. Error analysis for the ETB and ETH periods.

Mean of ETB (mm)	Mean of ETH (mm)	Error (mm)	t-test	SEE (mm)
3.92	2.81	0.64	0.50	2.1

Results in Table 17 strongly suggest that the average of error between ETB and ETH periods was not significant different from zero. However the value of SEE indicates that the error had a very high variation.

Inaccuracy in the neutron probe calibration, measurements of precipitation, and irrigation, and spatial variation of the soil probably decreased the performance of HBM to estimate $ETact$. Carrijo (1988) reported that the hydrologic model used to short period of time produced a very large variation in estimating $ETact$ due to inaccuracy in the calibration equation, spatial variation, and variation in probe reading.

Cumulative ET estimated by the BREB method and HBM are presented in Figure 13. This Figure shows that the hydrologic balance method underestimated the daily ET during all periods. The total cumulative ET obtained using the hydrologic balance was about 13 % less than the total cumulative ET computed using the BREB method. Comparison of ET measured with a neutron moisture meter and weighing lysimeter realized by Wright (1990) shown similar results. Wright observed that the total seasonal neutron meter ET was about 10 % less than lysimeter ET when drainage was neglected.

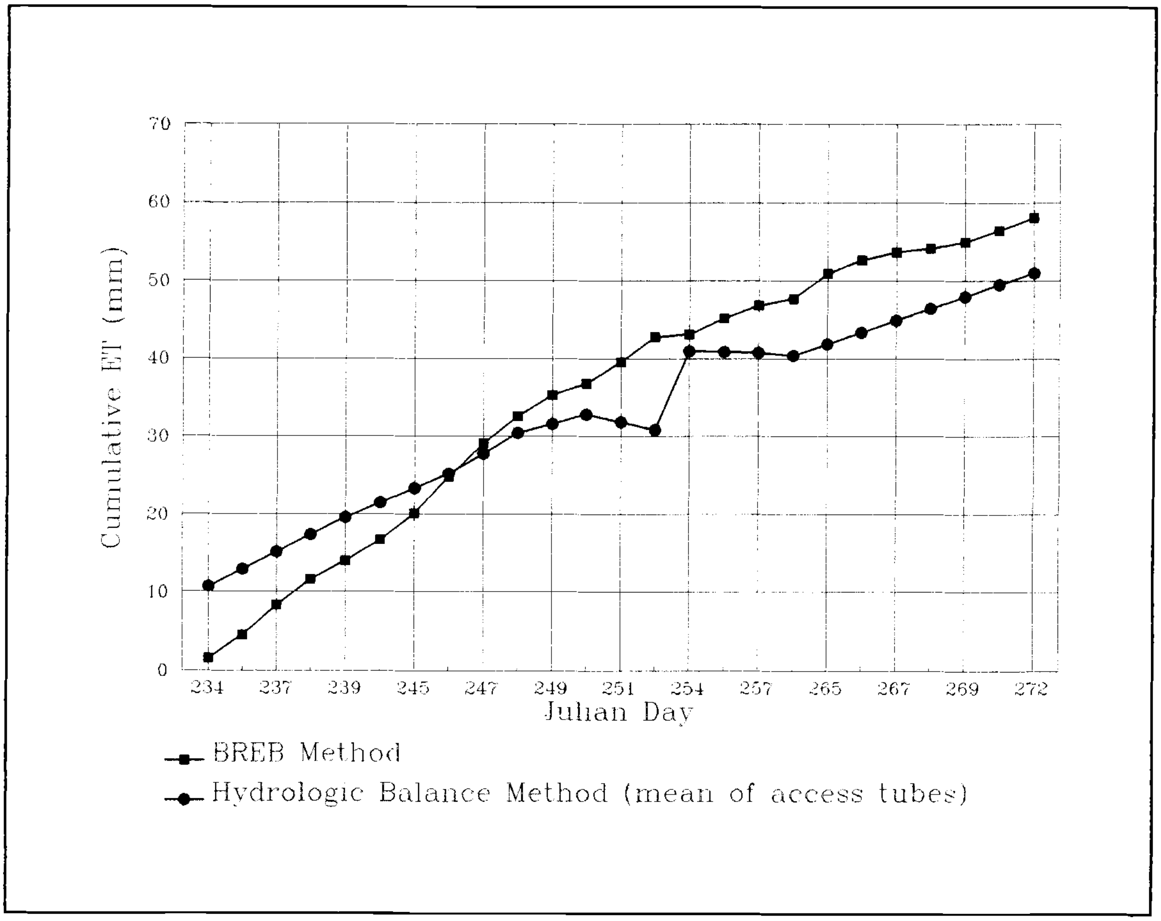

Figure 13. Comparison between BREB method and hydrologic balance method.

5 SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary and Conclusions

The main objectives of this project were: a) to evaluate the performance of the Bowen ratio energy balance (BREB) method on an hourly basis, b) to compare the performance of the BREB method versus the Penman CIMIS for estimating hourly and daily evapotranspiration, and c) to compare the performance of the BREB method versus hydrologic balance method (HBM) for estimating actual evapotranspiration.

The experimental site was the Evapotranspiration Investigation Plot (ETIP) at the OSU Schmidt Farm, 15 km north of Corvallis, Oregon. Meteorological, radiation, and soil parameters were measured in Alta fescue (*Festuca elatior*). The data set was collected in October 1989 and from July to October of 1990. Only 67 complete days of data were available for the study basically due to technical problems in the Bowen ratio station. Meteorological parameters were measured on a 15 minute interval on an automatic weather station. Solar radiation components were measured on a 15-minute interval on a radiation station. Energy balance components were measured or computed on a 20-minute interval using the BREB station. Station performance checks for the automatic weather station and BREB station were performed using data from manual meteorological station at the ETIP site. Data processing was performed to obtain hourly evapotranspiration from the BREB and automatic weather station data.

Soil water content, precipitation, irrigation and drainage were used to compute actual evapotranspiration from an hydrologic balance model (ETMASTER) developed by Cuenca (1988). Water applied was measured as cumulative values during a 15-minute interval. Soil moisture content was measured using the neutron moderation technique. Drainage was computed by ETMASTER as a function the field capacity of the profile. When the amount of water applied was greater than the field capacity of the profile, the excess of water was computed by ETMASTER as deep percolation or drainage.

5.1.1 Performance of the Bowen Ratio Energy Balance Method at the Oregon Evapotranspiration Investigation Plot (ETIP)

To evaluate the performance of the BREB method at ETIP, values of the Bowen ratio (β) between -0.5 and 0.85 were assumed to indicate acceptable performance criterion . This performance criterion was based on studies by Angus and Watts (1984) and Pruitt et al. (1987).

From 600 h to 1700 h, the hourly averages of β were between -0.5 and 0.9 and from 1700 h to 500 they were between -0.67 to -3.33 for clear sky conditions. For cloudy sky conditions, the hourly averages of β were between -0.48 and 0.65 from 200 h to 1700 h and they were between -0.84 and -2.25 from 1800 h to 100 h. According to these results, the performance of the BREB method was within acceptable performance criteria from sunrise to sunset. However, from sunset to sunrise the performance of the BREB method was not within the acceptable performance criteron for clear days and most of the time for cloudy days.

During the night period, the t-confidence interval with a 95 percent of confidence level indicated that there was a large variation in the hourly average of B under clear and cloudy sky conditions. However, this variation was much greater for nights following clear days than nights for following cloudy days. During the day period, the t-confidence interval indicted that the variation of hourly values of B was very small for cloudy days. For clear days, the variation was relaively large from 600 h to 1300 h. However, only at 1000 and 1200 h were the confidence interval values not within the performance criteron. These results indicate that the performance of the BREB method under cloudy conditions was more consistent than the performance under clear days.

The cumulative evapotranspiration computed at night represented about 2, 5, and 3 percent of daily cumulative evapotranspiration for the clear, cloudy and combined data sets, respectively. Assuming that the values are representative these results, the cumulative evapotranspiration computed during the night period did not have a considerable effect on the daily evapotranspiration and could be considered negligible. The BREB method, therefore, can be considered a very good method to estimate daily evapotranspiration. However, poor performance was observed at night, especially following clear days.

The usefulness of the BREB method was limited due to serious technical problems in the air intakes and dewpoint hygrometer. The data proccesing indicated that the vapor pressure difference (Δe) between levels decreased abruptly for more than 1 hour during the day. This problems were observed in the system following rainfall, irrigation, and sometimes after cleaning of dewpoint hygrometer. These errors affected about 49 percent of the total collected data. The cause of these problems was water in the air intake system and probably was related to the accumulation of humidity in the dewpoint hygromenter. Erroneous estimates of Δe occurring for less than 1 hour were also observed. These problems occurred especially early in the morning when the relative humidity was high. The cause has not discovered, but it was apparently related to an accumulation of humidity in the dewpoint hygrometer. Problems in retrieving data from the magnetic tape storage medium were also observed. These problems were associated with extreme atmospheric conditions such as high temperature, high net radiation and heavy precipitation or irrigation. The magnetic tape was affected such that data could not be read off correctly. The tape reading problems affected about 9 percent of the total collected data.

5.1.2 Comparison Between the Bowen Ratio Energy Balance Method and the CIMIS Penman Method

The distribution and magnitude of the hourly average of net radiation (R_n) had a considerable impact on the agreement between the BREB method and CIMIS Penman during day and night periods. In general, as R_n increased the agreement of the methods decreased until there was a maximum departure at midday. After that point, the agreement between the methods increased as R_n decreased. The agreement between BREB and CIMIS Penman methods decreased drastically after sunset and increased rapidly after sunrise.

For clear days, the error between the hourly average evapotranspiration estimated by the BREB method (ETB) and evapotranspiration estimated by the CIMIS Penman (ETP) was significantly different from zero during the night period and from 800 h and 1400 h during the day period. The error for cloudy days was not statistically different during the night and day periods except at 1300 h. For the combined date set, the differences between ETB and ETP were markedly different from zero at night from 1800 h to 500 h and at midday from 1000 h and 1400 h. The standard error of estimate (SEE) was maximum when R_n was maximum and it decreased as R_n decreased. Maximum values of the SEE observed at midday were 0.17 mm h^{-1}, 0.12 mm h^{-1}, and 0.13 mm h^{-1} for the clear, cloudy, and combined data sets, respectively. These results indicate that the SEE and the difference between ETB and ETP were highly related to the level of R_n. Under high levels of R_n, especially under clear sky conditions, the grass was under large water stress and conditions defined for obtaining the hourly reference evapotranspiration were not maintained. Under these conditions, CIMIS Penman tended to overestimate hourly ET because it did not account for the stomatal resistance and the dissipation of $R_n - G$ into latent heat flux and sensible heat flux as the BREB method did. This could explain the disagreement found under high R_n conditions, especially at midday. During the night period significant differences between ETB and ETB were observed for the clear and combined data sets particularly following days with high R_n conditions.

Hourly regression analysis with a nonzero offset along the ordinate axis indicated that there was a strong linear association between ETB and ETP for the three data sets from sunrise to sunset. F-test values and the coefficient of determination (r^2) decreased drastically at sunset when R_n became negative. At sunrise, these statistical parameters increased rapidly when R_n became positive. On clear days a strong linear association between ETB and ETP was observed from 700 h to 1900 h. In this period, the coefficients of determination were between 48 and 93 percent. The strongest correlations, between 84 and 93 percent, were observed from 1300 h to 1900 h. For cloudy days, the linear regression model was statistically significant from 800 h to 1800 h. The coefficients of determination were between 18 and 90 percent. The poorest coefficients of determination were found at 800 h, 1500 h, and 1900 h at which time 74, 76 and 18 percent, respectively of observed variations were explained by the linear model. For the combined data set, the variance analysis indicated that there was a strong correlation between ETB and ETP from 800 h to 1900 h. During this period, the coefficients of determination were between 77 and 94 percent. During the night period, this analysis indicated that there was no linear correlation between the two methods for the three data sets. These results suggest that the linear correlation between the BREB method and the CIMIS Penman to estimate the hourly reference evapotranspiration (ETo) were highly affected by levels of R_n during the night and day periods. During the night period, R_n was negative and there was no linear correlation between the two methods for the three data set. This was probably produced by problems either in the BREB method or CIMIS Penman. In the BREB method, according to the hourly Bowen ratio variation, important errors in the estimation of latent heat flux were produced at night, especially for the clear and combined data sets. In CIMIS the Penman method, problems in the aerodynamic wind function could produce consistent errors in the computation of ETo. During the day period when R_n was positive, linear correlation between the two methods and coefficients of determination were not affected considerably by levels of R_n.

The regression analysis through the origin using all data indicated that there was a very strong linear association between ETB and ETP for the entire data set. 92.6, 90.5, and 93.5 percent of observed variations were successfully explained by the linear regression model through the origin for the clear, cloudy, and combined data sets. These results indicate an excellent agreement and goodness of fit for the three data sets. However, this analysis indicated that the CIMIS Penman overpredicted hourly ETo by about 13 and 11 percent for the clear and combined data sets, respectively. This overprediction was produced at midday when the conditions to obtain ETo were not maintained and the grass was under high water stress. Under cloudy conditions the CIMIS Penman overpredicted ETo by about 8 percent, however the difference between the two methods was not statistically different from zero. The small differences observed at midday under cloudy conditions could be attributed to inaccuracy in the aerodynamic wind function. In general, these results indicated a remarkable closeness of the methods because the ETP values were computed using an equation with an empirical-determined wind function based on Davis, California studies.

The error analysis on a daily basis indicated that the error between daily averages of ETB and ETP was not different from zero for the three data set. However, the daily values of the SEE as compared to daily errors indicated that the error between ETB and ETP had a large variation. Values of SEE were 0.73 mm d^{-1}, 0.46 mm d^{-1}, and 0.68 mm d^{-1}, for the clear, cloudy and combined data sets, respectively. The SEE did not decreased appreciably when the moving average was used. The variation observed for entire data set could be explained by the variation of hourly atmospheric conditions, especially of the R_n. The conditions defined to obtain the hourly ETo varied during the day period for the clear and combined data sets. This produced erroneous estimation of ETo by the CIMIS Penman method. For cloudy days, the distribution and intensity of the hourly wind speed could affect the computation of ETo. The inaccuracy of the aerodynamic term in CIMIS Penman did not efficiently account for the effect of wind speed on the hourly ETo.

A strong linear correlation on a daily basis between ETB and ETP was observed for the three data sets. The coefficients of determination using a regression model with a nonzero offset along the ordinate axis were 85, 79, and 87 percent for the clear, cloudy, and combined data sets, respectively. The daily regression analysis forcing the regression through the origin indicated that after a 3-day-averaging interval, the data set had a coefficient of determination higher than 0.88. The cloudy data set had a coefficient of higher than 85 percent after a 7-day-moving average and the clear data set reached the same level after a 15-day interval. The linear correlation on a daily basis was strongly affected by the hourly atmospheric conditions during the day period. Under clear days, the hourly weather conditions were more unstable than for cloudy days. This could produce a considerable reduction of the coefficients of determination when the linear regression was forced through the origin.

5.1.3 Comparison Between the Bowen Ratio Energy Balance Method and the Hydrologic Balance Method

The average daily difference between ETB and evapotranspiration estimated by the hydrologic balance method (ETH) was not significantly different from zero. The values of SEE compared to the error indicated that difference between ETB and ETH had a very large variation. The large variation between ETB and ETH was associated with inaccuracy in the neutron probe calibration equations and spatial variation of soil water properties.

The hydrologic balance method underestimated the evapotranspiration during the total period. The total cumulative evapotranspiration obtained using the hydrologic balance was about 13 percent less than that obtained using the BREB method. This underprediction was probably produced by inaccuracy in the calibration equation. This could produce erronoeus estimation of the field capacity.inaccuracy in the calibration equation produced important errors in the computation of the volumetric water content in the soil.

5.2 Recommendations

Several recommendations for future research evolved from this investigation.

1. Special protection of the air intake system is required to avoid loss of data after rainfall or irrigation. A additional study to evaluate accumulation of humidity in the dewpoint hygrometer should be performed, especially early in the morning.

2. An anemometer at each measurement level of the Bowen ratio station should be added to study the influence of atmospheric stability on the performance of the BREB method. This could help to understand the behavior of the Bowen ratio during the night and day periods.

3. The effect of soil water content on the Bowen ratio should be studied. An error analysis as a function of soil water content should be performed for the latent heat flux, sensible heat flux, and soil heat flux.

4. Compare the performance of the BREB method with the Penman-Monteith method to estimate the evapotranspiration under different soil water status and atmospheric conditions. Monitoring of soil moisture content could be

done using the neutron probe technique, but more accurate neutron probe calibration and field capacity constants, especially for the first 20 cm, are required.

5. The hydrologic balance method requires accurate measurement of precipitation and drainage to compute the actual evapotranspiration over short periods of time. Drainage and infiltration models should be added to the hydrologic balance program. Furthermore, a subroutine to correctly assign cumulative precipitation during the 1-hour interval should be incorporated in ETMASTER. This subroutine could help avoid erroneous distribution of water applied to an evapotranspiration period.

6. The response of the hydrologic balance method to rapid changes in atmospheric conditions should be studied on a daily basis. This requires precise measurement of all hydrologic water components, including soil moisture content, on a daily basis.

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