SIMPLIFIED APPLICATION OF PENMAN'S EQUATION

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ABSTRACT

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A sensitivity analysis was performed on the Penman equation; from this analysis, it was determined that wind velocity and the dew point temperature have relatively little affect on ET prediction by Penman's method which is more sensitive to changes in extraterrestrial radiation, maximum temperature, and percent of sunshine.

Approximations were introduced to estimate wind velocity and percent of sunshine. In addition, minimum temperature of the night before was used instead of dew point temperature in the determination of saturated vapor pressure.

The simplified equation was evaluated in the summer of 1981, using evapotranspiration from corn, measured by the gravimetric method and evapotranspiration from potato, measured by the neutron scattering method.

A very good correlation was obtained with the neutron scattering method (R = 0.954) and the sum of the evapotranspiration obtained by both methods for the season was almost the same. The gravimetric method gave higher values of evapotranspiration and its correlation with the simplified equation was lower (R = 0.65).

To my beloved father and in the memory of my mother.

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CHAPTER I

INTRODUCTION

Irrigation is one of the most important management practices in agriculture. Its role can be easily explained by the fact that although irrigated areas represented only 13% of the global arable land, it accounts for 34% of the world's crop production (FAO, 1979). Through history, irrigation has enabled the establishment of florescent civilizations in otherwise useless land and the increase of productivity to sustain the increasing world population.

In the U.S. there has been a steady increase in irrigated areas in the last 50 years, a fact which has played an important role in the agricultural revolution that has transformed agricultural production, making economically feasible the utilization of the modern techniques used nowadays in agriculture (introduction of improved varieties of crops, use of pesticides, fertilizers, equipment for agricultural practice, etc.). The estimated irrigated area in the United States in 1979 was 24,746,000 has., representing a growth of 136% in relation to the 1949 figures, which gives a 4.5% average rate of growth per year (Jensen, 1980).

Michigan receives less rainfall than any other of the states east of the Mississippi River which is one of the reasons why crop yield increases had been lower than those of the other states (drought stress is a probability two years out of every five for each summer month) (Lucas and Vitosh, 1978). These facts help explain the large increase of irrigated area in Michigan, estimated at 23% for the last three years up to 161,149 has. in 1980 (Vitosh et al., 1980).

However, because of the high costs of the energy required in any method of irrigation, as well as the high investments needed for its implementation, the farmers must irrigate in the most efficient way in order to obtain benefits or even survive in today's business. In addition, the competition for limited fresh water supply between industrial, urban, and agricultural needs is already a matter of concern and will be a very hot issue in the future. Continuous depletion of the groundwater supply (by far the main source of irrigated water) is making pumping costs more and more expensive and putting more and more pressure on irrigation, the main consumer of water.

In order to irrigate efficiently, it is imperative that the irrigators know the amount of water to apply to avoid an excess in application which increases the costs of operation and may damage the crop, or to avoid a deficiency of water which causes stress in the plant, thus a decrease in production. The amount of water to apply and the time to appy it is determined by the soil type (water holding characteristics), the crop and the water requirement of the crop.

The water requirement depends mainly on evapotranspiration, leaching requirement, effective rainfall, soil moisture content, the ascension of groundwater and irrigation efficiencies. The relative importance of these parameters varies with the climate and some local conditions. For example in Michigan, under normal conditions, the important parameters are evapotranspiration, effective rainfall, and irrigation efficiencies. The role of evapotranspiration is very important in the determination of water requirement. As Shockley (1966) said: "Evapotranspiration is an important part of the over-all water requirement problem and accuracy in its determination is desirable. However, the relatively indeterminate nature of most of the other factors involved indicates that complex and time consuming procedures to achieve extreme precision seldom will be justified for farm irrigation planning for on-farm irrigation water management."

One of the most used methods to calculate evapotranspiration is the Penman Equation. This is a theoretically sound method which yields relatively accurate evapotranspiration estimates (Doorenbos and Pruitt, 1977). However, the model requires some climatalogical data (percent of sunshine, wind velocity, and dew point temperature) which generally are not easily available for individual farmers.

The objectives of this study are:

1. To analyze the sensitivity of the Penman equation to variation of its parameters.
2. To propose simplifications which will enable Penman's Equation to be used by individuals possessing hand-held programmable calculators and a minimum of climatological data gathering equipment.

3. To evaluate the results of the application of these simplifications, relating them to field measurements of evapotranspiration.

CHAPTER II

LITERATURE REVIEW

Plant Water Requirements

There is no theory which completely explains the process of water passing through a plant, but water is known to be important in every stage of a plant.

Water is essential in the photosynthesis process by which the plant produces its food. It is also indispensable in the respiration by which the plant uses this food for growing, reproducing or sustaining itself, depending on its stage of development. Water also acts as a solvent and medium of transportation of food within the plant. It gives internal support to the plant: "Under pressure within the plant cells, water furnishes support to the plant" (Merva, 1975).

Finally, but not less important, water evaporating from the plant cells and soil absorbs much of the radiant energy the plant does not use for photosynthesis, thus keeping the plant temperature from being higher than those values convenient for its functions.

The evaporation from plants and soil comprises more than 95% of the water used by the plant (Kramer, 1969). Pallas et al. (1962) conducted an experiment in a controlled environment growth room and found that transpiration cools the plants as generally acceptable. However, they reported that the amount that transpiration lowers the leaf temperature, and whether or not it does this below air temperature depends on the species and the environment. They also suggested that their failure, as well as the failure of others who had worked on the topic, to recognize interactions between radiant energy, soil moisture tension, and air vapor pressure deficit, reflected existing discrepancies found in the literature as to what extent transpiration is important to the plant.

Although only a small proportion of the water taken by the plants is used for photosynthesis and other biological processes in which water is needed, Pallas et al. in the same work noted a decrease in photosynthesis with an increase in moisture tension. In This they concurred with Gingrich and Russell (1957) who concluded that most plants show a decrease in production when moisture stress is more than one atmosphere.

While evaporation may not be the most important water consumed by the plant because it constitutes such a great proportion of the total, it can be used to determine the water used by a crop.

Evaporation

Historical Developments

Deacon, Priestley, and Swinbank (1958) in a review of literature related to evaporation and the water balance, defined evaporation from natural surfaces such as open water, bare soil or plants as "a diffusive process by which water in the form of vapor is transferred from the underlying surface to the atmosphere."

The first individual who understood the role of evaporation in the hydrologic cycle was Vetruvius Pollio (50 B.C.). He said that the sun heated up the water in rivers, springs, marshes, and seas, forming vapors which rise to form clouds. Leonardi da Vinci (1500) explained: "where there is life there is heat and where there is vital heat there is movement of vapor." Lavoisier regarded evaporation as the combination of fire and water while Benjamin Franklin said it was due to the solution of water in air (Penman, 1948a).

Dalton (1834) reviewed by Deacon, Priestley, and Swinbank (1958) and Penman (1948a) was the first to study scientifically the evaporation process. His statements about the properties of vapors (mainly the partial pressure law and the dependence of vapor transfer on pressure differences) were the foundation for most of the scientific studies of evaporation up to the present time. He performed many experiments to explain the factors controlling evaporation and found that the space above a water surface could have only a limited amount of water vapor whose maximum partial pressure was dependent on temperature. Dalton demonstrated that when the partial pressure was not at its maximum, there would be evaporation at a rate proportional to the partial pressure deficit and the wind speed.

He developed the formula:

$$E = a\ (e_s - e_d)\ (1 + b\ u) \tag{1}$$

where:

E = rate of evaporation

e_s, e_d = saturation vapor pressures at the evaporating surface and dewpoint temperature respectively

u = wind speed

a, b = empirical constants

During the following century, most of the work on evaporation was mainly based on the estimation of evaporation from small open water surfaces which was used as a standard for the calculation of evaporation from larger bodies of water. The majority of these studies were performed in arid areas of the United States and generally yielded models which followed the form of Dalton's Equation.

Since the 1940s many scientists have studied evaporation with different approaches, obtaining empirical formulas relating evaporation to temperature, or more theoretical models, using sophisticated parameters for calculating it. In the last 15 years the studies have focused mainly on modifying earlier formulas to adapt them to local conditions. More recently, computer models are being used to estimate and predict evaporation.

General Facts

Natural evaporation can occur from open water surfaces, from bare soil and from plants. Evaporation from open water is known to be entirely dependent on weather conditions and may be influenced by the shape of the water body. However, evaporation from bare soil and plants can be limited by other factors. Penman (1948a) summarized the works of Eser, Wollny, and others who found that in addition to the effect of weather conditions, the amount of evaporation from bare soil is restricted by the moisture tension of the soil, and by the resistance of soil to transmit water at a moisture content less than saturation. The vaporation from plant surfaces (also called transpiration) is affected by biological-physical factors of the plants stomata aperture, leaf area, root depth, stage of development, species, etc.), as well as by the factors which influence evaporation from bare soil.

In their research on plant transpiration, Pallas et al. (1962) found a strong relationship between transpiration and leaf area. White (1932) reported by Penman (1948a), studied the effects of the control of stomatal opening by daylight and other factors in alfalfa cropped under semi-arid conditions. The results showed the variations in the rate of transpiration during the day and a steady daily increase of transpiration rate until the alfalfa was cut. Especially notable was the cessation of effective transpiration after removing the evaporating surfaces and the gradual resumption when the surfaces grew again.

Penman (1948a) concluded from the literature he reviewed that the crops with enough water available will have a transpiration rate similar to the evaporation rate from an open water surface. Also that they will exhibit a behavior similar to that of a highly conducting channel between a source (available water to the crop in the soil) and a sink (atmosphere). Penman also cited the results of Schofield (1935) and coworkers who, investigating the thermodynamics of the soil-water-plant continuum, found that, measured in terms of the free energy of the soil water, the available moisture content resembled closely a soil moisture constant nearly independent of soil or crop.

Lawes and Gilbert (1871), Hendrick (1921) and Hendrick and Welsh (1938), also reported by Penman (1948a) found from experiments that when the available water is renewed adequately by irrigation or precipitation, transpiration is not limited by moisture content of the soil and the behavior of cropped soil in the summer is nearly the same as the behavior of bare soil, being entirely dependent on weather conditions and independent of crop yield.

McIlroy and Angus (1964), reviewed by Dilley and Shepherd (1972), working on pasture and potatoes at Aspendale, Victoria found that changes in plant especies composition caused grass evaporation to fall in spite of continued liberal irrigation. From that they concluded that even under potential conditions, some species can exert a physiological constraint on evaporation.

Actual and Potential Evapotranspiration

The most used definition of evapotranspiration (ET), describes it as "the combined process by which water is transferred from the earth's surface to the atmosphere; this includes evaporation from soil and plant surfaces plus transpiration of water through plant tissues expressed as the latent heat transfer per unit area or its equivalent depth of water per unit area" (Jensen, 1980).

Because of the difficulties involved in the estimation of evapotranspiration due to the fluctuations originating from physical characteristics and moisture conditions of the soil as well as the effects of physical and physiological plant features, a parameter was needed to estimate an evapotranspiration factor which did not take into account these fluctuations. Thornthwaite (1948) introduced the term POTENTIAL EVAPOTRANSPIRATION, (PET) which has been universally adopted.

The most widely accepted definition for potential evapotranspiration was given by Penman (1956): "Potential evapotranspiration is the amount of water transpired in unit time by a short green crop, completely covering the ground, of uniform height and never short of water." In recent years, there has been an increasing use of the term REFERENCE EVAPORTRANSPIRATION, (RET) to replace PET because of the vagueness involved in the interpretation of the later (Jensen, 1980). Jensen, Wright, and Pratt (1971) defined RET as "the upper limit or maximum evapotranspiration that occurs under given climatic conditions with a field having a well-watered agricultural crop with an aerodynamically rough surface, such as alfalfa with 12 in. to 18 in. of top growth." However, the potential evapotranspiration term is by far the most widely used.

Both terms depend on meteorological conditions, mainly radiant energy available and the partial pressure difference between the evaporating surface and the surrounding atmosphere.

Crop Coefficient (K_c)

To account for the difference between PET and the restriction on evapotranspiration imposed by crop species, crop growth stage, and crop density, a dimensionless parameter, the crop coefficient is used.

The coefficient is the ratio of actual evapotranspiration (AET) to potential or reference ET for a crop:

$$K_c = \frac{AET}{PET} \text{ or } K_c = \frac{AET}{RET} \tag{2}$$

The most popular method to measure AET is the use of a properly located sensitive weighing lysimeter with water table not affecting the data. PET or RET can be obtained by measuring the ET from the reference crop (grass or alfalfa) under ideal conditions or by using one of the well known methods for predicting PET.

Many studies have been done to obtain coefficients for the most important agricultural crops in every climatic condition. Baier and Robertson (1968) took into account the moisture tension characteristics of the soils in computing K_c while Rijtema (1959) considered the apparent diffusion resistance of crops and its relation to degree of cover.

Jensen, Wright, and others worked in the early 70s to develop crop coefficients and crop water requirement and irrigation scheduling at Kimberly, Idaho. They developed a crop coefficient which included the effects of wet soil surfaces in evapotranspiration (after irrigation or precipitation).

Jensen, Wright, and Pratt (1971) and Jensen, Rob, and Franzoy (1970) estimated:

$$K_c = K_{co} K_a + K_s \tag{3}$$

where:

K_c = crop coefficient

K_{co} = the mean crop coefficient based on experimental data where soil moisture was not limited

K_a = the relative coefficient related to available moisture

K_s = the increase in the coefficient where the soil surface is wetted by irrigation or rainfall

The studies were performed using the Penman combination equation for estimating PET, and soil sampling for estimating AET. In the following studies, conducted mainly by Wright in the late 70s and early 80s, a revised procedure was used to obtain revised crop coefficients for semi-arid conditions. A revised method for calculating reference evapotranspiration and weighing lysimeter data were used to obtain the revised coefficient for most of the irrigated crops of the region. Wright (1981) developed a formula to adjust these revised coefficients for the effects of surface soil wetness and soil tension properties:

$$K_c = K_{cb} + (1-K_{cb})\ [1 - (t/td)^{½}]\ f(w) \qquad (4)$$

where:

K_c = the adjusted crop coefficient

K_{cb} = crop coefficient designed to represent dry soil surface conditions and called by Wright "basal ET crop coefficient."

t = the number of days after major rain or irrigation

td = the usual number of days for the soil surface to dry

fw = the relative portion of the soil surface originally wetted

Wright (1981) also reported a new mean crop coefficient for some crops at different stages of growth which gives seasonal estimates for typical crop development and local management practices where root zone soil moisture does not limit growth and for the rainfall and irrigation patterns of the area.

Doorenbos and Pruitt (1977), on a study published by the Food and Agricultural Organization (FAO), reported values of crop coefficients for most of the irrigated crops, where the physiological features of the crops are taken into account, as well as the prevailing relative humidity and wind speed of the locality. They gave two values for each crop, one for the mid-season stage and the other for the harvest/maturity stage. These numbers, along with another value obtained from an average K_c for initial crop development stage related to level of PET and frequency of irrigation and/or significant rain are used to develop a crop coefficient curve which gives daily value of K_c during the crop season.

Methods for Determining Evapotranspiration

We will classify the methods for determining ET as:

1. Those which are based on direct measurements of water evaporated
2. Those which are based on the use of meteorological data

Direct Measurements

The most important are pan evaporation and water balance field measurement.

Pan Evaporation

This may be the most widespread method for estimating evapotranspiration. Evaporation data from pans have been collected in many climatological stations for many years all over the world and have been widely used in empirical studies of the topic. The main objective has been to get means of applying this evaporation measurement to obtain indications of evaporation from large bodies of water and from bare and cropped soils. This is because both are influenced by the same climatic factors: solar radiation, wind velocity, temperature and humidity (Westesen and Hanson, 1981).

Different types of pan evaporation. The most widely used is the U.S. Weather Bureau Class A pan which is well described by Jensen

(1980). Also important are the U.S. Bureau of Plant Industry Sunken plant (set into the ground), the USGS floating pan (placed on a raft for measuring lake evaporation), Colorado Sunken pan, Class B pan, wash tub evaporation pan, standard British tank and standard Australian evaporation tank.

They differ only in shape, color, and/or size and are used to calculate PET using coefficients which have been estimated empirically.

There have been many studies conducted to verify the relationship between evaporation from pan or tank and evapotranspiration. Penman (1948a) in the Rothamsted experimental station in England, found a high correlation between evapotranspiration from short grass well watered and evaporation from open water surfaces. Pruitt (1966) reported a high correlation between pan evaporation data and evapotranspiration from grass grown in a lysimeter. He also reported the success of similar comparisons in Nigeria, England, and Israel (Stanhill, 1958, 1961, 1962, 1963) using standard British tank, Zaire (Congo) (Brutsaert, 1965). Canada (Wilcox, 1963) using a Class A pan, a sunken pan, and a black Bellami plate anemometer, Denmark (Aslyng, 1965) using an open 12 square meter tank, Australia (McIlroy and Angus, 1964) using the standard Australian evaporation tank. Sims and Jackson (1971) found that a No. 1 wash tub could be used to acceptably measure evaporation.

Coefficients to be used with evaporation pans. To calculate the potential evaporation rate from pan evaporation data, a pan coefficient is used with the relation:

$$PET = K_p * E_p, \quad RET = K_p * E_p \tag{5}$$

where:

E_p = pan evaporation in mm/day

K_p = dimensionless pan coefficient

Jensen (1980) gives a table of pan coefficients to be used with Class A and Class B pans with different values of relative humidity, pan exposure, wind velocity and distance of homogeneous material to the windward side. A similar table is given by Doorenbos and Pruitt (1977).

McIllroy and Angus (Pruitt, 1966) found an average pan coefficient of 0.84 for Class A pans, 1.05 for standard Australian evaporation pans, and 1.6 for the 1.6 meter weighing evaporimeter using a grass-clover mixture as the reference crop. Pruitt also reported values of 0.87 for shallow pans, 0.86 for Class A, and 1.13 for Bureau of Plant Industry Sunken pans as found by Abon-Khaled at Davis, California, who used grass as the reference crop. Middleton et al. (1962) using a Class A pan evaporation at Washington State, found coefficients from about 0.8 for corn, grapes, and peaches in periods of near maximum vegetative cover with no cover crop to a maximum of 1.05 for Delicious Apples with a grass cover crop;

Middleton found also a 0.9 coefficient for sugar beets, soybeans, red beans, ladino cover, late potatoes, wheat, as well as alfalfa in humid western Washington. For green peas, early potatoes, raspberries, and peaches with an alfalfa cover crop, they found a coefficient of about 1.0. For arid Central Washington, they found a coefficient of 0.95 for alfalfa.

Hargeaves and Christiansen (1966) reported by Westensen and Hanson (1981) found a seasonal pan coefficient of approximately 1.0 for alfalfa at full cover and 0.75 at 25% into the growing season; for small grain, they found 0.33 at 25% into the growing season and 0.90 at full cover (65% or more into the growing season).

Disadvantages of the Pan Evaporation Method. There is some certainty in the effect of some local environmental factors as regards to pan evaporation. Pruitt (1966) showed a "very marked" effect of immediate upwind condition in evaporation pan readings, with a near linear decrease in evaporation as a function of the logarithm of upwind fetch of grass. He also recommended a standardization of the local environment of evaporation pans and a consideration of the proximity of any major difference in crop height or roughness. He also found a wide variation from the coefficient average value during three strong wind, high advention days which could not be predicted by any single correction. From the same studies on evaporation pans, an effect of the pan size and shape on evaporation has been observed.

Water Balance Field Measurement

These methods are primarily used for calibrating and evaluating other methods to measure evapotranspiration. Because they require actual measurements, the tendency has been to develop models to measure and predict ET from climatalogical data. The most important field measurement methods are as follows.

<u>Soil Moisture Budget</u>. Despite the objection to the validity of this method, it is widely used in the determination of water evapotranspired. It consists of periodic measurements of root zone water content and an inventory of the water entering and leaving the soil-plant system (rainfall, irrigation, and drainage). The budget method considers evaportranspiration as the difference between water into the system minus water out.

In an abstract about soil profile sampling, Davidson and Nielsen (1966) reported some of the objections usually used against this method. The most serious objections were the errors introduced by the simultaneous redistribution of water during extended periods of drainage, the ascension of water from below the greatest sampling depth, and the assumption that no water moves out and/or into the sampling zone between sampling periods.

The most widely used methods for determining the moisture content of the soil are the gravimetric sampling technique and the neutron scattering method.

Bowaman and King (1965) considered the neutron meter a more appropriate method because it averages over a larger volume of soil and because the measurements are taken at the same location each time, which eliminates the distortions caused by nonuniform moisture distribution in the soil. They found a variation of 18% to 24% by volume in the gravimetric determination of moisture content of 500 cc soil samples taken within a 0.91 meter (3 ft) radius, in the A horizon, and a variation of 7% to 31% by volume in the gravelly C horizon.

In their study, Bowaman and King found the neutron scattering method "accurate" to 3.8 mm (0.15 in) of water for one week, or 17 mm (0.62 in) over a three-month period on a 1.3 mt (51 in) profile.

The neutron scattering method has the disadvantages of an initial high investment in the equipment used and the time required for installation and calibration.

Lysimeters. The use of lysimeters (soil tanks in which crops are grown) has been traced back to 1688 in France (Kohnke, Dreibelkis, and Davidson, reported by Harrold, 1966), but its use for determining ET began in the early 1900s. After about 1930, attention was given to measurement of runoff and the effect of lysimeter cover different from that of the surrounding area. At the present, lysimeters are used for a broad range of purposes; Penman (1948b) worked with lysimeters at Rothamsted to study the effects of weather and soil conditions on ET. Dilley and Shpeherd (1972) used lysimeters at Aspendale as a standard for evaluating pan evaporation and the McIllroy combination formula. Jensen, Wright, and Pratt (1971) and Jensen, Robb, and Franzoy (1970) used weighing lysimeters to evaluate the Penman Equation and the von Bavel Equation to develop a model for irrigation scheduling; Wright and Jensen (1972) used the same lysimeters to determine peak water requirements of some crops in Southern Idaho; von Bavel (1966) used precision weighable lysimeters to evaluate his combination equation; Pruitt (1966) reported the use of lysimeters at California and Washington to evaluate the application of pan evaporation to determine ET. Boonyatharokul and Walker (1979) used hydraulic weighing lysimeters at Colorado State University to study the effects of depletion of soil moisture on ET.

To get meaningful results from lysimeters, they must meet certain physical requirements in location, construction, and operation. The most important requirements were reviewed by Harrold (1966) who reported that Makkind (1959) indicated that to yield real values, lysimeters have to represent what occurs in nature. Makkind suggested that discontinuities of vegetation in and out of the lysimeter give erroneous results, and that small lysimeters with large unnatural borders allow extra radiation to reach the vegetation, causing higher values of ET. Harrold also reviewed the conclusion of Popov (1959) that the thermal regimen of the lysimeter must be similar to that of the soil its data are to represent. He also reported the opinion of King, Tanner, and Suomi (1956) that errors introduced in measurements of ET are likely to be larger for small lysimeters than for larger ones.

Harrold (1966) gives detailed information on physical and operational features of different kinds of lysimeters.

Methods Based on Climatological Data

After years of checking and calibrations of models used in the calculation of ET from climatological records, the use of models has become more and more important. There are mathematical models for practically every climatic condition although "No single existing method using meteorological data is universally adequate under all climatic regimes, especially for tropical areas and for high elevations, without some local or regional calibration" (Jensen, 1980).

These methods yield potential or reference ET which are multiplied by the crop coefficient to estimate actual ET.

Primary methods to predict PET based on climatological data are as follows.

Empirical Equations

Though almost all the equations used to calculate PET have some empirical approach, we define as empirical those which are based on empirical relations of the parameters involved (usually two or three), yielding satisfactory results only in the conditions in which they are developed.

Jensen (1966) gave three circumstances where the use of empirical equations is reasonable:

1. When there are not adequate meteorological and soil-crop data available for the use of completely rational equations

2. When there is no need for an accuracy beyond that supplied by the empirical equations

3. When the use of rational equations requires greater technical ability and experience in meterology, physics, and agronomy than that which the users of ET data have or can obtain.

He said that even though some rationally developed empirical methods of determinating ET using solar radiation approximate solutions based on the energy balance approach, qualified technicians have no justification using empirical methods when there are the meteorological parameters available for the use of rational equations. This can be said also of the other empirical approaches.

The first empirical equations were used to predict evaporation from open water surfaces, i.e., Dalton's formula and many others expressed in the same form (Deacon, Priestly, and Swinbank, 1958).

<u>Blaney--Criddle Method</u>. In 1941-47, Morin and Blaney developed formulas for computing evaporation and consumption use from temperature, daytime hours, and humidity records (Blaney, 1955). Later, the formula was simplified by eliminating the humidity factor because humidity records were not readily available at many stations (Blaney and Criddle, 1962). The procedure was to develop coefficients from the correlation of existing consumptive use data for different crops with monthly temperature, percentage of daytime hours, precipitation, frost-free (growing) period, or irrigation season. These coefficients are used to transpose the consumptive-use data from the area where they were developed to other areas for which only climatological data are available.

The formula is:

$$U = \frac{KP\ (45.7t + 813)}{100} \tag{6}$$

where:

U = monthly consumptive use, in mm

K = empirical consumptive use crop coefficient for the growing period

P = monthly percentage of daytime hours of the year

t = mean monthly temperature, in °C

The method has been widely used and it has been revised and varied many times. The crop coefficient and the percentage of daytime hours of the year are easily found in literature on the topic.

Lowry and Johnson Method. The Lowry and Johnson method (Lowry and Johnson, 1942; Israelsen and Hansen, 1962) was one of the first empirical models to be developed and was designed for computing water requirements for irrigation projects of the Bureau of Reclamation. It applies to a region not to individual farms or individual crops. The formula assumes a linear relationship between the accumulation of maximum daily temperatures above 32°F during the growing season (termed by them effective heat) and consumptive use. It was applied with good results to irrigation projects in Western U.S.A. where the data for its development were collected. The formula was:

$$U = 0.8 + 0.156F \quad (7)$$

where:

U = valley consumptive use in acre-feet per acre

F = effective heat in thousands of day degrees

Thornthwaite Method. An empirical formula was developed by Thornthwaite (1948), who found a close relationship between mean temperature and potential evapotranspiration when the variation in daylength is adjusted. Its computation only requires mean monthly values of temperature and the location of the station (latitude).

The equation is of the form:

$$e - 1.6\ (10t/I)^{a} \quad (8)$$

where:

e = monthly PET in cm

t = mean monthly temperature, in °C

$I = \Sigma i$ for the year or growing season, the heat index

$i = (t/5)^{1.514}$, monthly index

$a = 0.000000675I^{3} - 0.0000771I^{2} + 0.01792I + 0.49239$

This yields unadjusted values of PET which must be multiplied by a factor that varies with the month and with the latitude. This factor takes into account the variation in number of days in a month (28-31 days) and the variation in the number of possible hours of sunlight with the season and the latitude.

Thornthwaite gives a table with the factor for Northern and Southern Hemispheres at different latitudes. The formula was very popular in the humid Eastern U.S.A. Thornthwaite and Mather (1955) reported that annual average of PET had been computed for about 3,500 Weather Bureau Stations in the United States, using the Thornthwaite Method.

Empirical formulas based on solar radiation. The last group of empirical models to be considered are those in which solar radiation is the primary variable. Jensen (1966) gave simplified versions of the models:

$$LE = K_e \, \phi_1 \, R_n$$
$$LE = K_e \, \phi_2 \, R_s$$
$$LE = K_e \, \phi_3 \, R_a \qquad (9)$$

where:

K_e = a crop coefficient

R_n, R_s, and R_a = net, solar, and extraterrestrial radiation, respectively

ϕ_1, ϕ_2, ϕ_3 = net, solar, and extraterrestrial radiation coefficients, respectively.

The crop coefficient takes into account the period of leaf area development, minor differences between field crops at effective full crop canopy, and the stage of maturation of the crop. The product of the two other variables represents PET from agricultural crops surrounded by sufficient buffer area (generally 30.5 m wide is enough) to avoid advection errors.

Some of the most used empirical solar radiation equations were developed by Makkink (1957), Ture (1961), Jensen-Haise (1963), Stephens-Steward (1963), Grassi (1964), and Stephens (1965). These were reviewed by Jensen (1966) who pointed out the major advantages of empirical equations using solar radiation as being simplicity, facility of calibration for an area, and reliability of estimates sufficient for most engineering or water management applications.

Energy Balance Approach

The thermal balance at the evaporating surface can be used to calculate evapotranspiration if there is a quantitative measurement of the other factors that contribute to this balance.

This appraoch was first used by Schmidt (1915) and later by Angstrom (1920) (reported by Deacon, Priestley, and Swinbank, 1958, and Thornthwaite and Mather, 1955). In general, the heat budget at the evaporating surface can be expressed as:

$$R = LE + H + G$$

where:

R = net radiative flux at evaporating surface

E = rate of evaporation per unit area

L = latent heat of evaporation of water

H = rate of transfer of sensible heat per unit area of the evaporating surface

G = rate of heat storage per unit area below evaporating surface

R and G can be measured thus:

$$R - G = LE + H \tag{11}$$

Cummings (1925) assumed that the net radiation energy must be assigned to evaporation, neglecting the rate of transfer of sensible heat. This assumption was rebutted by Bowen (1926) who showed that the heat losses by conduction and convection should be considered in the energy balance. He regarded the process of evaporation and diffusion of water vapor from a surface into the layer of air above it as exactly the same as that of the diffusion of specific heat energy from the surface into the layer.

Bowen developed the ratio, β, of the heat loss by diffusion to that by evaporation:

$$\beta = 0.46 \left(\frac{T_s - T_a}{e_s - e_a}\right) \frac{P}{760} \tag{12}$$

where:

T_s = the temperature of the layer of air in contact with the evaporating surface, °C

e_s = the vapor pressure of the layer of air in contact with the evaporating surface, in mm of mercury

T_a = the original temperature of the air passing over the surface, in °C

e_a = the vapor pressure of the air passing over the surface, in mm of mercury

P = the atmospheric pressure, in mm of mercury

From Equation (11), Cummings and Richardson (1927) derived an equation for evaporation from lakes:

$$LE = \frac{R - G}{(1 + \beta)} \tag{13}$$

They tested the formula experimentally and found that it supported Bowen's theory.

Although developed for evaporation from water surfaces, the formula has been used for the determination of potential evapotranspiration by considering evaporation from a plant cover well watered and water surface as being proportional (Penman, 1949).

Gerber and Decker (1961) stated as the main requirements for the use of the model, that the borders of the experimental area be large, that the measurements of the environmental factors used be taken a short distance above the top of the crop, and that the heat stored in the crop mass be very small.

Fritschen (1966) reported that the method had been tested on agricultural crops in humid and arid regions with valid results; however, he warned that care be taken to assure proper instrumentation and compliance with the assumptions of the model. He emphasized the careful measurement of R under all conditions and β especially in arid conditions.

Mass Transfer Method

There are two different approaches for the calculation of evaporation with the mass transfer theory: Profile Method and Eddy Flux Method.

The profile method is based on the measurement of the vertical gradient of water vapor concentration. Although there are different versions of the method, they generally follow the approach reported by King (1966) who used the ratio of the general equations of vertical water vapor and shear stress diffusion:

$$E = PK_w \left(\frac{\partial q}{\partial z}\right) \tag{14}$$

$$T = PK_m \left(\frac{\partial u}{\partial a}\right) \tag{15}$$

to get:

$$E = - P\, U_*^2 \frac{K_w}{K_m} \frac{q_2 - q_1}{U_2 - U_1} \tag{16}$$

where:

E = the vertical flux density of water vapor (ET)

P = the density of air

K_w = the turbulent transfer coefficient

$\frac{\partial q}{\partial Z}$ = the vertical gradient of specific humidity

T = the vertical flux of horizontal momentum of shear stress

K_m = the turbulent transfer coefficient for momentum

$\frac{\partial U}{\partial z}$ = the vertical gradient of wind speed

U_* = the friction velocity

$(U_2 - U_1)$ and $q_2 - q_1)$ = the difference in wind speed and specific humidity between z_2 and z_1 above the ground

Assuming $K_w = K_m$ and an adiabatic wind profile (neutral stability) he obtained:

$$U_* = K \frac{(U_2 - U_1)}{\ell n\ (z_2/z_1)} \tag{17}$$

thus:

$$E = \frac{-P\ K^2\ (U_2 - U_1)\ (q_2 - q_1)}{[\ell n\ (z_2/z_1]^2} \tag{18}$$

The model given by Equation (18) is called the Thorthwaite-Haltzman aerodynamic equation which, besides the assumptions of adiabatic profile and $K_w = K_m$, is based on the assumption that the surface is flat and uniform and U_* is constant with height.

For diabatic conditions causing thermal stratification near the ground and change of vapor and wind profiles, several equations have been developed to model the wind profiles.

Monin and Obukhov (1954) proposed an equation on the form:

$$U = \frac{U_*}{K} \left(\ln \frac{z}{z_o} + \alpha \frac{z}{L'}\right) \qquad (19)$$

where:

α = constant with value from 0.6 to 10

Brooks (1963) suggested:

$$U = \frac{U_*}{K} \left[\ln \frac{z}{z_0} + 2\ \gamma\ \left(\frac{z}{L'}\right)^{\frac{1}{2}}\right] \qquad (20)$$

and Swinbank (1964) developed the equation:

$$U = \frac{U_*}{K} \quad \ln \left[\frac{\exp(z/L)}{EXP(z_o L)}\right. \qquad (21)$$

where

$$L' = \frac{U_*^3}{KgH/c_p \rho \theta}$$

θ = absolute potential temperature

U_* is determined from any of Equations (19) to (21) and substituted in Equation (16). Assuming $K_m = K_w$ in the equation, a value of PET can be determined.

There are contradictory reports of the use of the method and it appears to be very difficult to reliably measure surface stress from a wind profile (Barry, 1966).

The Eddy Blux Method is based on the mean and instantaneous fluctuations of velocity, temperature, and fluid properties introduced into the momentum, energy, and continuity equations. This yeilds a transfer equation containing a molecular diffusion term and a turbulent diffusion term.

From Goddard and Pruitt (1966):

$$H = C_p \ (D_h \frac{dt}{DZ} + Pw`t`) \tag{22}$$

$$LE = - L \ (D_e \frac{dq}{dz} + Pw`q`) \tag{23}$$

where:

H = sensible heat flux

LE = latent heat flux

$w`$ = vertical velocity

z = vertical distance

t = air temperature

$q`$ = absolute humidity

D_h = molecular diffusivity of heat

D_e = molecular diffusivity of water vapor

C_p = specific heat

L = latent heat of vaporization

ℓ = air density

For atmospheric conditions the molecular terms can be neglected, then:

$$H = C_p \ \ell w`t` \tag{24}$$

$$LE = L \, \ell w' q' \qquad (25)$$

The values thus obtained are then used in the energy balance Equation (10).

Combination Equations

For the determination of ET for the energy balance method and the mass transfer profile method, the surface temperature or the surface vapor pressure are required. Because of the difficulty involved in the measurements of these parameters, Penman (1948a, 1948b, 1949), used both methods to obtain an equation which only requires parameters easily available in any "routine records of weather stations." This is the combination equation.

From Dalton's Law:

$$E_o = (e_s - e_d) \, f \, (u)$$

He represented by E_a, the value of E with e_a instead of e_s so $E_a = (e_a - e_d) \, f \, (u)$ and got the ratio

$$\frac{E_a}{E_o} = (e_a - e_d)/(e_s - e_d) \qquad (26)$$

From Equation (13):

$$E_o = (R - G)/(1 + \beta)$$

and $$\beta = r \, (T_s - T_a)/(e_s - e_d)$$

the ratio $((R - G)/E_o) = 1 + \gamma(T_s - T_a)/(e_s - e_a)$

and putting $(e_s - e_a) = \Delta (T_s - T_a)$

then $$((R - G)/E_o) = 1 + \gamma [(e_s - e_a)/(e_s - e_d)]/\Delta \qquad (27)$$

and finally, combining equations (26) and (27) and eliminating vapor pressure, his equation becomes:

$$E_o = [\Delta(R - G) + \gamma E_a]/(\Delta + \gamma) \qquad (28)$$

where:

E_o = rate of evaporation, mm/day

R, e_a, e_s, T_s, T_a, G are as given in Equations (10) and (12)

Δ = the slope of the e:T curve at $T = T_a$

γ = the psychrometric constant

e_d = saturation vapor pressure at dewpoint temperature

f (u) = wind function

Ferguson (1952), reported by Deacon, Priestley, and Swinbank (1958), worked independently from Penman but following the same approach and obtained a similar formula using implicitly the Bowen's ratio. He proposed a numerical integration of the differential equation representing the energy balance to determine T_s and e_s.

Penman, on the other hand, substituted $\frac{\delta e}{\delta T}$ for $(e_s - e_a)/(T_s - T_a)$ and neglected heat storage. Although it has more approximations, Penman's method gained popularity and presently is one of the most used models in the determination of ET.

McIlroy developed another combination model to predict potential evapotranspiration (Slatyer and McIlroy, 1961; McIlroy, 1968) which was reported by Dilley and Shepherd (1972).

From the general form:

$$E = \frac{S}{S + \gamma} \left(\frac{R}{L} - \frac{G}{L}\right) + \frac{h}{L} (D - D_o) \qquad (29)$$

He neglected G (small in comparison to R for averages over a day or more). He also neglected D_o for the case of ET, when the liquid water supply to the evaporating surface is adequate for the demand, thus creating a near saturated condition in the air adjacent to the evaporating surface. So for PET:

$$PET = \frac{S}{S + \gamma} \frac{R}{L} + \frac{h}{L} D \qquad (30)$$

where:

E = actual evaporation

PET = potential ET

$\frac{D}{S+\gamma}$ = a temperature dependent weighting function

$\frac{h}{L}$ = an atmospheric conductance for the air layer from surface to reference height

D = the wet-bulb temperature depression at reference level, °C

D_o = wet-bulb temperature depression at evaporating surface, °C

$\frac{G}{L}$ = evaporation equivalent of net heat flux into the ground, mm/day

$\frac{R}{L}$ = evaporation equivalent of net radiation flux, mm/day

γ = ratio of specific heat of air to latent heat of vaporization of water

van Bavel (1966) tried to eliminate the empiricism from the Penman Equation and developed a model to calculate the instantaneous evaporation:

$$LE_o = \frac{\Delta/\gamma \ H + L \ B_v d_a}{\Delta/\gamma + 1} \tag{31}$$

where:

B_v = a transfer coefficient for water vapor, in cal cm^{-2} $min^{-1} mb^{-1}$

d_a = the saturation vapor pressure deficit of air, mb

E_o = potential evaporation rate, g cm^{-2} min^{-1}, mm hours $^{-1}$, or mm day^{-1}

H = sum of energy inputs at surface, exclusive of sensible heat transfer in air and LE ($calcm^{-2}min^{-1}$)

and:

$$Bv = \frac{\rho\ \varepsilon\ K^2}{P} \cdot \frac{U_a}{[\ell n\ Z_a/A_o]^2} \tag{32}$$

where:

ρ = density of air, g cm^{-3}

ε = the water-air molecular weight ratio

K = the Van Karman constant

P = the ambient pressure

U_a = the wind speed at height a, cm min^{-1}

A_a = the elevation above the surface, cm

Z_o = the roughness parameter, cm

Penman Equation

Being aware of the difficulty of measuring the parameters required for the solution of Equation (28), Penman (1948a, 1948b, 1949) tried to simplify the model.

For the total amount of energy available for evaporation and heating of the air, R, Penman used various empirical expressions which relate net long- and short-wave radiation to temperature, vapor pressure, cloudiness and the reflectance of the evaporation surface.

Brunt (1932, 1939) had developed the expression:

$$R = Rc\ (1 - \gamma - u) - \sigma T^4 [0.56 - 0.092(e_d)^{\frac{1}{2}}](1 - 0.9\frac{m}{10}) \tag{33}$$

where:

R_c = short-wave radiation from sun and sky in the evaporation equivalent of mm/day

r = radiation reflection coefficient (albedo) 0.05 for water surface

u = fraction of Rc used in photosynthesis

σT^4 = theoretical black-body radiation with T as temperature in °K and σ the Stefan-Boltzman constant

e_d = saturation vapor pressure at dew point temperature, in mm of mercury

$\frac{m}{10}$ = the fraction of sky covered by cloud

(1 - 0.9m/10) takes into account the effect of the sky cover on net radiation and $[0.56 - 0.092\ (e_d)^{\frac{1}{2}}]$ the effect of vapor pressure on net radiation.

From Brunt's expression, Penman neglected u (very small in realtion to the other parameters) and used the correlation:

$$\frac{R_c}{R_a} = a + b\,\frac{n}{N}$$

where:

a, b = constants

R_a = the theoretically calculatable amount of radiation that would reach the earth in the absence of the atmosphere which had been used satisfactorily in Virginia, U.S.A., and Camberra, Australia, with different values for a and b. He found the values of a = 0.18 and b = 0.55 as being the adequate values for Rothasmsted. So:

$$R_c = R_a\ (0.18 + 0.55\ \frac{n}{N}) \tag{34}$$

He also considered the influence of cloud type on the control of cloud cover on long-wave radiation and proposed to set $\frac{m}{10} = 1 - \frac{n}{N}$ so that Equation (31) became:

$$R = R_a\ (1 - \gamma)(0.18 + 0.55\ \frac{n}{N}) - \sigma T^4\ [0.56 - 0.092\ (e_d)^{\frac{1}{2}}](0.1 + 0.9\ \frac{n}{N}) \tag{35}$$

where:

R_a = the theoretically calculable amount of radiation that would reach the earth in the absence of the atmosphere

$\frac{n}{N}$ = the ratio of actual to possible hours of sunshine

For the determination of E_a, Penman obtained the wind function:

$$f\ (u) = (1 + 0.0098\ u_2) \tag{36}$$

where

U_2 = the wind speed at a height of 2 meters, in miles per day (m.p.d.)

and developed the expression:

$$E_a = 0.35\ (1 + 0.0098\ u_2)\ (e_a - e_d) \tag{37}$$

Equation (28) can then be solved with relatively readily available weather parameters, i.e., mean air temperature, mean dew point temperature, mean wind velocity, and duration of sunshine; and some information obtainable from standard souces (R_a, α, Δ, σ, γ) to yield the amount of evaporation.

The equation was tested at the Rothamsted experimental station (Penman, 1948b) on open water surface, wet bare soil surface and turf with an adequate supply of water and the last two were found to be a fraction of the water surface evaporation. Also, Penman reported a good agreement of the equation with other methods when the model was used with published data from four different places in America and Europe and also agreed closely with estimates of evaporation from the British Isles.

In order to use the equation to predict ET from turf with a plentiful water supply, Penman gave some seasonal values of $\frac{ET}{E_o}$ for southern England:

Mid-Winter (November-February)	0.6
Spring and Autumn (March-April, September-October)	0.7
Mid-Summer (May-August)	0.8
Whole Year	0.75

In later studies, Penman (1963) indicated that the equation could be used to estimate potential evapotranspiration directly using r = 0.25 (for grass) instead of 0.05 (for water). He suggested a modification of the wind function: $f(u) = (0.5 + 0.01u_2)$ for water and $f(u) = (1 + 0.01u_2)$ for grass to account for the extra roughness of grass compared to that of open water surface.

Modified Versions of the Penman Equation

The Penman Equation is one of the most popular methods for calculating ET and it has been modified by many authors to adapt it to specific conditions, or to try to improve its accuracy.

Wright and Jensen (1972) developed a new wind function:

$$f(u) = (0.75 + 0.0185 (u_2) \qquad (38)$$

for alfalfa, to account for the roughness of the surface of alfalfa in relation to that of a grass surface.

Tanner and Penton (1960) obtained another wind function using the Businger (1956) neutral profile approach. Doorenbos and Pruitt (1977) defined a wind function to be used in any climate to avoid the need for local calibration in the wind function:

$$f(u) = 0.27 (1 + 0.01 u_2) \qquad (39)$$

where:

u_2 is given in Km/day at 2 mt height

They recommended an adjustment factor to take into account the differences in weather conditions during day-night which affect the level of ET.

Effectiveness of Penman Equation

The Penman Equation has been tested more than any of the other equations used for predicting ET and most of the reports show the Penman model to be the most effective, in terms of its accuracy and adequacy.

Even van Bavel (1966) who reported a poor agreement between the Penman Equation and measured evapotranspiration on a 24-hour basis on alfalfa, found an excellent agreement for 24-hours when all empiricism was excluded form the model.

Tanner and Pelton (1960) concluded that the Penman Equation was suitable for estimating PET for periods as short as one day. However, they found the estimates to be too low for vegetation rougher than short grass, unless the wind function was modified. This was due to the fact that the wind and the vapor pressure are affected by surface roughness, so the wind function has to be modified to combine it with the vapor pressure deficit measured over the rough surface.

Jensen, Wright, and Pratt (1971) found that over long time periods, Penman's version gave the same results as van Bavel's version and both yielded satisfactory results on their irrigation scheduling computer program. Wright and Jensen (1972) in a study concerning peak water requirements determined from lysimeter measurements and a slightly modified Penman Equation, found an acceptable agreement between both methods in Southern Idaho. Wright and Jensen (1978) used several years of data from two precision weighing lysimeters and their modified version of Penman Equation to develop a crop coefficient to be used in the USDA-ARS Computerized Irrigation Scheduling Program. They concluded that the expected errors in computing PET were well within acceptable limits and the expected errors in estimating daily actual ET using the crop coefficients developed, were about the same as those in estimating PET.

The Irrigation Water Requirements Technical Committee of the American Society of Civil Engineers (Jensen, 1974), published the results of a study of the sixteen common methods of predicting ET. It was concluded that the combination methods were the most accurate with local calibration of the wind function and vapor pressure deficit terms, but even without calibration, they performed better than the other methods.

The methods were ranked considering the accuracy of seasonal estimates in percent of the measured ET for the season and the root mean square of the monthly differences.

The Penman method ranked second for inland-semi-arid to arid regime after the Jensen-Haise and van Bavel-Businger methods which were tied for first place.

Kruse et al. (1977) made a study to check ET estimates from the USDA Irrigation Scheduling Program with lysimeters measurements of ET from irrigated corn and alfalfa, in Colorado. A modified version of the Penman Equation was used, along with the crop coefficients used in the USDA-ARS Scheduling Program (Jensen et al., 1970);

they concluded that the estimates of PET given by the modified Penman Equation were in good agreement with the values measured by the lysimeters.

Doorenbos and Pruitt (1977) on the study by FAO reviewed earlier, worked on four of the best known methods to predict ET (Blaney-Criddle, Radiation Method, Penman Method and pan evaporation method). They stated that the Penman Model offered the best results, with possible error of 10% in the summer and a maximum of 20% in the winter (low evaporative conditions).

Shih et al. (1981) evaluated five different methods of estimating potential ET as they compared with the basin-wide water budget method used in the Everglades, Florida. The methods evaluated were the Penman Method, the pan evaporation method, Thornthwaite Method, Blaney-Criddle Method, and the modified Blaney-Criddle Method. They showed that the average annual difference between the Penman and water budget method was insignificant. They also calculated an absolute deviation between the water budget and the other methods evaluated which was used as a criterion for testing the applicability of the methods, the smaller absolute deviation indicating a better prediction. The Penman Equation gave the best prediction and the Thornthwaite Method gave the worst.

Limitations of the Model

The Penman Equation has been criticized by its empiricism and the assumptions upon which it was developed. van Bavel (1966) expressed his concern in the empiricism in the radiation part of the formula and in the wind function, and in the use of average values for temperature, humidity, and wind speed (he believed instantaneous values were required).

Deacon, Priestley, and Swinbank (1958) warned that for relatively short periods, the heat storage (neglected by Penman) may have to be considered and that the approximation Penman used to eliminate the surface temperature and vapor pressure through substitution of:

$$\left(\frac{e}{T}\right)_a \text{ for } \frac{e_s - e_a}{T_s - T_a}$$

could seriously underestimate evaporation, mainly in the case of a strongly evaporating vegetation cover. They also concluded that the formula to estimate incident solar energy in terms of cloud cover does not discriminate as to times of cloud occurrence.

Tanner and Pelton (1960) remarked that all the work in the Penman Equation was related to short grass and that because most of the agricultural crops were taller and aerodynamically rougher than grass, data were needed for rougher surfaces.

However, as Penman (1956) pointed out, "any meteorological physicist will find easy to criticize the formulae for their sweeping simplifications of complex meteorological phenomena. Soil physicists, however, might support a claim that crude as the method is, it can give estimates of changes in soil water content as accurate as any simple field method at our disposal."

CHAPTER III

PROCEDURE

A sensitivity analysis of the Penman Equation was performed. The most used techniques for performing sensitivity analysis are the log derivative method and the probable error analysis, both methods based on partial derivatives. Another technique consists in varying the values of a variable to compare the changes in the variables and the amount of change in the equation introduced by the changes in the variables. This technique is very useful to analyze equations whose derivatives are difficult to evaluate (Fritschen and Gay, 1979). Such is the case with the Penman Equation and this is the technique followed in this research.

The approach was the following:

A computer program for the Penman Equation was developed. The equation used was basically the one developed by Penman, but modified to accept the inputs in SI units, as reported by Schwab (1981):

$$PET = \frac{\Delta(Rn - G) + \gamma\ E_a}{\Delta + \gamma}$$

where:

PET = potential evaportranspiration, cal/cm^2 day

Δ = slope of the saturated vapor vs. temperature curve (mb/°C)

γ = psychrometric constant, mb/°C

R_n = net radiation, cal/cm^2 day

G = soil heat flux toward the surface, generally assumed to be 0, cal/cm^2 day

E_a = $15.36\ (1 + 0.0062\ u_2)\ (e_a - e_d)$

e_a = saturation vapor pressure at mean air temperature, mb

e_d = saturation vapor pressure at mean dewpoint temperature, mb

u_2 = wind speed at 2 net, Km/day

The net radiation equation proposed by Penman (Equation [35]) is used:

$$R_n = R_a\ (1 - r)(0.18 + 0.55\ \frac{n}{N}) - \sigma\ T_a^4\ (0.56 - 0.092e_d^{\frac{1}{2}})$$
$$(0.1 + 0.9\ \frac{n}{N})$$

where:

R_a = extraterrestrial radiation, cal/cm^2 day

r = albedo

$\frac{n}{N}$ = ratio of actual to possible hours of sunshine in percent

σ = Stefan-Boltzman constant, $11.71x10^{-8}$ cal/cm^2 day

T_a = mean daily temperature, °K

The saturation vapor pressures are calculated using the expression by Bosen (1960):

$$e_s = 33.8639\ [(0.00738t + 0.8072)^2 - 0.000019$$
$$|1.8t + 48| + 0.0013116] \qquad (40)$$

where the vapor pressure is in milibars and t the mean daily temperature or the mean dew point temperature is in degrees Celsius. The delta function (slope of the vapor pressure-temperature curve) is obtained from the first derivative of Equation (40).

$$\Delta = 2.00\ (0.00738T + 0.8072)^7 - 0.0016 \qquad (41)$$

For the psychrometric constant, the expression proposed by Brunt (1952) was used:

$$\gamma = \frac{0.386P}{L} \qquad (42)$$

where:

P = average barometric pressure, mb

L = latent heat of vaporization, cal/g

P is assumed to be constant for a given location and can be calculated using a straight line approximation of the U.S. standard atmosphere (Jensen, 1980):

$$P = 1013 - 0.1055E \qquad (43)$$

where:

E = sea level elevantion, m.

L is calculated by the following expression by Brunt, 1952:

$$L = 595 - 0.51T \tag{44}$$

where:

T is temperature in °C.

The following step was to select average values for the parameters, normal in the humid area of the North Central United States. Three situations were chosen: low, average, and high values for the parameters, which would give low, average, and high PET values, respectively.

The parameters in the equation were then varied independently from minus 20% of the given values to plus 20% of the given values. R_a was held constant at 937 cal/cm^2 day for all three situations because it does not have much lower or higher values in the cases of interest; albedo was held at 0.22 inasmuch as this is the value assumed appropriate for grass.

The variable analyzed were maximum temperature, minimum temperature, wind speed, percent of sunshine, albedo, extraterrestrial radiation, and mean dew point temperature.

The parameters considered for modifications were those whose values are most difficult to obtain without having access to a first-order weather station: wind speed, percent of sunshine and mean dew point temperature.

Once the decision had been made as to how to modify the use of a particular parameter, the accuracy of prediction was tested using the values obtained from the Local Climatological Data sheets (LCDs) for the Lansing Airport. PET as predicted by a modified parameter was correlated to PET as predicted by the original data and the same was done with the combination of the modifications. Values for June, July, and August from 1978 to 1981 were used. Three months were selected because they are the critical months for irrigation practices in the area.

To evaluate the effectiveness of the simplifications introduced in the Penman Equation, the equation was used in the summer of 1981 to calculate daily potential evapotranspiration for June, July, and August, and after adjusting potential evapotranspiration with the crop coefficient, the actual evapotranspiration values were correlated to the evapotranspiration values obtained from a water balance, with the soil moisture determined by two methods: gravimetric and neutron scattering technique.

The measurements were made at the Crop Science Research Center, Michigan State University, in a sandy loam soil with a bulk density of 1.50 g/cm^3 in the first 30 cm, 1.69 g/cm^3 from 30 to 61 cm (there is a clay layer in the profile) and 1.58 g/cm^3 from 61 to 91 cm.

The gravimetric measurements were made by the author in irrigated and nonirrigated corn. The neutron measurements were made by James Jenkens, Crop and Soil Science M.S. candidate in irrigated potato, as part of an experiment, to evaluate the effectiveness of the method for his thesis.

The potato and the irrigated corn were irrigated by sprinkler and the precipitation was measured by a pluviometer located in the research center. The crop coefficient for each day was determined from a crop coefficient curve for the season for each crop as was proposed by Doorenbos and Pruitt (1977).

CHAPTER IV

RESULTS AND DISCUSSION

Analysis of Sensitivity

Table 1 presents the values used to perform the sensitivity analysis, for low, average, and high evapotranspiration conditions; Figures 1 through 7 persent the results of the analysis. The graphs illustrate how ET changes when the specific parameter of each graph is varied, with the other parameters held constant; the three situations (low, average, and high ET) are presented in each figure with the values in percent.

As it can be seen from the graphs, the extraterrestrial radiation is the most influential parameter in the Penman Equation. It has almost the same influence at each of the three levels, affecting slightly more at the low values (Figure 1). The equation sensitivity to maximum temperature is about half that of extraterrestrial radiation and has about the same influence at average and high ET values and slightly less at low values (Figure 2). The percent of sunshine has almost the same influence as temperature (a little less) at average and high levels, but its influence decreases more at low level, (Figure 3). The albedo is as influential as percent of sunshine, but its effects are more constant at the different values and it varies inversely (negative slope) (Figure 4).

TABLE 1. Conditions assumed for the examination of the sensitivity of Penman Equation to its different parameters

Parameters	Condition		
	Low ET[1]	Average ET[2]	High ET[3]
Albedo	0.22	0.22	0.22
Ext. Rad. (R_a) cal/cm^2 day	937.0	937.0	937.0
T_{max} °C	21.7	29.4	32.8
T_{min} °C	6.7	15.6	23.3
$T_{dew\ point}$ °C	6.7	16.7	22.2
Percent of sunshine	67.0	85.0	94.0
Wind @ 6.09m (Km/day)	120.0	160.0	210.0

[1]Data for Lansing, July 5, 1972.

[2]Data for Lansing, July 17, 1972.

[3]Data for Lansing, July 20, 1972.

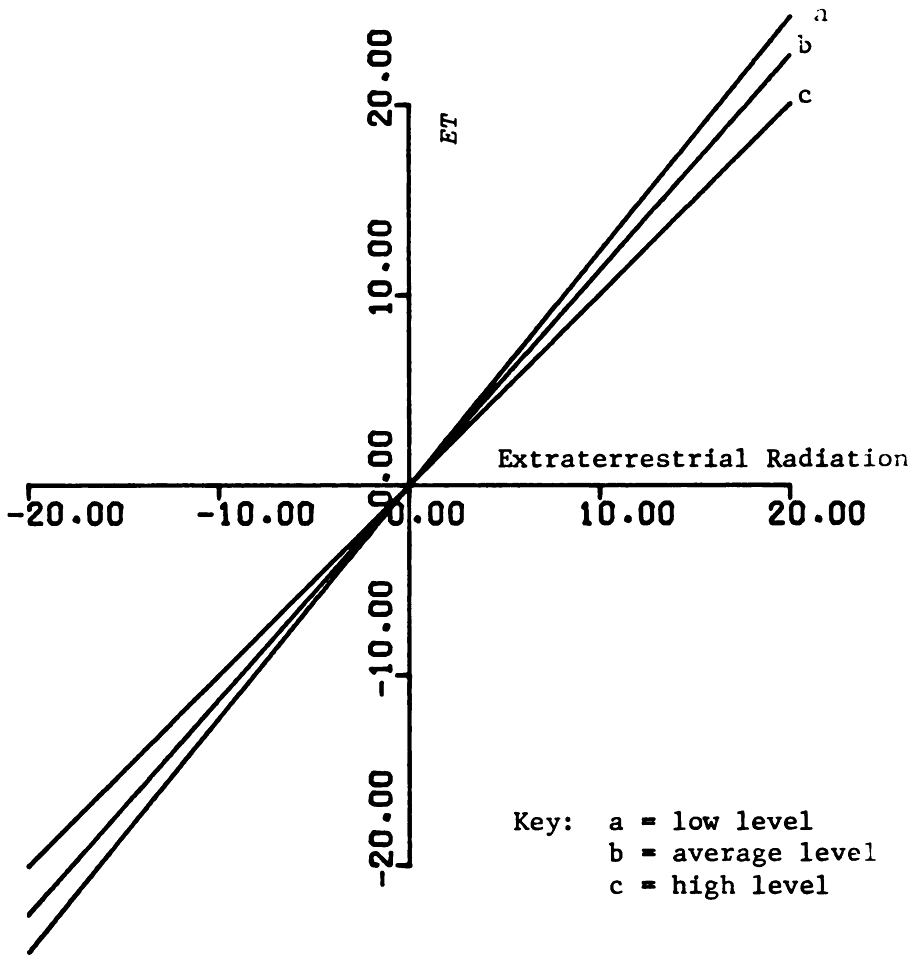


Figure 1. Sensitivity of the Penman Equation to extraterrestrial radiation; expressed in percent change.

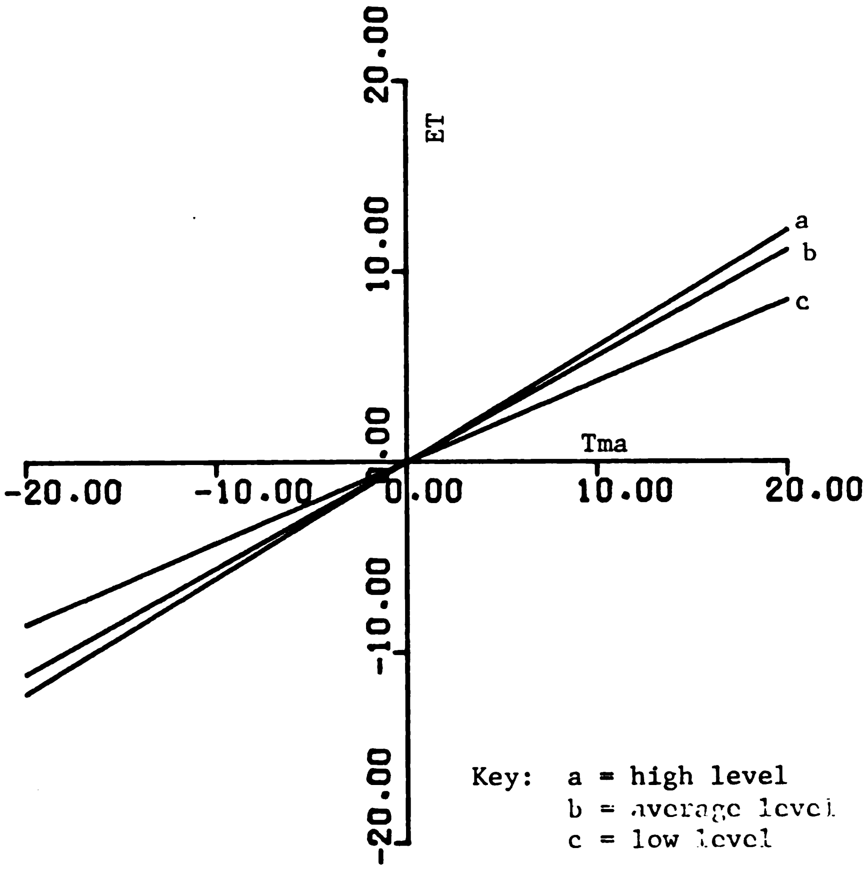


Figure 2. Sensitivity of the Penman Equation to maximum temperature, expressed in percent change.

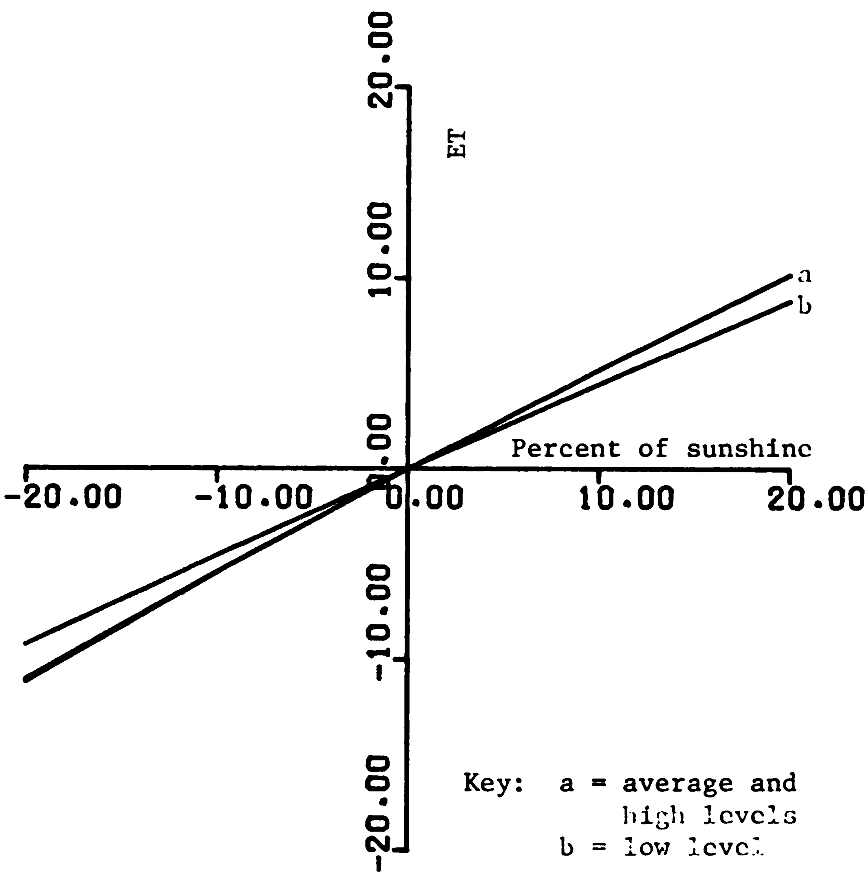


Figure 3. Sensitivity of the Penman Equation to percent of sunshine, expressed in percent change.

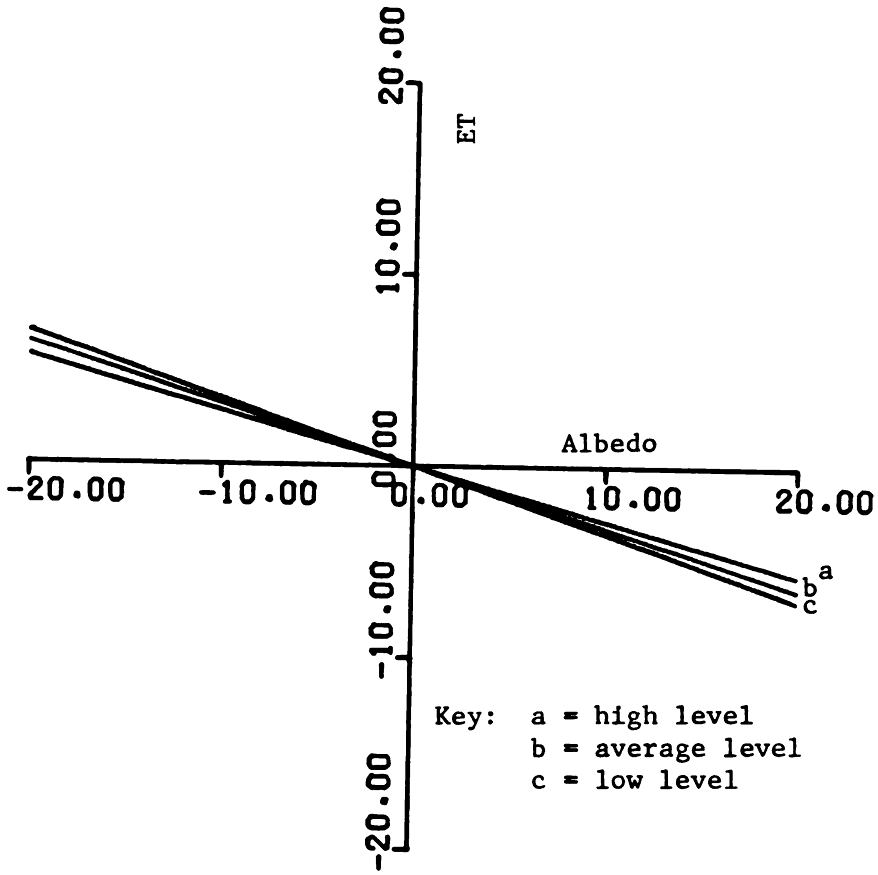


Figure 4. Sensitivity of the Penman Equation to Albedo, expressed in percent change.

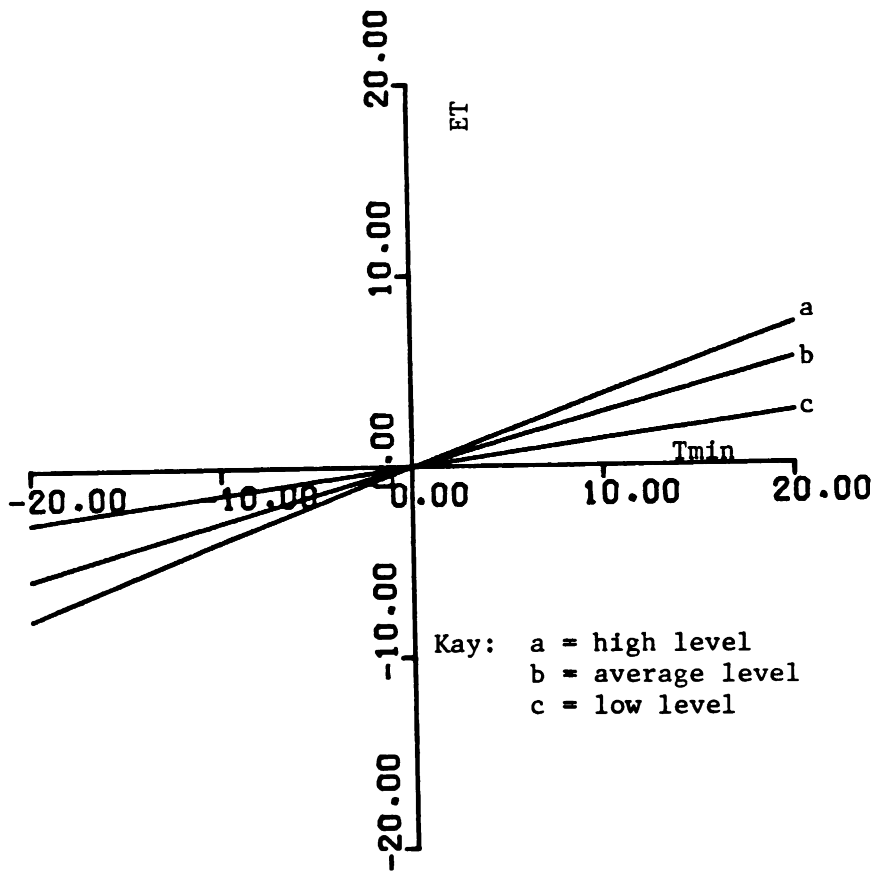


Figure 5. Sensitivity of the Penman Equation to minimum temperature, expressed in percent change.

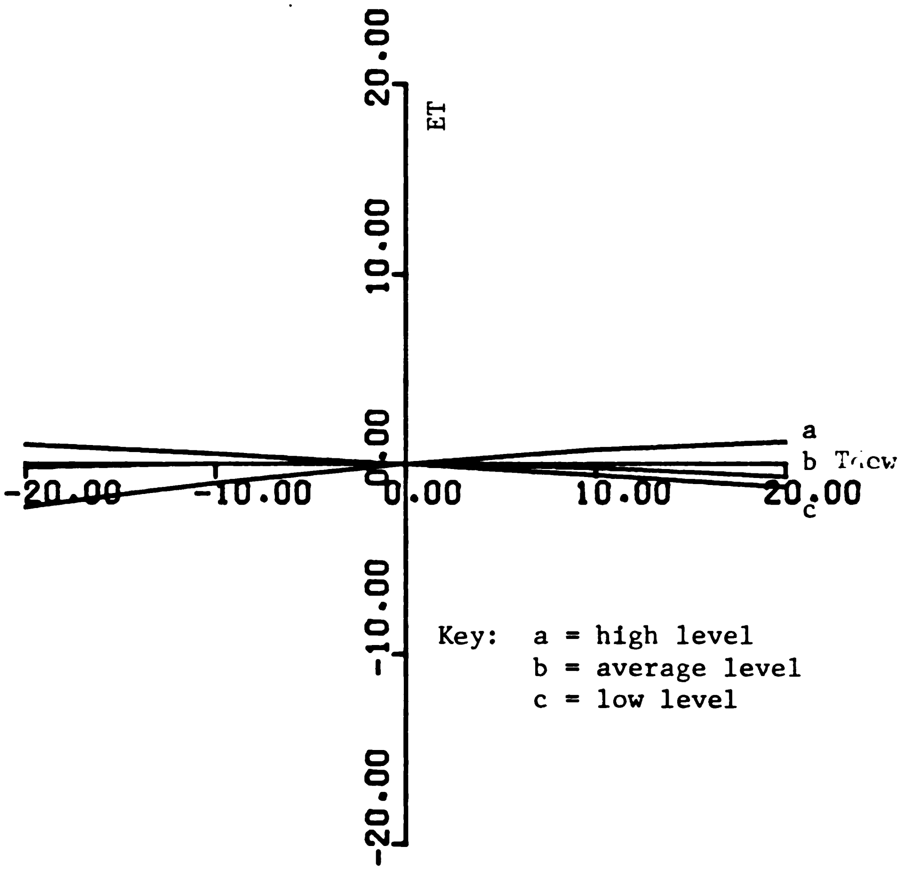


Figure 6. Sensitivity of the Penman Equation to dew point temperature, expressed in percent change.

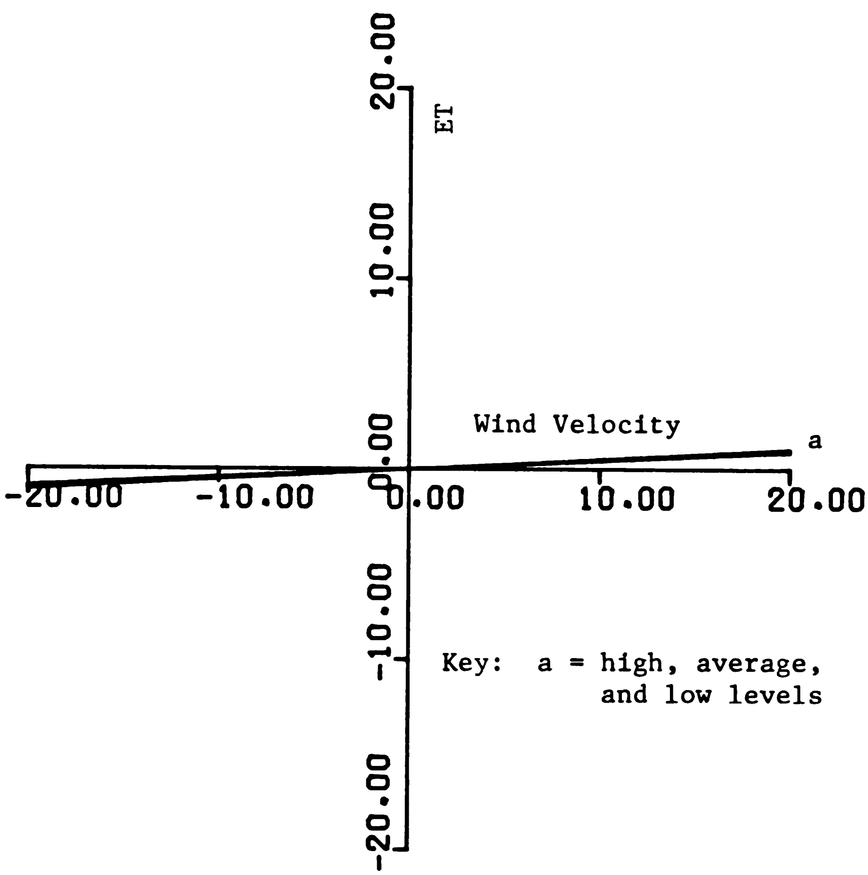


Figure 7. Sensitivity of the Penman Equation to wind velocity, expressed in percent change.

Minimum temperature has a little less effect than albedo and it varies more in the three levels than the rest of the parameters, having less effect at low level of ET and more effect at high level (Figure 5). The dew point temperature effect in the Penman Equation is very little as it is shown in Figure 6, and it differs from the other parameter by the fact that its slope is negative at low and average values and positive at high levels of ET.

The wind is the less influential value in the Penman Equation and in relation to most of the terms it could be considered insignificant. It has about the same effect at the three levels of ET.

Simplifications

The influence of wind in the calculation of ET is minimal, expecially in the humid North Central Region. Wind has two different effects on the rate of transpiration. First, wind over a crop canopy creates shear; the turbulence produced by the shear induces a vertical transport of vapor from the canopy to the atmospheric boundary layer. Most probably, any wind, regardless of its speed, will cause enough vertical transfer of vapor to prevent the microclimate within the canopy from becoming saturated with water vapor.

On the other hand, the wind has a more direct effect on evapotranspiration in the boundary layer thickness of the air around an individual leaf. The transfer of water vapor within the boundary layer is by molecular diffusion and the thinner the layer, the shorter the period of molecular diffusion. The determination of the exact thickness over a point on any specific leaf would be very difficult because it requires such data as orientation and magnitude of the wind velocity vector with regard to the leaf. As the leaf orientation is broadly more or less random and with the presence of turbulence in the canopy, the wind velocity vector will also be random, the effects of the boundary layer thickness must average out. These two facts explain the little effect wind has in the determination of ET.

From Figure 7 it is evident that only gross values of wind speed are necesary for the determination of ET by the Penman Equation. A wind speed change of -20% of low value to +20% of high value alters ET by only about 2%, a value well within the range of error acceptable in irrigation measurements. It is suggested that the irrigator select three levels of wind speed based on data from the closest weather station (low, average, and high) and that the irrigator use for the period in question a low, average, or high value, based on his individual judgment. For the Lansing, Michigan, areas values of 10 km/day as a low value, 35 Km/day as an average value, and 85 Km/day as a high value (wind speed at 2 m), appear to be usable values.

These values were used for the calculation of ET for the summer months of June, July, and August for the period 1978 to 1981 inclusive, and correlated to ET calculated with the exact values of wind speed for the same period. The wind speed data used to correlate the approximations were taken at 6.096 m (20 ft): so, the expression reported by Schwab (1981) was used:

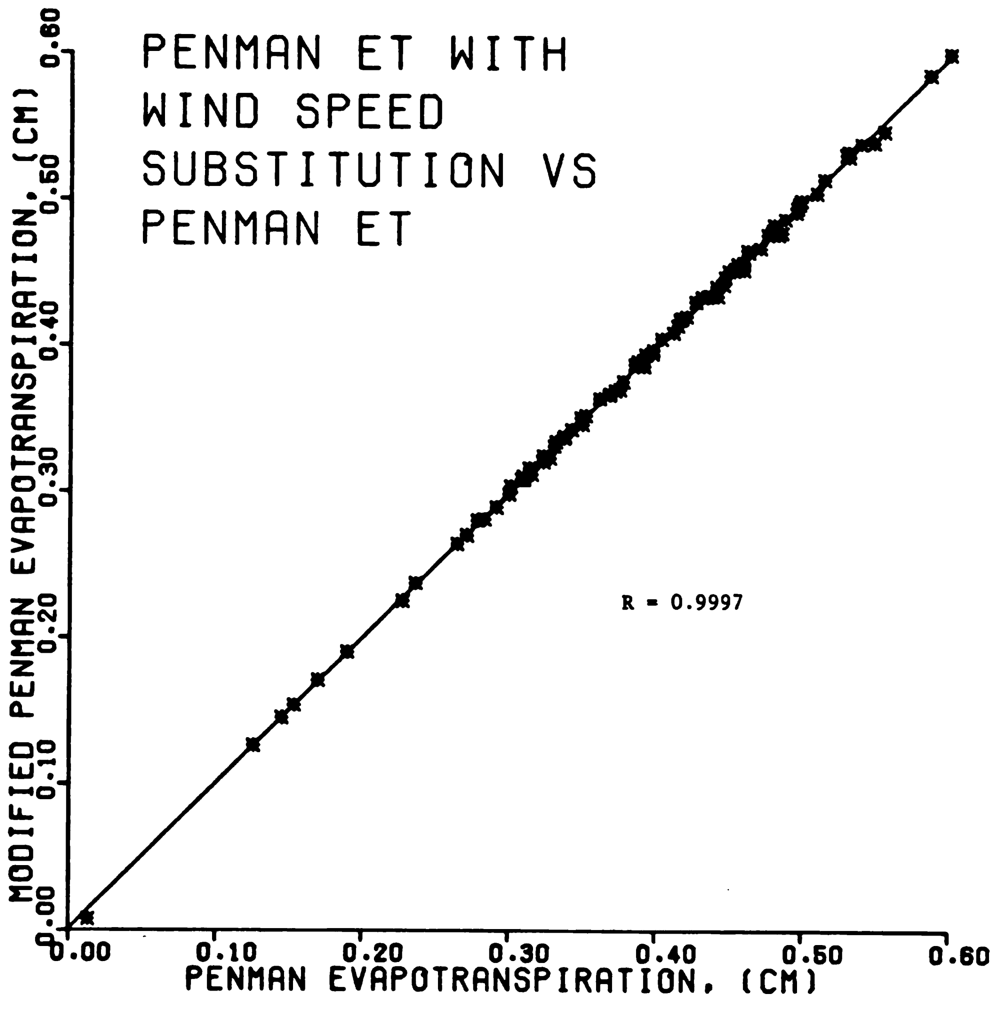


Figure 8. Regression of ET calculated by the Penman Equation and ET calculated by the Penman Equation with the wind velocity approximations.

$$u_2 = u_1 \ a \frac{\log 2}{\log h} \tag{45}$$

where:

u_2 = wind speed at 2 m

u_1 = measured wind speed

h = height at which the measurement was made

Both ET were calculated using weather data from the Lansing Airport and the correlation coefficient obtained was .9997 with a slope of 0.996 for the regression curve (see Figure 8). That shows that little gain was obtained with the use of wind velocities more accurate than the suggested approximations.

It was also shown how little influence the dew point temperature has in the Penman Equation (variation from -20% of low value to +20% of high value in dew point temperature causes only a variation of ± 2.3% in calculated ET); so, the determination of dew point temperature does not require a great deal of accuracy for its use in the Penman Equation. Some authors (Gentilli, 1955; Pachop, Morton, and Cornia, 1973) have found a close relationship between dew point and minimum temperature, mainly in the humid climate. Figure 9 is a regression of dew point temperature against minimum temperature for the summer months of June, July, and August from 1978 to 1981 inclusive. The correlation coefficient was 0.90 and the slope of the regression line was 0.94.

Because of the difficulty involved in the determination of dew point temperature and the other humidity variables and the

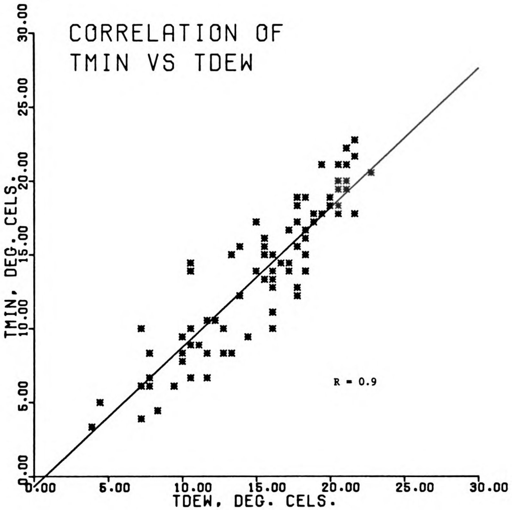


Figure 9. Regression of dew point temperature and minimum temperature for Lansing, Michigan, daily values.

little influence of dew point temperature in the equation, along with the closeness of fit of the variables, this author believes the substitution of minimum temperature for dew point temperature is a valid and sound approach toward the estimation of one of the most difficult to obtain weather data mong the parameters used in the Penman Equation.

The cause of the high correlation between minimum and dew point temperatures, anywhere there is dew formation at night and the immediate area is not affected by air flowing over large bodies of water is related to the lack of moisture entering an air mass which must travel long distance over land and the large quantity of latent energy surrendered by condensing dew. Because the latent heat of vaporization is so large (590 cal/g), a great deal of energy is released into the atmosphere in the process of dew formation. This energy counters the energy lost by radiation, hence the minimum temperature at night remains reasonably near the dew point temperature.

During the daytime, solar radiation warms the air, but the saturation vapor pressure is determined by the quantity of water vapor present. Since there is little additional humidity available to air moving over a land mass, there will be little change in the saturation vapor presure and therefore the dew point temperature is in general constant during the day.

This will not be true where there is not dew formation or when there is change in the air mass. If the latter is the case, a recent minimum temperature which occurred under the influence of the air mass present when most of the ET occurred should be used. For example, if a cold front enters an area early in the morning, the minimum temperature from the following evening should be used since the saturated vapor pressure of the air accompanying the cold front air mass would differ significantly from that of the air present before the cold air arrived.

Figure 10 represents the results of the correlation between Et calculated using minimum temperature to determine e_d and ET calculated using dew point temperature to calculate e_d. The correlation coefficient was 0.997 and the slope of the regression line was 0.945, indicating how little accuracy was lost with the substitution. Figure 11 is a graph of the correlation of ET calculated using the wind simplification along with the minimum temperature-dew point temperature substitution vs ET calculated with these parameters unchanged. The correlation coefficient was 0.997 and the slope of the line was 0.942, which is an excellent agreement.

The most difficult parameter to obtain a simplification for in the Penman Model is the percent of sunshine. Figure 3 indicates the importance of accurate assessment of this parameter to reliable ET estimates. Unfortunately, dependable data are gathered only at well-equipped weather stations and normally are not broadcast or published, except in LCDs. It is possible to estimate, in a rough manner, the degree of sunshine on any given day, however. As a first approximation, we can adopt the approach used for wind speed and proceed from this point. Long term records for Lansing, Michigan,

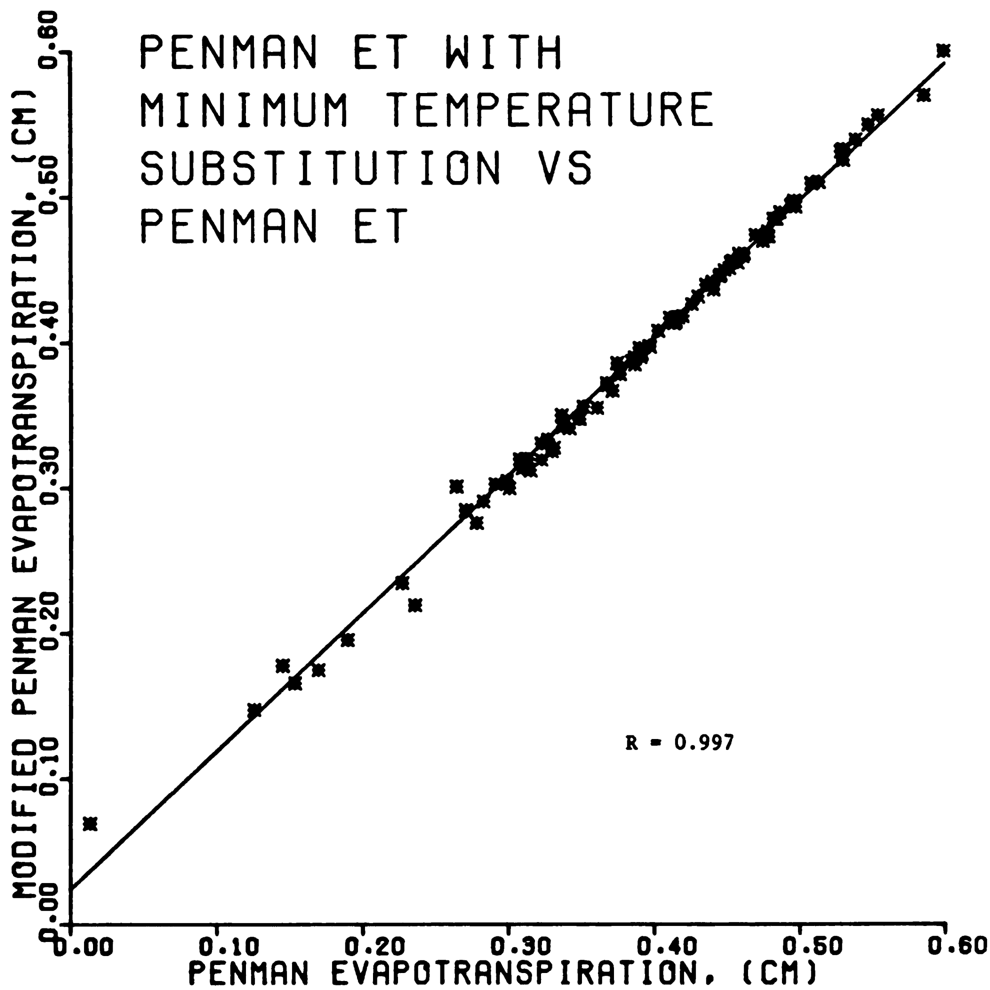


Figure 10. Regression of ET calculated by the Penman Equation and ET calculated by the Penman Equation with the minimum temperature substitution.

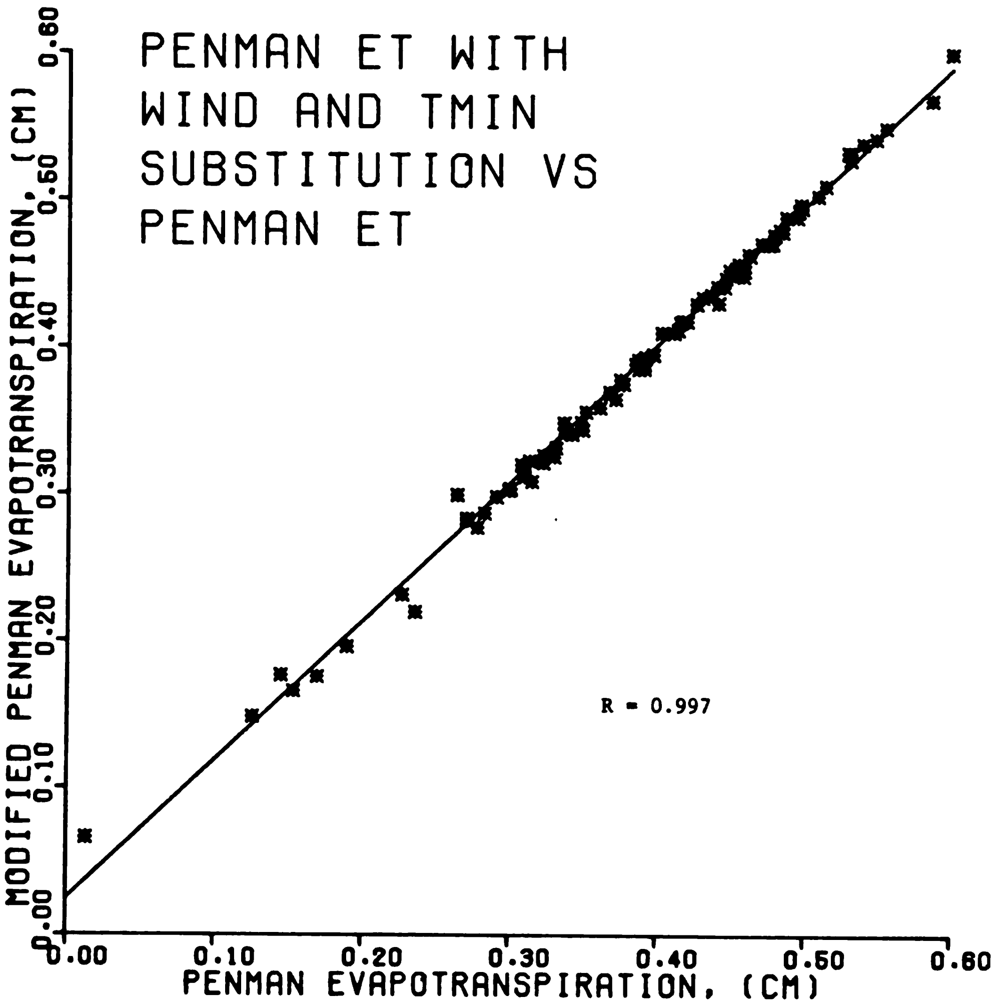


Figure 11. Regression of ET calculated by the Penman Equation and ET calculated with the wind approximations and the minimum temperature substitution.

indicate the average percent of sunshine for June as 75% with July and August slightly less at 67 and 58%. Analysis of the four years of Lansing data from 1978 to 1981 yielded standard deviations that are probably reasonable inasmush as the means obtained for the period agreed reasonably well with the long-term means. Based on the above analysis, it was decided to use values as shown in Table 2 to calculate ET. Figure 12 gives the results of the correlation of ET

TABLE 2. Simplified values of percent of sunshine based on monthly average values and standard deviations.

	Month		
	June	July	August
Low values (m - s.d.)	41%	36%	35%
Average (m)	67%	64%	63%
High values (m + s.d.)	92%	92%	92%

Note: m = mean

s.d. = standard deviation

using the percent of sunshine substitution as given in Table 2 and ET using the actual value. The agreement is reasonable with a correlation coefficient of 0.949 and a slope of 0.810. This approach was adopted as a reasonable first approximation and a final set of data were obtained using all simplifications proposed above. The results are presented in Figure 13 and yielded a correlation of 0.945 and a slope of 0.763.

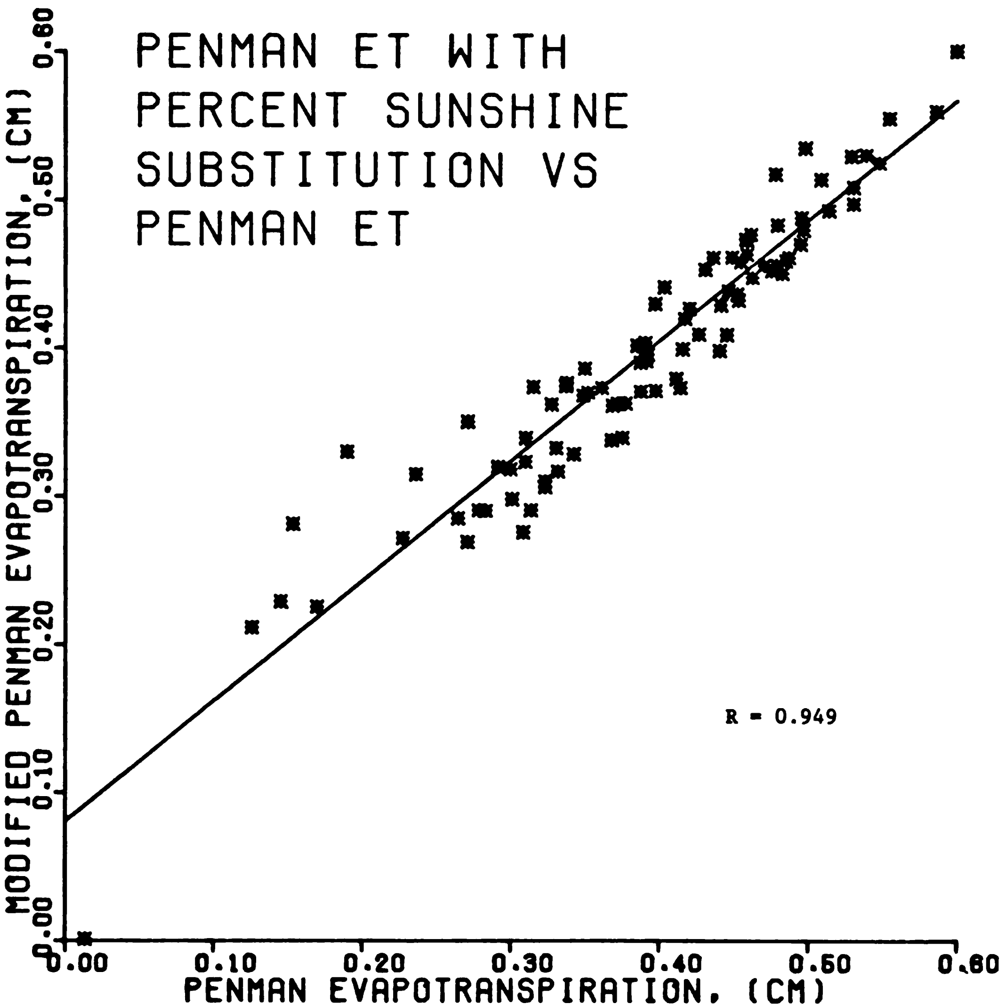


Figure 12. Regression of ET calculated with the Penman Equation and ET calculated with the percent of sunshine approximations.

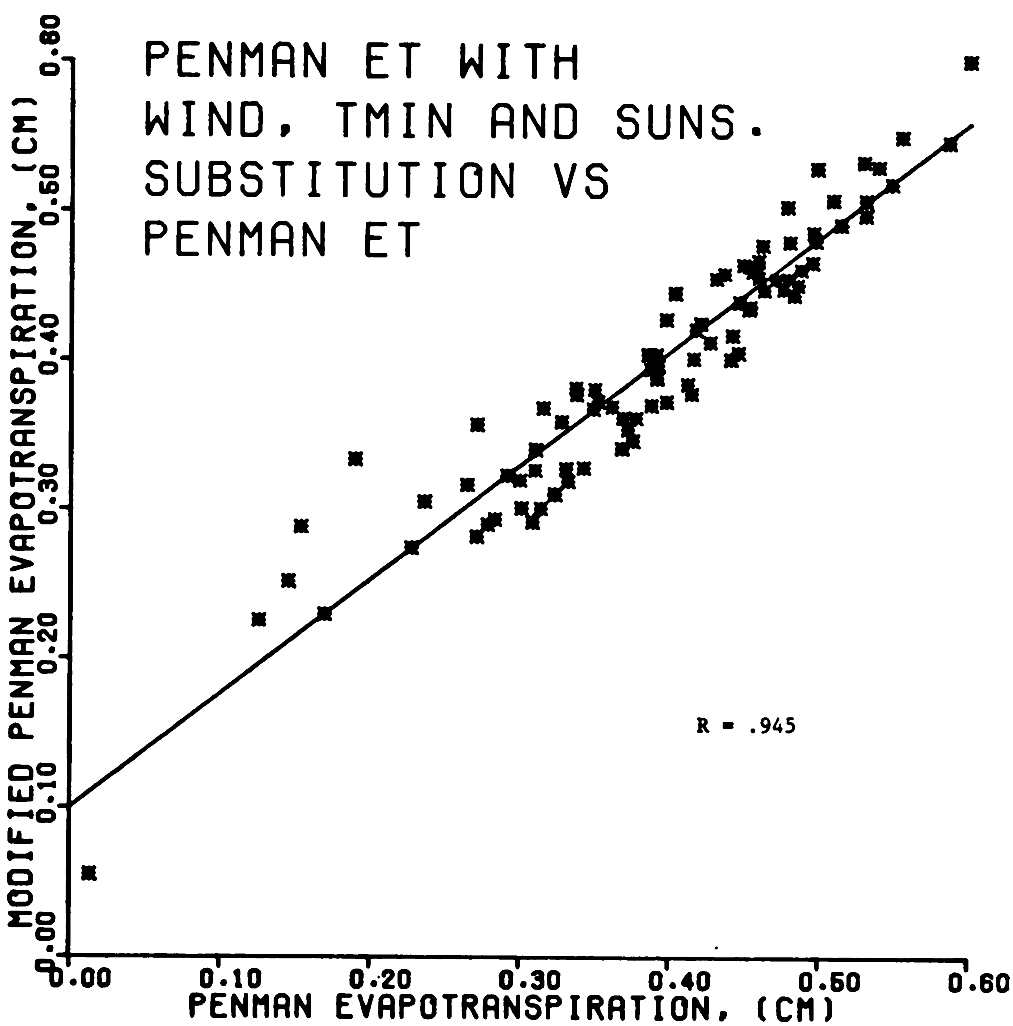


Figure 13. Regression of ET calculated with the Penman Equation and ET calculated with the wind and percent of sunshine approximations and the minimum temperature substitution.

The extraterrestrial solar radiation required for the Penman approach presents no problem if a programmable calculator or hand held calculator is used. In the current analysis, R_a was calculated for Lansing, Michigan, using the expression:

$$R_a = 660 - 342 \cos (0.0172d - 2.78) \qquad (46)$$

where:

d = day of the year measured from January 1

Appropriate values can be determined for any latitude.

Evaluation of the Simplified Penman Equation

Along with the water balance made in the corn and potato fields, estimations of some of the parameters used in the Penman Equation were made. The percent of sunshine and the wind velocity were estimated daily. The former was classified as high, average, adn low, depending on the cloud conditions. The wind was also termed as high, average, and low. After giving to those classifications the values assigned in the simplifications (Tables 1 and 2) and using minimum temperature to estimate e, the daily potential evapotranspiration was calculated and adjusted to evapotranspiration with the crop coefficient.

The crop coefficient curves for corn and potato for the season was developed following the FAO method (see Figures 14 and 15 and Appendix A). The emergence day for corn was June 1 and for potato was May 25; the average irrigation or precipitation period was a

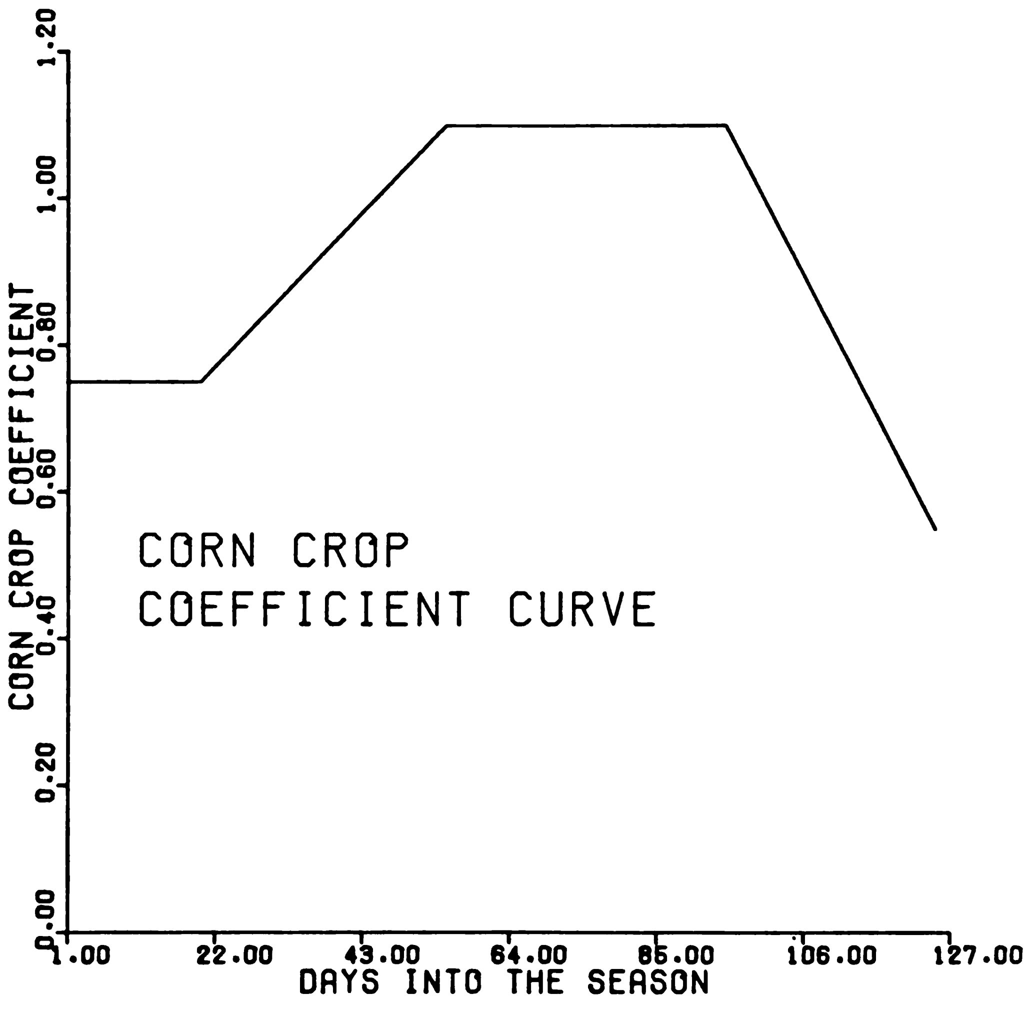


Figure 14. Crop coefficient curve for corn.

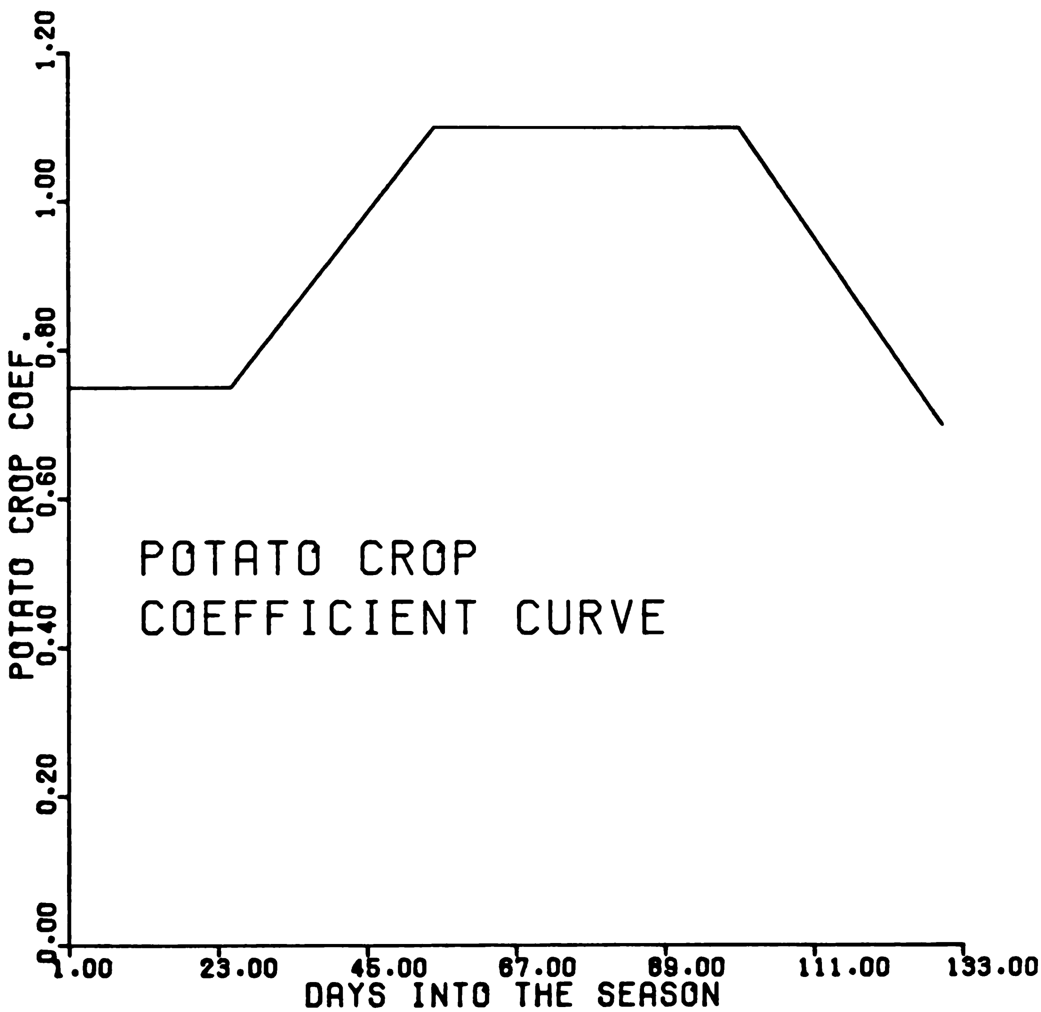


Figure 15. Crop coefficient curve for potato.

little less than 4 days for both crops in the initial stage and the level of PET was 4 mm/day. The crop coefficient curves were drawn from the crop coefficient values at different stages given in Table 3.

TABLE 3. Crop coefficient for the different stages of the crops.

	Corn		Potato	
	Kc	Duration (days)	Kc	Duration (days)
Initial stage	0.75	20	0.75	25
Crop development	Variable	35	Variable	30
Mid-season	1.1	40	1.1	45
Late stage	0.55	30	0.70	30

The values came from Figure 6 and Table 21 of Doorenbos and Pruit (1977).

The daily values of ET for each crop were classified by periods, each period corresponding to the interval between field measurement of moisture content in each plot. The period, as well as the evapotranspiration measured by the water balance (ETM) and by the modified Penman Equation (ETP) are given in Tables 4 and 5.

For the water balance method, the following model was used (Bowman and King, 1965):

TABLE 4. Table of ETM and ETP for corn for the different periods

Period	ETM (cm)	ETP (cm)
June 26 - July 1	2.78	2.04
July 2 - July 9	3.57	3.20
July 10 - July 16	4.65	3.11
July 17 - July 23	2.96	2.90
July 24 - July 30	3.25	2.80
July 31 - August 6	3.37	2.85
TOTAL	20.58	16.90

TABLE 5. Table of ETM and ETP for potato for the different periods

	ETM (cm)	ETP (cm)
June 1 - July 6	11.25	11.25
July 7 - July 12	3.87	3.40
July 13 - July 19	3.30	3.16
July 20 - July 26	2.82	2.85
July 27 - August 2	4.20	2.83
August 3 - August 9	2.68	2.74
August 10 - August 16	1.79	2.65
August 17 - August 22	2.65	2.38
August 23 - August 30	1.02	2.89
TOTAL	33.58	24.15

$$\Delta M_{av} = P_{av} + C_{av} - G_{av} + \Delta R_{av} - ET_{av} \quad (47)$$

where:

ΔM_{av} = net change in soil moisture in an arbitrary depth 0.76 M for both crops in this case) and for the specified period averaged over the plot

P_{av} = precipitation during the period

C_{av} = capillary rise from below the 0.76 m during the period

G_{av} = percolation of water to below the 0.76 m during the period

ΔR_{av} = net runoff in the plot during the period

ET_{av} = evapotranspiration during the period

In this case C_{av}, G_{av}, and R_{av} were assumed to be zero during the period.

The values of ETM presented in Table 4 are the average of irrigated and nonirrigated plots. For each plot, two sample locations were chosen for the gravimetric moisture content measurements and the moisture difference for each period calculated.

The correlation of the values given in Table 4 is presented in Figure 16. The correlation coefficient was 0.65, the intercept was 0.5 cm and the slope 0.51. Obviously, the gravimetric method gave higher values than the modified Penman Equation and the correlation was low in relation to other values found in some of the previous research. This was probably due to the fact that no data were

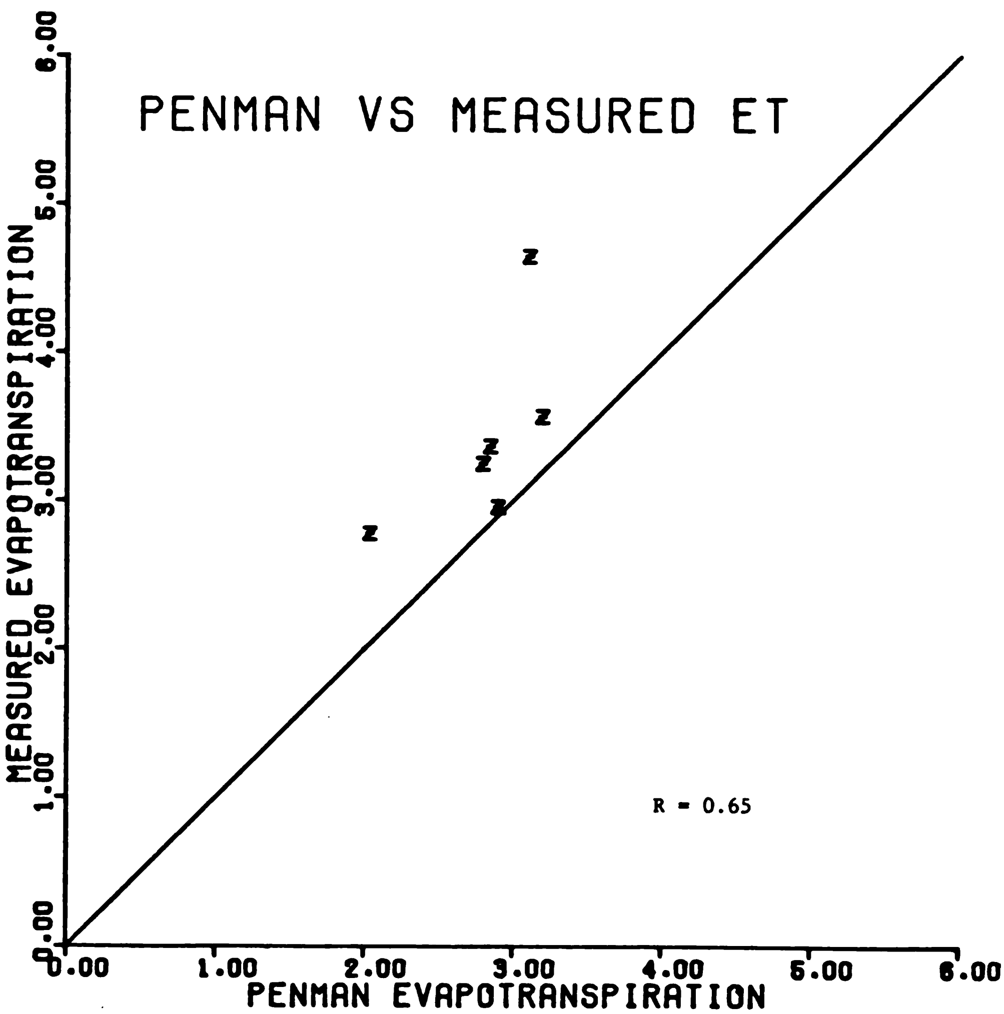


Figure 16. Regression of ETM for corn and ETP for the different periods with a 45° line to show what 1-1 correspondence would be.

taken about the uniformity of application in the irrigated plot. Other factors may have been soil variability, faulty soil moisture monitoring equipment and/or inaccurate measurement of irrigation (the author did not have control of the irrigation; instead, he was supplied with the information about the amounts applied).

In the case of the potatoes, three sets of measurement were made using a Troxler Neutron Moisture Meter, Model 3222. The moisture content in each set was obtained and the three values averaged. Figure 17 represents a correlation of these values with the modified Penman Equation results. A very good correlation coefficient was found (0.954) with an intercept of -0.11 cm and a slope of 1.012 for the nine periods. The last period (August 23-30) was the only one when the values did not agree substantially. This may be explained by the fact that 1.27 cm was applied on the 24th and 1.27 cm on the 26th and after the irrigation there was a precipitation of 0.79 cm on the 26th, 0.84 cm on the 27th, 1.37 cm on the 28th, 1.12 cm on the 29th, and 0.61 cm on the 30th. These conditions created an excess of water which may have caused runoff and/or percolation to below the profile considered, thus causing an underestimation of ETM. Neglecting that period results in a correlation coefficient of 0.978, an intercept of 0.22, and a slope of 0.983. The sum of ETM and ETP for the season was almost the same, being notable the fact that for the larger period (about 35 days) both values were equal.

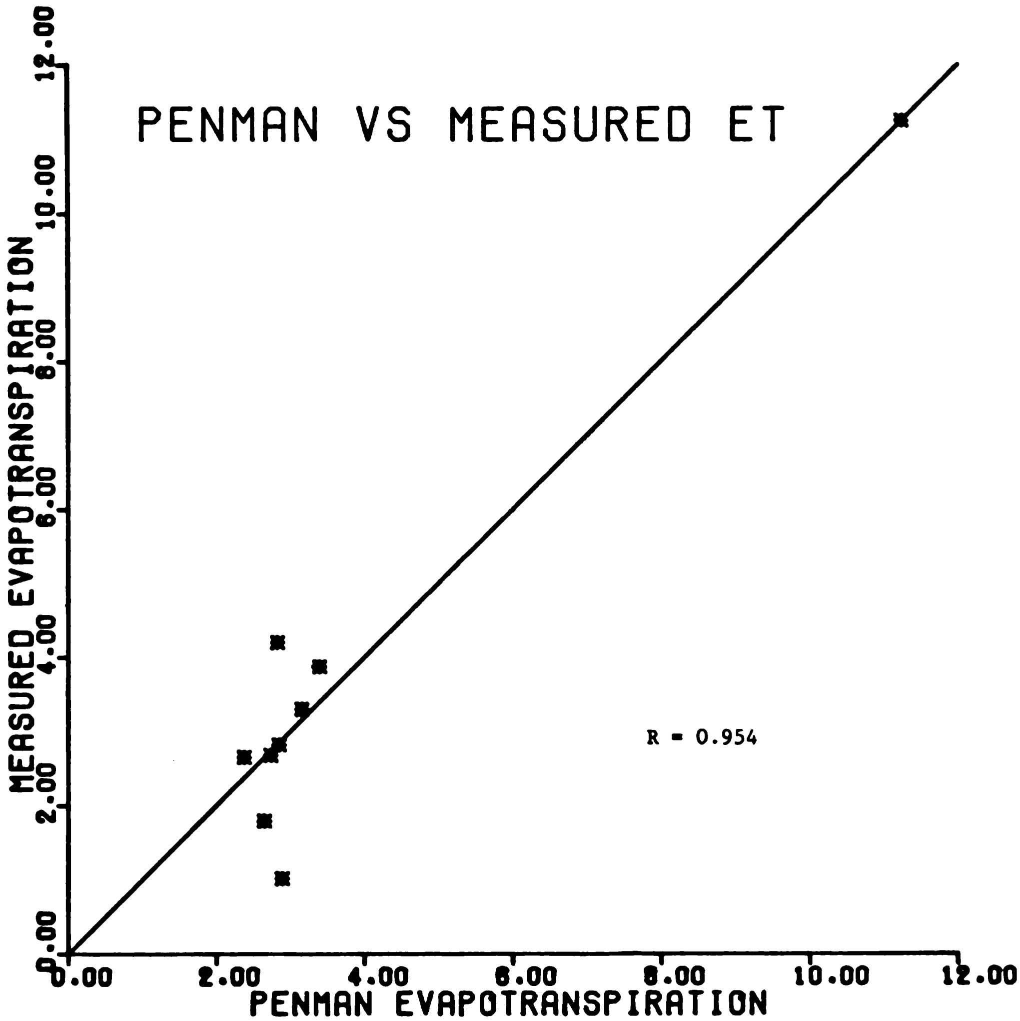


Figure 17. Regression of ETM for potato and ETP, for the different periods with a 45° line.

CHAPTER V

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

The Penman Equation sensitivity to wind velocity and dew point temperature is very low, hence great accuracy is not required in the determination of these parameters for the Penman Equation. The parameter with greater influence in the equation is the extraterrestrial radiation, with maximum temperature and percent of sunshine having more influence than the rest. Extraterrestrial radiation can be easily obtained from tables or from a computational formula adapted to a hand-held programmable calculator.

The use of generalized wind velocity and the substitution of dew point temperature by minimum temperature of the night before, does not alter significantly the results yielded by the Penman Equation in the humid climate, as evidenced by the very high correlation obtained with the introduction of these two simplifications and the original equation, with more than 360 samples.

Although it has a great influence on the Penman Equation, because of the difficulty of obtaining the information except from published LCDs, approximations to the percent of sunshine were introduced.

It is the belief of the author that the loss in accuracy caused by the introduction of the simplifications, are compensated by the availability of the model to any individual possessing a hand-held programmable calculator and a maximum-minimum temperature thermometer. Despite the simplifications, the model still can estimate the original equation closely enough.

The relatively low correlation coefficient of the modified Penman Equation against the gravimetric method may be explained by external factors, in addition to the inaccuracies inherent to the method. The good agreement between the simplified equation and the neutron scattering technique is very promising. However, some errors always present in this method and in both cases the few number of data as well as the use of the FAO method to determine the crop coefficient (the validity of the method is unknown for this area) make very difficult a definitive conclusion in regard to the effectiveness of the Penman Equation (and likewise its simplified version) in the determination of ET.

A more thorough study of the effectiveness of the Penman Equation in the area for the determination of ET and a development of crop coefficient curves for the most important crops is necessary. This study should be performed with weighing lysimeters (which appear to be the most effective direct method of measuring ET) or with the neutron scattering method well calibrated in terms of the count rate vs volumetric soil moisture.

APPENDIX

APPENDIX

DETERMINATION OF CROP CURVE COEFFICIENTS

DETERMINATION OF CROP CURVE COEFFICIENTS

The method developed by Doorenbos and Pruitt (1977) in a study for F.A.O. was followed.

First, some primary data are estimated:

1. Planting date: late spring for both crops

2. Length of growth stages

	Corn	Potato
Initial	20 days	25 days
Crop development	35 days	30 days
Mid season	40 days	45 days
Late season	30 days	30 days

3. Determination of the irrigation and/or precipitation frequency and the level of potential evapotranspiration for the early stage. The level of PET, calculated by the Penman equation = 4 mm/day. The average frequency of precipitation during the early stage was about 3.75 days.

4. From the information of Step 3, the crop coefficient for the early stage is estimated from Figure 6 of the appendix

$$K_c = 0.75$$

5. A straight line is plotted for the initial stage with the value obtained (see Figures 14 and 15).

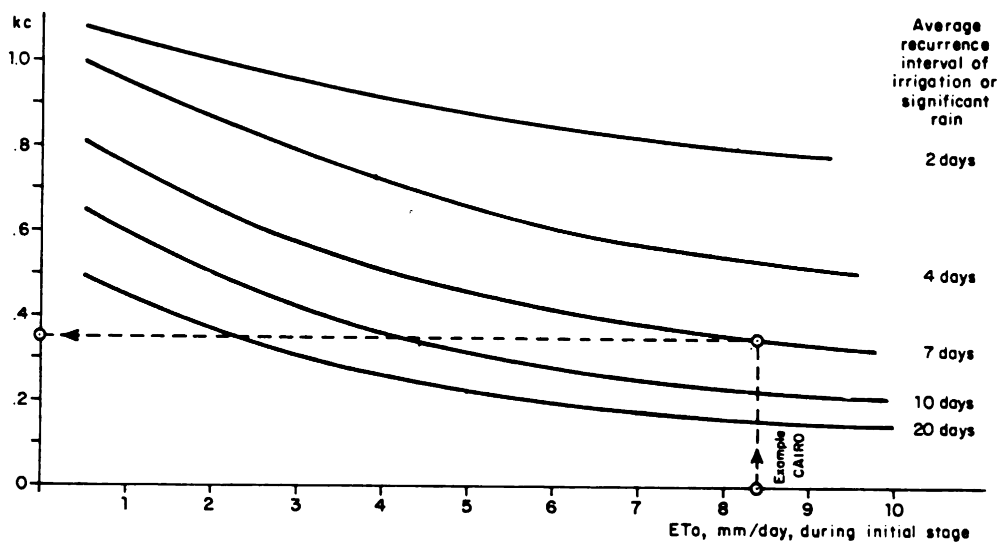
6. Selection of crop coefficient value for mid-season from Table 21. This value is plotted on a straight line (see Figures 14 and 15). K_c = 1.1 for both crops.

7. Selection of crop coefficient value for the late season from Table 21. This value is plotted at the end or the late season stage (see Figures 14 and 15). K_c = 0.55 for corn and 0.70 for potato.

8. For the crop development stage, a straight line is plotted from the initial to the mid-season stage (see Figures 14 and 15).

9. For the late season, a straight line is plotted from mid-season value to late season stage crop coefficient (see Figures 14 and 15).

NOTE: This method can be used with average data to predict the crop coefficient values for the season, but these curves were plotted with the actual values for the summer of 1981.



Source: Doorenbos, J. and W.O. Pruitt. 1977. Guidelines for predicting crop water requirements, FAO Irrig. and drain. paper 24 (rev) 156 pp.

Figure A-1. Average kc value for initial crop development stage as related to level of ETo and frequency of irrigation and/or significant rain.

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