WATER USE AND CROP COEFFICIENT DETERMINATION FOR IRRIGATED WINTER WHEAT IN ARIZONA

by

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A Thesis Submitted to the Faculty of the

SCHOOL OF RENEWABLE NATURAL RESOURCES

In Partial Fulfillment of the Requirements
For the Degree of

MASTER OF SCIENCE
WITH A MAJOR IN WATERSHED MANAGEMENT

In the Graduate College

THE UNIVERSITY OF ARIZONA

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ACKNOWLEDGEMENTS

I would like to thank my thesis director, Dr. Lloyd Gay, for providing the facilities, data, and financial assistance which made this study possible, and for his continuing support and assistance in interpreting the results. I also would like to thank Dr. Paul Brown for providing many insights and words of encouragement during the production of this thesis.

I also wish to express my appreciation to Dr. Malcolm Zwolinski and Dr. Donald Slack for their instructive comments, Bruce Russell for his assistance in acquiring data, and the American Meteorological Society and Hughes Information Technology Corporation for their financial assistance.

DEDICATION

"The pioneers who came West in the seventies in search of gold were no greater gamblers than the prosaic-looking ranchers planting wheat on the dry-land farms. They gamble with the weather that it will be neither too dry, nor too hot, nor too wet, nor too cold; that the wheat will not be destroyed by hail or grasshoppers; and when at last they have the ripe wheat cut and stored they gamble with the market that wheat will be selling for enough money to pay for all the summer's work."

-- Ellen Webb, in Winter Wheat by Mildred Walker

This thesis is dedicated to the victims of drought.

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ABSTRACT

Estimates of evapotranspiration (ET) were made for irrigated winter wheat in the spring of 1988 based on measurements of latent heat flux using Bowen ratio systems at the University of Arizona's Maricopa Agricultural Center (MAC). Data were examined over a 132 day period. For the same time period, reference ET estimates were made in the same region using a modified Penman equation based on data from the Arizona Meteorological Network (AZMET). A comparison of ET estimates for 118 days prior to wheat senescence shows excellent agreement ($r^2 = 0.94$). This implies that a simple crop coefficient can be used as a basis for irrigation scheduling for winter wheat grown under climatic conditions similar to those at MAC in 1988. In addition, the ET estimates were used to test the validity of a previously-determined crop coefficient for winter wheat based on heat units and to assess current groundwater allocations in Arizona.

CHAPTER 1
INTRODUCTION

Research Outlook and Definition

The benefits of water conservation in irrigated agriculture are vast in Arizona. Because water represents a major percentage of costs in crop production, activities that reduce the demand for water allow profits to be increased. In addition, water salvaged by conservation activities can be used for ecological, recreational, or other non-irrigation purposes.

In general, agriculture is highly water-consumptive because plants have a low capacity to store water. The water taken up from the soil by crops is soon evaporated or "transpired" to the atmosphere. Therefore, in areas with low rainfall (like most Arizona farmland), irrigation is necessary to ensure that enough water is available in the soil for crop uptake.

In arid regions, irrigation water may be lost quickly to the atmosphere by direct evaporation from the soil. In order to gauge crop water needs, therefore, irrigators need to estimate evapotranspiration (ET), the loss of water through the combined processes of plant transpiration and soil evaporation. Both atmospheric and vegetative characteristics affect ET. Important atmospheric factors include solar radiation, air temperature, wind movement, vapor pressure deficit, and soil moisture. Vegetative characteristics that affect ET include crop physiology, foliage geometry, and foliage density.

In the effort to develop accurate ET estimates, the Arizona Meteorological Network (AZMET) is a valuable tool. AZMET is a remote weather station network developed at the University of Arizona, comprised of 21 stations which measure several meteorological parameters on an hourly basis. The stations are located as shown in Figure 1. The data collected at these stations are used to estimate ET using a modified Penman equation, a well-known energy balance methodology.

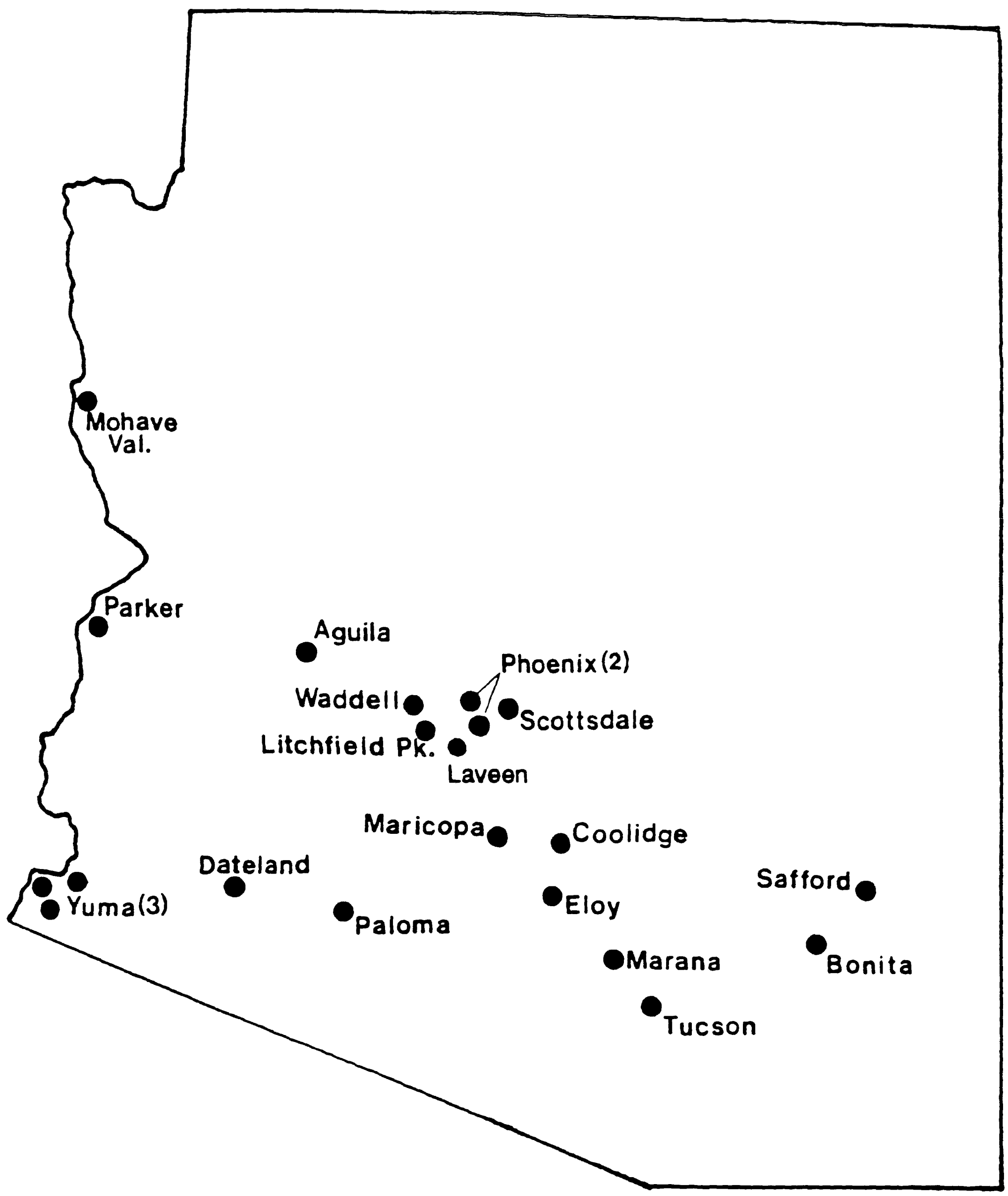

Figure 1. Locations of AZMET Stations

The ET values determined by AZMET, however, are not specific to any crop, and therefore are termed reference ET (ET_o). In order to reflect the effects of particular crop characteristics on evapotranspiration, "crop coefficients" are used. The crop coefficient, denoted k_c, is used to convert ET_o to actual water use, or actual ET (ET_a), for a specific crop. ET_a is thereby calculated using the relation:

$$ET_a = k_c * ET_o \tag{1}$$

Refined micrometeorological methods for estimating ET_a, such as the Bowen ratio energy balance (BREB) method, make it possible to solve for k_c, substituting AZMET ET_o estimates for ET_o and rearranging equation (1) to:

$$k_c = ET_a/ET_o \tag{2}$$

The value of k_c for a specific crop may change over the course of the growing season, reflecting the effects of crop growth and development on water needs. Therefore, k_c is often expressed as a function of time.

Valid crop coefficients for various crops need to be determined in order to apply AZMET ET_o. The resulting estimates of actual crop water use could be used for precise irrigation scheduling in regions around the AZMET weather stations. In addition, crop-specific ET_a estimates are important in determining water rights for farms in many regions of Arizona. ET_a is equivalent to the "consumptive use" (CU) of a crop, which is integrated by the Arizona Department of Water Resources (ADWR) in the process of allocating groundwater use.

Objectives

The primary objective of this study, therefore, is to develop a valid crop coefficient for winter wheat in the region of Maricopa Agricultural Center (MAC), Arizona. With some 21,600 acres of wheat planted in 1993 in Pinal County where MAC is located (Sherman et al., 1994), accurate estimation of crop water needs may facilitate water conservation on a large scale. In addition, with 21 AZMET stations operating throughout the state, the successful use of ET estimates in irrigation scheduling near MAC may have broad implications in Arizona agriculture.

A secondary objective of this research is to test the validity of crop coefficient values that have been developed previously for wheat in Arizona. Slack et al. (1994) developed a crop curve for wheat expressing k_c as a function of growing degree days (GDD), which index the amount of heat that has accumulated during the growing season. Because they account for year-to-year variability in climate and planting dates, crop coefficients given as a function of GDD are believed to be advantageous to coefficents given as a function of days after emergence or stage of crop growth (Slack et al., 1994). To test the validity of the wheat coefficient curve developed by the GDD-based approach, it will be compared to the k_c values determined using AZMET ET_0 and BREB ET_a values.

A third objective of this research is to assess the current legal criteria for allocation of groundwater resources in Arizona. Areas of severe groundwater overdraft are enclosed in Active Management Areas (AMAs), State of Arizona governmental boundaries. As defined by the Groundwater Management Act of 1980, the Arizona Department of Water Resources (ADWR) has regulatory authority over water resources in the AMAs. One component in ADWR's calculated groundwater allotments for farm units in the AMAs is the consumptive use (CU) of crops grown. Therefore, by comparing ADWR CU values to BREB ET_a values, the stringency of the legal standard can be assessed.

This thesis proceeds as follows:

- Chapter 2 outlines the theory and errors associated with the Bowen ratio energy balance (BREB) and Penman methods for estimating ET;
- Chapter 3 presents the materials and methods used in this research;
- Chapter 4 provides results and discussion, including evaluation of ET and development of k_c for winter wheat;
- Chapter 5 provides a summary of the main objectives, materials and methods, and the results and discussion.

CHAPTER 2
OVERVIEW OF BREB AND PENMAN METHODS

The Energy Budget

The basis for the BREB and Penman methods is the energy budget of the earth's surface, which is represented in Figure 2. The energy budget equation, which expresses the conservation of energy in a simple, "lumped" system, is typically written as:

$$Q_n + H + LE + G = 0 \tag{3}$$

where Q_n is the net radiant energy available at the surface when all incoming and outgoing radiation has been considered (W/m^2), H is sensible heat flux (W/m^2), LE is latent heat flux (W/m^2), and G is the flux of heat into or out of the soil (W/m^2). The term "available energy" is commonly used to refer to the sum of Q_n and G. Additional energy terms, such as the storage of heat within a crop, energy used for photosynthesis, and heat transfer by precipitation, are relatively small and are often ignored in the application of energy budget models.

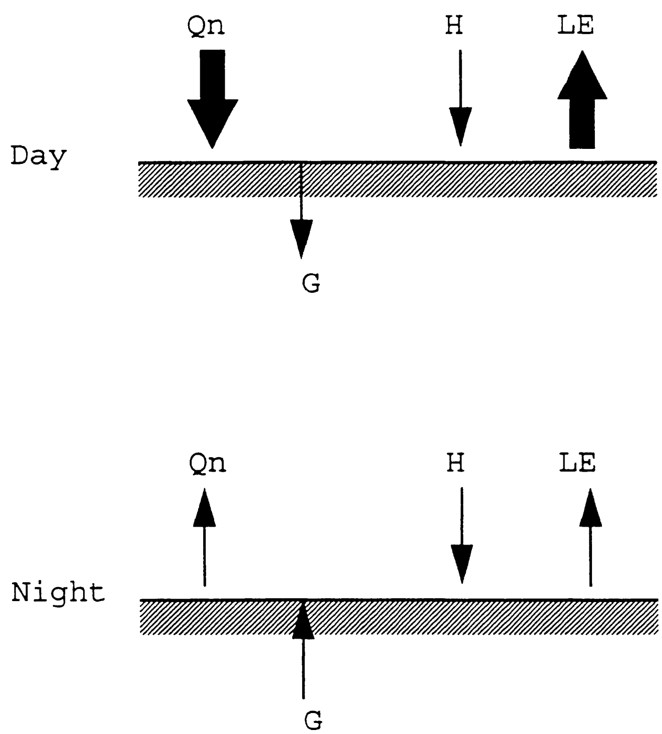

Figure 2. Schematic summary of energy balance fluxes
(arrow width displays relative magnitude)

Fluxes away from and toward the surface are commonly expressed as negative and positive, respectively. For a given time period, the sum of $Q_n + G + H + LE$ will always equal zero. On a daily basis, Q_n is typically positive, G is near zero, and H and LE are negative. For evaporating surfaces in arid regions, however, H is invariably positive, and LE is greater in absolute value than available energy and thermal storage (Gay, 1992). The energy fluxes for an irrigated winter wheat field at MAC are shown in Figure 3 to illustrate magnitudes and polarities typical of a winter day under cloudless skies.

BREB Method

Theoretical Basis

Dividing the energy budget equation (3) by LE and then solving for LE yields:

$$LE = -(Q_n + G)/(1 + \beta) \tag{4}$$

where β is the Bowen ratio, defined by Bowen (1926) as the ratio of sensible heat flux to latent heat flux:

$$\beta = H/LE \tag{5}$$

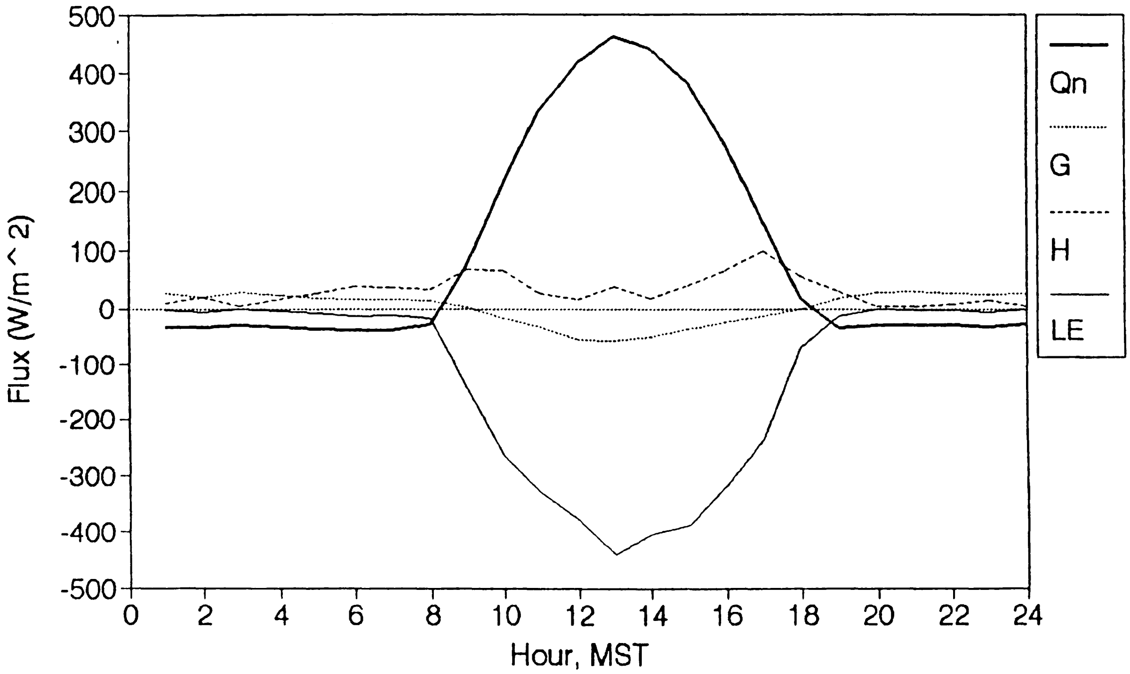

Figure 3. Energy budget of irrigated winter wheat field at Maricopa Agricultural Center, Day-of-Year 50, 1988

Mass and heat are efficiently transported in the atmosphere as air parcels (or eddies) set in motion by convective or turbulent processes. The turbulent flux of latent heat (LE, W/m^2) is described by the relation:

$$LE = -\rho_a \kappa_w \lambda_v (dq/dz) \quad (6)$$

where ρ_a is air density (kg/m^3), κ_w is the eddy diffusivity of water vapor (m^2/s), λ_v is the latent heat of vaporization (J/kg), and dq/dz is the change in specific humidity (kg/kg) over height z (m) (Sellers, 1965). In practice, specific humidity (q) in equation (6) is commonly replaced by vapor pressure (e, mb) from the relation:

$$q = 0.622\ e/P \quad (7)$$

where P is ambient atmospheric pressure (mb) and 0.622 is the ratio of molecular weights of water to dry air ($18\ g \cdot mol^{-1}$ / $29\ g \cdot mol^{-1}$) (Monteith and Unsworth, 1990). Combining equations (6) and (7) yields:

$$LE = -\rho_a \kappa_w\ 0.622\ \lambda_v/P\ (de/dz) \quad (8)$$

where de/dz is change in vapor pressure (mb) over height z (m).

The flux of sensible heat in the turbulent layer (H, W/m^2) is described by the relation:

$$H = -\rho_a c_p \kappa_h (dT/dz) \quad (9)$$

where c_p is the specific heat of air (J/kgK), κ_h is eddy diffusivity for heat transport (m^2/s), and dT/dz is the change in temperature (K) over height z (m). Combining equations (5), (8), and (9) and assuming similarity between κ_h and κ_w results in:

$$\beta = (c_p\ P)/(0.622\ \lambda_v)\ (dT/de) \tag{10}$$

The group of terms $(c_p\ P)/(0.622\ \lambda_v)$ is the "psychrometric constant" (γ), so equation (10) becomes:

$$\beta = \gamma\ (dT/de) \tag{11}$$

The psychrometric constant varies inversely with atmospheric pressure and has a standard value (γ_o) of 0.066 kPa/K at a standard sea level pressure of P_o = 101.3 kPa (Monteith and Unsworth, 1990). Therefore, γ can be calculated as:

$$\gamma = \gamma_o\ (P/P_o) \tag{12}$$

where P (kPa) is ambient atmospheric pressure. The ratio (P/P_o) can be estimated using pressure-height relations for a standard atmosphere (List, 1971):

$$P/P_o = [(288 - 0.0065\ z)/288]^{5.256} \tag{13}$$

where z is elevation (m) above mean sea level.

Therefore, to evaluate LE using the BREB method, the necessary variables to measure are: z, dT, de, Q_n, and G. Elevation data can be obtained from the U.S. Geological Survey or other references. The instrumentation used to measure dT, de, Q_n, and G is described in detail in Chapter 3. By substituting z into equation (13) and the resulting (P/P_o) value into equation (12), γ can be computed. The computed γ and measured dT and de values allow β to be estimated by equation (11). Using this estimate of β and measured values of Q_n and G, latent heat flux can then be estimated by solving equation (4) for LE.

The amount of energy used for evapotranspiration (LE) is related to the depth of evaporation (ET_a, mm) by the relationship (Dunne and Leopold, 1978):

$$ET_a = (LE) / (\lambda_v \rho_w) \tag{14}$$

where λ_v is latent heat of vaporization (MJ/kg) and ρ_w is the density of water (kg/m^3). Although λ_v and ρ_w may vary slightly with temperature, in this analysis λ_v and ρ_w are assumed to be 2.45 MJ/kg and 1000 kg/m^3, respectively (Oke, 1987).

Comments on BREB Method Errors

An array of techniques has been developed experimentally to estimate ET, each of which has been shown to have advantages and disadvantages. While the BREB method is generally considered to be consistent and accurate, some problems arise in its implementation. An inventory of these problems is provided below, including a discussion of the "similarity principle" and resolution limitations of the instruments. In addition, comments are provided below on intercomparisons of the BREB method with other methods in the literature.

Similarity Principle

Application of the BREB method assumes similarity between κ_h and κ_w so that $\kappa_h/\kappa_w = 1$. This assumption is well-founded under unstable atmospheric conditions that are typical over many natural surfaces (Denmead and McElroy, 1970). However, this assumption has not been verified for the highly stable conditions that form over cool, irrigated fields located in warm, arid environments. Two attempts at verification compared LE estimates from BREB and lysimetric methods. In the first, Verma *et al.* (1978) found the ratio κ_h/κ_w to be generally greater than one under advective conditions, and showed correlation between dT/de and κ_h/κ_w with r^2 values from 0.56 to 0.78. Similarly, Brownridge (1985) suggested that κ_h/κ_w tended to exceed one under advective conditions, proposing a linear relationship between κ_h/κ_w and β with an r^2 of 0.45. During the ten days analyzed, Brownridge observed κ_h/κ_w ranging from 0.68 to 2.42. In these cases, ET measured by the lysimeter was assumed to be accurate, but Brownridge concluded that lysimeter characteristics may have contributed to these discrepancies.

Although these results may indicate some limitation in the application of the BREB method to irrigated areas in arid regions, variable results in determining κ_h/κ_w have not allowed reliable relationships to be established. Gay (1992) concluded that no consistent corrections have been proposed in the few studies to date of Bowen ratios in stable (advective) conditions. Oke (1987) states that it is reasonably accepted that the transfer coefficients for heat and mass are reasonably similar. The problem is difficult to resolve experimentally, and so the results in this study are based upon the assumption that $\kappa_h/\kappa_w = 1.0$ over the full range of stabilities encountered at this site.

Resolution Limits of the Instruments

Ohmura (1982) proposed that the BREB method produces unacceptable estimates of LE under three conditions: (1) when errors occur in measurement of Q_n and G, (2) when β approaches -1, and (3) when the polarities of H and LE do not match the polarities of dT and de, respectively. Condition (1) is an inherent problem in any energy budget model, and can be minimized with consistent maintenance of instruments. Ohmura

(1982) developed objective criteria to eliminate data associated with conditions (2) and (3). First, the value of β is evaluated and data are rejected if it falls within a region determined from observations of system performance ($-1 \pm x$). If the β value is outside of the rejection region, the polarities are tested for agreement as prescribed by condition (3). Data rejected by these criteria are replaced by interpolated values. These criteria have been widely incorporated into the design of BREB analysis routines to allow for computerized partitioning of available energy when estimates were determined to be unacceptable. Conditions (2) and (3) are typically observed for short periods near dawn and dusk, when energy fluxes are usually small (as illustrated in Figure 3). Therefore, little uncertainty is introduced by the partitioning described above.

Intercomparisons

The BREB method has been demonstrated to be a highly consistent and accurate model for estimating ET over irrigated surfaces. Malek and Bingham (1993) compared ET estimates made by BREB and water balance methods and found excellent agreement (r^2=0.987). Denmead and McIlroy (1970) determined that ET estimates in a field of wheat showed excellent agreement (± 0.1 mm/hr) between the BREB method and lysimetry. In addition, Dugas *et al.* (1991) tested four different BREB systems, an eddy correlation system, and a portable chamber over a field of irrigated wheat. They found that daytime LE among the BREB systems differed by one to eleven percent, eddy correlation LE was 67 to 77 percent of BREB LE, and portable chamber LE was 125 percent of BREB LE. These studies and a range of others (e.g. Massman *et al.*, 1990; Gay, 1988; Osmolski and Gay, 1983) generally confirm that the BREB method agrees well with other methods for estimating ET.

As a result, BREB-based estimates can often be used as a "truth-set" in the analysis of ET. For example, Persson and Lindroth (1994) used BREB ET estimates to verify a physically-based soil water model. Petersen *et al.* (1992) also used the BREB method to "validate" the Penman-Monteith model. This study found that the Penman-Monteith energy balance equation yielded average daily ET within 5 percent of that measured by a heat pulse system and a BREB system. It seems clear, therefore, that the BREB method is widely accepted to provide consistent and accurate measurements of actual ET.

Penman Method

Measurement of ET is important in the scheduling of irrigations and in the design of water delivery systems. ET for different crops can be related to ET for a standard ground cover which can be measured directly. The standard proposed by Penman (1948) was a short, green crop completely shading the ground with a non-limiting supply of water. ET from such a surface is commonly called "potential ET," denoted ET_o.

Theoretical Basis

Each of the terms in Equation (3) is a flux that occurs between the atmosphere and the surface of the earth. The steady-state exchange of most forms of matter and energy is expressed as:

$$\text{flux} = (C_s - C_a)/r \tag{16}$$

where C_s is the concentration at the exchange surface, C_a is the ambient concentration, and r is the exchange resistance (Campbell, 1977). The Penman method is derived from this expression, substituting the appropriate climatological terms to define H and LE as:

$$H = \rho_a\ c_p\ (T_c - T_a)/r_a \tag{17}$$

$$LE = (\rho_a\ c_p\ /\ \gamma)\ [(e^*_c - e_a)/(r_a + r_c)] \tag{18}$$

where T_c is the temperature at the crop surface (°C), T_a is the air temperature (°C), r_a is aerodynamic resistance (s/m), e^*_c

is the saturation vapor pressure at the crop surface (kPa), and e_a is the vapor pressure of the air (kPa), and r_c is canopy resistance (s/m).

The aerodynamic resistance (r_a) term describes the role of atmospheric turbulence in the evaporation process. It is a function of wind speed, surface roughness, and atmospheric stability. The value of r_a tends to be high for open water surfaces and low for well-developed forest stands (Oke, 1987). Canopy resistance (r_c) characterizes the physiological control of evaporative water loss by a vegetative surface. Unless the surface is wet, the key resistance to water loss is that of the stomata. Under well-watered conditions, r_c=0 because the stomata play no regulatory role (Oke, 1987).

The e^*_c term, which has been historically difficult to quantify, is eliminated by the Penman model. Penman (1948) recognized that the slope of the saturated vapor pressure-temperature relation (or "SVP curve") between T_a and T_c was similar in magnitude to the slope (Δ) of the SVP curve at T_a. Therefore, $(e^*_c - e_a)$ can be replaced by a linear approximation as follows:

$$(e^*_c - e_a) \approx e^*_a - e_a + \Delta \ (T_c - T_a) \qquad (19)$$

where e^*_a is the saturation vapor pressure of the air (kPa) and

Δ is de^*/dt at T_a. By combining terms, substituting into equation (3), assuming well-watered conditions (r_c=0), and defining δ as an aerodynamic term equal to $0.622 \cdot \lambda_v(e_a - e^*_a)/r_a$, the Penman equation is determined to be:

$$LE = (\Delta\ Q_n + \gamma\ \delta)\ /\ (\Delta + \gamma) \qquad (20)$$

Equation (20) does not include the G term because soil heat flux is close to zero when summed over a daily period. In equation (20), LE is equivalent to potential ET (ET_o), which is also termed "reference ET."

The FAO-Penman equation (Doorenbos and Pruitt, 1977) is a modified version of equation (20). Estimates of ET_o (mm/hr) are calculated as:

$$ET_o = W(Q_n/\lambda_v\rho_w) + (1-W)(fU2)(VPD) \qquad (21)$$

where W is a dimensionless weighing function ($W = \Delta/(\Delta+\gamma)$), Q_n is net radiation ($W/m^2/hr$), $fU2$ is an empirical wind function (mm/hr/kPa) based on average hourly wind speed (m/s) at 2 meters height, and VPD is vapor pressure deficit (kPa) in the air at 2 meters height.

Comments on Penman Method Errors

Analogous to the BREB method, the Penman equation derived assumes similarity between aerodynamic resistance to heat and water vapor transport. Over heterogeneous surfaces, the sources and sinks of water vapor and heat may not have the same spatial distribution, and this could be a source of error if the resistances for sensible and latent heat transfer are calculated over different path lengths (Monteith and Unsworth, 1990).

The derivation of the Penman equation also is based on an assumption of $r_c=0$. Although this assumption is defined over an open water surface, most crop surfaces are only partially saturated. Because the appropriate resistance to water vapor at the surface is difficult to evaluate, however, the simplifying assumption of $r_c=0$ is widely utilized for the calculation of Penman's ET_0 (Oke, 1987).

The use of empirical estimates for fU2 can also lead to substantial errors in the Penman and modified Penman methods as the geometric conditions of the surface deviate from the low vegetation (~1 m high) envisioned by Penman. Also, various empirical methods can be utilized to estimate Q_n in the absence of direct measurements, with predictable decreases in precision. Batchelor (1984) reported that annual ET estimates made by the two methods differed by 23 percent, and that the main source of difference was the different empirical relationships used in the two methods.

Another potential source of error is derived from the application of Penman's linear approximation. Monteith and Unsworth (1990) noted that it is valid to assume that saturation vapor pressure is a linear function of temperature when surface temperature is close to air temperature. However, in irrigated fields in arid regions, this is frequently not the case. In addition, Paw U (1992) reported that under extreme conditions, such as a combination of large aerodynamic resistances (>50 s/m), air temperatures under 20°C, and/or equilibrium ET conditions, errors on the order of 10% to 15% may result from the usage of the Penman model.

Finally, a source of error in Penman-based ET estimates is derived from the use of mean daily meteorological data. Mean values do not reflect the diurnal fluxes of wind, radiation, temperature, and vapor pressure that occur over irrigated fields. Tanner and Pelton (1960) showed that most evapotranspiration occurs during the daytime. Consequently, they reported that the use of mean daily values causes error to arise from the strong weight given to nighttime values of weather parameters, when there is little available energy and ET. In this thesis, the analyses are based upon hourly data to reduce such error.

CHAPTER 3
MATERIALS AND METHODS

Study Description

Experimental Site

Energy budget measurements used in this analysis had been collected previously in an evapotranspiration project of the Arizona Agricultural Experiment Station, under the direction of Professor Lloyd W. Gay of the University of Arizona. Measurements were made from 16 January to 29 May, 1988 over irrigated winter wheat (*Triticum aestivium* L. 'Aldente') at the University of Arizona's Maricopa Agricultural Center (MAC) near Maricopa, Arizona. An AZMET weather station located at MAC was also operational throughout this period, under the direction of Dr. Paul Brown of the University of Arizona.

MAC is a 770-hectare farm formatted in 1988 as shown in Figure 4. MAC (33.07°N, 111.98°W) is located about 5 km east of Maricopa, in Pinal County. The mean elevation (z) of the site is 358 m above sea level and annual precipitation at the site is approximately 200 mm. Soils are reclaimed Casa Grande and Trix sandy clay loams.

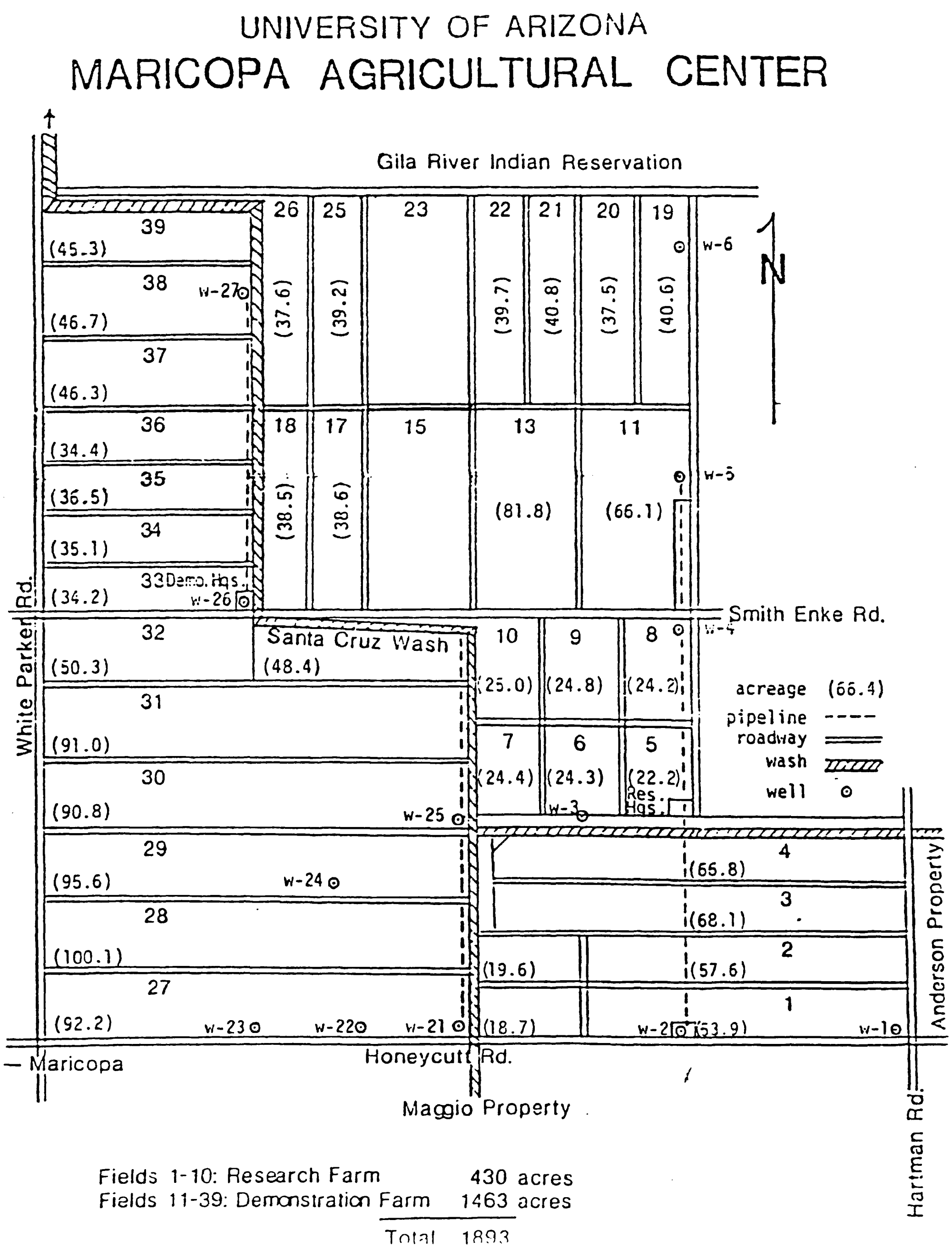

Figure 4. Map of Maricopa Agricultural Center

The basic measurements and data analysis are described by Cooper (1990) in his analysis of remote sensing techniques for estimating ET at the Maricopa winter wheat site. BREB instrumentation was situated over a 30-hectare field of irrigated winter wheat, denoted as Field 15 in Figure 4. The field had approximately 150 mm of irrigation applied on "day-of-year" (DOY) 351 (17 December) of 1987 and DOY 21, 53, 75, 98, 116 and 143 of 1988. Wheat was sown on DOY 361 (27 December), 1987 in north-south, 0.22 m wide rows. On DOY 58 (27 February) and DOY 115 (25 March), 1988, the wheat reached maximum density and crop height, respectively. The seed heads were full by DOY 130 (8 May) and senescence occurred on DOY 137 (15 May).

Measurements

Weather parameters measured and instruments used to make the measurements are summarized in Table 1. The BREB system (Gay, 1988) collected 12-minute data for dT, de, Q_n, and G. Two ceramic-wick, fan-aspirated psychrometers were used to measure dT and de. The psychrometers were mounted on a vertical exchange mast of length 1 m, with the lower psychrometer 0.2 m above the top of the wheat canopy. The

Table 1. Summary of BREB and AZMET systems

Measured Parameter	BREB			AZMET	
	Sensor	Height	Abbr.	Sensor	Abbr.
temperature difference	ceramic-wick psychrometer	0.5 to 2.0 m	dT	-	-
vapor pressure difference	ceramic-wick psychrometer	0.5 to 2.0 m	de	-	-
net radiation	single-dome, Fritschen-type net radiometer	1.9 to 2.8 m	Q_n	-	-
soil heat flux	soil heat-flux disks	-0.01 m	G	-	-
soil temperature	-	-	-	Type T thermocouple	Soil Temp
incoming solar radiation	Kipp pyranometer	1.9 to 2.8 m	KD	LiCor pyranometer	SR
air temperature	Ni-Fe resistance thermometer	1.5 to 2.0 m	T1	Fenwall thermistor	T_a
crop surface temperature	Everest infrared thermometer	-	T_s	-	-
wind speed	R.M. Young anemometer	2.0 to 2.1 m	U1	R.M. Young anemometer	U3
wind direction	-	-	-	Met One wind vane/ potentiometer	Wind Vec Dir
precipitation	-	-	-	tipping bucket with Hg switch	PPT
relative humidity	-	-	-	resistance chip	RH

Source: Cooper (1990) and Brown (1994)

exchange mast was used to interchange the position of the two psychrometers in order to mitigate systematic biases (Gay, 1988). As the crop height increased, the psychrometers were raised in order to maintain their relative position to the canopy.

Air temperature (T1) was measured as the dry-bulb temperature of the upper psychrometer. The sensor used for these specific measurements was a nickel-iron (Ni-Fe) resistance thermometer device (Gay, 1988).

Q_n was measured with a single-dome, Fritschen-type net radiometer positioned 1.7 m above the canopy. G was measured with two soil heat flux disks connected in parallel and installed 0.01 m below the surface. Based on these measurements, equations (4), (5), and (11) were used to partition available energy (Q_n + G) into LE and H.

The BREB system also collected 12-minute data for windspeed (U1), incoming solar radiation (KD), and thermal emitted surface temperature (T_s). These were measured with an R.M. Young anemometer, a Kipp pyranometer, and an Everest infra-red thermometer, respectively. The 12-minute data were compiled into hourly means for the 136-day period. The record is complete except for four days: DOY 36, 37, 68, and 76.

The Maricopa AZMET station has been operational since June 1986. In 1988, it was located in the northwest corner of Field 5 of the MAC, approximately 1200 m from the site where the BREB measurements were made, at an elevation (z) of 361 meters above sea level. The parameters measured and sensors used on the weather station are shown in Table 1. It should be noted that AZMET wind speed measurements (U3) are made at a height of 3 m. These values are corrected to 2 m values (U2) by multiplying by a factor of 0.93.

Calculations

Calculation of ET_a using BREB data

BREB data were imported from ASCII files into Quattro Pro software. As an illustration, mean hourly data for DOY 17, 1988 are shown in Table 2. Time data are expressed in fractions of day of year. For example, time 20.25 is equivalent to DOY 20, hour 0600. The convention of the BREB data is that fluxes away from and toward the surface are negative and positive, respectively. LE values were converted

Table 2. Sample hourly BREB data, DOY 17, 1988

TIME (DOY)	Qn (W/m^2)	G (W/m^2)	H (W/m^2)	LE (W/m^2)	Filtered B	T1 (C)	VP1 (mb)	VPD1 (mb)	U1 (m/s)	KD (W/m^2)
17.02	-30	34	0	-4		7.6	9.3	1.1	1.1	0
17.06	-28	38	0	-9		6.5	8.8	0.9	0.9	0
17.10	-25	40	0	-15		6.0	8.6	0.7	1.0	0
17.15	-19	38	0	-20		5.4	8.2	0.7	1.1	0
17.19	-16	27	0	-11		5.9	8.2	1.2	1.3	0
17.23	-15	22	0	-7		6.8	8.2	1.7	1.0	0
17.27	-15	23	0	-8		5.3	8.3	0.6	0.7	0
17.31	-13	21	0	-8		5.5	8.4	0.6	1.1	6
17.35	16	6	3	-26	-0.10	5.9	8.6	0.7	0.5	50
17.40	114	-28	1	-87	0.00	9.6	9.2	2.9	1.9	173
17.44	164	-40	-1	-124	0.00	12.2	8.9	5.3	3.3	251
17.48	244	-56	-7	-181	0.00	14.2	9.1	7.2	4.1	359
17.52	240	-72	8	-176	0.00	17.0	9.4	10.1	5.6	382
17.56	298	-70	-1	-227	0.00	18.7	8.7	12.9	8.8	479
17.60	149	-29	78	-198	-0.40	18.8	8.3	13.4	8.3	238
17.65	84	-25	49	-108		19.1	7.9	14.2	10.2	136
17.69	6	-4	1	-3		17.8	7.4	13.0	11.5	30
17.73	-8	-2	10	0		17.5	7.3	12.6	10.5	8
17.77	-16	7	9	0		15.9	8.3	9.7	10.2	0
17.81	-4	23	2	-21		9.9	9.2	3.1	9.6	0
17.85	-10	28	19	-38	-0.50	8.5	9.4	1.6	3.9	0
17.90	-16	25	10	-18		8.4	9.9	1.1	2.0	0
17.94	-30	31	4	-5		7.9	9.7	1.0	4.2	0
17.98	-33	35	2	-3		7.8	9.3	1.3	3.6	0

to hourly ET_a by equation (15), with 1 mm of evaporation assumed per 2.45 MJ/m^2 of energy leaving the surface. A sample calculation is shown below:

Illustrative example of calculating hourly ET_a from BREB measurements of LE (see equation (15))

Time (day.hr) = 17.56
LE (W/m^2) = - 227 ("away from the surface")

$$ET_a = LE / (\lambda_v \, \rho_w)$$

$$= \frac{227\ W/m^2 * 3600\ s/hr * 1000\ mm/m * 10^{-6}\ MJ/J}{1000\ mg/m^3 * 2.45\ MJ/kg}$$

$$= 0.33\ mm/hr$$

BREB values for LE were missing for eight separate hours over the 136-day experiment: 20.35, 22.52, 47.44, 89.35, 103.35, 131.35, 145.35, and 149.37. These values were estimated by linear interpolation between the previous and subsequent hour.

Calculation of ET_0 by AZMET

A central computer evaluates ET_0 from meteorological data collected at each weather station. The parameters identified in Table 1 are measured once per minute and compiled into hourly data. AZMET data can be downloaded from the AZMET

Computer Bulletin Board, (602) 621-1197, or obtained by mail or in person from the Extension Biometeorology Program, % AZMET, Soil and Water Dept., Room 429, Shantz Bldg., University of Arizona, Tucson, AZ 85712. For this study, hourly (and daily) ET_0 values from DOY 16 to DOY 151, 1988 were obtained from the AZMET office, along with measurements of the weather parameters in Table 1, vapor pressure deficit estimates and computed heat units (or growing degree days). A sample of these data is shown in Table 3. The discussion of AZMET data that follows will retain the symbols and units of that system, since these are closely related to those used in the preceding discussion of the BREB measurements.

The procedure used in the AZMET program to calculate ET_0 closely resembles that used by the California Irrigation Management Information System (Snyder and Pruitt, 1985). The inputs needed to compute ET_0 are: air temperature, relative humidity, solar radiation, wind speed, and elevation. Air temperature (T_a, °C) is used to approximate saturation vapor pressure at T_a (e^*_a) by the equation:

$$e^*_a = 0.6108 \exp \left[(17.27 * T_a) / (T_a + 237.3)\right] \qquad (22)$$

where e^*_a (kPa) is defined over a surface of pure water (Murray, 1967).

Table 3. Sample hourly AZMET data, DOY 17, 1988

DOY	Hr of Day	Mean Ta (C)	RH (%)	VPD (kPa)	SR (MJ/ m^2)	PPT (mm)	2" Soil Temp (C)	4" Soil Temp (C)	Mean U3 (m/s)	Wind Vec Mag (m/s)	Wind Vec Dir (deg)	Wind Dir St Dv (deg)	Max U3 (m/s)	ETo (mm)	Heat Units
17	1	7.5	90.1	0.1	0	0	11.8	10.8	1.6	0.7	229	62	2.6	-0.02	0
17	2	6.2	91.1	0.1	0	0	11.4	10.5	1.2	0.9	164	45	2.4	-0.02	0
17	3	5.7	92.9	0.1	0	0	11.0	10.2	2.2	1.9	155	29	2.8	-0.02	0
17	4	5.6	91.8	0.1	0	0	10.7	9.9	2.1	1.8	120	31	3.0	-0.02	0
17	5	6.3	87.7	0.1	0	0	10.6	9.7	1.7	1.1	148	51	3.1	-0.01	0
17	6	6.7	86.4	0.1	0	0	10.6	9.6	2.3	1.4	140	51	3.9	-0.01	0
17	7	6.3	85.9	0.1	0	0	10.5	9.5	1.4	0.3	236	73	2.7	-0.01	0
17	8	5.1	92.2	0.1	0	0	10.5	9.4	1.4	0.7	5	56	2.3	-0.02	0
17	9	5.4	93.1	0.1	0.15	0	10.5	9.4	1.0	0.9	320	31	2.2	0.00	0
17	10	9.1	81.0	0.2	0.59	0	11.1	9.5	2.7	2.5	118	21	5.9	0.05	0
17	11	11.7	64.4	0.5	0.89	0	12.0	9.9	3.9	3.9	139	8	5.3	0.14	0
17	12	13.4	58.7	0.6	1.23	0	12.8	10.5	4.5	4.5	151	11	6.5	0.23	0.03
17	13	16.5	47.8	1.0	1.52	0	14.3	11.2	6.1	5.8	168	18	9.3	0.35	0.16
17	14	18.6	39.3	1.3	1.59	0	15.1	11.9	9.4	9.3	204	8	11.8	0.48	0.24
17	15	18.3	37.1	1.3	0.94	0	15.0	12.2	9.5	9.3	198	11	12.4	0.35	0.23
17	16	18.8	34.8	1.4	0.57	0	15.6	12.4	11.2	11.1	196	9	15.1	0.32	0.25
17	17	17.3	35.2	1.3	0.12	0	15.5	12.3	12.6	12.4	195	10	16.8	0.26	0.19
17	18	16.8	36.0	1.2	0.04	0	15.1	12.2	12.1	12.0	181	7	14.8	0.23	0.17
17	19	15.4	41.1	1.0	0	0	14.8	12.0	12.5	12.4	190	9	16.4	0.20	0.11
17	20	10.8	73.6	0.4	0	3	14.5	11.8	10.5	9.9	232	20	18.8	0.06	0
17	21	8.2	87.7	0.1	0	1	13.9	11.4	5.1	5.0	228	12	8.9	-0.01	0
17	22	7.9	90.8	0.1	0	0	13.5	11.1	2.0	1.3	136	46	3.5	-0.02	0
17	23	7.5	91.8	0.1	0	0	13.2	10.9	4.8	4.7	149	12	6.3	-0.01	0
17	24	7.3	91.0	0.1	0	0	12.8	10.6	4.6	4.5	174	11	5.9	-0.01	0

Relative humidity (RH), measured as a percent, is used to compute e_a by the relation:

$$e_a = RH/100 * e^*_a \tag{23}$$

Vapor pressure deficit (VPD, kPa) is then computed as:

$$VPD = e^*_a - e_a \tag{24}$$

Solar radiation (SR, $MJ/m^2 \cdot hr$) measurements are used to estimate net radiation (Q_n, $MJ/m^2 \cdot hr$) by the following relations (Brown, 1994):

$SR \geq 0.21\ MJ/m^2 \cdot hr$:

$$Q_n = -0.3 + 0.767 * SR \tag{25}$$

$SR < 0.21\ MJ/m^2 \cdot hr$:

$$Q_n = -0.17 + 0.767 * SR + 0.56\ e_a \tag{26}$$

The effect of wind on ET_0 is captured by an empirically determined wind function (fU2, mm/hr/kPa), computed as:

$$fU2 = a + b(U2) \tag{27}$$

where U2 is mean hourly wind speed (m/s) at a height of 2 meters and *a* and *b* are fitted coefficients. Tanner and Pelton (1960) showed that this function differs under daytime and nighttime conditions and so it is advantageous to use mean hourly wind speed data, as opposed to mean daily data. Doorenbos and Pruitt (1977) suggested, due to a wide range of conditions that may occur at different sites, local calibration is necessary for the application of a wind function. The coefficients *a* and *b* substituted into equation (27) by AZMET are shown in Table 4.

Slight, temperature-related variations in the psychrometric constant (γ), latent heat of vaporization (λ_v), and density of water (ρ_w) are accommodated by the AZMET system. Ambient atmospheric pressure (P, kPa) can be estimated as a function of elevation with equation (13), and then used to compute γ as (Brown, 1994):

$$\gamma = 0.000646 * (1 + 0.000946 * T_a) * P \qquad (28)$$

Calculation of λ_v and ρ_w is accomplished by the equation (Brown, 1994):

$$\lambda_v \ \rho_w = 694.5 * (1 - 0.000946 * T_a) * P \qquad (29)$$

Air temperature in Kelvin (T_{aK}) is equal to T_a + 237.16. This value is used to compute using the following equation (Brown, 1994):

$$\begin{aligned}\Delta = [e^*_a / (T_{aK})^2] * [6790.5 - 5.02808*T_{aK} \\ + 4916.8*(T_{aK})^2 * 10\hat{}(-0.0304*T_{aK}) \\ + 174209 * 10\hat{}(-1302.88/T_{aK})\end{aligned} \qquad (30)$$

Table 4. Coefficients used by AZMET in the calculation of the wind function (fU2)

	a	b
$Q_n \leq 0$	0.125	0.0439
$Q_n > 0$	0.03	0.0576

Source: Brown (1994)

The dimensionless weighing factors (W, 1-W) are calculated by the equation:

$$W = \Delta/(\Delta+\gamma) \tag{31}$$

W is the weighing factor for the effect of radiation on ET_0, while (1-W) is the weighing factor for the effect of wind and humidity on ET_0. Substituting the values computed by equations (24), (25) or (26), (27), (29), and (31) into equation (21) yields hourly estimates of ET_0 (mm/hr).

Calculation of 24-hour ET estimates

Irrigation systems are typically managed using daily estimates of ET. Daily ET_0 values are generated by AZMET as a sum of all 24 hours. In this thesis, however, "24-hour" ET values were derived using only daytime hours when AZMET SR ≥ 0.21 MJ/m² (Brown, 1994). The reasons for this are three. First, possibilities for errors increase at night when evaporation is small. Second, this problem is exacerbated by instability of the BREB model when β approaches -1.0 which is most likely at night. Third, the Penman model tends to overestimate ET_0 at night because evapotranspiration is reduced with stomatal closure at night.

24-hour ET_a and ET_0 totals were computed by summing the daytime values and correcting by a factor of 1.03 (Gay, 1986).

As discussed below, nighttime data were more consistent than expected and could be used directly if attention were paid to the outlier values. For purpose of illustration, Table 5 demonstrates my calculation of 24-hour ET_a and ET_o for DOY 17, 1988.

Figures 5a and 5b show nighttime ET as a percent of total daily ET, illustrating the possible instabilities of the two methods. ET is defined as positive into the atmosphere (in contrast to LE). Excluding the two large excursions for each method, nighttime values were about 12 percent of the daily total for AZMET potential ET, and about seven precent of the daily total for BREB actual ET.

Comparison of BREB and AZMET Data

To assess the relationship between BREB and AZMET data, linear regressions were developed between: 1) BREB 24-hr ET_a estimates and AZMET 24-hr ET_o values; 2) BREB net radiation and net radiation estimated from AZMET solar radiation measurements; 3) BREB and AZMET wind speed measurements; and 4) BREB and AZMET air temperature measurements. Osmolski (1985) found that, in arid regions, radiation input is the most important climatic variable affecting evapotranspiration from moist sites, followed by wind speed input.

Table 5. Calculation of 24-hour BREB ET_a and AZMET ET_o for DOY 17, 1988

Hour of Day	AZMET ET_o (mm)	BREB ET_a (mm)	SR Index*	Daytime AZMET ET_o (mm)	Daytime BREB ET_a (mm)
1	-0.02	0.01	0	0.00	0.00
2	-0.02	0.01	0	0.00	0.00
3	-0.02	0.02	0	0.00	0.00
4	-0.02	0.03	0	0.00	0.00
5	-0.01	0.02	0	0.00	0.00
6	-0.01	0.01	0	0.00	0.00
7	-0.01	0.01	0	0.00	0.00
8	-0.02	0.01	0	0.00	0.00
9	0.00	0.04	0	0.00	0.00
10	0.05	0.13	1	0.05	0.13
11	0.14	0.18	1	0.14	0.18
12	0.23	0.27	1	0.23	0.27
13	0.35	0.26	1	0.35	0.26
14	0.48	0.33	1	0.48	0.33
15	0.35	0.29	1	0.35	0.29
16	0.32	0.16	1	0.32	0.16
17	0.26	0.00	0	0.00	0.00
18	0.23	0.00	0	0.00	0.00
19	0.20	0.00	0	0.00	0.00
20	0.06	0.03	0	0.00	0.00
21	-0.01	0.06	0	0.00	0.00
22	-0.02	0.03	0	0.00	0.00
23	-0.01	0.01	0	0.00	0.00
24	-0.01	0.00	0	0.00	0.00
SUM				1.92	1.62
1.03*SUM (24-hr total)				1.98	1.67

* 0 = AZMET SR < 0.21 $MJ/m^2 \cdot hr$
  1 = AZMET SR ≥ 0.21 $MJ/m^2 \cdot hr$

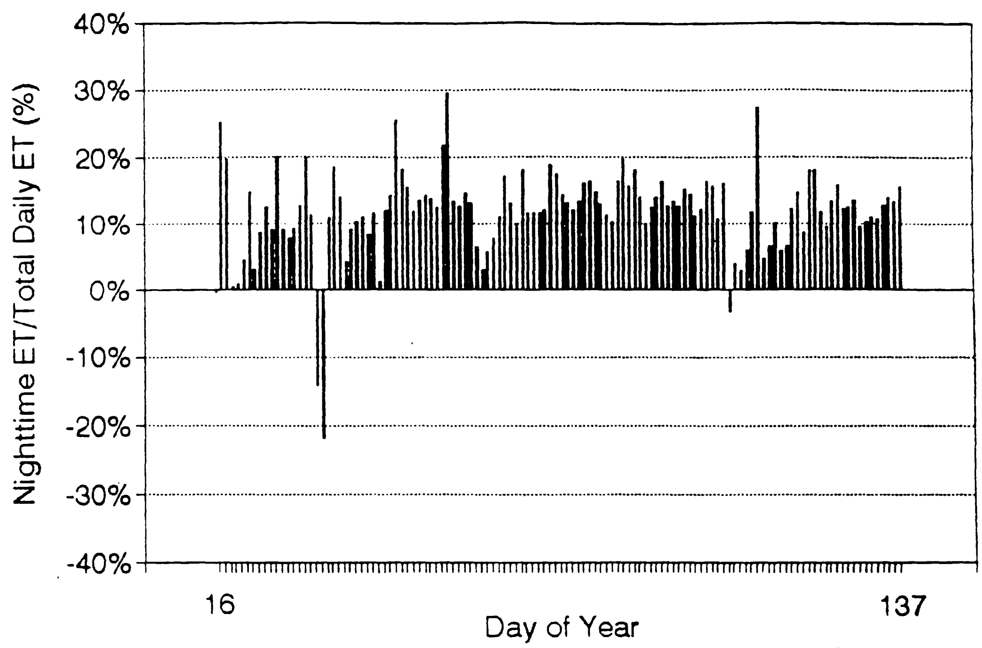

Figure 5a. Nighttime ET as a percent of the daily total for AZMET data

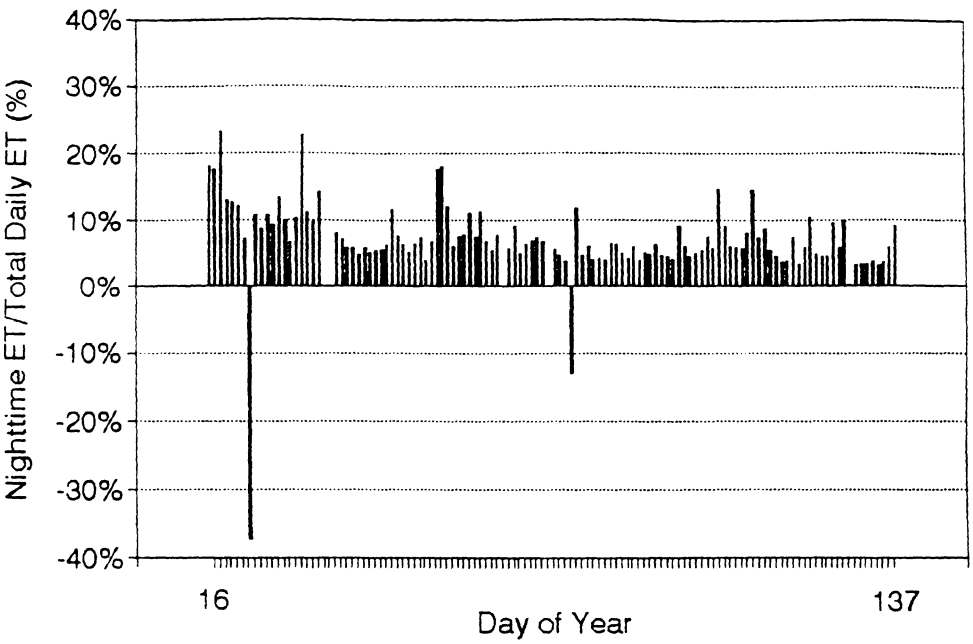

Figure 5b. Nighttime ET as a percent of the daily total for BREB data

Computation of Crop Coefficients

The value of k_c is typically a function of crop growing stage: initial, rapid growth, mid-season, and late season, as shown in Figure 6 (Snyder et al., undated). For many crops, the estimated number of days in each stage has been empirically determined. For example, Doorenbos and Pruitt (1977) indicate that winter wheat is expected to spend 15, 25, 50, and 30 days in the initial, rapid growth, mid-season, and late season stages, respectively. These values are recommended as a reference only, and are likely to vary depending upon local climatic conditions.

Delineation of development stages

The four crop development stages can be delineated based on local field observations, as follows (Doorenbos and Pruitt, 1977). The initial growth stage begins on the day of seeding and continues until approximately 10% ground cover is in place. The rapid growth stage then begins, ending when the crop has attained effective full ground cover. The mid-season stage follows, ending when the crop starts to mature as indicated by leaf discoloration or defoliation, from which time the late season extends until full maturity or harvest.

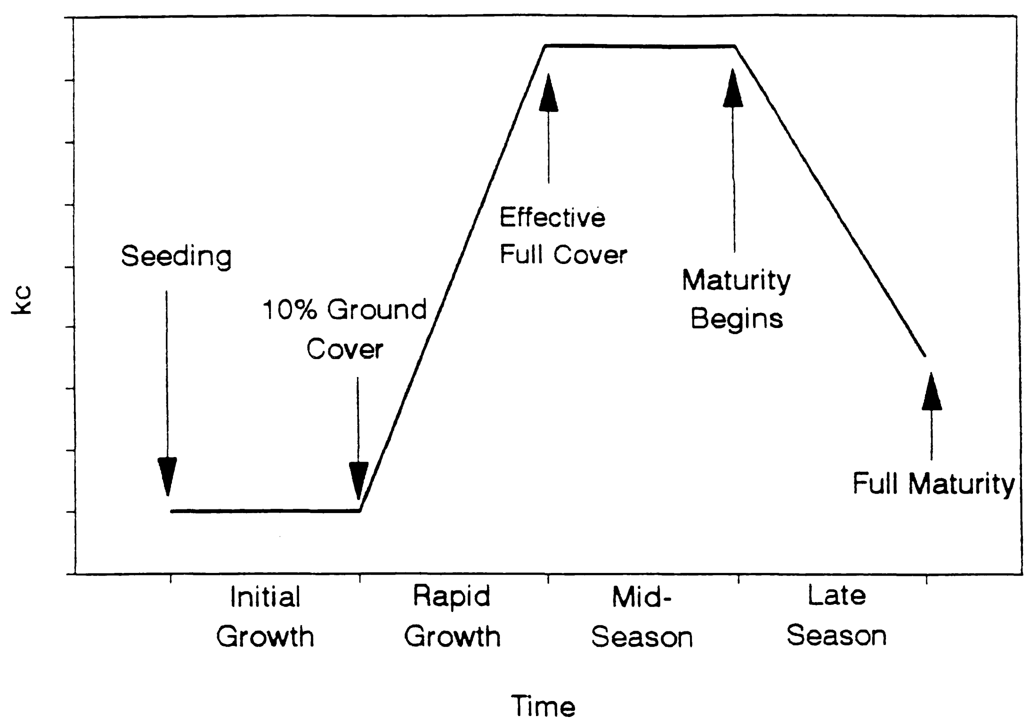

Figure 6. Prototypical crop coefficient curve

For this research, BREB data were available beginning 20 days after planting (DOY 16), which is approximately when the rapid growth stage for winter wheat begins. The BREB field campaign ended 155 days after planting (DOY 151) and full maturity, or senescence, of the wheat is thought to have occurred on DOY 137 (Cooper, 1990). Therefore, it is assumed that the rapid growth, mid-season, and late season stages ended on DOY 50 (when the wheat reached maximum density, effective full crop cover), DOY 115 (maximum height, maturity begins), and DOY 137 (senescence, full maturity), respectively.

Development of a linear crop coefficient

For each day in the period of analysis, a crop coefficient (k_c) value can be calculated by substituting the 24-hr BREB ET_a and 24-hr AZMET ET_o values into equation (2). For each crop development stage, a mean or median daily k_c value can then be computed. In addition, a mean k_c value for each crop development stage can be determined by substituting total ET_a and total ET_o for the crop stage into equation (2). Similarly, a single k_c value can be computed for the full study period by dividing total ET_a from DOY 16 to 137 by total ET_o.

Development of a crop coefficient based upon GDD

Crop coefficients can also be expressed as a function of GDD. For a particular crop, GDD are defined by the equation:

$$GDD = T_{mean} - T_{base} \tag{32}$$

where T_{mean} is daily mean temperature (°C) and T_{base} is the minimum daily air temperature (°C) required for crop growth. Growing degree days are accumulated over the season as long as T_{mean} does not exceed T_{max}, a daily mean air temperature above which crop growth is constant. In this analysis, GDD were assumed to begin accumulating on the day of seeding (DOY 361, 1987). The day of seeding is ususally easier to determine than day of crop emergence.

Expressed as a function of GDD, k_c was calculated based on the following equation (Slack *et al.*, 1994):

$$\begin{aligned} k_c = {} & c1*\sin(y) + c2*\sin(2y) + c3*\sin(3y) \\ & + c4*\sin(4y) + c5*\sin(5y) + c6*\sin(6y) \end{aligned} \tag{33}$$

where c1 through c6 are empirically-determined regression coefficients and y is defined as:

$$y = \pi * (GDDCUM / c0) \tag{31}$$

where GDDCUM = accumulated GDD and c0 = the value of GDDCUM at which k_c returns to zero, which is equivalent to the point of senescence in winter wheat.

CHAPTER 4
RESULTS AND DISCUSSION

Comparison of BREB and AZMET Data

It should be noted that the AZMET and BREB data sets are time series collected in short (one-hour) intervals. As a result, meteorological measurements at one time period (t) are likely to be correlated with measurements in the preceding time period (t-1). In addition, due to the expected seasonal pattern of the data, the assumption of normality is likely to be violated. Serial correlation and non-normality of the data each tend to make the "goodness of fit" criteria appear better than they are in actuality.

AZMET ET_o vs. BREB ET_a

Estimates of evapotranspiration were made from DOY 16 to DOY 151 using Bowen ratio energy budget (BREB) and Arizona Meteorological Network (AZMET) systems. The BREB system yielded hourly actual ET (ET_a) values for winter wheat, while the AZMET system produced hourly reference ET (ET_o) values. 24-hour totals for ET_a and ET_o were computed by multiplying the sum of the daytime hourly ET values by 1.03. The results are shown in Appendix I. The AZMET ET_o data were found to be normally distributed, while the BREB ET_a data were non-normal.

Regression Analysis

For the period prior to wheat senescence (DOY 16 to DOY 137), a linear regression between 24-hour totals of AZMET ET_0 and BREB ET_a estimates resulted in an $r^2 = 0.94$. The r^2 value (or coefficient of determination) indicates the amount of variation in y (AZMET ET_0) that is explained by x (BREB ET_a). This suggests that only six percent of the variation between AZMET ET_0 and BREB ET_a can be attributed to external factors such as climatic differences or crop development stage. The regression relation is $ET_0 = 0.11 + 0.98\ ET_a$, with a standard error of 0.56. A graphical representation of this relationship is shown in Figure 7.

The r^2 value is surprisingly high given that the data span the period from rapid growth to maturity. The precipitation records provide a plausible explanation for the observed similarity of the values between growth stages. As shown in Figure 8, the presence of precipitation early in the growing season (when the cover was sparse) may have contributed to the similarity between ET_0 and ET_a. Furthermore, the best relationship was expected during the mid-season crop growth stage (DOY 51 to 115), but regression between ET_0 and ET_a during this period yielded somewhat lower correlation (r^2=0.92) than over the entire period.

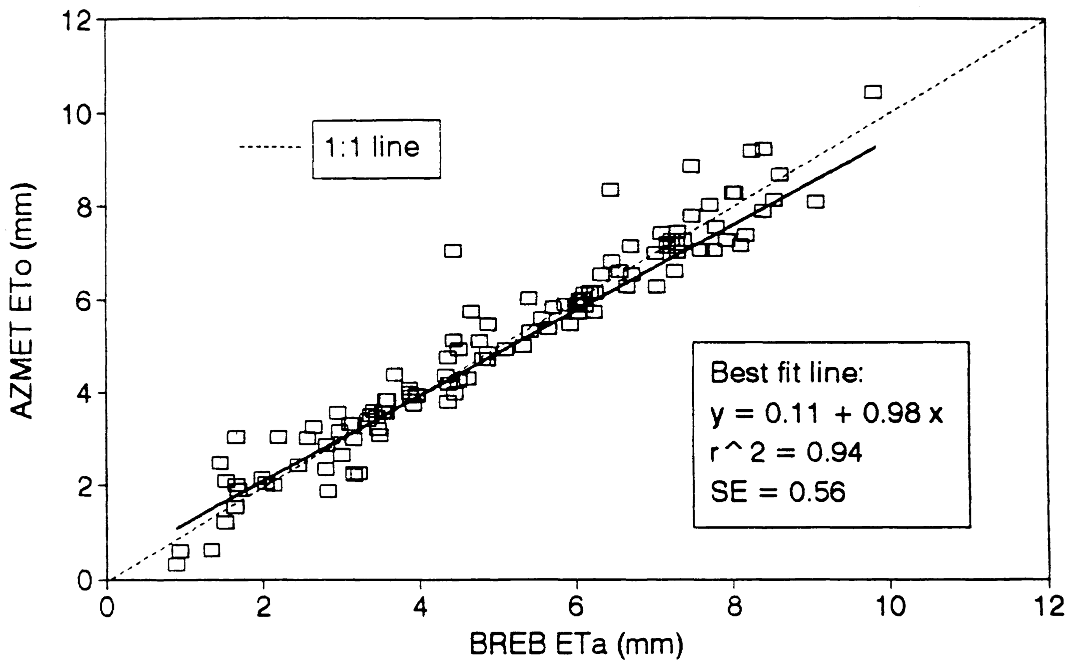

Figure 7. BREB ET_a vs. AZMET ET_0, DOY 16 to 137, 1988

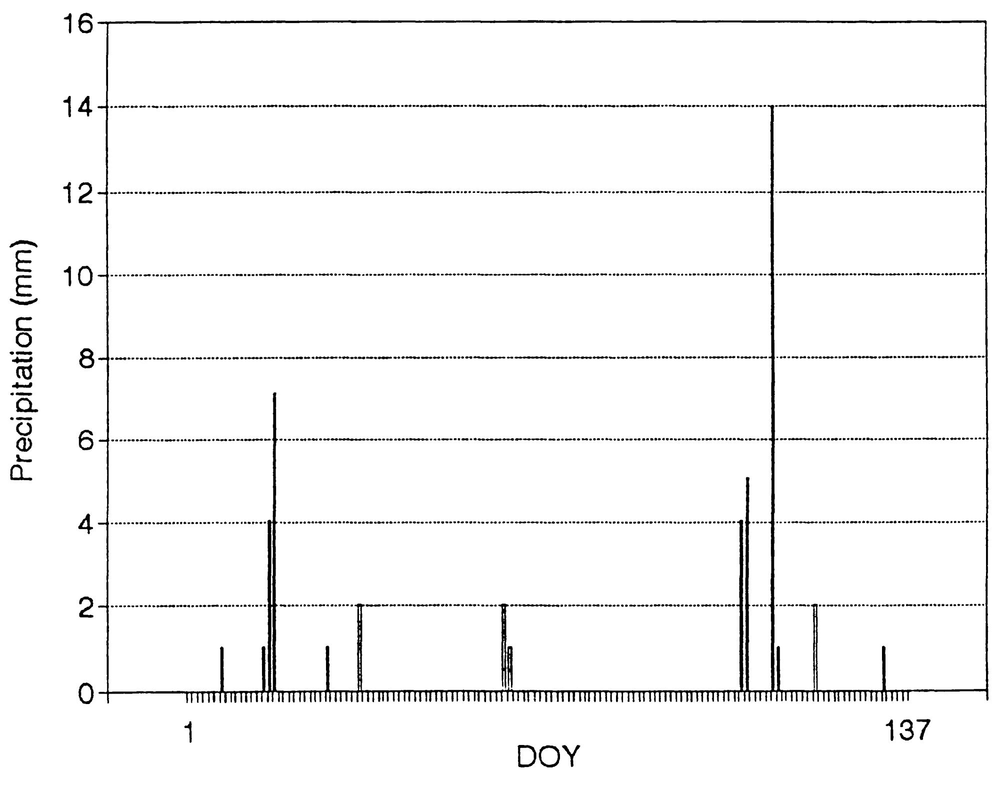

Figure 8. Precipitation events during the 1988 growing season

Hypothesis Testing

To assess the difference between daily BREB ET_a and AZMET ET_o values, a Student's *t* test was performed. Because equal smaple sizes are needed for this test, AZMET ET_o values were discarded for the four days in which BREB ET_a values are missing. The total sample size (n) was therefore 118.

The "null hypothesis" (H_o) tested in this case was that the mean difference between AZMET ET_o and BREB ET_a is zero. Because H_o would be rejected if either AZMET ETo or BREB ETa were significantly larger than the other, the test is referred to as a "two-tailed" test. The Student's *t* test supports or refutes the null hypothesis based on the test statistic (T). T was compared to a tabulated *t* statistic, which is a function of the degrees of freedom of the sample (n-1), by computing the probability (p) that T is less than or equal to *t*. If p is greater than 0.05, the null hypothesis is rejected at the 5 percent level. As demonstrated in Table 6, the two estimates of mean daily ET are equal to two decimal places (5.02 mm = 5.02 mm), and, not surprisingly, H_o could not be rejected at the 5 percent level. The probability that the null hypothesis was true was 90 percent.

Table 6. Paired two sample Student's *t* test for mean differences in daily BREB ET_a and AZMET ET_o

	BREB ET_a	AZMET ET_o
Mean	5.02	5.02
Variance	4.73	4.62
Observations	118	118
Hypothesized Mean Difference	0	
Degrees of Freedom	117	
t statistic	0.125	
P ($T \leq t$) for two-tailed test	0.90	

Climatic Data: AZMET vs. BREB

To assess differences between BREB and AZMET climatic data, linear regressions were developed for solar radiation, wind speed, and air temperature data as measured by the BREB and AZMET systems. In addition, AZMET Q_n values were computed via equation (25) and plotted against BREB Q_n measurements. In each regression, BREB data were treated as independent variables and AZMET data were dependent variables. Linear regression coefficients that were computed and tabulated include: y intercepts, x coefficients (slopes), and their associated standard errors, correlation coefficients (r^2), regression line standard error (SE), and sample size (n).

For each day, only daily means of daylight hours (SR $\geq$ 0.21 $MJ/m^2 \cdot hr$) were included in this analysis. From DOY 16 to DOY 137 (excluding four missing days), there were 1,291 daylight hours and 1,541 nighttime hours. As illustrated in Figure 3, the magnitude of energy fluxes drops substantially at night. If nighttime data had been included in this analysis, regression statistics would likely be heavily biased by the large population of subdued night and early morning climatic conditions.

A comparison of BREB KD and AZMET SR allows the adequacy of the AZMET SR measurements to be verified. A close inspection of the BREB KD data indicated that the measurements dropped during the last 14 days prior to senescence. This may have been caused by some problem with the sensor. Therefore, linear regression was developed between BREB KD and AZMET SR from DOY 16 to DOY 123, as shown in Figure 9. The regression coefficients are shown in Table 7.

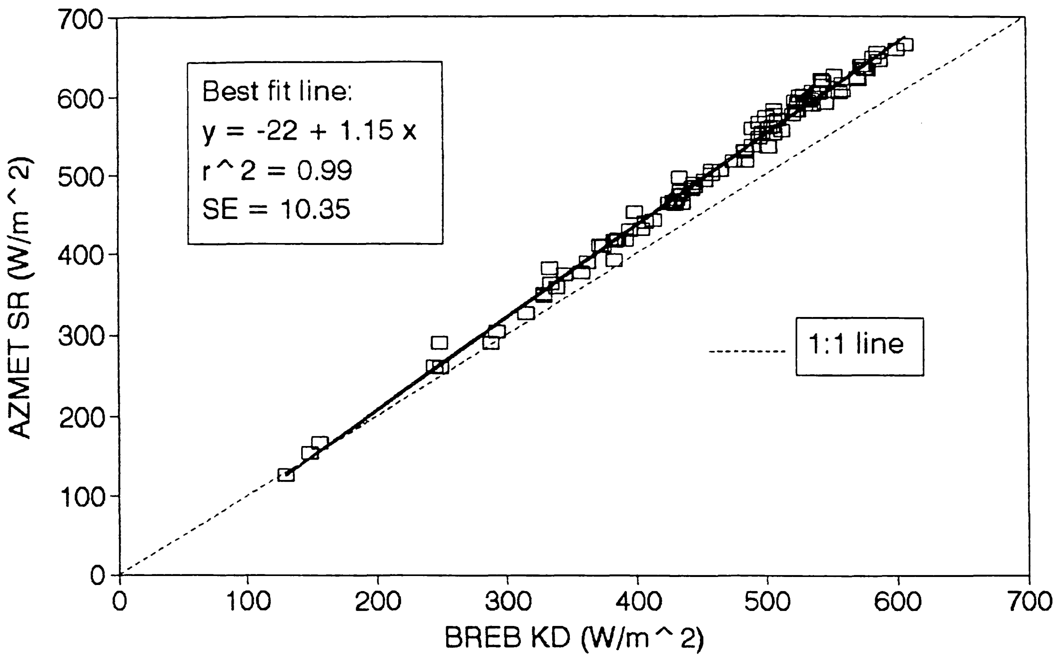

Figure 9. Daily mean BREB KD vs. AZMET SR, DOY 16 to 123, 1988

Table 7. Summary of regression analyses between AZMET and BREB weather data collected during daytime hours from DOY 16 to 137, 1988 (presented as x vs. y)

Regression variables	y intercept	x coeff. (slope)	SE	r^2	n
Daily mean BREB KD vs. AZMET SR (DOY 16 to 123 only)	-22.0 ± 4.7	1.146 ± 0.010	10.35	0.992	104
Daily mean BREB Q_n vs. AZMET Q_n	50.0 ± 10.9	1.183 ± 0.036	28.48	0.903	118
Daily mean wind speed (BREB U1 vs. AZMET U2)	0.48 ± 0.05	1.060 ± 0.022	0.263	0.952	118
Daily mean air temperature (T1 vs. T_a)	-0.83 ± 0.16	1.073 ± 0.008	0.461	0.994	118

Although the BREB KD measurements were ancillary and not included in the computation of LE, the values help confirm the validity of AZMET SR data. Daily mean KD and SR are highly correlated (r^2=0.99), but the slope of the regression line deviates from 1.0 (SR = -22 + 1.15 KD). This implies that calibration standards do not agree between the two systems. AZMET SR values are consistently higher than BREB KD values. The mean daylight value of AZMET SR was 10% higher than that of BREB KD.

Based on these results, it is expected that AZMET Q_n will be higher than BREB Q_n. This is verified by regression analysis. Mean daily Q_n values from the two systems are plotted against each other in Figure 10, and the results of the analysis are included in Table 7 (AZMET Q_n = 50 + 1.18 (BREB Q_n)). At the AZMET station, the mean daylight value of Q_n was 35% higher than at BREB field site.

As stated previously, Osmolski (1985) determined net radiation input to be the most significant of the climatic variables affecting ET from moist sites in arid regions. Therefore, if Q_n values from the two systems were adjusted and brought into agreement, ET_a and ET_o values would not be in such good agreement. Becasue AZMET Q_n estimates are higher than BREB Q_n measurements, AZMET ET_o is calculated assuming greater available energy than BREB ET_a.

The BREB system used in this field campaign made ancillary measurements of wind speed (U1). The wind function (fU2) factors directly into the calculation of AZMET ET_o by the Penman method, so BREB U1 measurements provide important evidence regarding the validity of the AZMET data. A linear regression was developed between the daily means of BREB U1 and daily mean wind speed estimates at 2 m (U2 = 0.93 U3) made

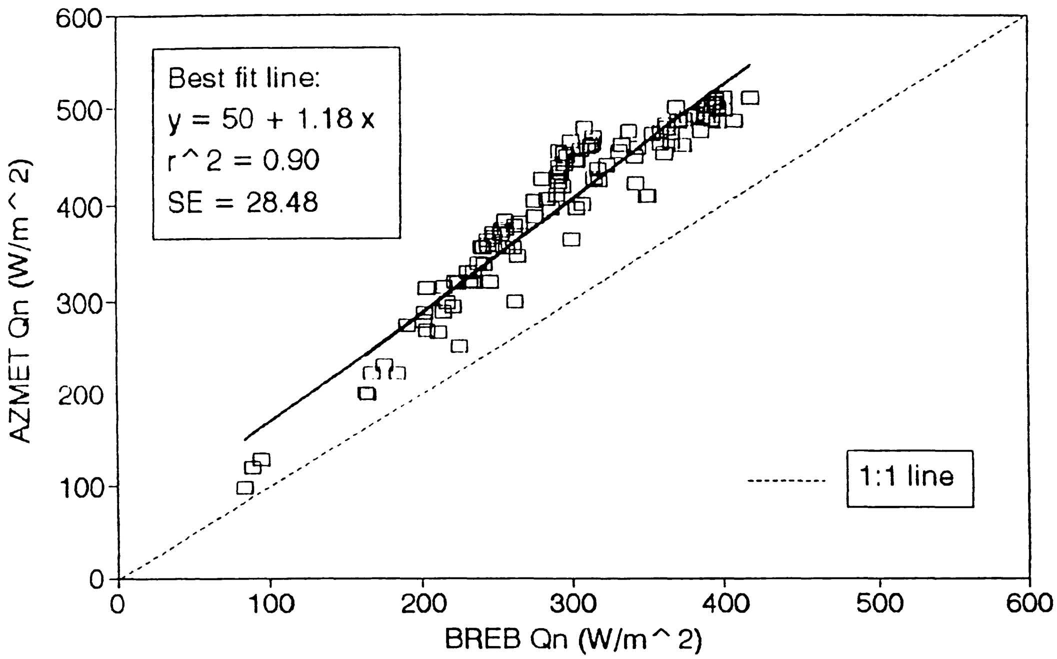

Figure 10. Daily mean BREB Q_n vs. AZMET Q_n, DOY 16 to 137, 1988

by the AZMET system. The results, tabulated in Table 7 and plotted in Figure 11, show that U2 = 0.5 + 1.06 U1. The correlation coefficient indicates good agreement (r^2=0.95), but mean daylight wind speed at the AZMET site was about 30% greater than at the BREB site. Some variation was expected due to differences in surface roughness and stability of the two field sites.

BREB measurements of air temperature (T1) provided another means to verify AZMET data. T1 was regressed against AZMET T_a, with results as shown in Figure 12 and Table 7 (T_a = -0.8 + 1.07 T1). These results show a strong linear relationship between the measurements.

In general, the data in Table 7 show strong correlations between climatic measurements made by the BREB and AZMET systems. Even with data restricted to daylight hours, r^2 values were greater than 0.90 for all four parameters. Greatest agreement occurred between measurements of mean daily air temperature at the two sites. Regression analyses for solar radiation and net radiation suggested that calibration needs to be standardized between the two systems in order for the data to be extended with confidence into a range of analyses.

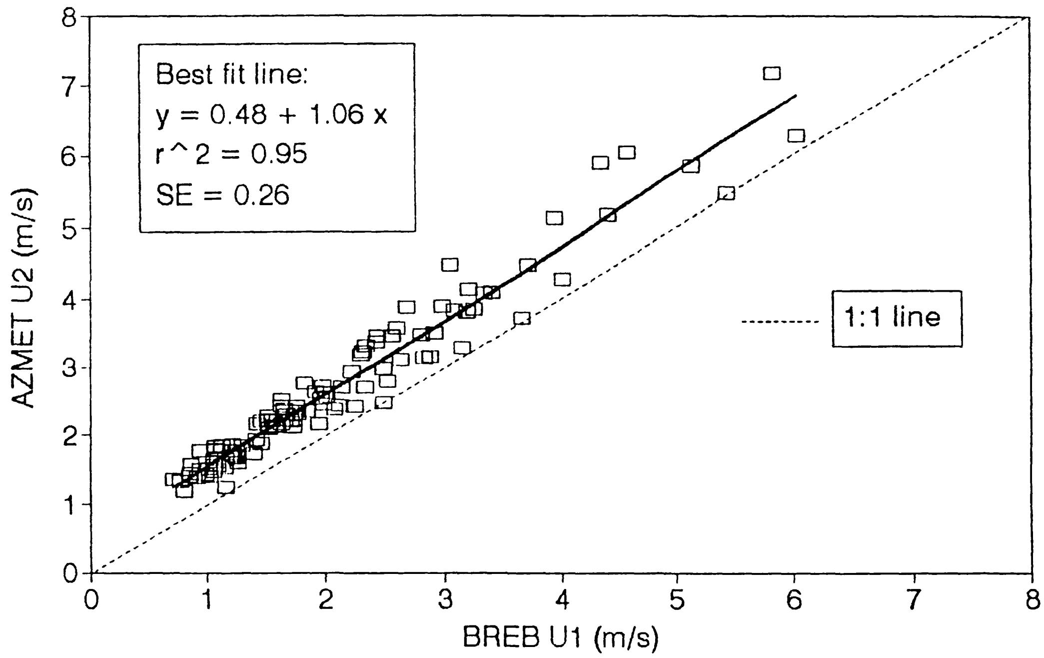

Figure 11. Daily mean BREB U1 vs. AZMET U2, DOY 16 to 137, 1988

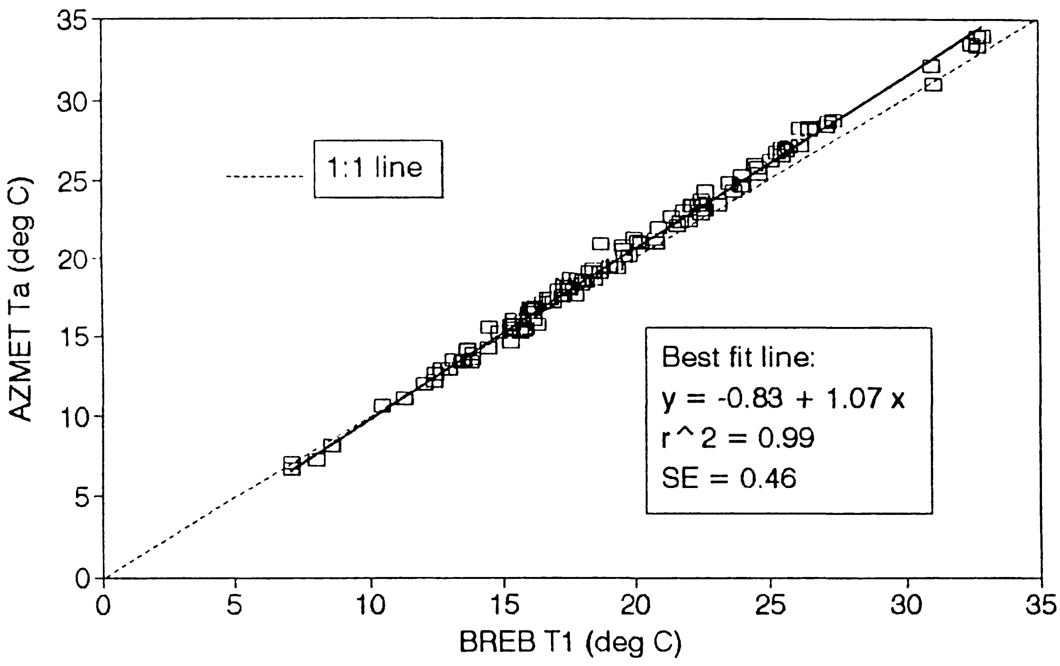

Figure 12. Daily mean BREB T1 vs. AZMET T_a, DOY 16 to 137, 1988

Development of crop coefficients

This study demonstrated the need to bring calibration standards into agreement for net radiometers in BREB and AZMET systems. In this study, however, the values of ET generated by each system were not corrected, primarily because it had not been determined which data set was in need of correction. This may be addressed in future research. Furthermore, the objective herein is to establish a relationship between existing AZMET and BREB data over the growing season. This can be accomplished without adjusting the data.

The linear approach

As illustrated in Appendix I and Figure 13, daily crop coefficient (k_c) values computed based on equation (2) had a mean value of 1.03 for the period prior to senescence. To account for variation due to crop physiology, values were delineated into three stages of crop development: rapid growth, mid-season, and late season. As shown in Table 8, analysis of variance (one-way classification) showed that k_c values were not statistically different (α=0.05) in the different crop stages. Therefore, a single k_c value over the entire study period is appropriate.

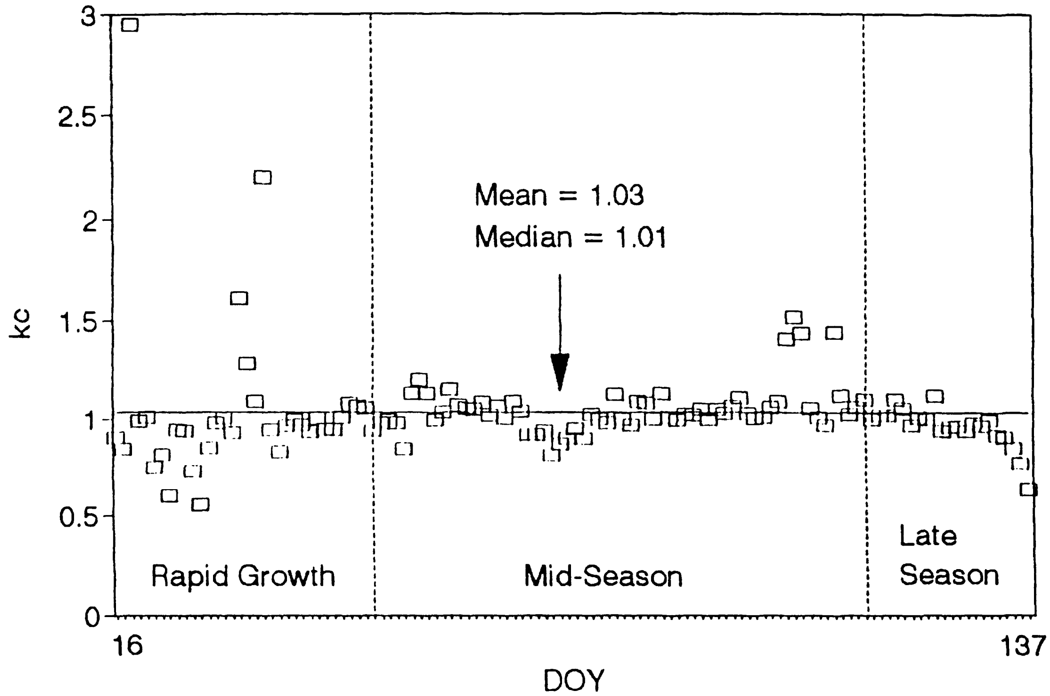

Figure 13. Daily crop coefficients for winter wheat, 1988 (k_c = BREB ET_a/AZMET ET_o)

Table 8. Analysis of variance (one-way classification) of computed wheat k_c values in different stages of crop development

Summary

Stage	Count	Sum	Mean	Variance
Rapid growth	33	34.74	1.05	0.20
Mid-season	63	66.15	1.05	0.02
Late season	22	21.22	0.96	0.01

Analysis of Variance

Source of variation	Sum of squares	Degrees of freedom	Mean square	F ratio
Between groups	0.13	2	0.0665	1.014
Within groups	7.54	115	0.0656	
Total	7.68	117		

$P = P[F_{2,32} > 1.01] = 0.37\ (>0.05)$

The presence of outliers (see Figure 13) within the daily k_c estimates, however, implies that the median is a better measure of central tendency for k_c over the growing season. A median daily value of 1.01 was determined over the period of analysis. Alternatively, the effect of outliers could be mitigated by calculating discrete k_c values for each crop growth stage. As shown in Table 9, k_c estimates developed in this manner remain close to unity. Similarly, a single k_c value for the entire study period was found to be 1.00.

Table 9. Crop coefficients for different growth stages and for the entire study period

DOY	Period	Total BREB ET_a (mm)	Total AZMET ET_o (mm)	k_c
16 - 50	Rapid Growth	87.44	91.94	0.95
51- 115	Mid-Season	337.69	327.36	1.03
116-137	Late Season	167.00	173.58	0.96
16-137	Entire Study Period	592.13	592.88	1.00

Regression analysis between AZMET ET_o and BREB ET_a produced a correlation coefficient of 0.94. This implies that only six percent of the variation between AZMET ET_o and BREB ET_a was attributable to external characteristics such as crop physiological stage. Analysis of variance indicated no difference in k_c (with 95 percent confidence) between crop stages. Values of k_c tended to be close to unity in most cases. As a result, it is submitted here that the median k_c value of 1.0 could be substituted into equation (1) to develop estimates of ET_a over the entire period prior to senescence.

The GDD approach

An alternative crop coefficient based on growing degree days (GDD) has been developed for wheat at the Maricopa

Agricultural Center (Slack et al., 1994). The GDD coefficient for 1988 was developed from AZMET daily mean air temperature data. GDD, or heat units, were assumed to begin accumulating on the day of seeding (day 361, 1987). For wheat, Slack (1994) indicated that T_{base} = 4.44°C and T_{max} = 27.2°C. The GDD coefficient was developed using equations (32), (33), and (34) and coefficients determined by Slack et al. (1994) at MAC. These coefficients are shown in Table 10.

Table 10. Regression coefficients used in calculation of GDD-based k_c for wheat

Coefficient	Value
c0	2000
c1	1.067792
c2	-0.27092
c3	-0.02558
c4	0.092963
c5	-0.01232
c6	-0.00046

Source: Slack (1994)

Using the GDD-based k_c values and AZMET ET_o values, alternative estimates of ET_a (GDD-based ET_a) were made by equation (1). A scatter diagram was developed between GDD-based ET_a values and BREB ET_a values. The results are shown in

Figure 14, and it is evident that the GDD model does not conform to the estimates of ET_a and ET_o.

The data in Figure 14 imply that the GDD-based model underestimates ET_a when ET is low, and overestimates ET_a when ET is high. This is attributed to the imprecision of the GDD-based model in timing crop maturity. Slack et al. (1994) developed the coefficients in Table 10 based on the physiology of a number of wheat varieties. Peak water use of individual cultivars, however, may not be synchronized with the model.

In addition, the GDD-based model does not explicitly account for soil surface wetness. This may have caused the GDD-based k_c values to be too low in the early stages of the growing season. Irrigation and precipitation that occurs when the canopy is sparse may completely wet the surface, causing ET_a to be similar to ET_o.

Assessment of legal consumptive use standard

Irrigated areas within Pinal County are contained within the Pinal Active Management Area (AMA). As indicated in ADWR (1988), the maximum annual groundwater allotment (MAGA, ac-ft) for each farm in the AMA is calculated based on the following equation:

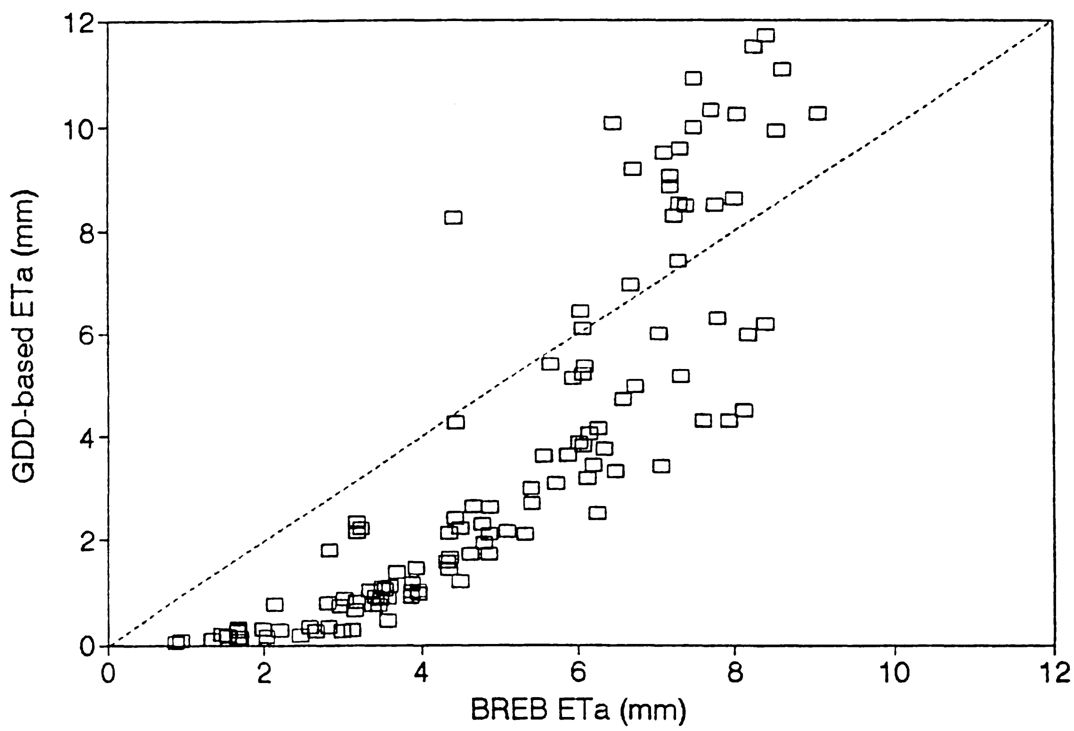

Figure 14. BREB ET_a vs. GDD-based ET_a

$$MAGA = IWD * WDA \tag{35}$$

where IWD is irrigation water duty (ac-ft/ac) and WDA is "water duty acres" (ac) defined as the maximum number of acres irrigated on the farm in any one year in the five years preceding January 1, 1980.

The irrigation water duty (ac-ft/ac) for each farm unit is calculated by the equation:

$$IWD = (\text{average } TIR)/AE \tag{36}$$

where average TIR is the average total irrigation requirement (ac-ft/ac) between 1975 and 1979 and AE is the assigned irrigation efficiency for the farm unit (percent). In each year, the TIR is computed by the equation:

$$TIR = CU + ON + LR - EP \tag{37}$$

where CU is consumptive use of the crop grown (ac-ft/ac), ON is "other needs" for water for crop production (ac-ft/ac), LR is the leaching requirement (ac-ft/ac) for the farm unit, and EP is "effective precipitation," or the amount of annual precipitation available to the crop (ac-ft/ac). In the Pinal AMA, the EP term is ignored due to the minimal and sporadic nature of precipitation in the region (ADWR, 1988).

ADWR assigns CU and ON values for various crops based on Erie *et al.* (1981). For wheat, the Erie study proposed CU and ON values of 2.15 ac-ft/acre and 0 ac-ft/acre, respectively, and these are the values used in the Pinal AMA (ADWR, 1988). When ON = 0, ADWR computes LR based on the following relation:

$$LR = CU * [(1 - (EC_w / (5EC_e - EC_w))^{-1} + AE - 1.85] \quad (38)$$

where EC_w is electrical conductivity of the irrigation water (mmhos/cm) and EC_e is crop tolerance to soil salinity in electrical conductivity of the soil saturation extract (mmhos/cm).

The consumptive use term in equations (37) and (38) is equivalent to ET_a. As shown in Appendix I, total ET_a for the period from DOY 16 (20 days after seeding) to DOY 137 (senescence) was estimated to be 592 mm. Four days of BREB data were missing, and these values were estimated using the regression equation AZMET ET_o = 0.11 + 0.98 BREB ET_a, re-written as BREB ET_a = (AZMET ET_o - 0.11) / 0.98. Adding in the four resulting values, which totaled 20 mm, the adjusted total ET_a for 122 days is 612 mm.

To extend the ET_a values to the day of planting, a simple estimation was made based on Figure 15, which shows ET_a as a function of time. A curve was manually fit to the time

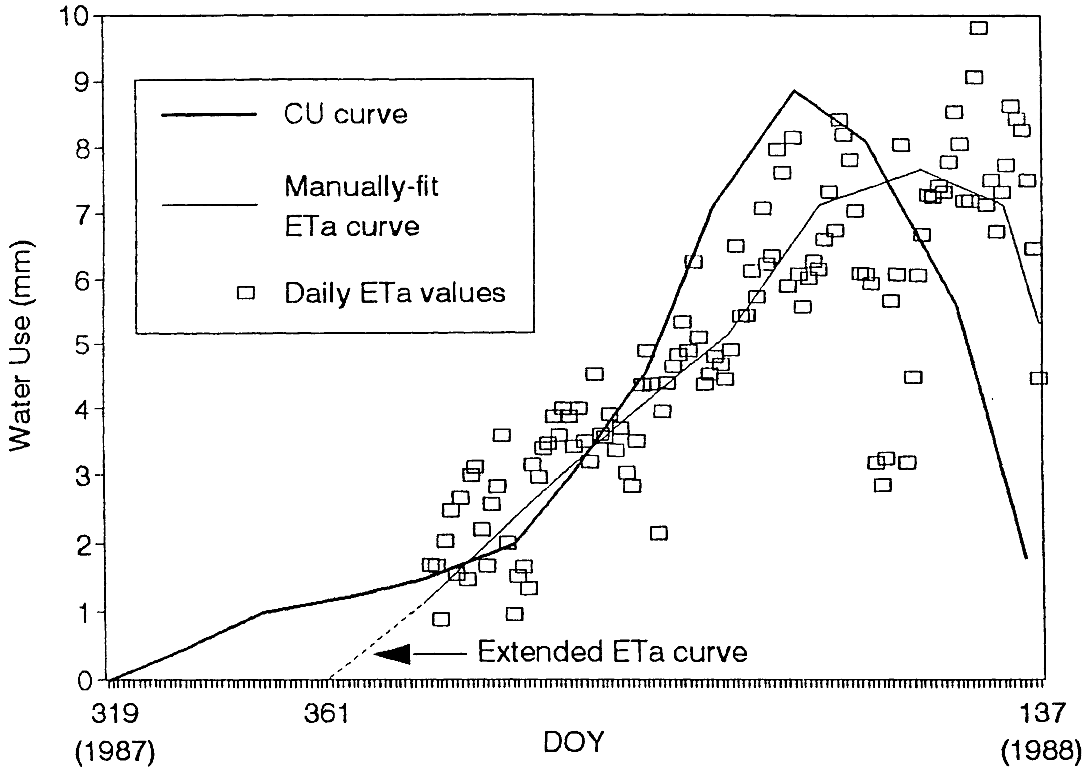

Figure 15. Comparison of BREB ET_a and CU values from Erie et al. (1981)

distributions of ET_a and extended to 0 mm at the day of planting (DOY 361). For the 20 additional days, 10 mm of water use are thereby approximated, resulting in a total ET_a of 622 mm for the growing season (DOY 361 to DOY 137). By comparison, Cooper (1990) estimated ET to be approximately 613 mm for the period prior to senescence. In calculating this sum, Cooper did not include ET prior to DOY 1, 1988.

As stated above, the ADWR CU value for wheat in the Pinal AMA is 2.15 ac-ft/ac. As an equivalent depth, this value is equal to 2.15 ac-ft/ac * 12 in/ft * 25.4 mm/in, or ~655 mm. This value is slightly greater (33 mm) than the total ET_a measured over the winter wheat field. The legal standard therefore does not limit crop production.

Figure 15 also shows the temporal distribution of CU values from Erie *et al.* (1981). As this graph shows, the CU curve begins on DOY 319, 1987, although BREB ET_a measurements were made over a wheat crop planted on DOY 361, 1987. In addition, CU values peak earlier than ET_a values. Brown (1994) indicated that advances in genetics and plant production practices have changed cropping seasons somewhat since the Erie research was conducted, and this could be responsible for the differences observed in Figure 15.

CHAPTER 5
SUMMARY AND CONCLUSIONS

Measurements from a Bowen ratio energy balance system and an AZMET weather station were compared for a duration of 122 days under variable weather conditions. Excellent agreement between the two systems in evaluating evapotranspiration during the daytime hours was observed for the period prior to senescence. The analysis of 118 daily (24-hour) totals showed that the average absolute difference between actual ET from BREB and reference ET from AZMET was 0.39 mm with a standard deviation (SD) of 0.40, standard error of 0.04 and a range from 0 to 2.59 mm. The agreement between these values implies that a simple crop coefficient can be used for winter wheat in areas similar to Maricopa, Arizona. Daily crop coefficients were calculated by equation (2), showing no statistical difference (α=0.05) between crop stages, and yielding a median value of 1.01. A single crop coefficient for the full study period was computed to be 1.00.

The utility of this crop coefficient may be undermined by the fact that net radiation measurements by the two systems differed significantly. AZMET Q_n values were consistently higher than BREB Q_n values. If these values were brought into agreement, AZMET ET_0 would drop accordingly in relation to

BREB ET_a values. As a result, the crop coefficient value ($k_c = ET_a/ET_0$) would be increased.

In comparison to the BREB-based estimates of ET_a, ET_a estimates made with the GDD-based crop coefficient did not show good agreement in the period prior to senescence. GDD-based crop coefficients are considered advantageous becasue they account for year-to-year variability in climate and planting dates. However, because AZMET provides hourly ET_0 estimates, the effect of climate on crop water requirements is accommodated. In addition, although the median k_c value was computed for a specific planting date, our analysis demonstrated no statistical difference between ET_a estimates in different crop growth stages.

The Groundwater Management Act of 1980 gave the Arizona Department of Water Resources regulatory authority over groundwater resources in Active Management Areas. The consumptive use values used by ADWR in its groundwater allocation process are regularly refined. Because AZMET ET_0 values provide an excellent estimate of ET_a (or CU) for winter wheat near MAC, AZMET is a valuable tool in the determination of groundwater rights.

In order for water conservation to be encouraged in irrigated agriculture in Arizona, planners and researchers need to find economical and easy methods for irrigation scheduling. Demonstrating the value of AZMET in this effort was the main objective of this research. In this case, AZMET data proved to be stongly correlated with proven Bowen ratio energy budget systems. AZMET data are available from 21 stations across the state and are easily accessible. In order for AZMET ET_0 values to be used effectively to quantify irrigation needs, valid crop coefficients for different crops need to be developed and made readily available.

Appendix I. Comparison of 24-hour AZMET ETo and BREB ETa values and computed kc for winter wheat at MAC from DOY 16 to 137, 1988

Day of Yr	AZMET 24-hr ETo (mm)	BREB 24-hr ETa (mm)	kc (BREB ETa/ AZMET ETo)	Absolute Difference |BREB ETa- AZMET ETo|
16	1.87	1.69	0.90	0.18
17	1.98	1.67	0.84	0.31
18	0.30	0.88	2.95	0.58
19	2.05	2.03	0.99	0.02
20	2.43	2.46	1.01	0.03
21	2.07	1.55	0.75	0.53
22	3.24	2.64	0.81	0.61
23	2.46	1.46	0.59	1.00
24	3.15	2.98	0.95	0.17
25	3.31	3.11	0.94	0.20
26	3.02	2.19	0.73	0.82
27	3.02	1.67	0.55	1.35
28	3.01	2.56	0.85	0.45
29	2.85	2.81	0.98	0.05
30	3.54	3.57	1.01	0.03
31	2.14	1.98	0.93	0.16
32	0.59	0.95	1.61	0.36
33	1.18	1.52	1.29	0.34
34	1.51	1.65	1.09	0.14
35	0.61	1.34	2.20	0.73
36	3.63	-	-	-
37	4.49	-	-	-
38	3.32	3.14	0.95	0.17

Appendix I. (continued)

Day of Yr	AZMET 24-hr ETo (mm)	BREB 24-hr ETa (mm)	kc (BREB ETa/ AZMET ETo)	Absolute Difference |BREB ETa- AZMET ETo|
39	3.54	2.96	0.83	0.59
40	3.50	3.38	0.96	0.12
41	3.47	3.45	0.99	0.02
42	3.98	3.87	0.97	0.11
43	3.82	3.57	0.93	0.25
44	3.94	3.98	1.01	0.03
45	4.07	3.87	0.95	0.20
46	3.61	3.41	0.95	0.19
47	3.91	3.97	1.01	0.05
48	3.21	3.47	1.08	0.26
49	2.97	3.17	1.07	0.20
50	4.25	4.50	1.06	0.25
51	3.82	3.59	0.94	0.23
52	3.58	3.53	0.99	0.05
53	3.89	3.88	1.00	0.01
54	3.40	3.33	0.98	0.07
55	4.37	3.69	0.84	0.68
56	2.65	3.00	1.13	0.36
57	2.33	2.80	1.20	0.47
58	3.07	3.48	1.13	0.41
59	4.36	4.33	0.99	0.03
60	4.68	4.86	1.04	0.19
61	3.77	4.35	1.16	0.58
62	1.99	2.14	1.08	0.15

Appendix I. (continued)

Day of Yr	AZMET 24-hr ETo (mm)	BREB 24-hr ETa (mm)	kc (BREB ETa/ AZMET ETo)	Absolute Difference |BREB ETa- AZMET ETo|
63	3.74	3.94	1.05	0.20
64	4.16	4.37	1.05	0.21
65	4.26	4.62	1.08	0.36
66	4.70	4.80	1.02	0.10
67	4.99	5.32	1.07	0.34
68	5.29	-	-	-
69	4.82	4.87	1.01	0.05
70	5.72	6.25	1.09	0.54
71	4.89	5.09	1.04	0.20
72	4.74	4.36	0.92	0.38
73	4.89	4.50	0.92	0.39
74	5.07	4.78	0.94	0.29
75	5.73	4.66	0.81	1.07
76	6.42	-	-	-
77	5.11	4.43	0.87	0.67
78	5.44	4.88	0.90	0.56
79	6.82	6.48	0.95	0.34
80	6.03	5.41	0.90	0.62
81	5.29	5.42	1.02	0.13
82	6.13	6.13	1.00	0.00
83	5.81	5.72	0.99	0.09
84	6.27	7.06	1.13	0.79
85	6.18	6.20	1.00	0.02
86	6.52	6.33	0.97	0.19

Appendix I. (continued)

Day of Yr	AZMET 24-hr ETo (mm)	BREB 24-hr ETa (mm)	kc (BREB ETa/ AZMET ETo)	Absolute Difference |BREB ETa- AZMET ETo|
87	7.26	7.95	1.09	0.68
88	7.06	7.61	1.08	0.56
89	5.88	5.88	1.00	0.01
90	7.17	8.13	1.13	0.96
91	5.98	6.06	1.01	0.07
92	5.58	5.57	1.00	0.01
93	5.85	6.01	1.03	0.16
94	6.15	6.26	1.02	0.11
95	5.86	6.13	1.05	0.27
96	6.59	6.59	1.00	0.00
97	6.99	7.32	1.05	0.33
98	6.53	6.74	1.03	0.21
99	7.88	8.41	1.07	0.53
100	7.36	8.19	1.11	0.82
101	7.55	7.80	1.03	0.25
102	6.97	7.03	1.01	0.06
103	6.02	6.09	1.01	0.07
104	5.70	6.06	1.06	0.36
105	5.45	5.94	1.09	0.49
106	2.25	3.16	1.41	0.92
107	1.85	2.82	1.52	0.97
108	2.25	3.22	1.43	0.97
109	5.38	5.67	1.05	0.29
110	5.97	6.06	1.02	0.09

Appendix I. (continued)

Day of Yr	AZMET 24-hr ETo (mm)	BREB 24-hr ETa (mm)	kc (BREB ETa/ AZMET ETo)	Absolute Difference |BREB ETa- AZMET ETo|
111	8.28	8.02	0.97	0.26
112	2.19	3.16	1.44	0.97
113	3.97	4.46	1.12	0.49
114	5.91	6.05	1.02	0.14
115	6.28	6.67	1.06	0.39
116	6.59	7.29	1.11	0.70
117	7.25	7.24	1.00	0.01
118	7.26	7.40	1.02	0.14
119	7.18	7.31	1.02	0.13
120	7.06	7.78	1.10	0.73
121	8.11	8.54	1.05	0.44
122	8.27	8.05	0.97	0.22
123	7.11	7.19	1.01	0.08
124	7.20	7.19	1.00	0.01
125	8.10	9.07	1.12	0.97
126	10.43	9.81	0.94	0.62
127	7.42	7.12	0.96	0.30
128	7.78	7.51	0.97	0.27
129	7.14	6.72	0.94	0.42
130	7.45	7.32	0.98	0.12

Appendix I. (continued)

Day of Yr	AZMET 24-hr ETo (mm)	BREB 24-hr ETa (mm)	kc (BREB ETa/ AZMET ETo)	Absolute Difference |BREB ETa- AZMET ETo|
131	8.00	7.73	0.97	0.27
132	8.65	8.62	1.00	0.03
133	9.21	8.42	0.91	0.79
134	9.17	8.27	0.90	0.90
135	8.85	7.51	0.85	1.34
136	8.34	6.45	0.77	1.89
137	7.03	4.44	0.63	2.59
SUM	612.71	592.13	122.12	45.66
MEAN	5.02	5.02	1.03	0.39
MAX	10.43	9.81	2.95	2.59
MIN	0.30	0.88	0.55	0.00
MEDIAN	5.03	4.83	1.01	0.26
SD	2.14	2.14	0.26	0.40
SE	0.19	0.20	0.02	0.04
COUNT	122	118	118	118

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