Technical Report TR01-7

Agricultural Extension Station | Cooperative Experiment | Department of Soil and Crop Sciences | Southwestern Colorado Research Center | November 2001

Assessment of Irrigation Water Management and Demonstration of Irrigation Scheduling Tools in the Full Service Area of the Dolores Project: 1996-2000

Part II: Calibration of the Watermark Soil Moisture Sensor and ETgage Atmometer

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Knowledge to Go Places

Acknowledgments

We thank John Porter, General Manager of the Dolores Water Conservancy District (DWCD) and Patrick Page, Coordinator of the Water Conservation Programs for the Upper Colorado Bureau of Reclamation Region for their encouragement and support throughout the study. Special thanks are extended to Clinton C. Shock of Oregon State University, Calvin Pearson of Colorado State University, and Reagan Waskom of Colorado State University who reviewed this report and provided valuable comments.

Disclaimer

Trade names are included for the benefit of the reader and do not imply any endorsement or preferential treatment of the products by the authors or Colorado State University.

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Part II: Calibration of the Watermark Soil Moisture Sensor and ETgage Atmometer

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ABSTRACT

Watermark sensors and Etgage atmometers were used in 1997, 1998, and 1999 in the Full Service Area (FSA) of the Dolores Project to demonstrate and encourage the use of sound irrigation scheduling methods. A strong correlation was found between the Watermark sensor Model 200SS readings and water content of the predominant soil type in the FSA. A third degree polynomial provided an excellent fit for the data. Slow Watermark sensor response to soil drying was observed at readings of approximately 0 to 10 kPa and above 150 kPa. Close agreement between alfalfa reference evapotranspiration (ETr) values measured with ETgage Model A or computed using the 1982 Kimberly-Penman equation was achieved at Yellow Jacket during the growing season (May to September) in 1997, 1998, and 1999. The highest correlation was obtained when ETr values were averaged over three and seven-day periods. The linear regression of weekly ETr averages for all three years was ETgage ETr (inches) = 1.014 Kimberly Penman ETr (inches) with $r^2 = 0.98$. ETgage appears to underestimate ETr values during rainy days, possibly due to the saturation of the canvas cover with rainwater.

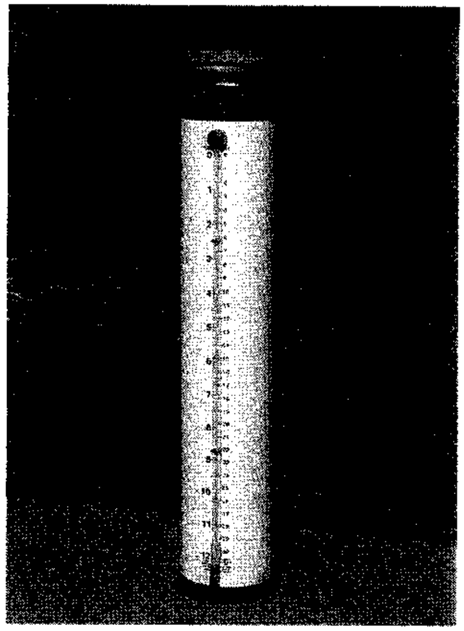

Figure 1. Atmometer device for the estimation of evapotranspiration.

Figure 2. Watermark resistance-type soil moisture sensor and meter.

PART II_A: WATERMARK SOIL MOISTURE SENSOR CALIBRATION

Introduction

Watermark sensors (Irrometer Co., Inc., Riverside, CA) operate on the same principle of electrical resistance as gypsum blocks. They contain a wafer of gypsum imbedded in an insoluble granular fill (matrix) material held in a fabric tube supported in a metal or plastic screen (Shock and Barnum, 1994). The granular matrix material approximates compressed fine sand and silt (Ley, 1994). Two electrodes are imbedded in the granular matrix material and measure the resistance to electrical current flowing between them. Higher resistance readings mean lower block water content and lower (more negative) soil water tension. The granular matrix material enhances the movement of water to and from the surrounding soil. It reduces the problems inherent to gypsum blocks such as inconsistent pore size distribution and loss of contact with the soil by dissolving. The gypsum wafer of the Watermark sensor dissolves slowly, buffering the effect of salinity on electrical resistance of the soil solution between the electrodes (Eldredge et al., 1993).

Watermark sensors have been used successfully to monitor soil water status and as a tool for scheduling irrigation (Eldredge et al., 1993; Meron et al., 1996; Mitchell and Shock, 1996; Orloff and Hanson, 2000; Shock et al., 1998b, 1998c, 2000). They are low cost, low maintenance, and are well suited for automated irrigation systems. Watermark sensors are reportedly more adaptable to a wider range of soil textures and irrigation regimes than gypsum blocks (Ley, 1994). They are also more stable and have a longer life than gypsum blocks.

Different soils have different water content versus matric potential curves, thus the calibration of a porous block against matric potential may be more reasonable and more useful than calibration against water content (Gardner, 1986). The matric potential is related to the adsorptive forces of the soil matrix. The matric potential of a completely saturated soil is zero. The matric potential of water above the water table is always negative. Matric potential increases (in absolute terms) as the soil dries out (Baver et al., 1972). Ideally, two calibration curves are needed: one for drying, extending from very wet to very dry, and one for wetting, where the starting point is the very dry range. The wetting curve is usually not fitted since it is difficult to wet a soil only partially.

Thomson and Armstrong (1987) and McCann et al. (1992) produced Watermark sensor Model 200 calibration equations that express soil water potential as a function of electrical resistance and soil temperature. The two equations deviate significantly from each other due to differences in excitation methods of the sensors (Thomson et al., 1996). A modified Watermark sensor 200SS followed the same calibration curve as the one generated by Thomson and Armstrong (1987). Spaans and Baker (1992) found excellent correlation (second-order polynomial, $r^2>0.98$) between electrical resistance of Watermark sensor Model 200 and soil matric potential of a silt loam and loamy sand. However, calibration curves were unique for each block and each soil. Moreover, repeated calibration of selected blocks in the same soil produced different results. Better repeatability of the results can be achieved with newer Watermark sensor models (Bill Pogue/Irrometer Co., personal communication, 2001). Also, Shock et al. (1998a) found that stainless steel models used in their experiment had "greater accuracy with less sensor to sensor variation than the model 200" (p. 145). They developed the following calibration equation for Watermark sensor Model 200SS (same as used in this study):

$$S = -(4.093 + 3.213\ R)/(1-0.009733\ R - 0.01316\ T) \qquad [1]$$

$(n=729, r^2=0.945)$

Where S is soil water potential in kPa, R is electrical resistance in kΩ, and T is soil temperature in °C.

Equation [1] was later built into the Watermark digital meter Model 30 KTCD-NL (Irrometer Co., Inc., Riverside, CA), which was also used in this study. Equation [1] was developed using data in the range -10 to -75 kPa of soil water potential as measured with Irrometer Model RSR 32 cm Tensiometer. It was done at controlled room temperature of 15 °C (59 °F) and 25 °C (77 °F). Calibration of the 30 KTCD-NL meter for soil water potentials 0 to -10 kPa was drawn from Fig. 1, p. 143 of Shock et al. (1998a). A linear relationship was used by Irrometer to extrapolate data for water potential <-75 kPa (Bill Pogue, personal communication., 2001). It is not the same as the one built into the Model 30 KTC meter and reported by Eldredge et al. (1993, eq. 2, p. 1229) and by Shock et al. (1998a, eq. 1, p. 141).

Shock et al. (1998a) noted that for all Watermark sensor models used in their study, the effect of temperature on soil water potential was greater as the soil became drier. They cautioned against using equation [1] or the other equations they developed outside the range (–10 to –80 kPa) of soil water potential the sensors were calibrated against. Eldredge et al. (1993) found a strong correlation between Watermark Model 200 readings and tensiometer soil water potential. The relationship was linear over the range 0 to –80 kPa. Watermark readings were also closely related to soil water content measured gravimetrically or with a neutron probe.

Objective

The objective of this study was to establish a calibration equation that relates the Watermark sensor readings to water content for the predominant soil type at the Full Service Area (FSA) of the Dolores Project. This was part of a project to evaluate irrigation water management in the FSA and demonstrate the use of irrigation scheduling tools (Berrada et al., 2001a, 2001b). Local calibration is important for accurate interpretation of Watermark sensor readings. Data generated by the calibration equation can also be used to verify the accuracy of ET-based water balance computations.

Materials and Methods

Calibration of the Watermark sensor Model 200SS (Irrometer Co. Inc., Riverside, CA) for three different soil depths was carried out in the year 2000 by following procedure 21-3.2.2.2 in Gardner (1986, p. 516-517) with some modifications. Wetherill[1] silty clay loam (fine-silty, mixed, superactive, mesic Aridic Haplustalfs) samples were taken from three ranges of depth:

[1] The Wetherill soil type represents over 50% of the soils in the Full Service Area (Doug Ramsey, NRCS, personal communication, 2001).

0-12 in.(0-30.5 cm), 12-24 in.(30.5-61.0 cm), and 24-36 in.(61.0-91.5 cm) at the Southwestern Colorado Research Center at Yellow Jacket. Bulk density (D_b) of three soil samples within each range of depth was determined by the core method (Blake and Hartge, 1986, p. 364-367). The three samples were averaged to obtain a D_b value for each range of depth (Table 1). The soil was packed into the calibration blocks to about the same D_b as was determined by the core method. The volume of the sensor within the calibration block was accounted for when calculating D_b for the soil in the block.

Three, new Watermark sensors were soaked in water overnight. Three wire screen boxes, 5 x 5 x 7 in. high, were constructed by brazing one-eighth in. mesh screen, leaving an open top. The size of the screen boxes allowed for 2 in. of soil around each sensor. The screen boxes were lined with one-sixteenth in. mesh screen to hinder soil particles from washing out. To obtain a tare weight, each saturated sensor, its attached leads, and its screen box were weighed together with a shallow polypropylene container that they would be placed in.

The tare weights were adjusted as each sensor in a calibration block dried out. A Watermark sensor was soaked in water for 24 hours and then weighed with a Precision Plus Ohaus electronic scale (Model TP4KD, Ohaus Corporation, Florham Park, NJ). A reading was then taken with a Watermark digital meter[2] (Model 30 KTCD-NL, Irrometer Co. Inc., Riverside, CA). Subsequent weights and readings were taken as the sensor dried out. The readings of that sensor were compared to the readings of the sensors in the calibration blocks as their soil dried to deduce the approximate weight of the water that was lost from the sensors in the calibration blocks. This weight was then subtracted from the original tare weights.

A soil sample from one of the three depths sufficient to fill a screen box to about three-sixteenths in. from the top was moistened to near saturation. A saturated sensor was carefully covered with some of the moistened soil to insure good contact and was then packed into the center of a screen box with more of the moistened soil. The entire apparatus (wet soil plus tare) was weighed with an Ohaus large capacity electronic scale (Model I 10, Ohaus Corporation, Florham Park, NJ). A subsample of the remaining moistened soil was then taken and its water

[2] Meter readings are in kilopascal (kPa) or centibars (cbars). 1 kPa = 1 cbar = 0.145 pounds per square inch.

content determined by the oven-drying gravimetric method (Gardner, 1986, p. 503-507). Dry mass of the soil in the calibration block was calculated as:

Soil dry mass (grams) = [(wet mass + tare) – (tare)]/[(% water content/100) + 1]

Where water content is on a dry mass basis. The procedure was repeated for the remaining two soil depths. Since the soil in the screen box apparatus was already near saturation, the first kPa reading was taken to determine the first calibration point. (The temperature setting of the meter was adjusted to the approximate soil temperature of the block before each reading). The water content percentage (dry mass basis) at this and subsequent calibration points was calculated as:

Water content (%) = 100[(tare + wet soil mass) – (tare + dry soil mass)]/dry soil mass

Calibration points were separated by approximately 0.5% water content. The above equation was used to back calculate to the desired weight for the next calibration point and water was allowed to evaporate from the apparatus until the desired weight was reached. At this point, the entire apparatus was enclosed in a plastic bag to prevent further water loss and placed in a dark cabinet overnight to allow for the water in the sensor and soil to equilibrate. The procedure was repeated for the other two apparatuses. A kPa reading was taken the following morning for the next calibration point and water was allowed to evaporate from the apparatus until the next desired weight was reached. The procedure was repeated with the three apparatuses until the upper limit (driest soil) of the Watermark digital meter was reached, 199 kPa. Water content (%) was regressed against the kPa readings to obtain a calibration equation for each of the three soil depths. SAS GLM was used to test the significance of depth on soil water content and generate estimates of the calibration equation parameters and their standard error (SAS Inst., 2000).

Results and Discussion

Watermark sensor readings were highly correlated with soil water content at all three depths. Soils at depths 12-24 in. and 24-36 in. were grouped together since they have similar texture and water release characteristics (Table 1 and Fig. 1). The effect of depth on water content was highly significant, which reflects the difference between the topsoil and the soil beneath it. The best fit was obtained with a third-degree polynomial equation (Table 2). Eldredge et al. (1993) established a curvilinear relationship between Watermark sensor (Model 200X) readings using a 30KTC meter and volumetric soil water content determined with the gravimetric method:

$$Y\ (m^3m^{-3}) = 0.256/(1+(0.0438x^{29})^{0.224} \quad [2]$$

(n=94, RMSE=0.017)

Where x is the sensor reading in J kg^{-1}[3]

Equation [2] was established for a coarser soil and an older Watermark sensor model than used in this study, which could explain the differences in water content simulated using equation [2] or the equations developed here (Table 3). Our calibration appears to adequately represent the entire range of Watermark meter readings (0 to 199 kPa) and soil water availability. Note that the starting water content for all three depths falls much below the saturation point as measured by the pressure plate method (Klute, 1986). Assuming that complete saturation occurs at zero bar (10^2 kPa) tension, then water content (by weight) at saturation was 45.5, 53.9, and 52.7% at depths 0-12 in., 12-24 in., and 24-36 in., respectively (Fig. 1). In contrast, water content at the first reading was 32.6, 39.1, and 36.8% at depths 0-12 in., 12-24 in., and 24-36 in., respectively (Table 5). These values are probably closer to what Klute (1986, p. 637) referred to as the "*natural saturation* or the *satiated* water content". Natural saturation is reached as the pressure head approaches zero, but not all the pore space in the soil can be occupied by water due to the presence of entrapped air.

Watermark sensor response to variations in soil water content was slow early in the drying cycle (first 10 to 15 days) and reached a plateau approximately 50 (loam) to 70 days (clay loam) after the start of the calibration measurements (Fig. 2a, b, and c). This corresponds to readings of approximately 0 to 10 kPa at the lower end and 150 kPa at the upper end. The upper limit of the sensor's range coincides roughly with the wilting point as indicated by the simulated data in

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[3] 1 J kg^{-1} = 1 kPa

Tables 2 and 3. Readings between 10 and 150 kPa increased in a somewhat linear fashion with time, particularly for the loamy soil. Watermark meter readings became erratic at around 120 kPa for the loam and 90 kPa for the clay loam. Several readings were made at each measurement point before a stable reading was recorded. Variations in Watermark sensor readings became larger as the soil became drier. The highest reading recorded was 199 kPa.

Great care was exercised to make sure that the contact between the soil and the sensor in this study was initially achieved. However, as the soil dries some of the contact with the sensor will inevitably be lost or weakened. Poor contact between the soil and the sensor could cause high readings, which is most likely to occur in heavy soils and during peak crop water use when water from irrigation or rain is not enough to meet the demand. The dynamic response of Watermark sensor Model 200 was found to be adequate during typical soil water drying cycles following complete rewetting (McCann et al., 1992). The sensor did not respond fully to rapid drying or partial rewetting of the soil (Portneuf silt loam). Soil water potentials greater than approximately –10 kPa were deemed necessary for complete rewetting. Good response was obtained down to about –50 kPa when the sensors were initially and fully rewetted. McCann et al. (1992) concluded that the equilibrium between the soil and the porous block might be hard to maintain below –50 kPa.

Slow Watermark sensor response could present problems for irrigation scheduling. This could happen during periods of high evaporative demand or when the sensor is placed below the wetting front. Bausch and Bernard (1996) found that the Watermark sensor response lagged behind that of tensiometers following an irrigation by –4 to –9 kPa. Watermark sensors were also less responsive to small rains (0.5 in.). This also has implications regarding the depth of placement of the sensors. For example, irrigation amounts tend to be smaller with center pivots than with siderolls (wheel-line systems), which makes it more difficult to refill the entire root zone with center pivots (Berrada et al., 2001a). It is therefore important to place some of the sensors at a shallow depth under center pivots. The manufacturer's recommendation is to place one sensor in the top and bottom one-fourth of the root zone (http://www.irrometer.com, 1999). One sensor may be adequate for crops with a shallow root system. The manufacturer also recommends one soil monitoring station per 10 to 15 acres. Six to eight sensors per station is desirable (Clinton Shock, personal communication, 2001). Fewer stations, i.e., one station per 30 acres may be adequate in uniform fields with large irrigation blocks. McCann et al. (1992) deduced from a study in a controlled environment that three to six sensors at each location and depth would yield estimates of soil water potential within 10% of the actual water with a 90% confidence level. Obviously, the more sensing stations, the more accurate soil moisture assessment will be.

Watermark sensor readings at wilting point, field capacity, and MAD (50% AWC)[4] were generated using equations in Table 2. These estimates can be used to evaluate soil water availability and make informed decisions on when to irrigate and how much water to apply (Berrada et al., 2001a). They are somewhat in agreement with the manufacturer's recommendations for fine-textured soils (Table 4).

Conclusions and Recommendations

Calibration equations relating Irrometer Watermark sensor Model 200SS readings using the 30KTCD-NL meter to soil water content were successfully established for a loam and a clay loam in southwestern Colorado. The sensor's response to variations in soil water content was slow below approximately 10 kPa and above 150 kPa. Readings became erratic at about 90 kPa for the clay loam and at 120 kPa for the loam. Other authors reported the greatest sensitivity of Watermark sensors (various models) between 0 kPa and –80 kPa or less of soil water potential, which corresponds to the range of operation of tensiometers. Calibrations at tensions greater than –80 kPa have not been reported but would be desirable, particularly in situations where soil water in the root zone cannot be maintained at optimum levels (MAD). Calibration equations developed in this study were used to generate Watermark sensor readings for field capacity, MAD, and wilting point, which proved extremely useful in interpreting the readings reported in Part III (Berrada et al. 2001a).

Watermark sensors give a good indication of water availability and could be used successfully to schedule irrigation in the FSA, although the latter was not tested in this study.

[4] MAD is Management Allowable Depletion and AWC is Available (soil) Water Capacity.

They are not very sensitive to drying near the upper limit of water availability, which should not be a concern in a well-managed irrigated cropping system. Well-maintained Watermark sensors should last at least as long as a well-managed alfalfa stand (5 to 7 years). A study that looked at Watermark sensor durability and reliability over time was not found in the literature search, but it is believed that a well-maintained Watermark sensor could last 10 years or more (Grant Cardon, personal communication, 1998). Four to six stations would be required per quarter section or full pivot, depending on soil variability. Each station would have two sensors placed at 18 and 36 in. as recommended by the manufacturer. Linking the stations to a central location would make it easier to read the sensors on a regular basis. The addition of a data logger would offer possibilities for automation and rapid data access and interpretation. Year 2000 prices were around $30.00 for a sensor and $275.00 for the meter. Prices will vary based on quantity, cable length, etc.

Important considerations for the use of Watermark sensors are:

- Proper installation, i.e., to ensure good contact between the soil and the sensor.
- Placement of the sensors at representative areas of the field and depths within the root zone.
- Temperature adjustment to compensate for seasonal variations in soil temperature.
- Frequent readings during the irrigation season, i.e., two or more readings per week.

Detailed instructions for the installation, operation, and maintenance of the Watermark sensors and meter are available from the manufacturer.

If calibration information is not available, use the readings over a period of time and the manufacturer's recommendations to determine when to irrigate and how much water to apply. It is important to know the water holding capacity of the soil, and to monitor the amount of precipitation (from rain or irrigation) in order to establish benchmark readings.

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PART II_B: EVALUATION OF THE ETGAGE ATMOMETER

Introduction

Several Model A ETgages (ETgage Co., Loveland, CO) were installed in southwestern Colorado in 1997, 1998, and 1999 to determine alfalfa reference ET (ETr). This was part of a study to demonstrate and encourage the use of sound irrigation scheduling methods in the Full Service Area (FSA) of the Dolores Project. Information on the Dolores Project can be found in Part I (Berrada et al., 2001b). Water balances generated using ETgage data are presented in Part III (Berrada et al., 2001a). In this report, ETgage data is evaluated against ETr computed using the 1982 Kimberly Penman equation (Wright, 1982).

ETgage is an atmometer where the ceramic evaporation cup (Bellani plate) is covered with a green canvas to more closely simulate evapotranspiration from a crop canopy. The "green color simulates the albedo, i.e., radiant energy reflectance of a crop canopy while the texture of the fabric simulates the resistance of the canopy to water vapor diffusion" (Altenhofen, 1992). The ETgage used in this study came with three styles of canvas cover, Style #30 for turf grass, Style #54 for agricultural crops, and a Gore-Tex fabric marked "G2". The Gore-Tex cover "does not account for bulk air resistance between the top of a crop and the evaporation surface. Therefore, when using Gore-Tex, the ETgage should be placed in the crop and level with its canopy " (ETgage Instructions Manual, ETgage Company, Loveland, CO). When using Style #30 or #54 cover, a PTFE (polytretafluoroethylene) membrane is placed between the canvas and ceramic plate. Both the Gore-Tex cover and PTFE membrane let water vapor through but "prevent rain from entering, or water from wicking from ceramic to canvas". Unlike Gore-Tex, air as well as vapor can pass through the PTFE membrane. The PTFE membrane is not needed when using the Gore-Tex cover.

Close agreement between ETgage data and ETr calculated from meteorological models, was reported by several investigators (Hess, 1996; Altenhofen, 1992; Blume et al., 1988; Law and Israeli, 1988). Parchomchuk et al. (1996) used the Model E (electronic) ETgage to automatically schedule irrigation of grapevines and dwarf apple trees, resulting in substantial water savings.

Model E has a higher resolution and is less prone to reading error than Model A, which has a calibrated sight tube on the side of the reservoir for visually reading water level. Reading errors cancel out when averaged over several days (Hess, 1996).

Objectives

The objectives of this study were to compare ETgage data to ETr calculated with the 1982 Kimberly Penman equation and assess the usefulness of ETgage for water management in FSA.

Materials and Methods

A Model A ETgage atmometer was placed next to a Campell Scientific automatic weather station at the Southwestern Colorado Research Center (SWCRC) at Yellow Jacket, CO (CoAgMet site) in May 1997. The ceramic cup of the ETgage was covered with the Style #54 canvas to simulate alfalfa reference ET (ETr). The ETgage was mounted on a 4 in. diameter wooden post. The evaporation surface of the ETgage was 2 to 3 in. above the top of the post and approximately 39 in. above ground.

Water level in the ETgage was recorded daily at approximately 8:00 AM, except on weekends and holidays. Daily ETgage ETr was adjusted to reflect a 24-hour period when readings were made ≥ 30 minutes past 8:00 AM. Readings were made in English units since that is preferred by growers. ETgage Model A is graduated in 0.1-in. increments. Measurements were made during the growing season in 1997, 1998, and 1999. The ETgage was stored indoors during the off-season. Kimberly Penman ETr daily estimates were downloaded from the Yellow Jacket CoAgmet site on the Internet (http://CoAgmet.atmos.colostate.edu, 1999). They represent ETr values from midnight to midnight.

ETgage ETr was regressed against Kimberly Penman ETr using SAS PROC REG (SAS Institute, 2000). Cumulative ETr values were compared using SigmaPlot Paired T-Test Procedure (SPSS Inc., 1998). For the regression analyses, ETgage and Kimberly Penman ETr data was processed as follows:

A. Daily readings and weekend averages, meaning that daily ETr was used on days when the ETgage was read and an average was used for readings that represented two or three days of evapotranspiration, i.e., weekends and holidays.

B. Three-day ETr averages.

C. Seven-day (weekly) ETr averages.

The first PROC REG analyses (results not shown) revealed that the intercept 'a' ($y = a + bx$) was not significantly different than 0 at $\alpha=0.05$ for all data sets and years. Therefore, the intercept was set at 0 for subsequent regression analyses resulting in greater R-square (coefficient of correlation squared) values. The results are reported alongside Fig. 3 through 5.

Results

A positive and highly significant correlation was found between ETgage ETr and Kimberly Penman ETr in 1997, 1998, and 1999 at Yellow Jacket, CO. There was substantial variation (CV[5] values of 23 to 32%) between ETgage and Kimberly Penman ETr daily values and weekend averages (Fig. 3a, 4a, and 5a). The variability decreased (lower CV values) and r^2 values increased when ETr was averaged over three and seven day periods (Fig. 3b and c, 4b and c, and 5b and c). In 1997 there were several conspicuously high ETgage readings (ETr of 0.55 in. to 0.75 in./day), which could be due to operator's error or maintenance problems. These were replaced by ETr values from a nearby ETgage (Table 6). Except for these outliers, the maximum daily ETgage ETr in 1997 was 0.50 in. on July 10. The maximum daily Kimberly Penman ETr was 0.45 in. on June 30. Maximum daily ETgage ETr rates similar to 1997 were recorded in 1998 and 1999 but the maximum daily Kimberly Penman ETr was slightly less in 1999 (0.41 in.) than in 1997 (0.45 in.) or 1998 (0.44 in.) (Tables 6, 7, and 8). As would be expected in southwestern Colorado, June and July had the highest ETr values in all three years (0.27 to 0.38 in. monthly averages). The overall ETgage and Kimberly Penman average ETr values were fairly similar (Tables 6 through 8).

[5] CV: Coefficient of Variation.

There was very good agreement between cumulative ETgage and Kimberly Penman ETr values over the measurement period in all three years (Fig. 6 through 8). Total ETr in 1997 (May 13 to Sept. 30) was 34.47 in. with Kimberly Penman and 33.35 in. with the ETgage or a daily average of 0.244 and 0.237 in. with Kimberly Penman and ETgage, respectively. In 1998, total ETr (and daily average) from June 16 through October 4 was 29.19 in. (0.263 in.) and 30.47 in. (0.274 in.) with Kimberly Penman and the ETgage, respectively. Greater ETr totals were obtained in 1999 due to the longer measurement period (May 7 to October 14) (Table 8). Daily averages in 1999 were 0.239 in. and 0.249 in. with Kimberly Penman and the ETgage, respectively. Daily ETgage ETr appears to be lower than Kimberly Penman ETr on days with measurable precipitation, but not always. Examples are the readings on August 4 and 26, 1997; July 23 and 28 and October 3, 1998; and June 17 and August 11, 1999.

Regression equations

The following equations represent the best fit for the data, based on the results of the linear regression analyses shown with Fig. 3 through 5. The slope of the regression line was very similar whether ETr was averaged over three or seven day periods. However, less variability and slightly higher R^2. values were obtained with weekly averages.

1997: ETgage ETr (in.) = 0.966 Kimberly Penman ETr (in.), $R^2 = 0.986$, CV = 12.56%

1998: ETgage ETr (in.) = 1.043 Kimberly Penman ETr (in.), $R^2 = 0.987$, CV = 11.93%

1999: ETgage ETr (in.) = 1.036 Kimberly Penman ETr (in.), $R^2 = 0.983$, CV = 13.57%

The combined analysis (three-year data) also revealed very good agreement between ETgage and Kimberly Penman ETr values (results not shown). The regression equation for the weekly ETr rates was as follows:

ETgage ETr (in.) = 1.014 Kimberly Penman ETr (in.), $R^2 = 0.984$, CV = 13.05%

Conclusions

Significant correlation was found between ETr values measured with a model A ETgage and ETr values computed using the 1982 Kimberly Penman equation in 1997, 1998, and 1999 at Yellow Jacket, CO. The strongest correlations were obtained when ETr values were averaged over three and seven day periods. This is consistent with the findings of Hess (1996) who showed close agreement (R^2=0.88) between 10-day average Penman-Monteith ET_0 (reference ET from a well-watered, short, green, grass surface) and ETgage readings. At Yellow Jacket, daily ETgage values tended to be somewhat on the high side, particularly during hot dry weather, when compared with Kimberly Penman ETr. Conversely, ETgage readings tended to be lower than Kimberly Penman ETr during rainy days, but not always. Law and Israeli (1988) reported high variability among ETgage atmometers during rainy periods. Early ETgage models did not use the Gore-Tex cover or PTFE membrane, which act as rain barriers while allowing water vapor through. Saturation of the canvas cover with rainwater could lead to a reduced ETr rate even when the PTFE membrane is used.

Recommendations

Close agreement between ETgage and Kimberly Penman ETr values at Yellow Jacket in 1997, 1998, and 1999 suggest that the ETgage can be used successfully for irrigation scheduling purposes in southwestern Colorado. The so-called "combination equations" such as Kimberly Penman and Penman-Monteith are generally considered the best methods for estimating reference ET (Jensen and Allen, 2000; Allen et al., 2000). However, in the absence of weather stations that provide detailed climatic data or localized ET estimates, the ETgage is a good alternative. This is particularly true if the day-to-day variation in ETr rate is not as important as the variation in average or cumulative ETr over time spans (three or more days) typical of an irrigation cycle. It is also reasonable to expect that ETgages be read once or twice a week during the growing season. The ETgage is relatively inexpensive compared to other irrigation scheduling tools ($150.00 for model A), durable, and easy to use and maintain. An electronic version (model E sells for about $550.00) is available and would be ideal for automated irrigation.

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Tables and figures

Table 1. Texture and bulk densities of the soil used in the study.

	Soil depth		
Particle size	0-12 in.	12-24 in.	24-36 in.
Sand (%)	43	38	41
Silt (%)	31	28	29
Clay (%)	26	34	30
Textural class	Loam	Clay loam	Clay loam
Field bulk density (Mg m^{-3})	1.55	1.44	1.41

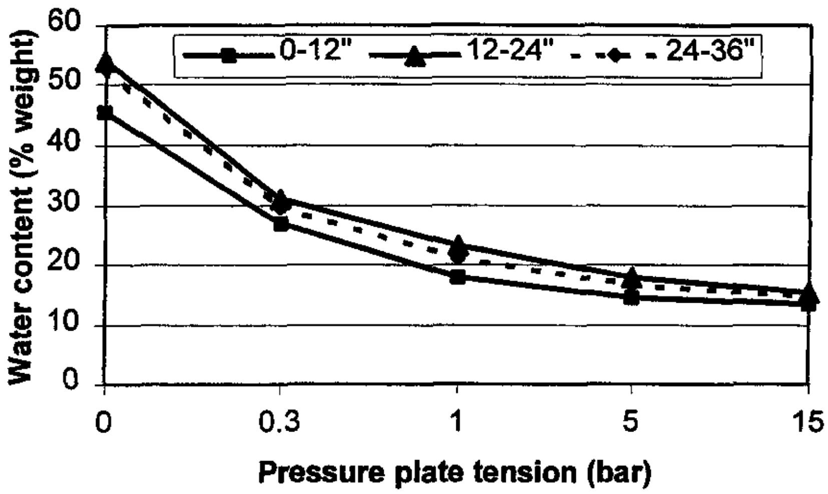


Figure 1. Soil moisture release curves.

Table 2. Watermark sensor calibration equation parameter estimates.

Water content (% weight) = $a + b\,x + cx^2 + dx^3$, where 'x' is Watermark sensor 200SS readings in kPa.

Soil	Loam (0-12 in.)		Clay loam (12-36 in.)	
Parameter	Estimate	Standard error	Estimate	Standard error
Intercept (a)	32.337886	0.731095	36.859211	0.478445
b	-0.213234	0.037147	-0.342445	0.024758
c	0.001575	0.000462	0.002844	0.000303
d	-0.000006	0.0000016	-0.0000097	0.0000010
Statistics	N=37, R^2 = 0.96, RMSE=1.42, CV=6.6%		N=93, R^2 = 0.97, RMSE=1.44, CV=6.5%	

Table 3. Simulated soil moisture for a loam, clay loam, and silt-loam.

Watermark sensor Reading	Soil Loam (L)[1]	Clay loam (CL)[1]	Silt loam[2]	Comment
kPa	Soil moisture (% dry weight)			
0.0	32.3	36.9	23.3	
10.0	30.4	33.7	21.8	
20.0	28.7	31.1	20.3	
23.0	28.2	**30.4**	19.9	Field capacity (CL)
30.0	27.2	28.9	19.1	
32.5	**26.9**	28.4	18.8	Field capacity (L)
40.0	25.9	27.1	18.1	
50.0	24.9	25.6	17.3	
60.0	23.9	24.5	16.6	
70.0	23.1	23.5	16.1	
79.0	22.4	**22.8**	15.6	MAD (CL)
80.0	22.3	22.7	15.6	
90.0	21.5	22.0	15.1	
100.0	20.8	21.4	14.7	
107.0	**20.2**	20.9	14.5	MAD (L)
110.0	20.0	20.7	14.4	
120.0	19.1	20.0	14.1	
130.0	18.1	19.1	13.8	
140.0	16.9	18.0	13.5	
150.0	15.5	16.7	13.3	
159.5	14.0	**15.2**	13.0	Wilting point (CL)
160.0	14.0	15.1	13.0	
162.5	**13.5**	14.7	13.0	Wilting point (L)
170.0	12.1	13.2	12.8	
180.0	10.0	10.8	12.6	
190.0	7.5	7.9	12.4	
199.0	5.0	4.9	12.3	

[1] See calibration equations in Table 2

[2] Calibration equation in Fig. 2b, p.1231 (Eldredge et al., 1993).
Volumetric water content was divided by 1.1 and multiplied by 100 to convert to % water content by weight.

Table 4. Simulated Watermark sensor readings at FC, WP, and MAD.

Limit of soil AWC	Loam	Clay loam	Avg.	Manufacturer's recommendations
	Reading (kPa)			
Field capacity	33	23	28	30-60 kPa: usual range for irrigation, except for
MAD (50% AWC)	107	79	93	heavy soil (60-100 kPa)
Wilting point	163	159	161	100-200 kPa: Dangerously dry soil

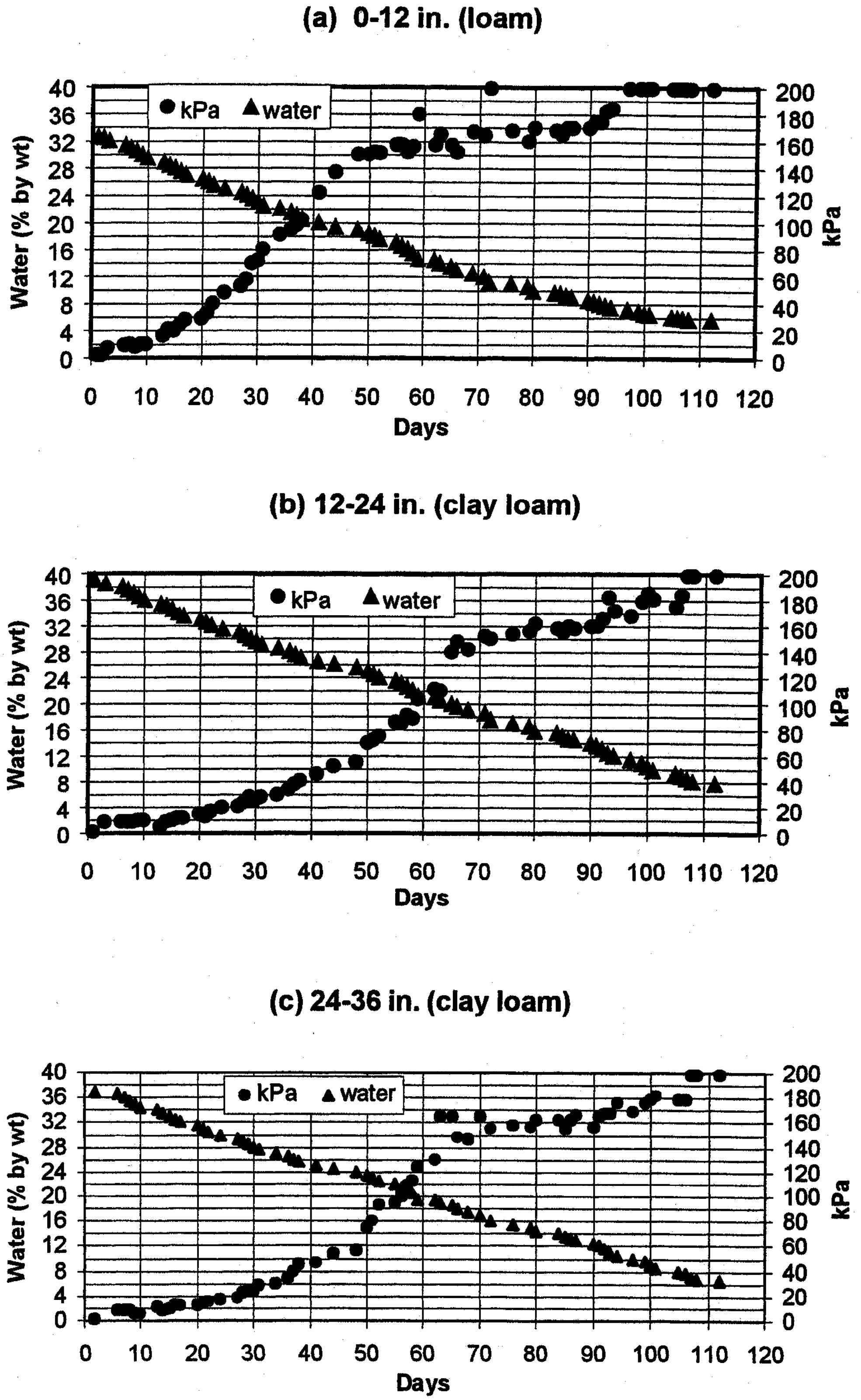
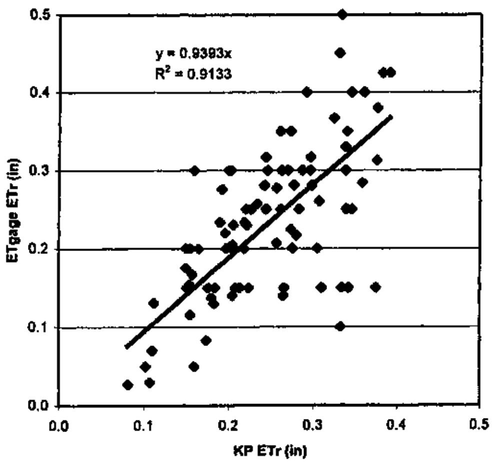


Figure 2. Watermark sensor reading and soil water content during calibration.

Table 5. Data used for the calibration of Watermark sensor 200SS at Yellow Jacket, CO.

0-12 in. depth		12-24 in. depth		24-36 in. depth	
Reading	Moisture	Reading	Moisture	Reading	Moisture
kPa	% wt.	kPa	% wt.	kPa	% wt.
2	32.60	1	39.10	2	36.80
7	31.99	5	35.40	5	34.40
8	30.50	9	37.20	6	35.00
9	31.39	10	35.67	8	34.50
10	30.90	12	33.75	9	36.25
16	28.88	15	33.00	10	33.00
20	28.00	17	32.00	12	32.00
21	28.42	20	31.40	14	31.00
24	27.48	21	31.00	16	30.50
28	26.95	24	30.50	19	29.40
29	26.40	26	29.50	22	29.00
33	25.99	28	29.50	24	28.25
40	25.48	30	28.50	28	27.50
48	24.90	34	28.00	30	27.00
53	24.38	38	27.50	34	26.50
58	24.00	41	27.00	39	26.00
70	23.50	46	26.50	45	25.50
72	23.00	52	26.00	46	25.00
80	22.40	55	25.50	53	24.50
91	22.00	70	25.00	56	24.00
95	21.50	72	24.50	75	23.50
98	21.00	75	24.00	80	23.00
102	20.50	85	23.00	93	22.50
122	20.00	86	23.50	94	22.00
137	19.37	91	22.50	100	21.50
150	18.40	104	21.10	108	21.00
151	17.50	110	20.50	112	20.50
152	15.67	140	20.00	124	19.50
156	15.50	142	19.00	130	19.50
157	15.38	148	19.50	146	17.50
160	10.50	150	17.50	148	18.00
164	12.00	152	18.50	155	14.75
165	11.75	154	17.00	156	14.90
167	12.50	155	15.00	157	12.50
168	10.24	156	16.50	158	15.50
170	9.15	158	15.00	162	13.80
199	8.27	160	14.03	165	16.65
		162	15.80	166	13.00
		166	13.00	167	11.50
		168	11.40	168	10.90
		172	12.00	169	10.00
		175	9.30	176	10.00
		179	10.90	179	8.57
		181	9.80	182	8.40
		182	12.40	199	7.10
		184	8.90		
		185	10.40		
		199	8.50		

(a) Daily readings and weekend averages



SAS Regression Procedure Results

Analysis of variance

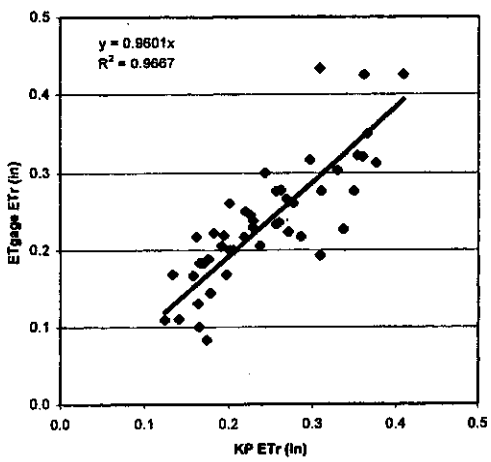
Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	5.0968	5.0968	938.30	<0.0001
Error	88	0.4780	0.0054		
Corrected Total	89	5.5748			

Root MSE	0.0737	R-Square	0.9143
Dependant Mean	0.2299	Adj R-Sq	0.9133
Coeff Var	32.05		

Parameter Estimate

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
KP ETr	1	0.9393	0.0307	30.63	<0.0001

(b) Three-day averages



Analysis of variance

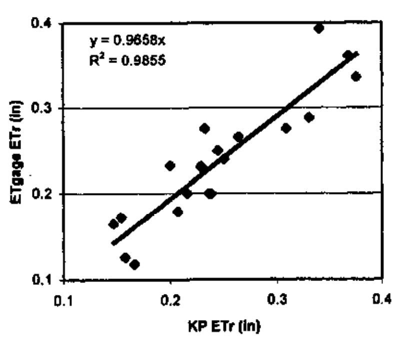
Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	2.8238	2.8238	1334.73	<0.0001
Error	46	0.0973	0.0021		
Corrected Total	47	2.9211			

Root MSE	0.0460	R-Square	0.9667
Dependant Mean	0.2365	Adj R-Sq	0.966
Coeff Var	19.45		

Parameter Estimate

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
KP ETr	1	0.9601	0.0263	36.53	<0.0001

(c) Weekly averages



Analysis of variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	1.2044	1.2044	1362.28	<0.0001
Error	19	0.0168	0.0009		
Corrected Total	20	1.2212			

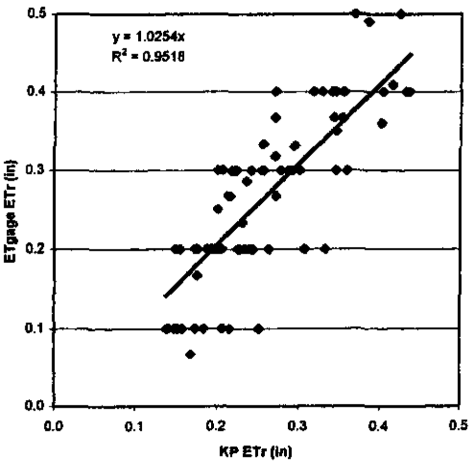
Root MSE	0.0297	R-Square	0.9862
Dependant Mean	0.2368	Adj R-Sq	0.9855
Coeff Var	12.56		

Parameter Estimate

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
KP ETr	1	0.9658	0.0262	36.91	<0.0001

Figure 3. Relationship between Kimberly Penman (KP) ETr and ETgage ETr at Yellow Jacket in 1997.

(a) Daily readings and weekend averages



SAS Regression Procedure Results

Analysis of variance

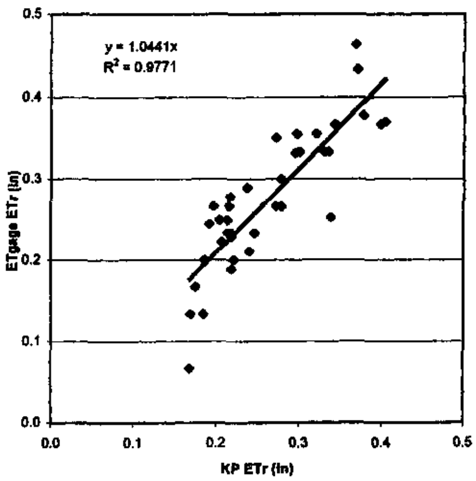
Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	6.0766	6.0766	1522.32	<0.0001
Error	76	0.3034	0.0040		
Corrected Total	77	6.3799			

Root MSE	0.0632	R-Square	0.9524
Dependant Mean	0.2675	Adj R-Sq	0.9518
Coeff Var	23.62		

Parameter Estimate

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
KP ETr	1	1.0254	0.0263	39.02	<0.0001

(b) Three-day averages



Analysis of variance

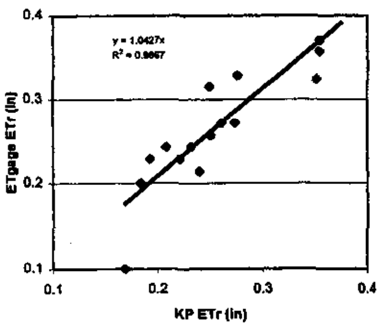
Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	2.9783	2.9783	1535.33	<0.0001
Error	36	0.0698	0.0019		
Corrected Total	37	3.0481			

Root MSE	0.0440	R-Square	0.9771
Dependant Mean	0.2745	Adj R-Sq	0.9765
Coeff Var	16.05		

Parameter Estimate

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
KP ETr	1	1.0441	0.0267	39.18	<0.0001

(c) Weekly averages



Analysis of variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	1.2643	1.2643	1192.17	<0.0001
Error	15	0.0159	0.0011		
Corrected Total	16	1.2802			

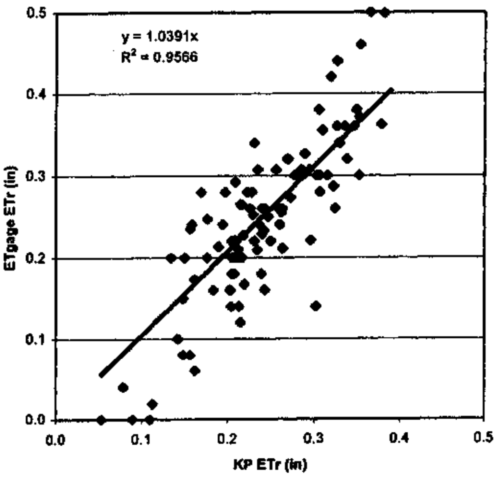
Root MSE	0.0326	R-Square	0.9876
Dependant Mean	0.2729	Adj R-Sq	0.9867
Coeff Var	11.93		

Parameter Estimate

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
KP ETr	1	1.0427	0.0302	34.53	<0.0001

Figure 4. Relationship between Kimberly Penman (KP) ETr and ETgage ETr at Yellow Jacket in 1998.

(a) Daily readings and weekend averages



SAS Regression Procedure Results

Analysis of variance

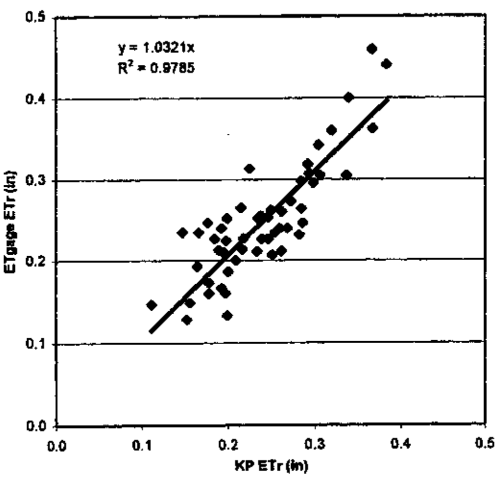
Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	7.0098	7.0098	2249.91	<0.0001
Error	102	0.3178	0.0031		
Corrected Total	103	7.3276			

Root MSE	0.0558	R-Square	0.9566
Dependant Mean	0.2471	Adj R-Sq	0.9562
Coeff Var	22.59		

Parameter Estimate

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
KP ETr	1	1.0391	0.0219	47.43	<0.0001

(b) Three-day averages



Analysis of variance

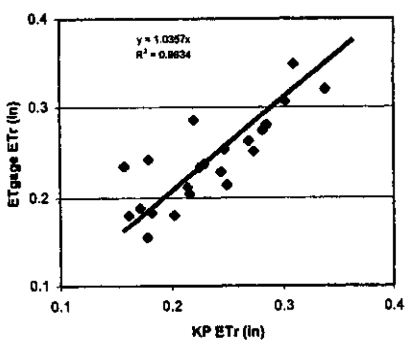
Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	3.4655	3.4655	2370.45	<0.0001
Error	52	0.0760	0.0015		
Corrected Total	53	3.5415			

Root MSE	0.0382	R-Square	0.9785
Dependant Mean	0.2488	Adj R-Sq	0.9781
Coeff Var	15.37		

Parameter Estimate

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
KP ETr	1	1.0321	0.0212	48.69	<0.0001

(c) Weekly averages



Analysis of variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	1.4879	1.4879	1306.71	<0.0001
Error	22	0.0251	0.0011		
Corrected Total	23	1.5129			

Root MSE	0.0337	R-Square	0.9834
Dependant Mean	0.2486	Adj R-Sq	0.9827
Coeff Var	13.57		

Parameter Estimate

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
KP ETr	1	1.0357	0.0287	36.15	<0.0001

Figure 5. Relationship between Kimberly Penman (KP) ETr and ETgage ETr at Yellow Jacket in 1999.

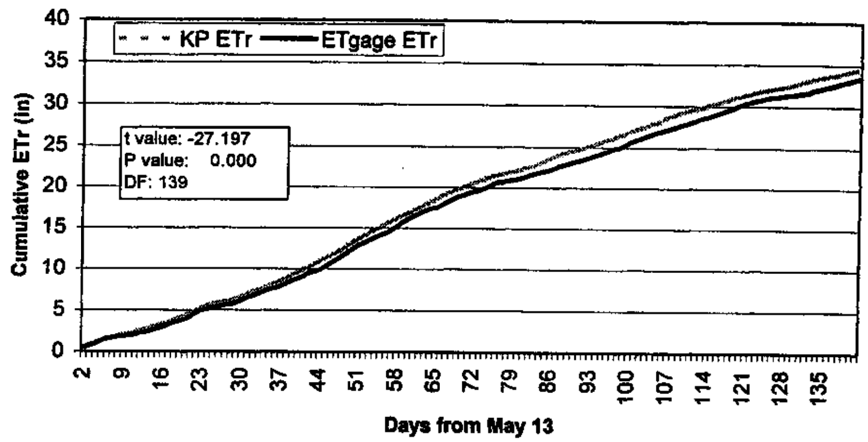


Figure 6. Cumulative ETr at Yellow Jacket in 1997
Statistics in the box are from a paired t-test of ETgage vs. KP ETr.

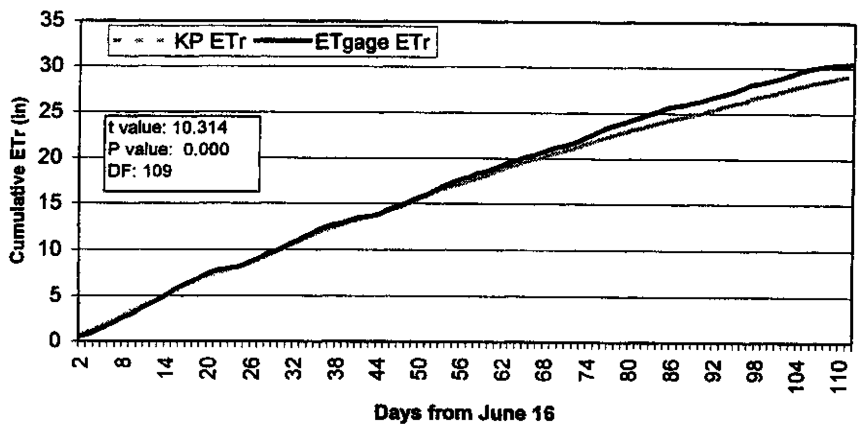


Figure 7. Cumulative ETr at Yellow Jacket in 1998.
Statistics in the box are from a paired t-test of ETgage vs. KP ETr.

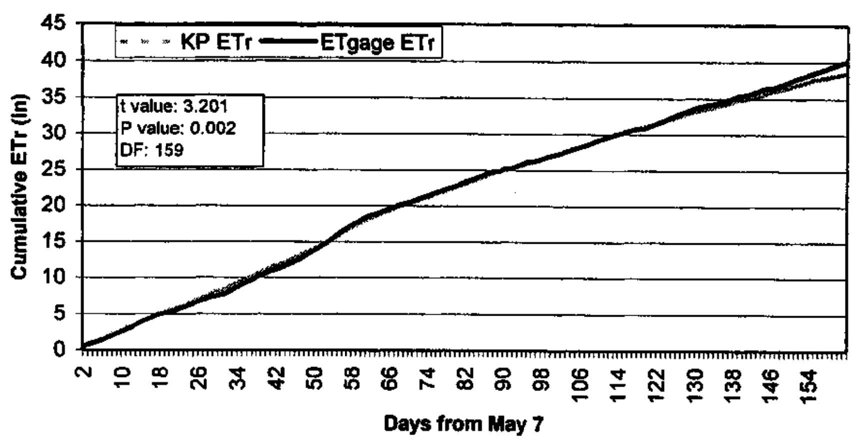


Figure 8. Cumulative ETr at Yellow Jacket in 1999.
Statistics in the box are from a paired t-test of ETgage vs. KP ETr.

Table 6. 1997 ET and climatic data.

Date	Day	Kimberly Penman Daily ETr in	Kimberly Penman Cum. ETr in	ETgage readings in[1]	ETgage daily in	ETgage Cum. ETr in	Avg. temp. Deg F	Solar radiation Lngly	Precip. in.	Min. RH %	Avg. wind speed mi/hr	Comments (ETgage)
05/13/97	1	0.265		0.00	0.250		59.3	721	0.01	15.1	3.8	
05/14/97	2	0.258	0.52	0.50	0.250	0.50	61.4	690	0.00	19.2	3.6	
05/15/97	3	0.257	0.78	0.65	0.207	0.71	62.5	692	0.00	21.5	3.3	Read at 2:30 PM
05/16/97	4	0.239	1.02		0.277	0.98	62.3	615	0.00	20.2	2.8	
05/17/97	5	0.278	1.30		0.277	1.26	64.0	679	0.00	19.1	4.4	
05/18/97	6	0.253	1.55	1.48	0.277	1.54	60.9	601	0.00	24.7	4.3	
05/19/97	7	0.205	1.76	1.62	0.140	1.68	60.7	447	0.10	31.7	4.0	
05/20/97	8	0.183	1.94	1.75	0.130	1.81	57.1	456	0.30	48.9	5.3	
05/21/97	9	0.107	2.05	1.78	0.030	1.84	52.5	264	0.16	66.4	4.5	
05/22/97	10	0.155	2.20	1.90	0.116	1.95	53.3	461	0.27	61.2	3.2	Read at 8:30 AM on 5/23
05/23/97	11	0.230	2.43		0.138	2.09	54.8	675	0.00	36.6	4.4	
05/24/97	12	0.106	2.54		0.138	2.23	47.7	252	0.44	56.0	6.2	
05/25/97	13	0.163	2.70		0.138	2.37	45.8	539	0.27	62.5	5.0	
05/26/97	14	0.222	2.92	2.45	0.138	2.50	43.6	753	0.00	42.2	5.6	
05/27/97	15	0.206	3.13	2.68	0.230	2.73	51.4	681	0.00	37.2	3.00	
05/28/97	16	0.196	3.32	2.90	0.220	2.95	56.3	671	0.00	31.0	1.17	
05/29/97	17	0.200	3.52	3.20	0.300	3.25	61.9	558	0.00	30.0	3.13	
05/30/97	18	0.281	3.80		0.217	3.47	64.7	700	0.00	35.2	6.33	
05/31/97	19	0.261	4.07		0.217	3.69	66.2	699	0.00	27.4	2.38	
06/01/97	20	0.298	4.36	3.85	0.217	3.90	65.8	748	0.00	16.4	3.25	
06/02/97	21	0.273	4.64	4.20	0.350	4.25	65.5	631	0.00	19.7	3.13	
06/03/97	22	0.291	4.93	4.60	0.400	4.65	67.7	672	0.00	15.3	2.92	
06/04/97	23	0.298	5.23	4.65	0.280	4.93	65.5	602	0.00	16.4	4.71	Daily from nearby ETgage[2]
06/05/97	24	0.342	5.57	0.15	0.150	5.08	62.8	721	0.00	14.6	5.08	Re-fill
06/06/97	25	0.241	5.81		0.167	5.25	60.5	516	0.00	27.2	3.54	
06/07/97	26	0.103	5.91		0.167	5.42	51.4	215	0.15	75.0	4.67	
06/08/97	27	0.129	6.04	0.65	0.167	5.58	49.7	355	0.00	64.7	3.50	
06/09/97	28	0.110	6.15	0.72	0.070	5.65	53.4	318	0.05	64.5	3.00	
06/10/97	29	0.222	6.37	0.95	0.230	5.88	61.0	673	0.05	37.5	4.04	
06/11/97	30	0.270	6.64	1.25	0.300	6.18	59.6	753	0.00	22.0	3.21	
06/12/97	31	0.296	6.94	1.55	0.300	6.48	59.3	699	0.00	22.2	5.63	
06/13/97	32	0.291	7.23		0.250	6.73	58.3	582	0.00	33.0	9.29	
06/14/97	33	0.221	7.45		0.250	6.98	58.4	435	0.00	28.5	4.13	
06/15/97	34	0.273	7.72	2.30	0.250	7.23	56.9	714	0.00	26.6	3.38	
06/16/97	35	0.277	8.00	2.58	0.280	7.51	59.6	684	0.00	29.6	4.38	
06/17/97	36	0.265	8.27	2.72	0.140	7.65	63.1	653	0.00	27.4	3.58	
06/18/97	37	0.307	8.57	3.35	0.260	7.91	67.9	745	0.00	16.7	3.46	Daily from nearby ETgage[2]
06/19/97	38	0.324	8.90	3.65	0.367	8.28	70.8	722	0.00	12.8	3.79	Read at 12:30 PM
06/20/97	39	0.358	9.25		0.283	8.56	66.6	781	0.00	11.3	3.67	

Date	Day	Kimberly Penman Daily ETr in	Cum. ETr in	ETgage readings in[1]	ETgage daily in	ETgage Cum. ETr in	Avg. temp. Deg F	Solar radiation Lngly	Precip. in.	Min. RH %	Avg. wind speed mi/hr	Comments (ETgage)
06/21/97	40	0.346	9.60		0.283	8.85	68.8	771	0.00	11.8	3.00	
06/22/97	41	0.370	9.97	4.50	0.283	9.13	68.3	769	0.00	12.3	4.33	
06/23/97	42	0.345	10.32	5.25	0.400	9.53	66.1	773	0.00	13.1	3.42	Daily from nearby ETgage[2]
06/24/97	43	0.334	10.65	5.40	0.150	9.68	66.2	755	0.00	12.5	2.79	
06/25/97	44	0.338	10.99	5.70	0.300	9.98	68.7	733	0.00	11.3	3.46	
06/26/97	45	0.376	11.36	6.25	0.380	10.36	69.7	655	0.00	12.3	6.46	Daily from nearby ETgage[2]
06/27/97	46	0.341	11.70		0.425	10.79	67.5	712	0.00	15.5	4.63	
06/28/97	47	0.369	12.07		0.425	11.21	65.9	745	0.00	14.9	5.17	
06/29/97	48	0.374	12.45		0.425	11.64	64.4	775	0.00	13.2	4.83	
06/30/97	49	0.445	12.89	7.95	0.425	12.06	65.8	779	0.00	11.7	8.08	
07/01/97	50	0.342	13.23		0.425	12.49	63.6	787	0.00	12.3	3.17	
07/02/97	51	0.440	13.67	8.80	0.425	12.91	66.5	793	0.00	11.0	6.83	
07/03/97	52	0.412	14.09		0.313	13.22	64.4	789	0.00	11.7	6.13	Re-fill
07/04/97	53	0.371	14.46		0.313	13.54	66.3	770	0.00	11.3	4.29	
07/05/97	54	0.346	14.80		0.313	13.85	66.6	712	0.00	11.3	3.83	
07/06/97	55	0.373	15.18	1.25	0.313	14.16	70.3	727	0.00	11.0	4.96	
07/07/97	56	0.346	15.52	1.50	0.250	14.41	70.4	645	0.00	11.9	5.13	
07/08/97	57	0.360	15.88	1.90	0.400	14.81	71.1	701	0.00	10.9	4.58	
07/09/97	58	0.330	16.21	2.35	0.450	15.26	70.2	594	0.00	14.1	4.38	
07/10/97	59	0.333	16.55	2.85	0.500	15.76	69.1	704	0.00	13.9	3.71	
07/11/97	60	0.262	16.81		0.350	16.11	66.0	517	0.00	24.5	3.46	
07/12/97	61	0.368	17.18		0.350	16.46	65.7	746	0.00	14.9	5.83	
07/13/97	62	0.367	17.54		0.350	16.81	67.8	746	0.00	14.0	5.00	
07/14/97	63	0.362	17.90	4.25	0.350	17.16	74.4	747	0.00	11.5	4.46	
07/15/97	64	0.339	18.24	4.50	0.250	17.41	74.5	753	0.00	9.2	2.58	
07/16/97	65	0.333	18.58	4.60	0.100	17.51	75.5	590	0.00	10.8	3.88	
07/17/97	66	0.338	18.91	5.25	0.330	17.84	73.5	679	0.00	13.2	3.54	Daily from nearby ETgage[2]
07/18/97	67	0.336	19.25		0.317	18.16	72.3	603	0.10	20.7	5.42	
07/19/97	68	0.272	19.52		0.317	18.47	69.2	530	0.09	35.5	4.96	
07/20/97	69	0.282	19.80	6.20	0.317	18.79	68.0	626	0.00	19.4	3.33	
07/21/97	70	0.263	20.07	6.50	0.300	19.09	70.0	519	0.00	31.7	4.54	
07/22/97	71	0.283	20.35	6.75	0.250	19.34	70.5	588	0.15	32.0	5.29	
07/23/97	72	0.224	20.57	6.90	0.150	19.49	66.9	581	0.00	43.7	2.71	
07/24/97	73	0.276	20.85	7.10	0.200	19.69	68.7	673	0.00	16.3	2.25	
07/25/97	74	0.293	21.14		0.317	20.01	71.6	629	0.00	15.2	3.42	
07/26/97	75	0.218	21.36		0.317	20.32	71.6	312	0.01	25.4	4.33	
07/27/97	76	0.220	21.58	8.05	0.317	20.64	68.1	463	0.05	40.8	3.92	
07/28/97	77	0.102	21.68	8.10	0.050	20.69	66.5	199	0.60	71.4	5.58	

Date	Day	Kimberly Penman Daily ETr in	Kimberly Penman Cum. ETr in	ETgage readings in[1]	ETgage daily in	ETgage Cum. ETr in	Avg. temp. Deg F	Solar radiation Lngly	Precip. in.	Min. RH %	Avg. wind speed mi/hr	Comments (ETgage)
07/29/97	78	0.204	21.89	8.30	0.200	20.89	77.5	444	0.00	46.1	4.00	
07/30/97	79	0.102	21.99	8.35	0.050	20.94	62.4	223	0.16	67.8	2.63	
07/31/97	80	0.176	22.17	8.50	0.150	21.09	67.7	498	0.96	56.1	2.00	
08/01/97	81	0.256	22.42		0.233	21.32	70.5	709	0.00	26.2	1.63	Re-fill
08/02/97	82	0.202	22.62		0.233	21.56	70.5	485	0.00	36.0	2.42	
08/03/97	83	0.200	22.82	0.70	0.233	21.79	72.8	468	0.10	38.5	2.50	
08/04/97	84	0.310	23.13	0.85	0.150	21.94	69.5	406	0.81	53.1	2.92	
08/05/97	85	0.266	23.40	1.00	0.150	22.09	71.2	359	0.05	56.7	2.83	
08/06/97	86	0.305	23.70	1.20	0.200	22.29	65.8	676	0.00	53.0	4.58	
08/07/97	87	0.287	23.99	1.50	0.300	22.59	66.1	674	0.00	39.4	1.67	
08/08/97	88	0.267	24.26		0.200	22.79	68.0	663	0.00	29.6	1.58	
08/09/97	89	0.210	24.47		0.200	22.99	68.0	528	0.00	38.1	2.79	
08/10/97	90	0.140	24.61	2.10	0.200	23.19	63.1	374	0.35	61.0	3.46	
08/11/97	91	0.184	24.79	2.25	0.150	23.34	63.6	468	0.00	49.1	3.17	
08/12/97	92	0.227	25.02	2.50	0.250	23.59	64.2	613	0.00	42.9	3.50	
08/13/97	93	0.244	25.26	2.75	0.250	23.84	66.2	610	0.00	35.7	4.50	
08/14/97	94	0.219	25.48	2.95	0.200	24.04	65.5	619	0.00	28.8	1.96	
08/15/97	95	0.234	25.72		0.257	24.30	67.3	626	0.00	20.4	2.21	
08/16/97	96	0.235	25.95		0.257	24.55	65.6	614	0.00	27.9	2.75	
08/17/97	97	0.232	26.18	3.75	0.257	24.81	66.5	629	0.00	24.2	2.33	
08/18/97	98	0.213	26.40	3.90	0.150	24.96	67.2	593	0.00	32.2	2.13	Read at 11:00 AM on 8/18
08/19/97	99	0.242	26.64	4.45	0.280	25.24	68.4	634	0.00	19.9	2.67	Daily from nearby ETgage[2]
08/20/97	100	0.261	26.90	4.80	0.350	25.59	70.4	663	0.00	15.6	2.83	
08/21/97	101	0.246	27.15	5.10	0.300	25.89	71.0	515	0.00	24.9	3.88	
08/22/97	102	0.223	27.37		0.250	26.14	72.6	497	0.00	30.3	3.38	
08/23/97	103	0.218	27.59		0.250	26.39	70.1	547	0.12	35.6	2.54	
08/24/97	104	0.234	27.82		0.250	26.64	70.6	584	0.00	35.4	3.13	
08/25/97	105	0.208	28.03	6.10	0.250	26.89	68.6	507	0.00	38.7	3.21	
08/26/97	106	0.375	28.40	6.25	0.150	27.04	69.8	386	0.54	49.9	4.04	
08/27/97	107	0.274	28.68	6.55	0.224	27.26	77.3	624	0.00	35.6	2.96	Read at 10:25 AM on 8/28
08/28/97	108	0.277	28.95		0.205	27.47	69.5	619	0.00	29.9	3.21	
08/29/97	109	0.250	29.20		0.205	27.67	69.0	553	0.00	33.8	2.33	
08/30/97	110	0.206	29.41		0.205	27.88	68.8	505	0.00	38.9	2.71	
08/31/97	111	0.119	29.53		0.205	28.08	68.2	299	0.27	52.2	2.75	
09/01/97	112	0.171	29.70	7.55	0.205	28.29	69.0	485	0.00	48.0	2.42	
09/02/97	113	0.203	29.90	7.85	0.300	28.59	70.2	496	0.00	29.6	3.13	
09/03/97	114	0.208	30.11	0.15	0.150	28.74	69.4	506	0.00	32.9	3.17	Re-fill
09/04/97	115	0.197	30.31	0.35	0.200	28.94	68.1	524	0.00	40.9	3.25	
09/05/97	116	0.203	30.51		0.233	29.17	68.4	567	0.00	33.9	2.25	

Date	Day	Kimberly Penman Daily ETr in	Kimberly Penman Cum. ETr in	ETgage readings in[1]	ETgage daily in	ETgage Cum. ETr in	Avg. temp. Deg F	Solar radiation Lngly	Precip. in.	Min. RH %	Avg. wind speed mi/hr	Comments (ETgage)
09/06/97	117	0.147	30.66		0.233	29.41	66.9	337	0.00	40.4	2.38	
09/07/97	118	0.219	30.88	1.05	0.233	29.64	66.2	589	0.00	20.1	2.46	
09/08/97	119	0.222	31.10		0.275	29.91	68.0	581	0.00	15.3	2.67	
09/09/97	120	0.162	31.26	1.60	0.275	30.19	68.8	435	0.00	32.7	2.04	
09/10/97	121	0.184	31.45		0.200	30.39	67.1	500	0.00	28.9	2.46	
09/11/97	122	0.146	31.59	2.00	0.200	30.59	64.4	368	0.70	40.5	2.71	
09/12/97	123	0.166	31.76		0.150	30.74	64.8	521	0.00	34.3	1.58	
09/13/97	124	0.142	31.90		0.150	30.89	65.2	392	0.13	43.7	2.42	
09/14/97	125	0.149	32.05	2.45	0.150	31.04	65.7	469	0.11	36.6	1.67	
09/15/97	126	0.081	32.13	2.55	0.027	31.07	65.9	232	0.55	62.6	3.25	Read at 1:30 PM on 9/16
09/16/97	127	0.112	32.24	2.65	0.131	31.20	68.8	344	0.00	60.4	2.04	
09/17/97	128	0.151	32.39	2.80	0.150	31.35	62.7	444	0.00	56.2	2.67	
09/18/97	129	0.160	32.55	2.85	0.050	31.40	65.8	436	0.02	45.4	4.25	
09/19/97	130	0.160	32.71		0.083	31.48	64.7	356	0.01	45.6	5.13	
09/20/97	131	0.202	32.91		0.083	31.56	63.9	449	0.03	41.5	9.04	
09/21/97	132	0.160	33.07	3.10	0.083	31.65	60.0	240	0.40	72.1	8.83	
09/22/97	133	0.159	33.23	3.40	0.300	31.95	60.1	333	0.00	53.3	4.42	
09/23/97	134	0.176	33.41	3.55	0.150	32.10	55.1	484	0.00	40.3	3.38	
09/24/97	135	0.150	33.56	3.75	0.200	32.30	57.1	509	0.00	34.8	0.92	
09/25/97	136	0.154	33.71	3.90	0.154	32.45	60.2	457	0.00	39.2	2.79	Read at 8:30 AM
09/26/97	137	0.066	33.78		0.175	32.63	62.9	239	0.05	65.0	3.00	
09/27/97	138	0.180	33.96		0.175	32.80	60.8	511	0.00	41.1	6.17	
09/28/97	139	0.186	34.15		0.175	32.98	62.5	508	0.00	26.1	4.13	
09/29/97	140	0.168	34.31	4.60	0.175	33.15	60.8	501	0.00	29.6	3.08	
09/30/97	141	0.155	34.47	4.80	0.200	33.35	61.7	499	0.00	18.8	2.08	
Total		34.468			33.351				8.16			
Average		0.244			0.237		65.2	568	0.06	31.8	3.71	

[1]ETgage readings were recorded the next day at approximately 8:00 AM unless specified otherwise, in which case daily ETgage ETr is adjusted to reflect ETr in 24 hours.
[2]Reading from an ETgage located approximately 800 ft. south of the weather station.

Table 7. 1998 ET and climatic data.

Date	Day	Kimberly Penman Daily ETr in	Kimberly Penman Cum. ETr in	ETgage readings in[1]	ETgage daily in	ETgage Cum. ETr in	Avg. temp. Deg F	Solar radiation Lngly	Precip. in.	Min. RH %	Avg. wind speed mi/hr	Comments (ETgage)
06/16/98	1	0.401		8.90	0.360		62.3	584	0.00	13.6	11.63	
06/17/98	2	0.307	0.71	9.10	0.200	0.56	51.4	731	0.02	13.8	7.50	Re-fill
06/18/98	3	0.308	1.02	0.20	0.200	0.76	55.5	770	0.00	16.2	4.33	Read at 8:45 AM
06/19/98	4	0.364	1.38		0.367	1.13	63.7	779	0.00	7.1	5.54	
06/20/98	5	0.314	1.69		0.367	1.49	64.1	666	0.00	13.5	4.92	
06/21/98	6	0.350	2.04	1.30	0.367	1.86	64.2	771	0.00	7.3	4.67	Read at 8:30 AM on 2/22
06/22/98	7	0.415	2.46	1.70	0.409	2.27	63.5	778	0.00	6.3	7.08	
06/23/98	8	0.436	2.90	2.10	0.400	2.67	64.1	771	0.00	4.9	8.46	
06/24/98	9	0.360	3.26	2.40	0.300	2.97	62.0	744	0.00	8.5	5.04	
06/25/98	10	0.424	3.68	2.90	0.500	3.47	65.2	784	0.00	3.7	7.17	
06/26/98	11	0.358	4.04		0.400	3.87	65.4	771	0.00	9.5	4.50	
06/27/98	12	0.329	4.37		0.400	4.27	70.7	775	0.00	8.7	2.83	
06/28/98	13	0.349	4.72	4.10	0.400	4.67	72.5	778	0.00	6.9	3.00	
06/29/98	14	0.368	5.08	4.60	0.500	5.17	73.7	773	0.00	6.7	3.50	
06/30/98	15	0.385	5.47	5.10	0.490	5.66	74.6	772	0.00	5.9	3.96	Read at 8:30 AM
07/01/98	16	0.432	5.90	5.50	0.400	6.06	70.5	756	0.00	6.3	6.50	
07/02/98	17	0.394	6.29		0.350	6.41	72.0	758	0.00	10.5	5.63	
07/03/98	18	0.369	6.66		0.350	6.76	73.2	713	0.00	13.5	5.88	
07/04/98	19	0.326	6.99		0.350	7.11	71.8	640	0.00	18.4	5.08	
07/05/98	20	0.295	7.28	6.90	0.350	7.46	73.6	503	0.01	24.8	5.42	
07/06/98	21	0.279	7.56	7.20	0.300	7.76	71.1	537	0.00	28.8	4.50	
07/07/98	22	0.139	7.70	7.30	0.100	7.86	63.9	214	0.54	48.2	3.46	
07/08/98	23	0.264	7.97	7.50	0.200	8.06	67.2	602	0.00	30.1	4.13	
07/09/98	24	0.152	8.12	7.60	0.100	8.16	66.8	297	0.00	44.8	3.17	
07/10/98	25	0.274	8.39		0.333	8.49	68.9	712	0.09	27.6	3.29	
07/11/98	26	0.305	8.70		0.333	8.83	71.5	651	0.14	17.8	4.25	
07/12/98	27	0.305	9.00	8.60	0.331	9.16	72.5	693	0.00	13.2	2.79	Read at 8:30 AM on 7/13
07/13/98	28	0.317	9.32	9.00	0.400	9.56	73.4	728	0.00	9.9	2.71	Re-fill
07/14/98	29	0.333	9.65	0.20	0.200	9.76	73.7	737	0.00	9.3	3.00	
07/15/98	30	0.355	10.01	0.60	0.400	10.16	74.4	761	0.00	8.3	3.08	
07/16/98	31	0.403	10.41	1.00	0.400	10.56	75.3	727	0.00	12.2	6.46	
07/17/98	32	0.365	10.78		0.367	10.92	72.6	745	0.00	11.3	4.21	
07/18/98	33	0.365	11.14		0.367	11.29	75.8	707	0.00	10.1	4.58	
07/19/98	34	0.330	11.47	2.10	0.367	11.66	78.2	506	0.00	10.9	4.46	
07/20/98	35	0.328	11.80	2.50	0.400	12.06	75.6	523	0.00	14.4	5.33	
07/21/98	36	0.302	12.10	2.80	0.300	12.36	75.4	662	0.12	16.2	2.79	
07/22/98	37	0.293	12.39	3.10	0.300	12.66	73.4	653	0.12	13.5	2.79	
07/23/98	38	0.216	12.61	3.20	0.100	12.76	68.2	436	0.36	35.1	3.25	
07/24/98	39	0.213	12.82		0.233	12.99	67.3	511	0.00	43.4	3.25	
07/25/98	40	0.252	13.07		0.233	13.22	69.9	621	0.08	34.2	3.50	
07/26/98	41	0.230	13.30	3.90	0.233	13.46	69.2	493	0.23	32.4	4.29	
07/27/98	42	0.174	13.48	4.00	0.100	13.56	67.7	419	0.02	42.6	2.63	
07/28/98	43	0.158	13.64	4.10	0.100	13.66	65.5	353	0.41	45.6	3.29	

Table 7 continued.

Date	Day	Kimberly Penman Daily ETr in	Kimberly Penman Cum. ETr in	ETgage readings in[1]	ETgage daily in	ETgage Cum. ETr in	Avg. temp. Deg F	Solar radiation Lngly	Precip. in.	Min. RH %	Avg. wind speed mi/hr	Comments (ETgage)
07/29/98	44	0.228	13.86	4.30	0.200	13.86	67.7	551	0.01	22.4	2.92	
07/30/98	45	0.271	14.14	4.70	0.400	14.26	68.8	679	0.00	20.5	2.96	
07/31/98	46	0.265	14.40		0.267	14.52	68.8	497	0.03	30.9	6.92	
08/01/98	47	0.245	14.65		0.267	14.79	66.7	565	0.00	22.3	3.83	
08/02/98	48	0.308	14.95	5.50	0.267	15.06	67.3	693	0.00	15.8	4.46	
08/03/98	49	0.354	15.31	5.90	0.400	15.46	68.2	684	0.00	16.0	6.63	
08/04/98	50	0.347	15.65	6.20	0.300	15.76	67.4	699	0.00	21.0	6.58	
08/05/98	51	0.288	15.94	6.50	0.300	16.06	67.3	700	0.00	16.9	3.58	
08/06/98	52	0.318	16.26	6.90	0.400	16.46	70.6	705	0.00	10.3	4.08	
08/07/98	53	0.296	16.56		0.333	16.79	71.2	690	0.00	10.5	2.92	
08/08/98	54	0.276	16.83		0.333	17.12	74.0	630	0.00	9.9	2.92	
08/09/98	55	0.197	17.03	7.90	0.333	17.46	71.7	390	0.00	18.2	1.88	
08/10/98	56	0.208	17.24	8.20	0.300	17.76	69.5	333	0.00	29.0	3.96	
08/11/98	57	0.244	17.48	8.40	0.200	17.96	70.0	509	0.00	25.0	3.54	
08/12/98	58	0.341	17.82	8.80	0.400	18.36	70.3	677	0.00	9.4	5.63	Re-fill
08/13/98	59	0.207	18.03	0.10	0.100	18.46	67.6	361	0.02	24.9	3.67	
08/14/98	60	0.290	18.32		0.300	18.76	69.6	668	0.00	16.8	3.75	
08/15/98	61	0.304	18.62		0.300	19.06	71.0	639	0.00	9.1	4.50	
08/16/98	62	0.271	18.89	1.00	0.300	19.36	70.9	574	0.00	16.8	3.92	
08/17/98	63	0.258	19.15	1.30	0.300	19.66	70.0	561	0.00	18.8	3.75	
08/18/98	64	0.241	19.39	1.50	0.200	19.86	67.4	517	0.00	22.8	4.42	
08/19/98	65	0.256	19.65	1.80	0.300	20.16	67.5	663	0.00	12.8	2.29	
08/20/98	66	0.244	19.89	2.00	0.200	20.36	71.8	441	0.07	25.3	5.13	
08/21/98	67	0.171	20.06		0.267	20.62	64.8	376	0.16	51.9	5.13	
08/22/98	68	0.232	20.30		0.267	20.89	70.1	604	0.00	25.3	2.67	
08/23/98	69	0.247	20.54	2.80	0.267	21.16	73.3	651	0.00	14.2	2.38	
08/24/98	70	0.234	20.78	3.00	0.200	21.36	70.8	484	0.10	26.4	4.63	
08/25/98	71	0.188	20.97	3.20	0.200	21.56	68.1	395	0.10	33.6	3.33	
08/26/98	72	0.237	21.20	3.50	0.286	21.84	69.6	603	0.00	30.4	3.21	Read at 9:22 AM on 8/27
08/27/98	73	0.272	21.47	3.80	0.318	22.16	70.4	538	0.00	18.0	5.33	
08/28/98	74	0.275	21.75		0.367	22.53	69.8	637	0.00	13.0	3.71	
08/29/98	75	0.269	22.02		0.367	22.90	72.2	615	0.00	17.0	3.96	
08/30/98	76	0.268	22.29	4.90	0.367	23.26	70.5	610	0.00	10.7	3.25	
08/31/98	77	0.243	22.53	5.20	0.300	23.56	69.6	449	0.00	23.8	5.29	
09/01/98	78	0.201	22.73	5.40	0.200	23.76	65.3	402	0.00	39.3	4.71	
09/02/98	79	0.226	22.96	5.60	0.200	23.96	67.0	551	0.00	27.4	3.42	
09/03/98	80	0.223	23.18	5.90	0.300	24.26	70.3	564	0.00	20.5	3.13	
09/04/98	81	0.194	23.37		0.250	24.51	69.4	359	0.00	17.5	4.25	
09/05/98	82	0.184	23.56		0.250	24.76	68.4	372	0.00	30.2	3.54	
09/06/98	83	0.203	23.76		0.250	25.01	67.2	484	0.00	22.9	2.88	
09/07/98	84	0.226	23.99	6.90	0.250	25.26	69.8	531	0.00	16.9	3.54	
09/08/98	85	0.225	24.21	7.20	0.300	25.56	70.6	396	0.00	17.4	4.79	
09/09/98	86	0.194	24.41	7.40	0.200	25.76	67.7	312	0.00	20.1	4.42	
09/10/98	87	0.141	24.55	7.50	0.100	25.86	66.4	241	0.04	31.0	3.50	

Table 7 continued.

Date	Day	Kimberly Penman Daily ETr in	Kimberly Penman Cum. ETr in	ETgage readings in[1]	ETgage daily in	ETgage Cum. ETr in	Avg. temp. Deg F	Solar radiation Lngly	Precip. in.	Min. RH %	Avg. wind speed mi/hr	Comments (ETgage)
09/11/98	88	0.152	24.70		0.167	26.03	65.9	323	0.10	40.9	3.88	
09/12/98	89	0.167	24.87		0.167	26.20	64.7	430	0.16	46.0	4.08	
09/13/98	90	0.208	25.07	8.00	0.167	26.36	63.9	551	0.09	24.8	3.96	
09/14/98	91	0.202	25.28	8.30	0.300	26.66	63.4	485	0.00	22.0	3.92	
09/15/98	92	0.206	25.48	8.50	0.200	26.86	65.6	417	0.00	18.2	5.33	
09/16/98	93	0.235	25.72	8.70	0.200	27.06	65.1	488	0.03	20.0	5.88	
09/17/98	94	0.198	25.91	8.90	0.200	27.26	63.8	562	0.00	17.8	2.42	
09/18/98	95	0.191	26.11		0.300	27.56	65.5	531	0.00	19.4	2.71	
09/19/98	96	0.203	26.31		0.300	27.86	63.1	558	0.00	9.5	2.92	
09/20/98	97	0.263	26.57	9.80	0.300	28.16	62.0	519	0.00	12.2	6.50	
09/21/98	98	0.252	26.82	0.10	0.100	28.26	58.5	545	0.00	8.5	5.83	Re-fill
09/22/98	99	0.150	26.97	0.30	0.200	28.46	56.2	315	0.00	27.3	3.63	
09/23/98	100	0.174	27.15	0.50	0.200	28.66	63.1	506	0.00	25.6	3.46	
09/24/98	101	0.227	27.37	0.70	0.200	28.86	62.8	524	0.00	14.7	5.42	
09/25/98	102	0.221	27.60		0.267	29.13	59.0	522	0.00	15.8	5.46	
09/26/98	103	0.217	27.81		0.267	29.40	55.6	521	0.00	13.2	4.96	
09/27/98	104	0.205	28.02	1.50	0.267	29.67	60.5	521	0.00	10.8	4.08	
09/28/98	105	0.155	28.17	1.70	0.200	29.87	64.3	293	0.00	17.9	4.38	
09/29/98	106	0.184	28.36	1.80	0.100	29.97	65.6	345	0.41	27.0	6.13	
09/30/98	107	0.176	28.53	2.00	0.200	30.17	61.8	401	0.01	25.7	5.63	
10/01/98	108	0.148	28.68	2.10	0.100	30.27	53.8	324	0.02	22.3	3.88	
10/02/98	109	0.156	28.84		0.067	30.33	52.8	477	0.00	22.7	2.83	
10/03/98	110	0.206	29.04		0.067	30.40	53.4	301	0.39	20.5	9.21	
10/04/98	111	0.144	29.19	2.30	0.067	30.47	41.9	408	0.03	19.3	5.79	
Total		29.186			30.465				3.91			
Average		0.263			0.274		67.3	562	0.04	19.8	4.37	

[1]ETgage readings were recorded the next day at approximately 8:00 AM unless specified otherwise, in which case daily ETgage ETr is adjusted to reflect ETr in 24 hours.

Table 8. 1999 ET and climatic data.

Date	Day	Kimberly Penman Daily ETr in	Kimberly Penman Cum. ETr in	ETgage readings in[1]	ETgage daily in	ETgage Cum. ETr in	Avg. temp. Deg F	Solar radiation Lngly	Precip. in.	Min. RH %	Avg. wind speed mi/hr	Comments (ETgage)
05/07/99	1	0.220			0.273		49.1	718	0.00	15.2	4.21	
05/08/99	2	0.286	0.51		0.273	0.55	55.7	719	0.00	13.4	8.67	
05/09/99	3	0.312	0.82	0.92	0.273	0.82	55.5	646	0.00	10.3	10.88	
05/10/99	4	0.263	1.08	1.14	0.211	1.03	44.0	713	0.00	13.7	8.00	Read at 9:00 AM on 5/11
05/11/99	5	0.234	1.32	1.34	0.209	1.24	45.1	639	0.00	18.2	6.38	
05/12/99	6	0.243	1.56	1.60	0.260	1.50	48.9	700	0.00	19.6	5.08	
05/13/99	7	0.329	1.89	1.94	0.340	1.84	57.1	675	0.00	14.7	11.29	
05/14/99	8	0.343	2.23		0.287	2.13	57.2	730	0.00	8.3	11.38	
05/15/99	9	0.339	2.57		0.287	2.41	53.0	726	0.00	11.9	9.83	
05/16/99	10	0.285	2.85	2.80	0.287	2.70	47.8	732	0.00	10.7	6.33	
05/17/99	11	0.284	3.14	3.10	0.300	3.00	48.7	752	0.00	7.0	5.08	
05/18/99	12	0.285	3.42	3.42	0.307	3.31	55.6	700	0.00	6.4	5.46	Read at 9:00 AM on 5/19
05/19/99	13	0.309	3.73	3.76	0.355	3.66	58.1	738	0.00	7.4	6.50	
05/20/99	14	0.269	4.00	4.08	0.320	3.98	56.7	742	0.00	9.8	3.63	
05/21/99	15	0.298	4.30		0.280	4.26	60.8	627	0.00	9.0	6.00	
05/22/99	16	0.331	4.63		0.280	4.54	62.6	656	0.00	10.2	8.25	
05/23/99	17	0.290	4.92	4.92	0.280	4.82	61.0	432	0.12	15.9	9.63	
05/24/99	18	0.239	5.16	5.10	0.180	5.00	53.9	537	0.02	31.6	7.88	
05/25/99	19	0.204	5.36	5.24	0.140	5.14	52.3	496	0.00	30.3	3.92	
05/26/99	20	0.205	5.57	5.42	0.180	5.32	53.6	578	0.02	33.9	3.75	
05/27/99	21	0.183	5.75	5.58	0.160	5.48	55.0	482	0.00	35.2	3.83	
05/28/99	22	0.241	5.99		0.255	5.74	56.8	685	0.00	24.1	3.54	
05/29/99	23	0.225	6.22		0.255	5.99	59.1	478	0.00	20.7	5.46	
05/30/99	24	0.250	6.47		0.255	6.25	58.4	522	0.01	18.7	5.75	
05/31/99	25	0.332	6.80	6.60	0.255	6.50	58.8	746	0.00	9.8	6.75	
06/01/99	26	0.303	7.10	6.90	0.300	6.80	54.9	735	0.00	9.6	4.75	
06/02/99	27	0.213	7.32	7.04	0.140	6.94	52.4	363	0.02	29.4	6.88	
06/03/99	28	0.352	7.67	7.34	0.300	7.24	53.8	752	0.00	12.8	8.96	
06/04/99	29	0.357	8.02		0.167	7.41	48.7	644	0.00	12.8	10.75	
06/05/99	30	0.078	8.10		0.167	7.58	35.6	162	0.43	45.0	4.33	
06/06/99	31	0.223	8.33	7.84	0.167	7.74	50.7	751	0.00	28.1	2.92	
06/07/99	32	0.326	8.65	8.20	0.360	8.10	58.6	780	0.00	9.4	6.75	
06/08/99	33	0.346	9.00	8.56	0.360	8.46	60.9	780	0.00	8.4	7.04	
06/09/99	34	0.305	9.30	8.94	0.380	8.84	58.5	778	0.00	9.0	3.46	
06/10/99	35	0.338	9.64	9.26	0.320	9.16	58.2	776	0.00	8.8	5.17	
06/11/99	36	0.271	9.91		0.327	9.49	58.6	561	0.00	12.7	4.29	
06/12/99	37	0.307	10.22		0.327	9.82	61.8	720	0.00	12.3	4.42	
06/13/99	38	0.288	10.51	10.24	0.327	10.14	62.9	695	0.00	13.5	3.50	refilled to 2.78
06/14/99	39	0.324	10.83	3.04	0.260	10.40	62.7	680	0.01	19.6	7.42	
06/15/99	40	0.277	11.11	3.34	0.300	10.70	63.4	582	0.03	20.8	5.13	
06/16/99	41	0.315	11.42	3.64	0.300	11.00	66.4	676	0.06	16.8	5.58	
06/17/99	42	0.215	11.64	3.76	0.120	11.12	59.2	484	0.48	36.5	6.00	
06/18/99	43	0.266	11.90		0.307	11.43	62.9	678	0.00	22.8	3.00	
06/19/99	44	0.326	12.23		0.307	11.74	66.1	785	0.00	10.2	3.46	
06/20/99	45	0.290	12.52	4.68	0.307	12.05	66.6	565	0.03	23.0	5.88	

Table 8 continued.

		Kimberly Penman		ETgage	ETgage	ETgage	Avg.	Solar		Min.	Avg. wind	
		Daily ETr	Cum. ETr	readings	daily	Cum. ETr	temp.	radiation	Precip.	RH	speed	
Date	Day	in	in	in[1]	in	in	Deg F	Lngly	in.	%	mi/hr	Comments (ETgage)
06/21/99	46	0.306	12.83	4.98	0.300	12.35	64.1	688	0.00	24.0	5.17	
06/22/99	47	0.335	13.16	5.34	0.360	12.71	65.4	753	0.00	12.4	4.54	
06/23/99	48	0.319	13.48	5.76	0.420	13.13	67.3	773	0.00	7.1	2.21	
06/24/99	49	0.326	13.81	6.20	0.440	13.57	68.1	768	0.00	8.5	2.58	
06/25/99	50	0.354	14.16		0.380	13.95	69.5	757	0.00	11.3	4.79	
06/26/99	51	0.338	14.50		0.380	14.33	66.7	668	0.02	9.0	4.88	
06/27/99	52	0.354	14.85	7.34	0.380	14.71	68.6	772	0.00	8.7	4.04	
06/28/99	53	0.365	15.22	7.84	0.500	15.21	68.7	786	0.00	5.2	3.33	
06/29/99	54	0.381	15.60	8.36	0.499	15.70	71.2	770	0.00	8.5	4.54	Read at 10:00 AM on 6/30
06/30/99	55	0.388	15.99	8.84	0.501	16.21	70.9	768	0.00	9.2	4.75	
07/01/99	56	0.353	16.34	9.30	0.460	16.67	73.6	764	0.00	9.1	3.29	refilled to 0
07/02/99	57	0.409	16.75		0.362	17.03	72.9	695	0.00	11.4	7.17	
07/03/99	58	0.367	17.11		0.362	17.39	69.8	684	0.00	18.7	7.04	
07/04/99	59	0.359	17.47		0.362	17.75	70.7	681	0.00	14.4	6.08	
07/05/99	60	0.376	17.85	1.48	0.362	18.11	74.3	761	0.00	12.4	4.67	Read at 10:00 AM on 7/6
07/06/99	61	0.352	18.20	1.82	0.371	18.48	72.9	724	0.42	22.8	5.46	
07/07/99	62	0.296	18.50	2.06	0.221	18.71	71.8	592	0.08	27.2	5.29	Read at 10:00 AM on 7/8
07/08/99	63	0.207	18.70	2.26	0.200	18.91	68.0	423	0.00	37.3	2.88	Read at 10:00 AM on 7/9
07/09/99	64	0.248	18.95		0.240	19.15	70.3	449	0.00	19.6	4.83	
07/10/99	65	0.238	19.19		0.240	19.39	67.2	543	0.39	37.4	3.88	
07/11/99	66	0.294	19.48	2.96	0.240	19.63	67.4	617	0.00	31.5	6.04	
07/12/99	67	0.285	19.77	3.26	0.300	19.93	69.0	597	0.00	21.6	4.08	
07/13/99	68	0.286	20.06	3.56	0.300	20.23	69.9	608	0.00	19.5	3.88	
07/14/99	69	0.148	20.20	3.64	0.080	20.31	64.6	290	0.14	46.7	3.50	
07/15/99	70	0.213	20.42	3.84	0.200	20.51	66.2	493	0.00	35.2	3.08	
07/16/99	71	0.269	20.69		0.252	20.76	65.2	679	0.00	29.2	3.00	
07/17/99	72	0.282	20.97		0.252	21.01	67.6	653	0.00	23.4	3.88	
07/18/99	73	0.188	21.16		0.252	21.26	63.9	344	0.00	46.2	5.29	
07/19/99	74	0.151	21.31		0.252	21.51	63.9	302	0.00	38.2	2.83	
07/20/99	75	0.258	21.56	5.10	0.252	21.77	67.7	623	0.00	16.4	2.63	
07/21/99	76	0.250	21.81	5.32	0.220	21.99	67.5	548	0.06	32.4	4.58	
07/22/99	77	0.207	22.02	5.50	0.180	22.17	65.6	493	0.01	35.6	2.92	
07/23/99	78	0.245	22.27		0.233	22.40	69.4	492	0.00	24.4	3.75	
07/24/99	79	0.244	22.51		0.233	22.63	69.1	499	0.21	32.9	4.63	
07/25/99	80	0.236	22.75	6.20	0.233	22.86	68.3	543	0.01	32.0	3.79	
07/26/99	81	0.270	23.02	6.52	0.320	23.18	70.8	640	0.00	28.0	3.42	
07/27/99	82	0.243	23.26	6.78	0.260	23.44	69.5	562	0.15	30.2	3.92	
07/28/99	83	0.259	23.52	7.04	0.260	23.70	69.5	652	0.00	33.9	3.21	
07/29/99	84	0.237	23.76	7.28	0.240	23.94	68.5	554	0.20	37.5	3.96	
07/30/99	85	0.253	24.01		0.260	24.20	66.3	665	0.01	40.9	3.88	
07/31/99	86	0.261	24.27		0.260	24.46	64.7	671	0.00	33.7	3.88	
08/01/99	87	0.274	24.54	8.06	0.260	24.72	67.6	641	0.09	26.1	4.63	
08/02/99	88	0.205	24.75	8.26	0.200	24.92	68.9	427	0.13	30.2	4.08	
08/03/99	89	0.110	24.86	8.26	0.000	24.92	61.5	247	0.08	61.8	2.54	error prob caused by wet canvas cover
08/04/99	90	0.223	25.08	8.54	0.280	25.20	65.1	637	0.00	45.2	2.92	
08/05/99	91	0.090	25.17	8.54	0.000	25.20	62.5	176	0.15	58.7	2.79	error prob caused by wet canvas cover

Table 8 continued.

Date	Day	Kimberly Penman Daily ETr in	Kimberly Penman Cum. ETr in	ETgage readings in[1]	ETgage daily in	ETgage Cum. ETr in	Avg. temp. Deg F	Solar radiation Lngly	Precip. in.	Min. RH %	Avg. wind speed mi/hr	Comments (E
08/06/99	92	0.195	25.37		0.260	25.46	64.6	577	0.00	35.9	1.83	
08/07/99	93	0.249	25.62		0.260	25.72	66.7	685	0.00	20.2	2.54	
08/08/99	94	0.234	25.85	9.32	0.260	25.98	69.3	457	0.04	26.0	4.50	
08/09/99	95	0.231	26.08	9.54	0.220	26.20	67.3	458	0.00	37.3	5.25	refilled to 0
08/10/99	96	0.113	26.19	0.02	0.019	26.22	61.3	236	0.06	55.7	2.92	Read at 9:00
08/11/99	97	0.243	26.44	0.18	0.160	26.38	62.9	624	0.44	25.7	4.33	Read at 9:00
08/12/99	98	0.247	26.68	0.42	0.250	26.63	62.3	687	0.00	20.5	2.21	
08/13/99	99	0.265	26.95		0.210	26.84	63.9	692	0.00	16.0	2.92	
08/14/99	100	0.207	27.16		0.210	27.05	66.0	370	0.02	26.2	4.83	
08/15/99	101	0.165	27.32		0.210	27.26	64.1	424	0.10	43.1	3.33	
08/16/99	102	0.213	27.53	1.26	0.210	27.47	65.8	520	0.09	27.8	3.67	
08/17/99	103	0.208	27.74	1.48	0.220	27.69	66.6	552	0.01	32.2	2.92	
08/18/99	104	0.240	27.98	1.74	0.260	27.95	69.9	568	0.04	24.4	3.83	
08/19/99	105	0.202	28.18	1.90	0.160	28.11	67.2	423	0.08	35.1	4.33	
08/20/99	106	0.191	28.37		0.227	28.34	66.9	425	0.29	37.9	4.04	
08/21/99	107	0.208	28.58		0.227	28.57	64.8	549	0.00	38.3	3.42	
08/22/99	108	0.255	28.84	2.58	0.227	28.79	67.2	658	0.00	26.4	3.75	
08/23/99	109	0.256	29.09	2.90	0.307	29.10	69.8	589	0.00	27.3	4.33	Read at 9:00
08/24/99	110	0.240	29.33	3.12	0.229	29.33	69.5	469	0.10	28.8	5.38	
08/25/99	111	0.210	29.54	3.34	0.220	29.55	68.5	466	0.02	32.9	3.83	
08/26/99	112	0.217	29.76	3.54	0.200	29.75	68.4	463	0.15	29.5	4.17	
08/27/99	113	0.189	29.95		0.200	29.95	66.7	408	0.08	38.1	4.17	
08/28/99	114	0.221	30.17		0.200	30.15	67.0	554	0.03	38.4	4.46	
08/29/99	115	0.222	30.39	4.14	0.200	30.35	66.8	532	0.00	34.1	4.42	
08/30/99	116	0.176	30.57	4.34	0.200	30.55	68.4	348	0.08	30.5	4.29	
08/31/99	117	0.203	30.77	4.50	0.160	30.71	65.1	482	0.43	35.7	4.54	
09/01/99	118	0.079	30.85	4.54	0.040	30.75	56.3	147	0.21	74.2	4.29	
09/02/99	119	0.156	31.01	4.62	0.080	30.83	60.5	358	0.21	48.3	5.83	
09/03/99	120	0.222	31.23		0.265	31.10	59.6	547	0.00	21.7	5.67	
09/04/99	121	0.204	31.43		0.265	31.36	58.3	615	0.00	15.6	2.50	
09/05/99	122	0.215	31.65		0.265	31.63	60.6	616	0.00	12.3	2.71	
09/06/99	123	0.226	31.87	5.68	0.265	31.89	64.4	590	0.00	16.4	3.75	
09/07/99	124	0.231	32.10	6.02	0.340	32.23	66.3	581	0.00	14.8	4.00	
09/08/99	125	0.235	32.34	6.34	0.307	32.54	66.0	597	0.00	10.9	3.29	Read at 9:00
09/09/99	126	0.209	32.55	6.62	0.292	32.83	64.3	446	0.00	14.8	3.63	
09/10/99	127	0.196	32.74		0.213	33.04	62.6	555	0.00	21.8	2.21	
09/11/99	128	0.204	32.95		0.213	33.26	59.1	513	0.05	36.0	4.50	
09/12/99	129	0.167	33.12	7.26	0.213	33.47	60.1	456	0.00	28.7	2.71	
09/13/99	130	0.197	33.31	7.54	0.280	33.75	61.7	557	0.00	14.4	2.88	
09/14/99	131	0.152	33.46		0.150	33.90	59.5	366	0.00	32.3	3.38	
09/15/99	132	0.144	33.61	7.84	0.150	34.05	56.0	393	0.10	41.6	3.58	
09/16/99	133	0.142	33.75	7.94	0.100	34.15	58.2	371	0.16	32.7	3.00	
09/17/99	134	0.168	33.92		0.173	34.32	58.1	499	0.00	25.6	3.13	
09/18/99	135	0.157	34.08		0.173	34.49	58.7	455	0.00	29.6	3.13	
09/19/99	136	0.158	34.23	8.46	0.173	34.67	57.6	400	0.06	27.7	4.67	
09/20/99	137	0.194	34.43	8.70	0.240	34.91	57.8	470	0.00	19.8	5.33	

Table 8 continued.

Date	Day	Kimberly Penman Daily ETr in	Kimberly Penman Cum. ETr in	ETgage readings in[1]	ETgage daily in	ETgage Cum. ETr in	Avg. temp. Deg F	Solar radiation Lngly	Precip. in.	Min. RH %	Avg. wind speed mi/hr	Comments (ETgage)
09/21/99	138	0.241	34.67	8.96	0.260	35.17	56.9	557	0.00	9.8	5.75	
09/22/99	139	0.158	34.83	9.20	0.240	35.41	56.9	439	0.00	13.4	2.75	
09/23/99	140	0.054	34.88	9.20	0.000	35.41	53.5	126	0.15	63.4	2.50	cloudy, rainy
09/24/99	141	0.123	35.00		0.200	35.61	58.8	435	0.00	44.8	2.33	
09/25/99	142	0.149	35.15		0.200	35.81	62.4	518	0.00	27.1	2.08	
09/26/99	143	0.177	35.33	9.80	0.200	36.01	63.6	527	0.00	14.0	2.96	
09/27/99	144	0.228	35.56	10.08	0.280	36.29	50.6	522	0.00	14.1	5.58	
09/28/99	145	0.302	35.86	10.22	0.140	36.43	43.4	526	0.00	8.9	11.08	refilled to 0
09/29/99	146	0.162	36.02	0.06	0.060	36.49	47.4	520	0.00	12.2	2.79	
09/30/99	147	0.134	36.16	0.26	0.200	36.69	54.7	518	0.00	8.2	2.00	
10/01/99	148	0.165	36.32		0.247	36.93	57.7	503	0.00	10.8	3.71	
10/02/99	149	0.163	36.48		0.247	37.18	55.1	484	0.00	10.2	3.38	
10/03/99	150	0.201	36.68	1.00	0.247	37.43	56.6	488	0.00	6.3	4.71	
10/04/99	151	0.169	36.85	1.28	0.280	37.71	55.6	496	0.00	5.7	2.92	
10/05/99	152	0.191	37.04		0.220	37.93	60.4	408	0.00	10.4	5.25	
10/06/99	153	0.218	37.26	1.72	0.220	38.15	58.8	286	0.00	16.6	8.67	
10/07/99	154	0.149	37.41		0.235	38.38	47.1	309	0.01	31.3	7.50	
10/08/99	155	0.209	37.62		0.235	38.62	53.6	467	0.00	20.7	7.21	
10/09/99	156	0.141	37.76		0.235	38.85	57.3	471	0.00	13.0	2.67	
10/10/99	157	0.126	37.89		0.235	39.09	60.7	468	0.00	9.6	2.21	
10/11/99	158	0.157	38.04		0.235	39.32	61.4	464	0.00	6.8	3.29	
10/12/99	159	0.159	38.20		0.235	39.56	60.1	459	0.00	9.5	3.21	
10/13/99	160	0.165	38.37		0.235	39.79	60.7	455	0.00	9.2	3.46	
10/14/99	161	0.145	38.51	3.60	0.235	40.03	57.9	450	0.00	7.5	2.54	
Total		38.513			40.028				6.39			
Average		0.239			0.249		61.7	560	0.04	23.1	4.60	

[1]ETgage readings were recorded the next day at approximately 8:00 AM unless specified otherwise, in which case daily ETgage ETr is adjusted to reflect ETr in 24 hours.