Daily Measurement and Calculation of Crop Water Use

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ABSTRACT

There is a need for an accurate method to calculate and to measure crop water use on a real-time basis. We implemented a system that combines current knowledge of crop water use and newly developed technology to control the timely application of water in the correct amount. The technologies involved are the measurement of plant water use with electronic stem flow gauges and measurement of soil water with time domain reflectometry. Measurements are coupled with calculated values of crop water use obtained with the mechanistic simulation model ENWATBAL. The system is integrated because all functions, e.g., measurements, model execution, activation of water delivery system, are controlled by a single computer. The system was tested over a 2-year period with cotton in Lubbock, TX using a surface drip irrigation system during the second year. The resulting system can be used to schedule irrigation by farmers, determine the water requirements of different crops, and as a research tool by scientists.

Keywords. Irrigation, Real-time, Simulation model, Transpiration, Soil evaporation

INTRODUCTION

Agriculture claims 2/3 of the water removed from rivers, lakes and aquifers thus making efficiency in irrigation a priority to move towards sustainable water use. Reducing irrigation needs by 10% would free up enough water to double domestic water use worldwide (Shiklomanov, 1990). Evapotranspiration (E_t), the sum of evaporative losses of water from the soil and the crop, is one of the most basic components of the hydrologic cycle. A major obstacle in evaluating water inventories and future demands is in determining crop water use and requirements. Evapotranspiration can either be measured or calculated. Under field conditions, accurate values of E_t can be measured using soil water depletion, lysimetry, and micrometeorological methods. However, these methods are laborious, time consuming, and are inapplicable to trees, shrubs, or vines. Furthermore, in many cases these methods are better suited for short-term studies, i.e., one week or less. Also, E_t can be calculated from models that use standard weather data as input, such as the mechanistic simulation model ENWATBAL (Lascano et al., 1987; Evett and Lascano, 1993). Alternatively, E_t can be estimated from its potential maximum value, using standard weather data, plus crop coefficients obtained from measured crop water use. Both methods have been shown to be accurate for a few major crops and the technology for obtaining and using such information is commercially available. Thus there is a need for a general method that is accurate and can be used to measure E_t with immediate application to major agricultural crops as well as for trees and shrubs.

The objective of this work was to use current knowledge and newly developed technology to measure crop water use in real-time and to control the timely application of water in the correct amount. In addition, measurements are coupled with calculated values of E_t obtained with the mechanistic ENWATBAL model (Evett and Lascano, 1993). This system was tested and evaluated using cotton grown in the semiarid climate of Lubbock, TX over a 2-year period.

MATERIALS AND METHODS

Description of the System

A schematic diagram of the integrated real-time measurement and calculation of crop water use system is shown in Fig. 1. The system consists of five components: measurement, calculation (simulation model), a 'feedback' loop that verifies calculated values of crop water use, water delivery (irrigation), and a central processing and control unit.

Measurement. This component includes the measurement of soil water, crop transpiration, soil temperature, soil heat flux and weather variables. A weather station measures

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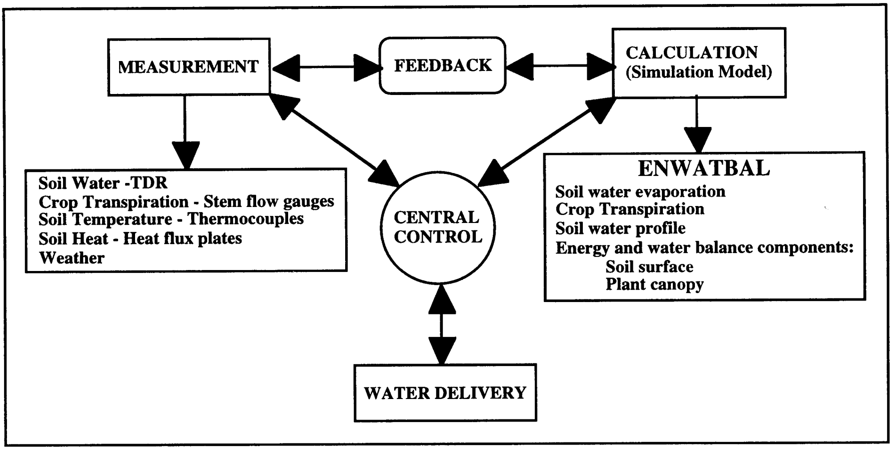

Figure 1. Schematic diagram of the integrated real-time system to measure and calculate crop water use.

air temperature and humidity, wind speed, global and net irradiance, and rainfall. Crop transpiration is measured with the stem heat balance method (Baker and Van Bavel, 1987; Lascano et al., 1992) using commercial gauges (Dynamax Inc., Houston, TX). Profiles of soil water content are measured with time-domain reflectometry (TDR) equipment (Topp et al., 1980) using a Tektronix cable tester and an automated system designed by the Vadose Zone Equipment Co. (Dynamax Inc., Houston, TX). Soil temperature profiles are measured with type-T thermocouples (e.g., Lascano et al., 1987) and soil heat flux is measured with heat flux transducers (REBS, Seattle, WA). Sensors are connected to three dataloggers all linked to a common computer used to down load raw data.

Calculation. The ENWATBAL model (Evett and Lascano, 1993) is used to calculate water evaporation from the soil and crop, soil water and temperature profiles, and soil surface heat flux. Output from the model also includes both the energy and water balance for the soil surface and plant canopy. The model is executed daily after midnight using the measured weather data from the previous day.

Feedback. This system measures crop transpiration in real-time, and soil water content and temperature profiles, allowing for the daily verification of calculated values obtained with the ENWATBAL model. This feedback loop, i.e., comparison of calculated and measured values, is a unique feature of this system. All measurements are automated and data can thus be collected and processed via a central computer in such a way that instantaneous as well as integrated values are obtained in real-time.

Water delivery. The amount of water to be applied via an irrigation system is calculated from the simulated values obtained with the ENWATBAL model and can be verified by independent measurements of crop transpiration and soil water content. This information is used to activate the water delivery system and to govern the amount of water applied. The system is applicable to several irrigation methods, e.g., overhead sprinklers including LEPA systems, surface and buried drip, and can be used in any type of irrigation schedule designed to replace daily E_t at several frequencies, e.g., Bordovsky et al. (1992) for cotton.

Central control. A single computer links all system components. The function of the main control is to download raw data from all the sensors. Raw data are further processed, reduced, and formatted for use with ENWATBAL. Software written for this purpose compares measured and calculated values of crop water use, and activates the water delivery system. In addition, the central computer has a graphical interface that provides the user with instantaneous, hourly, and daily values of all measured variables.

Data Acquisition Systems

Hardware. A diagram showing the connectivity of field measurements to dataloggers and to a central computer is shown in Fig. 2. Three criteria were used to select hardware and these were that it had to be 1) commercially available; 2) portable and for field use, and operate with

DC current for remote use; and 3) system had to be modular in design. Advantages of a modular design are that the user can customize application(s) and not all sensors are connected to a single datalogger. This avoids unnecessary down-time in case of catastrophic events, such as lighting, or failure of the single datalogger. Data back-up is enhanced because data are not only stored in individual dataloggers, but also in a common computer.

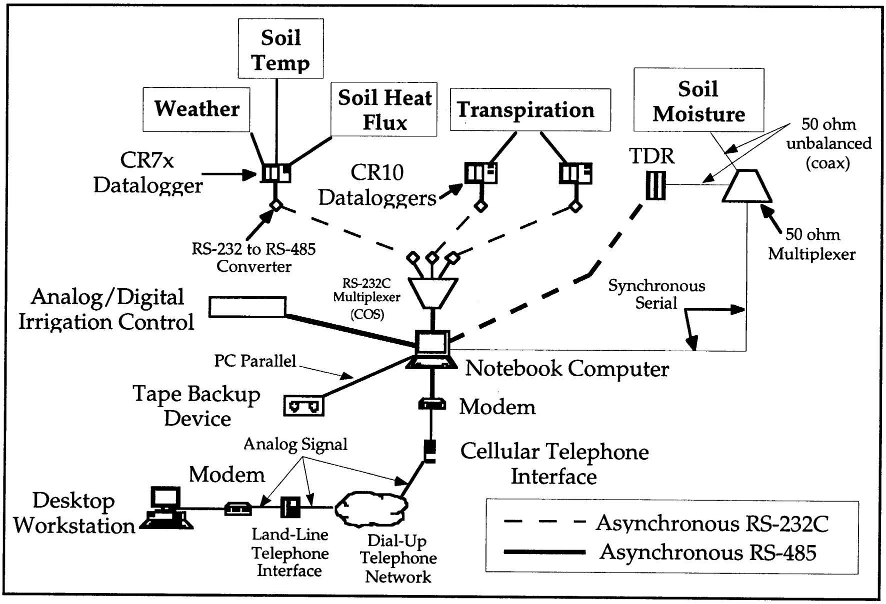

Figure 2. Connectivity of data acquisition systems to a notebook computer used to measure weather, soil temperature, soil heat flux, transpiration and soil water content.

Data acquisition systems used to measure all parameters, except TDR, were three dataloggers (one CR-7x and two CR-10's from Campbell Scientific, Inc., Logan, UT). The CR-7x was used to measure weather variables, soil temperature with thermocouples and soil heat flux with transducers. Frequency of sampling was 10 s and 30 min averages were calculated and stored. Measurement of crop transpiration was done with two CR10 dataloggers, each handling up to 32 stem flow gauges (Flow-32 System, Dynamax Inc., Houston, TX). Frequency of sampling was 15 s and 15 and 30 min averages were processed and stored. Output from the dataloggers were first converted from an asynchronous RS-232C to an asynchronous RS-485 signal (Signal Converters, Black Box Corp., Pittsburgh, PA) and then reconverted to a RS-232C asynchronous signal that was input to an 8 serial port multiplexer (Code Operated Switch II, Black Box Corp., Pittsburgh, PA) connected to a notebook computer (AST, 33 MHz, 80486-based PC).

Measurement of water content by TDR was done with a cable tester (Model 1502C, Tektronix, Beaverton, OR). A total of 90 three conductor wave-guides, each 0.20 m long, were multiplexed (wave-guides and coaxial multiplexer, Vadose Zone Equipment Co., Dynamax, Inc.). Each multiplexer handles up to 16 signals from TDR wave-guides connected by a 50 ohm coaxial (unbalanced) cable to one output. The output from the TDR cable tester was directly connected to the computer (asynchronous RS-232C signal). Frequency of sampling was 30 min.

The lap-top computer, RS-232C multiplexer, cellular phone, and irrigation control were all located in a portable shed (2.4 x 3.0 m) located next to the field. The cellular phone transmitted raw and processed data to a computer server, for network access, and to a desk-top computer located in the facilities of the Texas Agric. Exp. Stn. in Lubbock, TX. This data transmission facilitated data handling for further processing and reduction, e.g., preparation of graphs showing the distribution of water content in the soil profile, crop transpiration, weather, etc.

Software. Whenever possible public-domain and/or commercially available software was used to activate and control measurement sensors, and for data retrieval and processing. To monitor weather data we used PC-208, GraphTerm® V 2.0 (Campbell Scientific, Logan, UT), with the stem flow gauges we used FLOW-32® V 2.1 (Dynamax, Inc., Houston, TX), and for TDR data acquisition and control we used TACQ.EXE® (Vadose Zone Equip. Co., Dynamax, Inc.). An interface to provide the user with an Instrument Control Panel was written in Microsoft VisualBasic® V1.0 and we also used Norton pcAnywhere (Symantec) for remote monitoring. The interface is a shell that gives several options: 1) monitor in real-time the field dataloggers, 2) retrieve uncollected data, 3) invoke TDR measurements, and 4) copy all data files to a floppy drive. The shell interacts with all data acquisition systems and gives the user instantaneous access to monitor any sensor. Also, macro-files written in Microsoft Excel® V 5.0 were used to download data from the server, via an Ethernet network, and reduce data to plot and print 30-min values of all variables.

Field Experiments

The system to measure and to calculate crop water use in real-time was tested using cotton in 1994 and 1995. In 1994 the crop was furrow irrigated and in 1995 we added a surface drip system. Cotton (Atlas, All-Tex Co., Levelland, TX) was planted 10 May in 1994 and 22 May in 1995 in single bedded rows 1.0 m apart along an E-W orientation. The field was 76 m x 210 m located at the Texas Agric. Exp. Stn., Lubbock in an Olton soil (fine, mixed, thermic Aridic Paleustol). In 1994 the field performance and reliability of the system were tested and in 1995 irrigation strategies typically used for cotton in the Texas High Plains were followed and evaluated (e.g., Bordovsky et al. 1992). In addition, in 1995 alternate versus every furrow irrigation, and the effect of a plant growth regulator (PIX®) on the daily and seasonal water use was evaluated. The latter are two examples of using this integrated system to evaluate the impact of agronomic practices on crop water use.

Measurements. Soil temperature and water content, plant water evaporation, and weather variables were measured using the sensors and methods previously described. In addition, we measured soil water evaporation and leaf area index (LAI) as described by Hicks and Lascano, 1995. Soil temperature was measured at depths of 0.05, 0.10, 0.20, 0.25, 0.30, 0.50, 1.00, and 2.00 m from the top of the bed. Soil water content was measured bi-weekly using neutron attenuation and every 30 min with the TDR system. Neutron access tubes were installed to a depth of 3.0 m. The TDR system had six multiplexers connected to wave-guides at six locations. Duplicate 0.20-m long wave-guides were inserted into the bed and parallel to the surface at depths of 0.05, 0.10, 0.20, and 0.30 m. Other wave-guides were installed vertically in 0.2-m increments to a depth of 1.2 m starting at 0.4 m. Measurement of crop transpiration with stem flow gauges started in mid-July after the stem diameter reached 10-13 mm. Stem flow data were converted to crop transpiration per unit leaf area using bi-weekly measured LAI. In 1994, soil water evaporation was measured for a 12-d period after an irrigation with microlysimeters using the procedure given by Lascano et al. (1987). The automated weather station recorded short-wave and net irradiance, air temperature and humidity, wind speed, and rainfall. All sensors were at a screen height of 2.0 m.

RESULTS AND DISCUSSION

To illustrate measurements obtained with the TDR and stem flow gauges we selected data for two days in 1994 during which the cotton crop was irrigated. Volumetric soil water content measured with the automated TDR system at three depths during days 209 and 210 are shown in Fig. 3. The water content on day 209, prior to irrigation, at 0.05 and 0.10 m depths was less than 3% and about 15% at 0.30 m. The increase in water content after irrigation on day 210 clearly shows the rapid response of the TDR system to detect the wetting front moving down the soil profile. Water content increased to 30% near the surface and close to 40% at 0.30 m. In addition, the wetting of a 25 mm rain that occurred on day 210 at 0400 h is also shown. The water content at 0.05 and 0.10 m depths increased by 5%.

The hourly average crop transpiration measured with 9 stem flow gauges, before and after an irrigation, on days 209 and 210 are given in Fig. 4. Prior to irrigation on day 209, the peak transpiration rate was 50 g/h; however, after the irrigation on day 210 the peak transpiration increased by 70% to 80 g/h. Hourly fluctuations of transpiration, particularly in the afternoon hours on day 209, were due to cloud cover that reduces energy driving latent heat flux and due to stomatal closure.

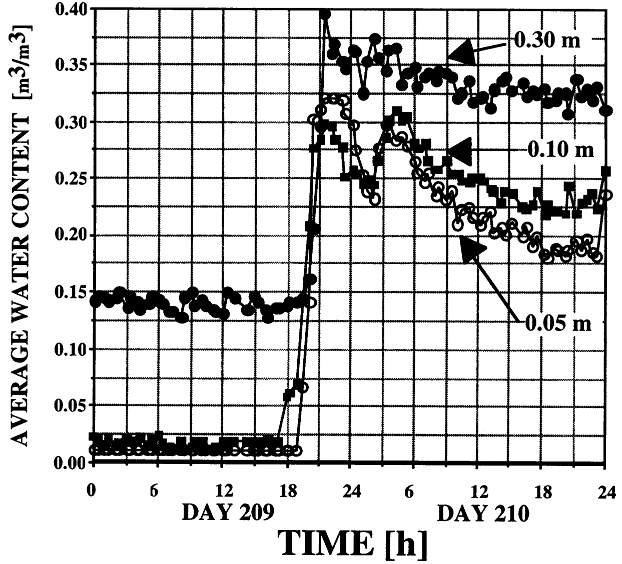

Figure 3. Soil water content at three depths measured with TDR following an irrigation on day 209 starting at 1600 h and a rain on day 210 at 0400 h.

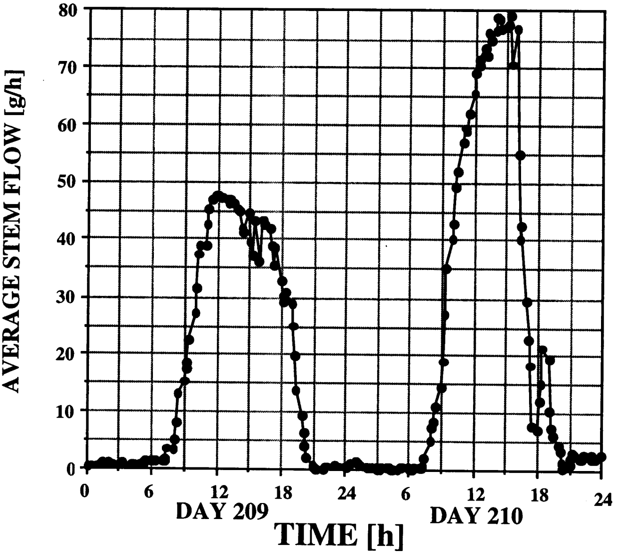

Figure 4. Hourly stem flow rate from cotton a day before and after irrigation.

These two examples show the type and quality of data that can be obtained with the system in real-time. In addition, instantaneous as well as integrated values of other variables, e.g., soil temperature, soil heat flux and weather, are also available. This capability gives the user the option of evaluating, e.g., the effect of a growth regulator or the application of different quantities of irrigation on transpiration as was done in our experiments in 1995 (data not shown).

Daily measured evaporative losses of water from the soil and crop for 12 d in 1994, following an irrigation is shown in Fig. 5. The decline of evaporation to < 1 mm on day 214 is the result of cloudy and cool weather. Crop transpiration was measured with stem flow gauges and soil water evaporation was measured with microlysimeters. Calculated PET was calculated from a Penman-Monteith model using as input hourly weather data measured in the field (Lascano and Salisbury, 1993). The LAI of the crop during this period increased from 2.1 to 2.5. These results clearly show that E and T continued at the potential rate immediately following the irrigation and slightly declined below PET after day 217. However, the dynamics of E and T are indicated by the reversal in their losses with respect to ET. For example, the ratio of T/ET increased linearly from 0.55 on day 210 to 0.95 on day 221, while the ratio of E/ET decreased linearly from 0.45 to less than 0.05 over the same time period. From an irrigation point of view the crop coefficient (k_c = (E+T)/PET) was close to 1.0 and these results illustrate how this system could be used to evaluate different irrigation strategies for a crop. This type of evaluation was done in 1995 (data not shown) using irrigation strategies designed for cotton production in the Texas High Plains (Bordovsky et al., 1992).

We conclude that an automated system to measure crop water use in real-time is feasible and accurate. The system can be used to schedule irrigation, to determine the water requirements of different crops, and as a research tool by scientists.

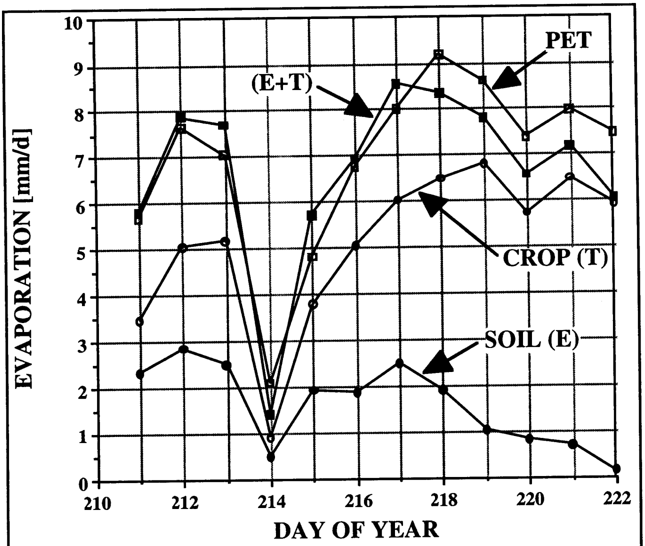

Figure 5. Daily measured evaporative losses of water from the soil and crop. Also plotted is the sum of (E+T) and the calculated potential evapotranspiration (PET).

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