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USE OF GRANULAR-MATRIX SENSORS, MODELS, AND EVAPORATION MEASURING DEVICES FOR MONITORING COTTON WATER USE AND SOIL WATER STATUS IN THE MISSISSIPPI DELTA

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Abstract

A study was conducted to obtain preliminary data for irrigation management of cotton in the Mississippi Delta. Data from soil moisture sensors, an atmometer, washtub evaporation pan, Class A evaporation pan, and several models were compared for their ability to determine crop water use and derive soil water status. Soil water potential from Watermark sensors was converted to soil water content by a published characteristic curve of the soil represented by each sensor. The resulting value was compared with soil water status derived in a 30-inch soil zone using the FAO56 crop water use model. The atmometer showed potential as a tool for estimating ET over periods longer than one day, but it lacked sensitivity for manual, daily readings. The washtub evaporation pan gave acceptable readings and could be used to estimate ET with proper calibration. Correlation between data from the atmometer and washtub was acceptable only when data for periods greater than one day were included. Data from the washtub correlated well with data from the Class A pan (r=0.75), having a slope close to one. The washtub will need to be convenient and easy-to-read for the farmer if it is to be adopted for irrigation scheduling. Model-based representations of ET indicated wide variability using data from the Stoneville weather station. However, if a suitable model is evaluated and proper temporal adjustments are applied, model-based ET estimation may be the most feasible of all methods since detailed weather data are readily available in the Delta. For widespread adoption of sensor-based irrigation scheduling methods, wireless transmission of signals and decision support tools may be required.

Introduction

Irrigation water is usually applied to cotton in the Mississippi Delta soon after planting to obtain a good stand. Subsequent applications are based on the farmer's "best guess," and this is still the predominant method of irrigation scheduling. Methods that use sensor or model-based approaches for scheduling are available but are seldom used due to their complexity or lack of guidelines for effective implementation. Many management decisions are required on the farm, and any task that takes too much time for a perceived minimal benefit is not usually performed. Taking frequent trips to the field to read soil water sensors, for example, would probably not be considered although their readings would be valuable if properly interpreted.

There are many types of sensors used for measuring soil water status. One low-maintenance type (called the Watermark sensor) works on the principle of changing electrical resistance in response to changes in water potential inside an internal granular matrix (Irrometer, 2001). Many researchers have provided calibration curves for these sensors, taking into account changes in soil temperature (Thomson and Armstrong, 1987; Eldredge et al., 1993; Thomson et al., 1996; Shock et al., 1998). Wireless telemetry devices (Adcon, 2001; Automata, 2001; Mitec, 2001 and others) can greatly ease the burden of reading several sensors, but proper interpretation of readings is still required to use them effectively for irrigation scheduling.

Models of crop water use (evapotranspiration or ET) can be labor-saving tools but require weather inputs of varying detail. Models range from mechanistic Penman-based versions that require many weather inputs to highly empirical or site-specific models that may only require one or two easily measured weather variables such as temperature or solar radiation. ET models are customarily modified by crop coefficients (Kc) that account for the crop and stage of growth, predominantly. Fortunately, detailed input data are available from the Stoneville weather station for most ET models including those described by Allen et al. (2000), Delta Agricultural Digest (1992) and Simpson and Fipps (2001).

Many soils favorable for crop production in the Delta have high water-holding capacities, which allow spacing irrigations relatively far apart. Irrigation customarily applies an inch or more of water, and is simply designed to replace water the crop has used over a short period, not to recharge the entire zone of active roots. Root-zone replenishment is not practical because of the water amounts required for high-retention soils. Although not a central theme of our study, it should be noted that irrigation might have the potential to enhance fiber quality by cooling the crop during critical periods of fiber development (Sassenrath-Cole, unpubl.).

Class A evaporation pans provide a measurement of the combined effect of temperature, humidity, windspeed and sunshine on the reference crop evapotranspiration, ETo, which is defined as water use from a well-watered grass (Allen et al., 1998). Pan coefficients are used to relate evaporation of water from the pan to reference ET, and crop coefficients further modify this reference value by crop type and stage of growth (Phene et al., 1992; DeTar et al., 2000). Evaporation pans using simple washtubs have been designed for use on the farm (Westesen and Hanson, 1981; Simonne et al., 1992), and have the potential of providing a simple method for determining when to irrigate. Simple rulers can be used to measure water level, or electronic devices attached to floats or other devices can provide continuous readings.

Evaporation devices called atmometers have received more attention recently in the research community as alternatives for estimating crop water use (Broner, 2001; Alam and Trooien, 2001). These devices use a covered, porous ceramic plate in the form of an inverted cup, supplied with water by a cylindrical reservoir. The drop in water level from evaporation is read from a glass tube connected by two ports to the reservoir and mounted on the outside of the reservoir. These devices can be used in concert with a rain gauge for water budgeting and have provisions for automatic data recording (ETgage, 2001).

The study outlined in this paper was designed to observe responses from in-field measuring devices and compare them to several model-based representations of ET using weather data obtained at the Stoneville Experiment Station. Preliminary observations will be outlined here to lend support for development of criteria and methods for effective water management of cotton in the Mississippi Delta.

Procedures

Three devices used in the experiment are illustrated in Figure 1. Watermark model 200SS soil water sensors were installed at ten stations in two fields labeled 4 and 13 (Figure 2). At eight stations shown in the figure, the sensors were glued to PVC pipe, sealed, and installed at three depths of 9, 18, and 27 inches. At stations 2 and 5, sensors were placed at 6 depths of 6, 12, 18, 24, 30 and 36 inches. Predominant soil types represented in Figure 2 are a Tunica clay (at stations 1,2,3,5,6,7, and 9), Sharkey clay (at stations 8 and 10), and a Dundee silty clay loam (at station 4). A soils map (USDA, 1961) was digitized into Arcview 3.2 to obtain soil zones represented in Figure 2.

A washtub with a screen mesh was installed adjacent to field 4, surrounded by low-cut grass. An evaporation device called an atmometer (Automata, 1991) was mounted on a post with a rain gauge. A canvas cover was placed over the atmometer's ceramic surface to limit evaporation and permit approximation of ETr, the ET from a well-watered crop. All sensors and instruments were read manually once a day, in the morning. The atmometer was supplied with a 0-1 psi pressure transducer to allow automatic readings. We did not record data automatically from the atmometer, but did take readings with a voltmeter to evaluate transducer response. A CR-7 Campbell micrologger and associated instruments are maintained at the Delta Research and Extension Center (DREC) weather station (Freeland, 2001) from which detailed daily weather data were input to ET models. Instrumentation at the weather station are part of a National Weather Service Cooperative Observer network site (Horvitz, 2001). Data from a Class A evaporation pan were also obtained, and results were compared with data from other methods used in this study.

After pre-plant fertilizer and herbicide applications in the Spring, fields 4 and 13 were planted in BXN-47, May 1, 2001 (Julian date 121). Field 4 was under plastic-pipe furrow irrigation, and field 13 was under a center-pivot sprinkler. Standard practices were used for weed and insect control throughout the season and fertilizer was applied to both fields June 18, 2001 (Julian date 169). An initial irrigation was applied May 16 and 17 to both fields to promote a good stand. An additional irrigation of 1.25 inches commenced June 25 for field 13, and June 27 for field 4. The latter irrigation was halted mid-day due to a rain, which accumulated 1.22 inches. Irrigation was scheduled by "feel" without the aid of soil water sensors, models, data from either evaporation pan, or atmometer.

Results

Preliminary Comparisions of Sensor- and Model-Based Methods for Determining Crop Water Use

Figures 3 and 4 approximate the seasonal water balance at several stations, derived by converting readings of sensor-derived water potential to water content, using standard soil-water retention curves (NRCS, 2001). Curves used were based on location of Watermark soil water sensors on the soils map of Figure 2. For comparison, results from the FAO-56 ET model with crop coefficients (Allen et al., 1998) are shown. Curves for both methods follow the same general trends, although sensor-based results suggest higher water uptake within the 30-inch zone of water regulation for field 13. Inaccurate characterization of soil-water retention curves in the sensor zones, imperfect sensor calibrations, and model inadequacies could all contribute to differences.

Figure 5a illustrates a comparison between two ET models modified with crop coefficients (Kc), two water use relationships referenced in the Delta Ag. Digest, the FAO56 model for reference ET (ETo), and data from our Class A evaporation pan (Epan). Figure 5b superimposes data from our washtub evaporation pan and atmometer. Significant variation can be seen between modified, model-based estimates. For example, two curves from the same publication (Delta Agricultural Digest, 1992) yielded different results for actual seasonal water use of cotton, depending on whether data were taken from a graph or derived from the tabular data of Pote and Wax (1986). It should be noted that later issues of the Delta Ag. Digest eliminated the water use graph but retained data presented by Pote and Wax (1986).

In figure 5a, the TAMU curve picks up later than the FAO curve, but follows the FAO curve through much of the peak period of crop water use. The TAMU curve uses crop coefficients for Northern Plains cotton (Simpson and Fipps, 2001). Figure 5b indicates that the washtub tracked the Class A pan well, although most washtub readings registered lower through mid-season. A similar relationship can be seen for the atmometer, as it tracked the washtub data fairly well, albeit at expected lower values.

A variety of models for estimating reference ET from weather data are available and in regular use. The different models were developed under specific climatic conditions, and many may not be appropriate for use under the Delta's humid conditions (see Allen (2000) for details on reference ET models). Output from several Reference ET models are illustrated in Figure 6, and estimates of daily ET can be seen to vary widely. Further evaluation of these models is planned to identify those that may be suitable for use under local conditions.

Preliminary Comparisions of Evaporation Data from Atmometer and Washtub Evaporation Pan

Figures 7 and 8 illustrate correlation of evaporation between the atmometer and washtub. Rain events and one event where the washtub overflowed were not considered in these correlations. For this experiment, both instruments were manually read. Entry to the field was occasionally delayed, so Figure 7 includes data that were accumulated for periods up to three days. The slope of the line on this graph is quite representative of what was observed. Changes in evaporation from one day to the next were smaller using the atmometer, and readings from the atmometer were not influenced by rainfall. A rain gauge was placed near the atmometer to account for rain. Figure 8 illustrates problems when we attempted to correlate the two instruments on a daily basis. Not only was the correlation poor, but the slope of the line was not representative of trends in our field data. Manually resolving small differences on a daily basis was subject to errors for both instruments, particularly the atmometer. Figure 9 illustrates relative cumulative responses from the manually-read atmometer and washtub evaporation pan. Rain events were subtracted from washtub evaporation data when needed. It is clear that the evaporation response from the washtub was more pronounced over the season.

The atmometer had a pressure transducer attached to allow automatic recording of data, but this was evaluated only to observe electronic characteristics. Voltage readings from the pressure transducer were taken each time a manual reading was recorded. The atmometer was refilled only once during the season, and the effect of the refill on output voltage can be seen in Figure 10. The bottom line of the figure represents data after refill, showing a baseline shift from the output of the pressure transducer.

Washtub, Class A Station Pan, and Model-Based ET Relationships

Figure 11 illustrates good correlation between the FAO56 representation of reference ET and the Class A evaporation pan at the experiment station. The slope of the line indicates a greater response from the evaporation pan for a corresponding change in the model-based estimate of daily ET. Correlation between data from the Class A station pan and our washtub was good if rain events were not considered. Figure 12 indicates rate of change in ET to be comparable between the two pans with a slope of almost 1:1.

Other Observations - The Effect of Compaction

Subsoiling has shown significant positive effects on water availability and final yield for cotton in Delta clay soils (Wesley et al., 2001). Although not central to our study, the effects of subsoiling and compaction should be discussed, as they are important components for water management in the Mississippi Delta. Aerial data of our field showed possible effects of compaction on yield from the prior year, as outlined below.

The effect of the previous year's field treatments can be seen on the yield map for field 4 (left field of Figure 13b). Yield was obtained using an AgLeader yield monitor on a Case harvester. Areas of low yield correspond roughly to horizontal striations from the NDVI image (Figure 13a). This image was derived using ENVI 3.4 image analysis software on an original image supplied by DigitalGlobe, Inc, a participant in the Mississippi Space Commerce Initiative (MSCI). The faint horizontal lines on the NDVI image correspond to compacted lanes between plot treatments run the previous year. Subsoiling was begun for 2001, but stopped due to weather considerations early in the year. Vertical lines of low yield on the field 4 plot were due to errors from the yield monitor.

Yield for field 13 (right field of Figure 13b) was lower overall, and the cotton was stunted all season as compared with field 4. The soils in that field were heavier than in field 4, consistent with the soils map (Figure 2) indicating a Sharkey clay. It should be noted that the soils map for field 13 splits the field into Tunica (a lighter clay) and Sharkey (a heavier clay). Aerial images from a spray plane suggested uniform, heavy clay over the entire field 13.

Further Observations

Soil Water Sensor Considerations

To improve characterization of water retention curves at each station and sensor depth (Figures 3 and 4), water content could be measured simultaneously with soil water potential, using a capacitive probe or other method as evaluated by Yoder et al. (1998). This could finely tune retention characterizations in specific soil zones, and may have an advantage over methods that externally characterize the soil using disturbed soil samples (textural analysis). Readings from the Watermark sensors were not compensated for soil temperature in preliminary data reported herein, although soil temperatures were measured. Temperature effects would have introduced some error, but soil temperatures at sensor depths were observed to be within a narrow range for most of the season. The manual-reading meter supplied with the sensors has a temperature compensation dial, but temperature compensation has been deemed too conservative (Thomson and Armstrong, 1987; Thomson et al., 1996). Further analysis of data will include temperature compensation for the sensors.

Atmometer Considerations

The atmometer was quite reliable and required refilling only once during the cropping season. Data were taken manually for this study, but voltage readings from the pressure transducer were also taken to determine suitability for automatic readings. A change in offset was noted when refilling the unit as has been indicated (Figure 10), and a counteracting offset could be applied to adjust for this hysteresis effect. The atmometer was purchased many years ago from Automata (1991), but is no longer available with the pressure transducer setup. ETgage (2001) manufactures a modified atmometer with automatic level detection that uses RF sensors to detect water level. The ETgage website has approximate Kc values that modify ET as a function of crop cover. Aerial images from a spray plane taken during the season will be analyzed at a later date to obtain approximate percent crop cover for determination of Kc.

Washtub Considerations

Water level in the washtub was measured using a metal ruler and there was no attempt to control water level in a narrow range as is customarily done (Simonne et al., 1992). There may be an effect of water level on evaporation rate, but this effect was not detectable or statistically significant in our limited study ($p=0.63$). The effect may have been masked by data variability, however. For practical use, washtub evaporation pans must ultimately be managed in such a way that does not require frequent attention. Westesen and Hanson (1981) described methods that address this issue. More recently, Thomas et al. (2001) developed a washtub-based pan that indicates water level against a large, clearly marked backboard that can be seen from the road. A pointer is attached to a float by a rod, which simply moves to a red line on the backboard to indicate when irrigation is needed.

Other Methods for Determining Crop Stress

Methods that have shown promise in arid regions involve detecting water stress with non-contact infrared temperature sensors or thermal images. Sensing canopy temperature has potential (Pinter and Reginato, 1981), but low resolution of canopy temperature in a humid region such as the Delta might preclude use of this method for fine delineation of crop stress. Non-uniform cloud cover in the region compounds the problem as most thermal-based algorithms are meant to be used under cloudless (or uniformly cloudy) conditions (Pennington and Heatherly, 1989). For our study, canopy temperatures and simultaneous solar radiation data were obtained using an Exergen IR thermometer, but these data have yet to be analyzed.

Conclusions

For practical irrigation scheduling in the Mississippi Delta, model - or evaporation device-based approaches may have the best chance of being adopted if reliable representations of ET can be obtained and implementation can be simplified. Of the instrument-based systems, properly calibrated atmometers might hold the most promise for ease-of-use. Although the atmometer lacked sensitivity for manually recorded daily readings in our study, it showed promise as a tool for estimating ET over periods longer than one day. Automatic recording may improve readable resolution.

Irrigation scheduling approaches that use soil water sensors such as the Watermark could be greatly enhanced by the use of a decision support system (DSS) (Thomson, 1996). A DSS has the potential to greatly aid the farmer in interpreting sensor readings for irrigation management. Water applications can be so infrequent in the Mississippi Delta, however, that labor required to manually read sensors might not be justified. Wireless transmission of signals from soil water sensors could provide the required labor savings.

Although actual crop water use can be inferred and valuable comparisons can be made between various methods for estimating crop ET, accuracy of any method cannot be judged properly without measuring actual crop ET directly. For this purpose, weighing lysimeters are being designed for installation in several of our fields (Fisher, 2001).

Disclaimer

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Figure 1. Atmometer evaporation device (top left), washtub evaporation pan (top right), and Watermark 200SS soil water sensor with 30KTCD-NL meter.

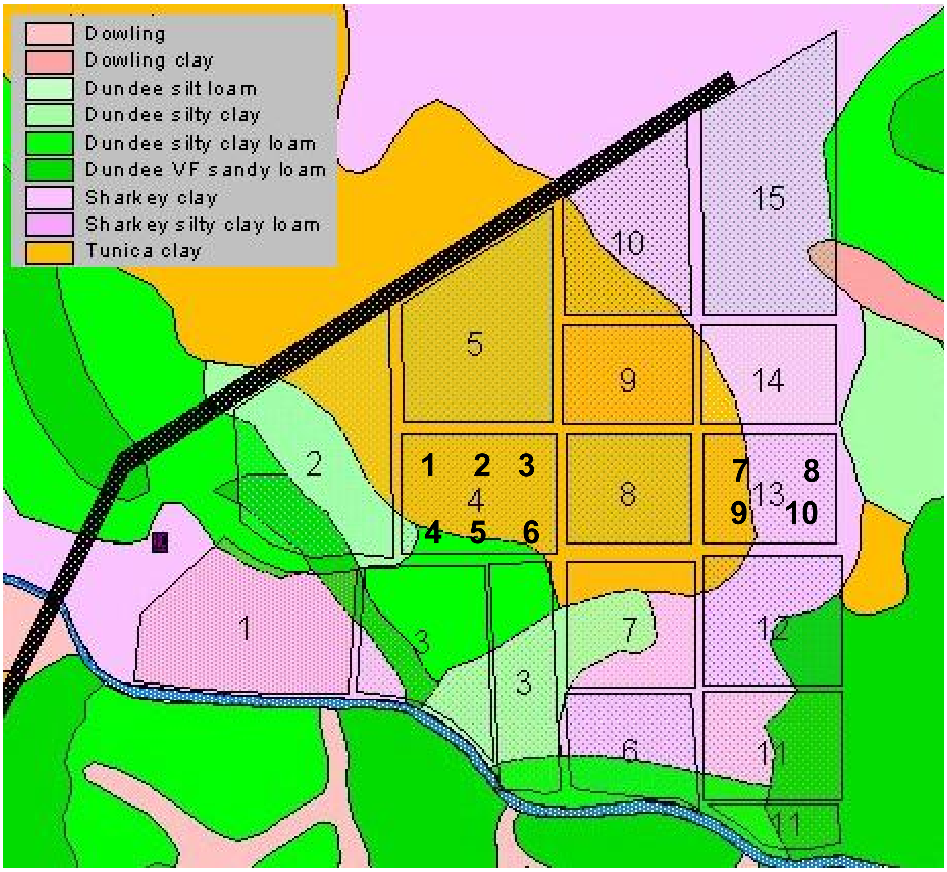

Figure 2. Soils map showing sensor stations in study field 4 (under furrow irrigation) and field 13 (under a center pivot).

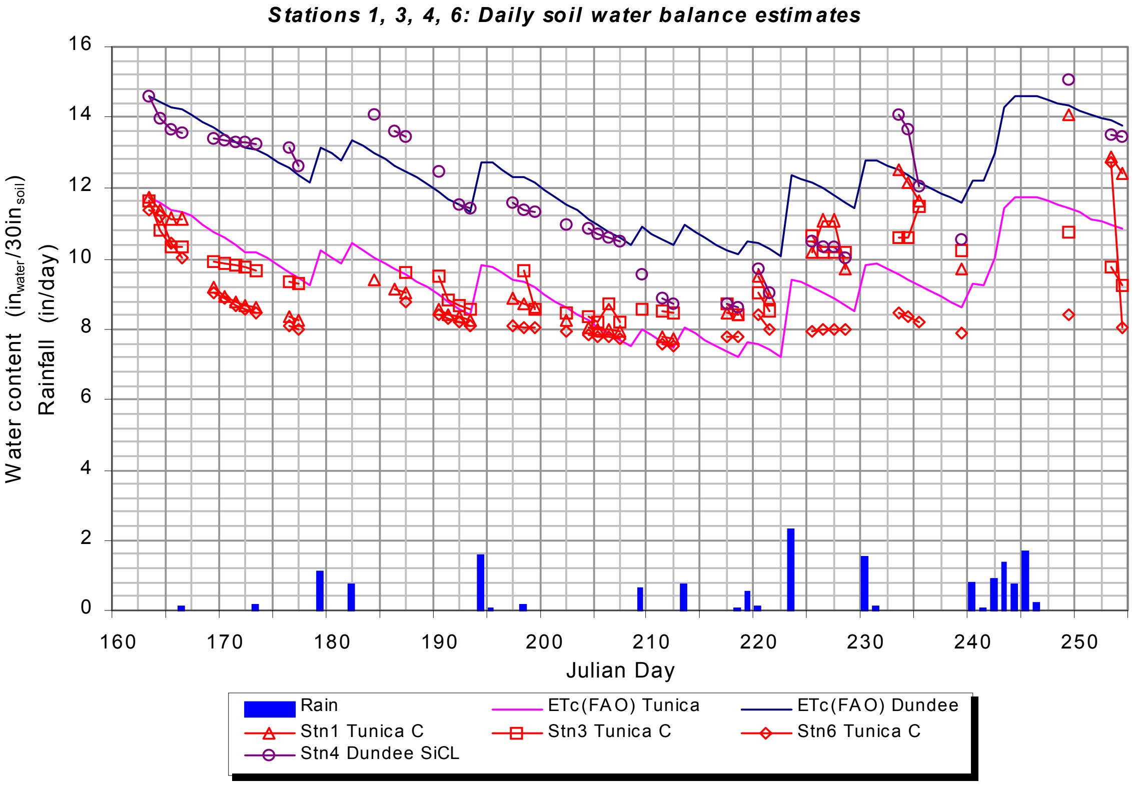

Figure 3. Seasonal water balance for stations 1,3,4, and 6 (field 4), obtained by converting Watermark sensor readings to water content using soil water retention curves.

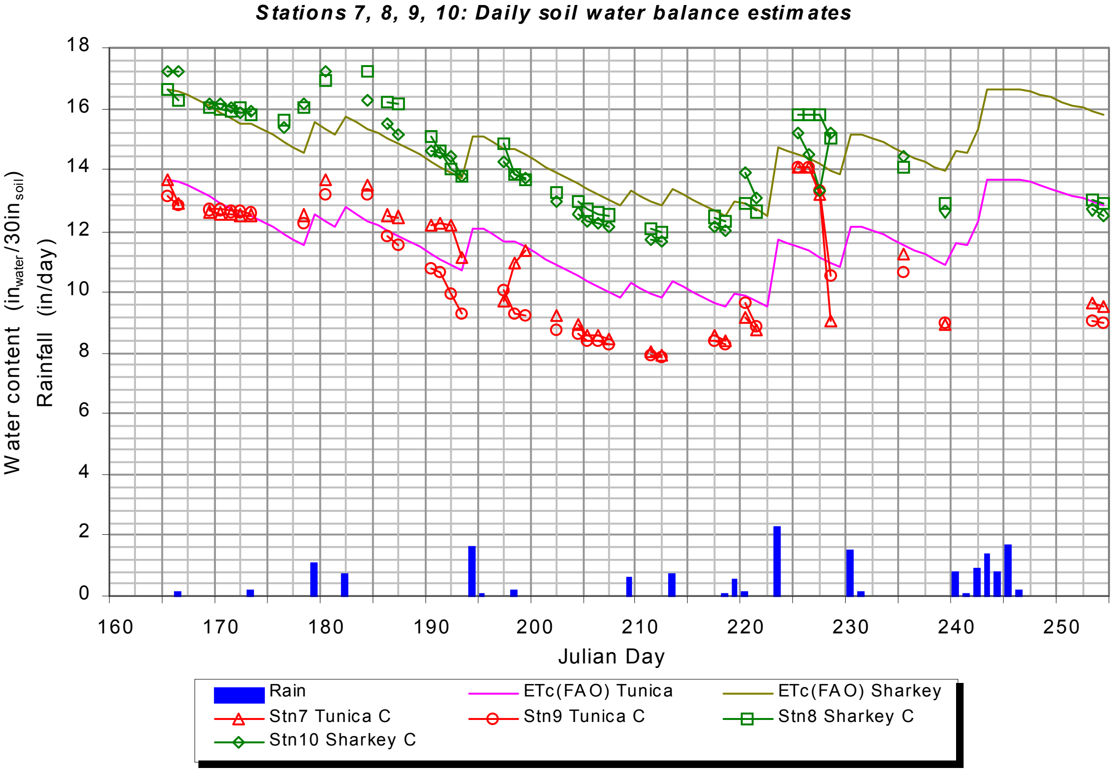

Figure 4. Seasonal water balance for stations 7,8,9, and 10 (field 13), obtained by converting Watermark sensor readings to water content using soil water retention curves.

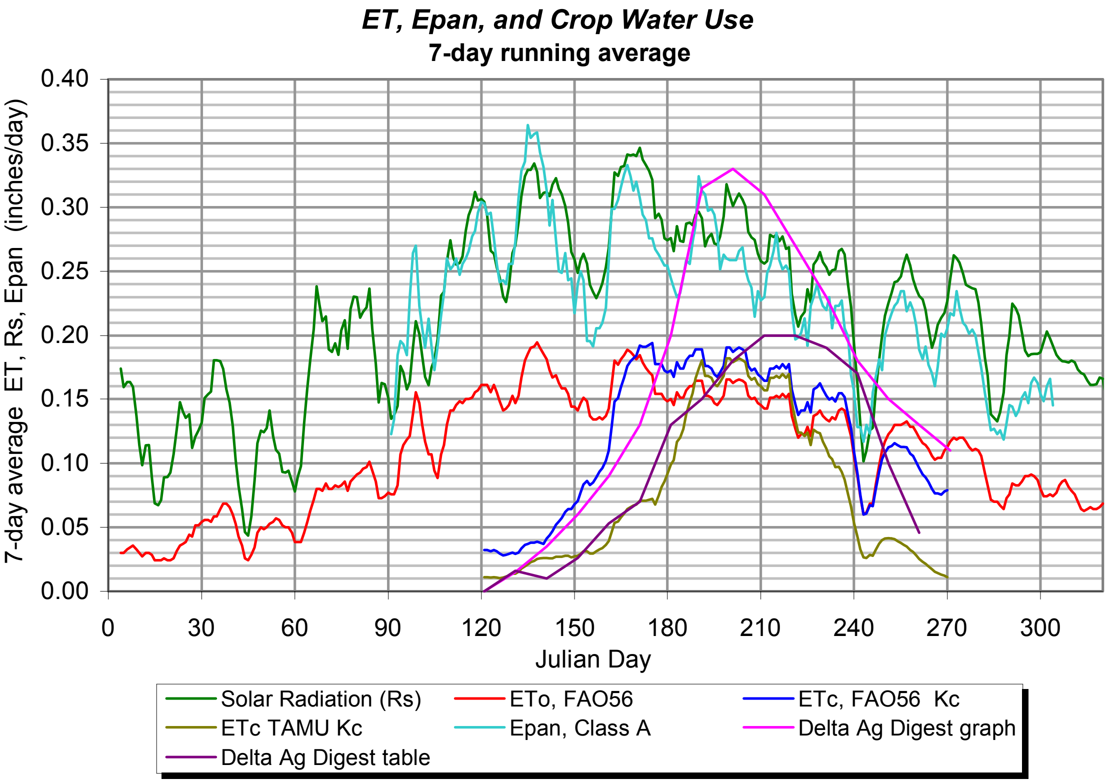

Figure 5a. Comparison of several methods for evaluating ET.

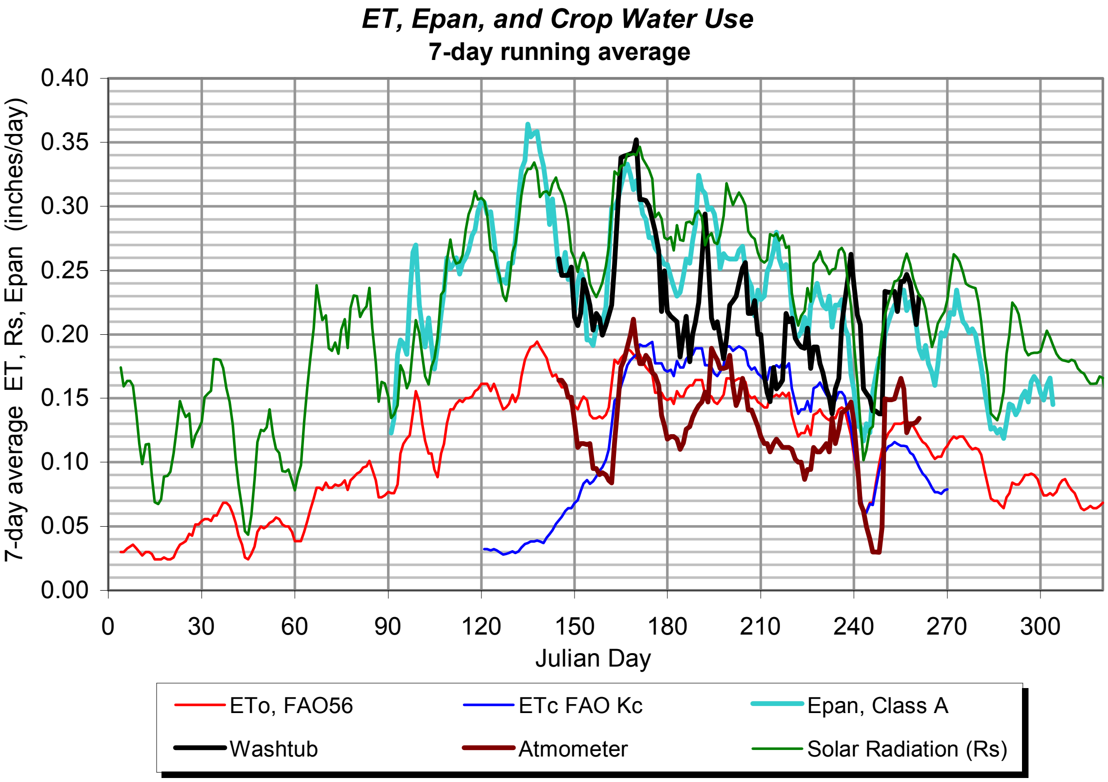

Figure 5b. Comparison of several methods for evaluating ET. This figure also illustrates additional data from washtub and atmometer.

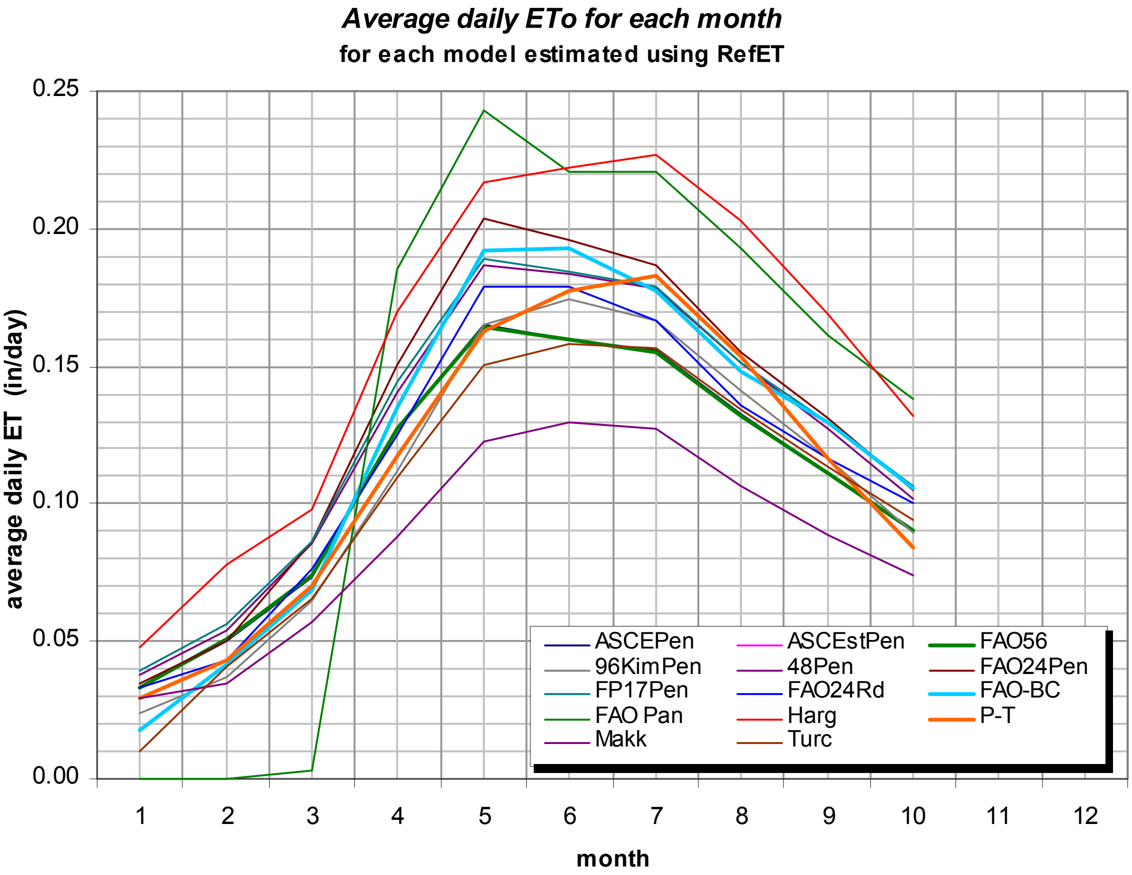

Figure 6. Comparison of several ET models using data from the Stoneville weather station. Models are described in documentation for ET software (REF-ET web site).

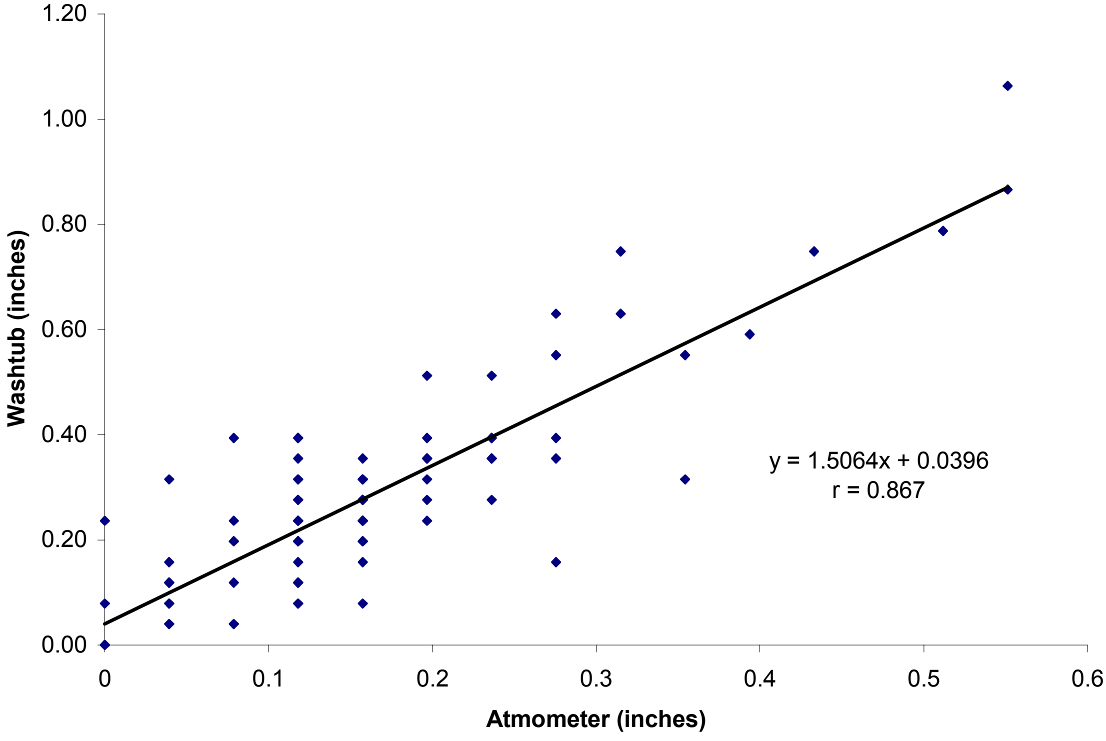

Figure 7. Comparison of evaporation from atmometer and washtub. Data obtained over periods greater than one day are included.

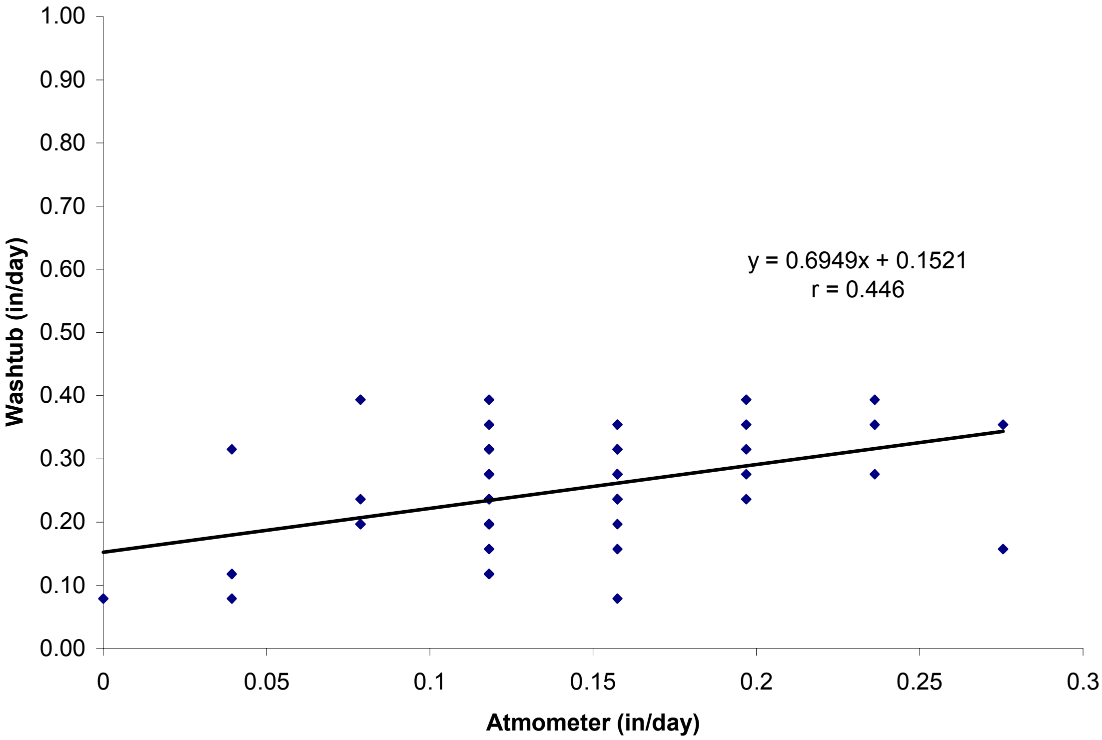

Figure 8. Comparison of evaporation from atmometer and washtub. Data are limited to one-day periods.

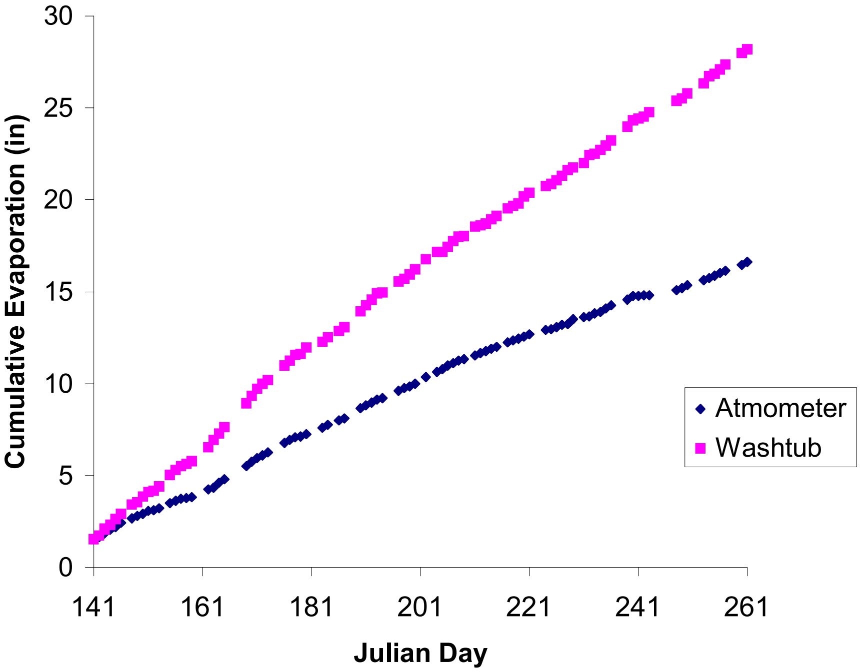

Figure 9. Cumulative evaporation from atmometer and washtub.

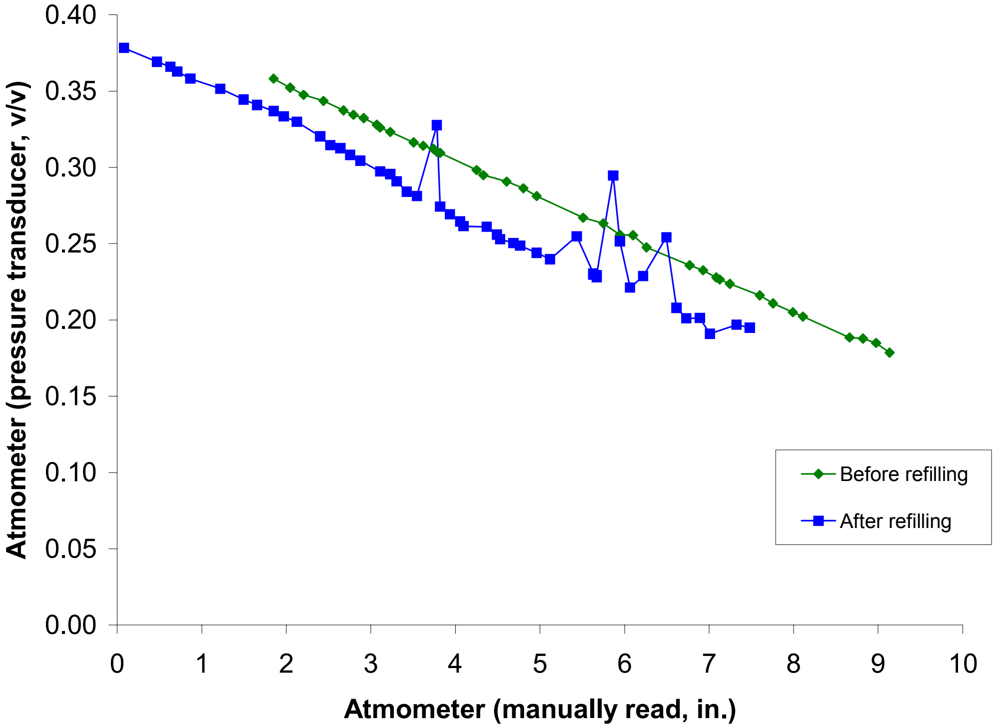

Figure 10. Electronic atmometer responses showing change in baseline reading of pressure transducer after refilling the atmometer.

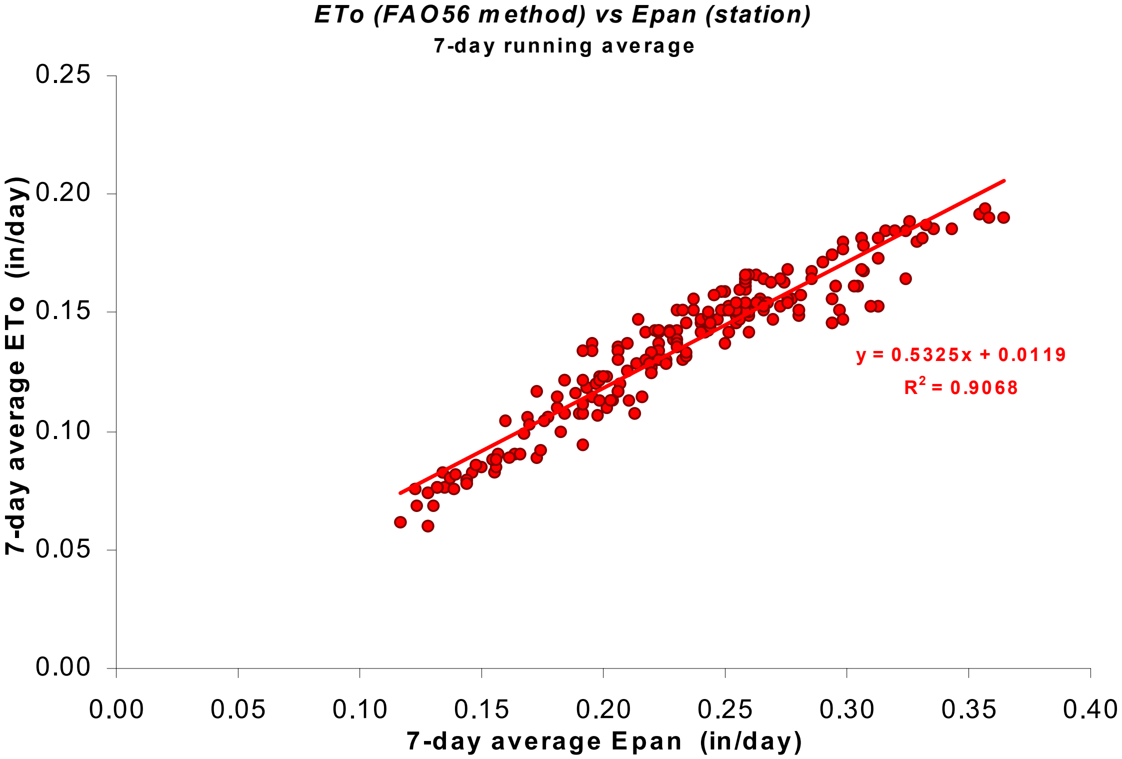

Figure 11. Relationship between ETo (FAO56) and evaporation from Class A station pan.

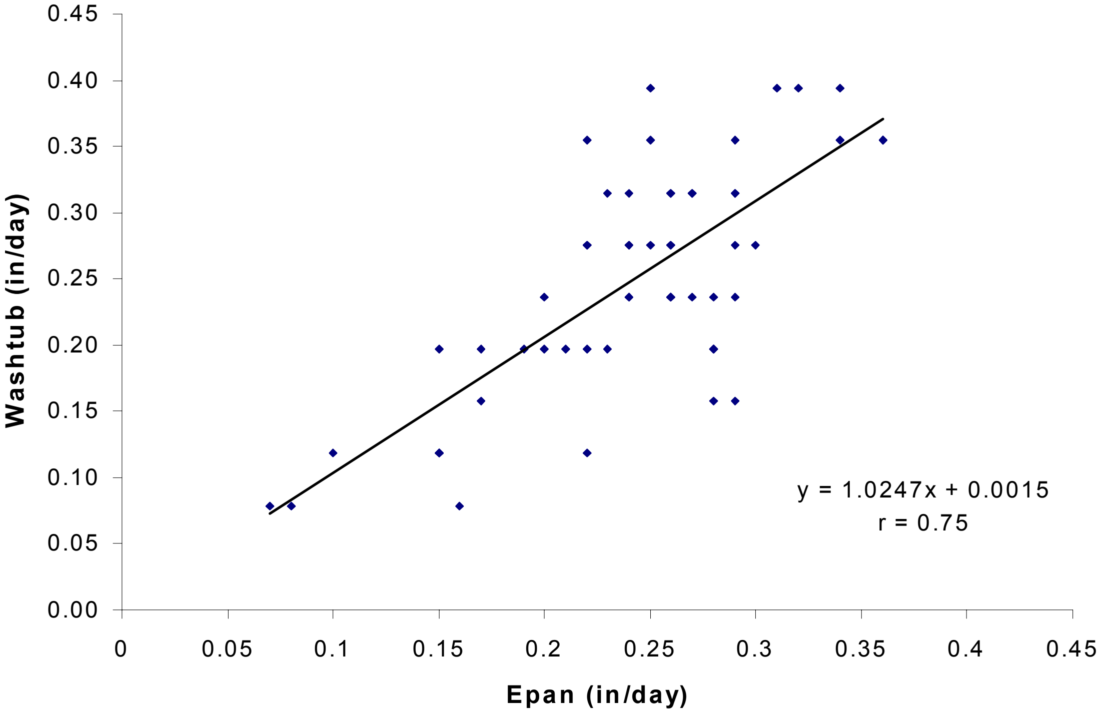

Figure 12. Relationship between evaporation from Class A and washtub evaporation pans.

Figure 13a. Image of the normalized difference vegetation index (NDVI) for field 4 obtained from low-flying aircraft and processed using ENVI 3.4. Three faint horizontal lines can be seen in the image.

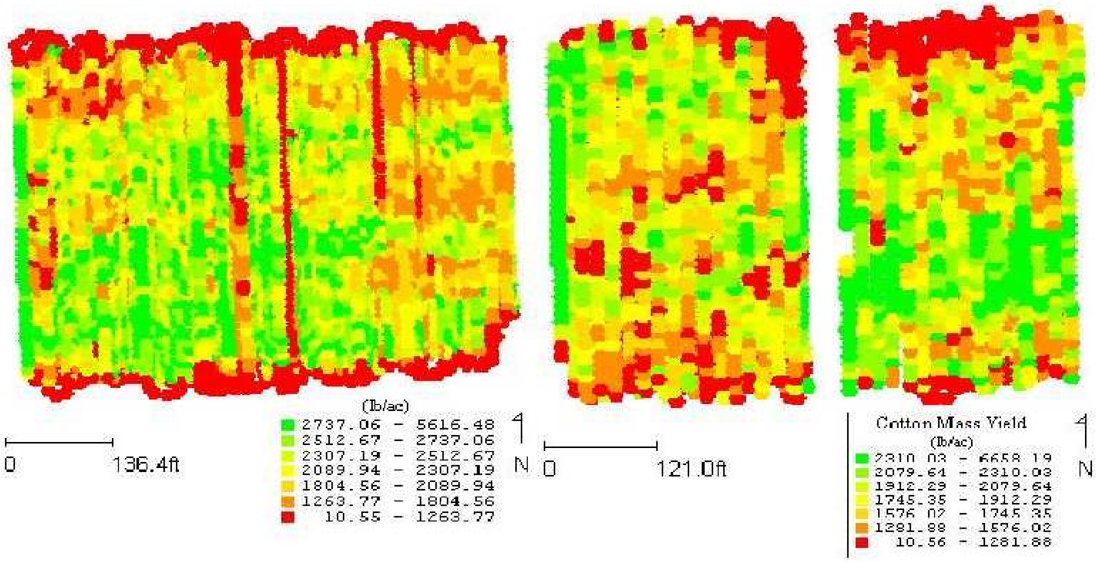

Figure 13b. Cotton yield map shows areas of low yield in field 4 (left) corresponding to horizontal striations in Figure 13a. Approximate yield from field 13 is represented at right.