Level basin approaches to improve water management in surface irrigation for northeast Louisiana

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LEVEL BASIN APPROACHES TO IMPROVE WATER MANAGEMENT IN SURFACE IRRIGATION FOR NORTHEAST LOUISIANA

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ABSTRACT

In the state of Louisiana surface irrigation is widely used due to the low start-up cost, typically high rainfall, and soil conditions. Irrigation scheduling is an important practice to achieve water use efficiency in agriculture. The objectives of this study were to compare three different methods to determine crop evapotranspiration (ET_c) for soybeans in addition to, evaluate a computer based irrigation scheduling program using real scale fields. Weather variables, soil moisture and irrigation water use collected during the summer months of 2005 and 2006 at a production agriculture farm in northeast Louisiana were studied. The ET_c estimates obtained using atmometers (ETgage); a weather station approach; an evapotranspiration algorithm from the computer based Arkansas Irrigation Scheduler (AIS). Three weeks of continuous ET_c values showed that the atmometer and the weather station methods estimated similar values. The AIS method estimated lower values than the other two methods. The higher estimates by the weather station compared to the AIS are related to higher ET_o values throughout the analyzed period. Similar estimation by the atmometer and the weather station methods suggest that these approaches were more suitable than the AIS method for estimating ET_c at Angelina Plantation. The AIS proved to be a good scheduling tool that accurately predicts the crop's irrigation needs. However, the results obtained at Angelina Plantation suggest that the farmer or irrigator programs the irrigation events modified by on-farm requirements. The AIS monitored the Maximum Allowable Depletion (MAD). Higher MAD values at the end of the crop cycle reduced the number of irrigations per field but increased the water use. Non-standard procedures implemented in leveled basins suggested a negative impact in the field drainage and made the irrigation process more labor intensive. Extra care is necessary to avoid waterlogging with level basins.

CHAPTER 1. INTRODUCTION

Irrigation in humid areas similar to Louisiana is considered a supplemental irrigation or an "insurance policy" for farmers to assure better crop yields, with the exception of rice production. The reason of this insurance is that during a drought year, seasonal rainfalls are inadequate or insufficient to supply for crop needs and irrigation provides these water needs (Jensen *et al.*, 1980). Nowadays, one of the most common methods used to irrigate crops like rice, soybeans, corn and cotton in the state of Louisiana is the basin irrigation system. There are more than 344,000 hectares (850,000 acres) of irrigated cropland. Most of this area is irrigated using the conventional sloped basin method, which has a difference in elevation (slope) from the top to the bottom of an individual field (Branch, 2004). In this traditional sloped method, a controlled amount of water is applied using a riser and/or polyethylene tubing from the highest elevation in the field. The water flows along the field covering the whole area with a certain depth of water. The water remains on the field for a sufficient period for infiltration to occur and provide water to plants (Dedrick, 1990). In sloped basins, direction of the water flow is determined by the field's gradient or slope. The basin is laid out following the maximum field gradient and the direction of the water flow would be determined by the field gradient or slope. With effective water management practices, this type of irrigation system can be operated at up to 85% irrigation efficiency (Clemmens, 2000).

Level basins are an alternative method to sloped basins where the field is completely leveled (zero slope) using laser leveling technology. Water is then distributed in the field by adjacent ditches located on three of the four sides of the field which also act as drains for excess water present during a high rainfall event. Spin ditches are shallow furrows cut across the field that direct the water throughout the field while irrigating and providing surface drainage for level basins. When the field is irrigated, the water is first channeled along the side ditches until these ditches are full in order to cover the field faster (Clemmens, 2000). Then, the water moves into the field through spin ditches from the three different sides to flood the area at a faster rate. In some cases, the water is discharged into the field by 0.4 meter (15 inches) polyethylene tubing with, or without, gates and by spin ditches. Clemmens and Dedrick (1982) says that the basic idea behind the design and management of these irrigation systems is to have an inflow rate that advances over the basin in a portion of the total infiltration time. A proper application of the aforementioned, would avoid long water logging times that can adversely affect crop yields and control excessive deep percolation losses that represent higher pumping costs (Badiger *et al.*, 1997).

Reductions of water requirements when irrigating crops have the potential to decrease groundwater withdrawals and reduce pumping costs. The rising trend of fuel prices and the declining levels of groundwater resources already established the need of implementing ways to irrigate more efficiently. A fundamental practice to achieve water use efficiency is irrigation scheduling (Alam and Elliot, 2003).

In general, irrigation application will depend on the crop, the type soil and the climate. Soybean *Glycine max* (L.) Merr., is grown in conditions (climate and soil) that are not the most suitable for growth. Water availability in the environment is constantly changing throughout the growing season and over the field. This availability changes affect in one way or another one the plant development. Too much or too little water at any growth stage may be negative. The plant is subject to stress due to deficient water supply in the root system (Scott, 1984). The period of peak water use for soybeans occurs during reproductive growth, when plants may need as much as 63.5 mm (2.5 inches) of water per week. Available soil moisture is often depleted by the time reproductive growth begins therefore, unless supplemental irrigation is provided and assuming no rainfall the plant will experience water stress (Linkemer, 1995). Moreover, soybeans are also stressed by excess water or waterlogging in their radical zone having a negative impact in the yield when applied at certain growth stages (Linkemer, 1995). Waterlogging is common where soils are not drain properly and have a low infiltration rate. In northeast Louisiana, Sharkey clay soils present those characteristics that become limiting factors for irrigation. The intake rate determines the amount of water required in order to supply the plant's needs without over watering (USDA-SCS, 1988).

Irrigation scheduling allows farmers and irrigators to determine when to irrigate and how much water would be necessary. This scheduling practice requires information on soil moisture conditions and crop evapotranspiration that can be estimated using monitoring devices (Alam and Trooien, 2001). Instruments such as the atmometer and the Watermarks that estimate crop evapotranspiration and soil moisture respectively are good alternatives. In addition, computer-based scheduling programs are available to help farmers achieve higher water use efficiency. Due to the importance of these practices the objectives of this study are:

- Compare three different methods to determine crop evapotranspiration
- Evaluate irrigation scheduling using the Arkansas Irrigation Scheduler
- Monitor irrigation water use in sloped and leveled basins

CHAPTER 2. LITERATURE REVIEW

2.1 Evapotranspiration

Evapotranspiration (ET) is the combination of two separate processes. It is used in different circumstances to be a process, amount, latent heat flux or rate of water loss. In this case will be a rate of water loss. ET measures how much moisture is lost or transpired from the crop's leaves and the amount lost from the soil surface by means of evaporation. Evaporation and transpiration occur at the same time therefore there it is very difficult to distinguish between the two processes. Evaporation from a cropped area is mainly determined by the portion of solar radiation that reaches the soil surface. Then throughout the crop cycle solar radiation decreases as the crop grows and creates more and more shade over the ground. When the crop is small the water loss is mainly by evaporation. Once this crop is developed and covers the ground the predominant process is transpiration (Allen *et al.*, 1998).

Reference evapotranspiration (ET_o) is the actual loss by a specific crop that covers a soil surface with unlimited water supply. ET_o is a climatic parameter that can be determined using climate data and not taking into account crop characteristics or soil aspects (Hatfield and Fuchs, 1990). However, when estimating ET_o it is important to consider if the reference crop on which the equation is based is suitable for that region. The most common reference crops are alfalfa and short grass and the FAO Penman-Monteith is recommended as the exclusive method to obtain ET_o. This method closely estimates the grass ET_o at the evaluated site (Allen *et al.*, 1998).

2.2 Crop Coefficients

According to Martin *et al*. (1990) the crop coefficient (K_c) is the ratio of a particular crop evapotranspiration (ET_c) to a reference crop evapotranspiration (ET_o) expressed as

$$K_c = \frac{ET_c}{ET_0} \qquad \text{(Eq. 2.1)}$$

The crop coefficient incorporates the effect of characteristics that distinguish a typical field crop from the grass reference. As a result, different crops will have different K_c coefficients. Characteristics of the crop that vary throughout the season affect the Kc coefficient. Close spacing of plants and taller canopy height of various fully developed agricultural crops make those crops to have K_c values larger than 1 (Allen *et al.*, 1998).

Differences in climate from one area to another one, like wind speed, modify the aerodynamic resistance of crops and therefore, their K_c coefficient specially for crops taller than the grass reference. For many crops when the wind speed increases their ratio ET_c/ET_o also increases and the relative humidity decreases. Arid areas and high wind speed conditions will have higher K_c values than humid climates and low wind conditions (Hatfield and Fuchs, 1990). Another factor that causes variation in K_c values is the difference in soil evaporation. After an irrigation or rainfall event the effect of the evaporation is greater when the crop is small and does not provide good shade to the ground. In those conditions the K_c value is determined mainly by the regularity with which the soil is watered. Then the evaporation will be considerable and the $K_c$value may exceed 1. Conversely, where dry soil conditions are present evaporation is limited and the K_c value will be small and as low as K_c = 0.1 (Allen *et al.*, 1998). One of the most important factors that produce changes in K_c values is the crop growth stage. While the crop develops there are variations in the ground cover, the plant height and the area of the leaf. Due to expected changes in evapotranspiration throughout several growth stages the value of K_c for a specific crop will vary over the growing season. This growing season is divided into four stages: initial, crop development, mid-season and late season. During the initial season the plant is small and evapotranspiration is mainly in the form of evaporation. The value of K_c is large when the soil is wet (irrigation and rainfall) and becomes low when is dry. The next stage is the crop development where the K_c value corresponds to amounts of ground cover. Then for a dry surface $K_c = 0.5$ corresponding to 25-40% cover. $K_c = 0.7$ corresponds to 40-60% cover. For the next which is stage mid-season, K_c is equal to 1 and any deviation form this values is related to variations in crop height. Finally during the late season stage the estimation of K_c ends when the crop is harvested. This value at the end of the season shows crop and water management practices. If the Kc value is high the crop was irrigated often until harvest fresh. If the crop is allowed to dry out in the field previous to harvesting Kc value will be small (Jensen *et al.*, 1990).

2.3 Estimation of Reference Crop Evapotranspiration

To estimate reference crop evapotranspiration there are several models such as: combination, radiation, temperature, and evaporation. Combination models bring together energy balance and aerodynamic equations to measure crop evapotranspiration. The energy term is required to convert water to vapor, and the wind component carries the vapor. Penman applied in 1948 the combination method on free water surface evaporation The equations is described as follows (Hatfield and Fuchs, 1990):

$$\lambda E = \left\{ \frac{\{(R_n - G)\}}{\left[1 + \gamma \frac{(T_0 - T_z)}{(e^o{}_0 - e_z)}\right]} \right\} \qquad \text{(Eq. 2.2)}$$

where λE is the latent heat flux (MJ m^{-2} d^{-1});

R_n is the net radiation (MJ m^{-2} d^{-1});

G is the heat flux (MJ m^{-2} d^{-1});

γ is the psychrometric constant;

T_o is the surface temperature of water (°C);

T_z is the temperature at height z meters (°C);

e°_{o} is vapor pressure at the surface of water (kPa);

e_z is the vapor pressure at height z m (kPa).

λ is the latent heat of vaporization

λ = 2.47 MJ kg^{-1}

E = evaporation rate (mm d^{-1})

The modified Penman, also known as the 1963 Penman (Eq. 2.3) was developed since the beginning to measure evapotranspiration. However, the equation estimates grass reference evapotranspiration. The modified Penman equation is described as follows (Jensen *et al.*, 1990):

$$\lambda E = \left[\Delta \frac{(R_n - G)}{(\Delta + \gamma)} + \gamma \times 6.43 W_f \frac{(e^o{}_z - e_z)}{(\Delta + \gamma)} \right] \quad \text{(Eq. 2.3)}$$

where Δ is the slope of saturation vapor pressure-temperature curve (kPa $°C^{-1}$);

W_f is the wind function;

e°_{z} is the saturation vapor pressure of air at height z m (kPa);

a_w and b_w are wind coefficients;

$$W_f = a_w + b_w u_2 = 1.0 + 0.53 u_2 \quad \text{(Eq. 2.4)}$$

u_2 is the wind speed at 2 m height (m s^{-1}).

The Penman-Monteith approach includes all parameters that bring together thermodynamic and aerodynamic aspects. In addition, the approach includes the aerodynamic and surface resistance to sensible heat and vapor transfers. The majority of parameters are determined or can be calculated from weather data. The equation is describes as follows (Allen *et al.*, 1998):

$$\lambda E_{tr} = \frac{\left[\Delta(R_n - G) + \rho \times c_p \frac{(e^o{}_z - e_z)}{(r_a)}\right]}{(\Delta + \gamma^*)} \qquad \text{(Eq. 2.5)}$$

where ρ is the air density (kg m^{-3});

c_p is the specific heat at constant pressure (kJ kg^{-1} $^oC^{-1}$);

r_a is the aerodynamic resistance to sensible heat and vapor transfer (s m^{-1});

$\gamma^* = \gamma\ (1 + r_c/r_a)$;

r_c is the surface resistance to vapor transfer (s m^{-1}).

2.4 Irrigation Scheduling and Monitoring

Deciding when and how much to water should be applied should be based on the management plan. This plan is based on long-term data representing average conditions, or may be based on the season progress (Martin *et al*, 1990). In this last case daily values and short-term predictions will be made. However, regardless of the plan information about crop, soil, climate, irrigation system and water delivery must be considered to suit the scheduling process to particular situations (Martin *et al*, 1990).

The Arkansas Irrigation Scheduler is a computer based irrigation scheduler program suited for the humid mid-south region. The program utilizes a soil water balance computation that represents the soil water deficit. Inputs to the program are maximum daily temperature, rainfall and irrigation (Tacker, 2006). Since the methods for scheduling in the mid-south are different from other areas of the country the techniques for scheduling irrigations are different as well. The system has its own algorithms that uses easily obtained weather data to determine pan evaporation based on empirical relationships. Other standardized equations were not used because they demand extensive data input or are not suitable for the area. One of the most important features of the program is the ability to provide recommendations regarding future irrigation dates, and application times and amounts (Cahoon, 1990).

CHAPTER 3. MATERIALS AND METHODS

3.1 Materials

3.1.1 Crops

Soybeans *Glycine max* (L.) Merr., maturity group 4 (MG IV) was utilized and different varieties were planted. The assumed growth stages analyzed in this research were focused on the reproductive stages according to Board (2006), Fehr and Caviness (1977). These stages for the 2006 season are described in Table 3.1.

Board (2006) says that days to R5 is important for final yield because it sets the time limit for the crop achieving its vegetative mass (stem, leaves, petioles); and the crop has to have a certain mass of each component for optimal yield potential. Drought before R5 will be harmful to yield if it reduces crop mass below what it needs for optimal yield. Soybean is most prone to drought stress during the flowering and pod formation periods (R1-R5).

Table 3.1. Description of the assumed[a] reproductive stages for soybeans during 2006

Stage number/ stage title	Number of days since VE[b]	Date	Root depth (m)	Effective root depth @70% (m)
R1/Beginning of bloom	40	July 4	>0.5	0.35
R5/Beginning of seed	60	July 24	0.6	0.42
R7/Beginning of maturity	105	September 7	0.9	0.63

[a]Not verified in the field
[b]Emergence (VE)

3.1.2 Instrumentation

The instrumentation employed for this study was used to monitor the local meteorological conditions at Angelina Plantation (Monterey, LA) and selected infield conditions. Figures A.1 and A.2 (Appendix A) show the different instruments and their location in the studied fields. The monitored meteorological conditions were: the rainfall in different locations on the farm with Texas Electronics 0.15 m (6 inches) tipping buckets (Texas Electronics, Inc., Dallas, TX) were placed on the edges of the fields. One portable Campbell Scientific weather station (Campbell Scientific, Inc., Logan, UT) was used to monitor air temperature and relative humidity using a HMP50 Vaisala Temperature and RH sensor; rainfall with a tipping bucket; solar radiation using a LI200X-L LI-COR silicone pyranometer; and wind speed with a 03101-L R.M. Young Wind Sentry Anemometer. The weather station program computed the reference evapotranspiration (ETo, reference).

Crop evapotranspiration (ETc) was one of the infield variables measured using an automated atmometer Model E from ETgage (ETgage Company, Loveland, CO) connected to a Hobo H7 Event Data Logger from Onset (Onset Computer Corporation, Bourne, MA). Moreover, the inflow of irrigation water to the fields was recorded by a propeller type flowmeter from McCrometer (McCrometer, Hemet, CA). The soil moisture was monitored using a Watermark Monitor (Irrometer Co., Riverside, CA) at depths of 0.15, 0.30, 0.46 and 0.61 m (6, 12, 18 and 24 in) connected to an automatic soil moisture data recorder (Watermark Monitor).

3.2 Methods

3.2.1 Field Layout for 2005 and 2006

The research site was at the Angelina Plantation which is a production agriculture farm located in Concordia Parish (Northeast Louisiana). Soil in all studied fields was classed as Sharkey clay. The data collection process took place in seven fields planted with cotton, rice and soybeans during the summer of 2005 and cotton and soybeans during the summer of 2006. The fields analyzed included:

- 10.5 hectare (26 acre) level field 2-8
- 26.7 hectare (66 acre) level field 2-9
- 15.4 hectare (38 acre) sloped field 2-10

- 14.9 hectare (37 acre) level field 2-11
- 25.5 hectare (63 acre) level field 2-12
- 24.3 hectare (60 acre) level field 2-18
- 24.3 hectare (60 acre) sloped field 2-19
- 32.4 hectare (80 acre) sloped field 2-20

Figure A.3 (Appendix A) shows the distribution of the fields at Angelina Plantation. Fields 2-8, 2-9, 2-10, 2-11, and 2-12 were on the west part of the farm. Fields 2-18, 2-19, and 2-20 were located 1.6 km (1 mile) to the east.

3.2.2 Field and Crop Management

The following table presents a summary of the crop management for the seven fields studied:

Table 3.2. Crop management for the 2006 level basin research project at Angelina Plantation.

Field #	Net area (ha)	Crop	Variety/ maturity group	Plant date	Emergence date
2-8	10.5	Cotton	DPL 555 Flex	May 12	May 19
2-9	24.8	Soybeans	Asgrow, Delta King, Hornbeck Pioneer /Group 4	May 15	May 22
2-10	15.3	Soybeans	Dekalb 46-51/ Group 4	May 15	May 22
2-11	14.7	Soybeans	Dekalb 46-51/ Group 4	May 16	May 22
2-12	23.6	Soybeans	Delta King, Dyna-Gro, Hornbeck, NK, Stine, Terral / Group 4	May 16	May 23
2-19	22.7	Soybeans	Delta King, Progeney, Schillinger, Terral / Group 4	May 16	May 23
2-20	25.0	Soybeans	Delta Grow, Delta King, DPL, DK, Morsoy, Terral, / Group 4	May 5	May 12

3.2.2.1 Irrigation Management

The irrigation management at Angelina Plantation was a combination of practices. This combination consisted of procedures successfully implemented by the managers and research procedures established by the USDA-ARS Water Conservation Laboratory (Phoenix, AZ). Those practices were standard because they are proved and documented. On the other hand, some other practices were implemented because of local farm requirements. These practices were non-standard because they are recommended but not documented. Non-standard practices were decisions taken or modified by the local management in order to contain immediate needs. The use of sandbags and dirt piles to control water movement in the field were examples of non-standard procedures. Holding back irrigation indicated by the Arkansas Irrigation Scheduler due to rain forecast or because another field was not finished was non-standard.

3.2.3 Meteorological and Infield Methods

3.2.3.1 Atmometers

According to Alam and Trooien (2001), the atmometer measures crop evapotranspiration (ETc) similar to modified Penman known as the 1963 Penman, reference to alfalfa-based ETo whereas other references are to grass-based ETo. The equation is described as follows (Jensen *et al.*, 1990):

$$\lambda E = \frac{\Delta\left(R_n - G\right)}{\left(\Delta + \gamma\right)} + \gamma 6.43 W_f \frac{e_z^o - e_z}{\Delta + \gamma} \qquad \text{(Eq. 3.1)}$$

where λ is the latent of vaporization;

$\lambda = 2.47$ (MJ kg^{-1})

E = evaporation rate (mm d^{-1});

Δ is the slope vapor pressure curve (kPa °C^{-1});

W_f is the wind function;

$W_f = a_w + b_w u_2 = 1.0 + 0.53 u_2$ (Eq. 3.2)

e^o_z is the saturation vapor pressure of air at height z m (kPa);

a_w and b_w are wind coefficients (empirically derived);

u_2 is the wind speed at 2 m height (m s^{-1});

$(e^o_z - e_z)$ is the vapor pressure deficit.

$$\left(e_z^o - e_z\right) = \frac{\left[e^o\left(T_{\max}\right) + e^o\left(T_{\min}\right)\right]}{2 - e^o\left(T_d\right)} \qquad \text{(Eq. 3.3)}$$

where T_{max} and T_{min} are the mean of saturation vapor pressure at maximum and minimum air temperatures;

T_d is saturation vapor pressure at mean dew-point temperature.

The event data logger (Hobo) recorded the ETc measurements from the atmometer. This atmometer uses a fabric covered ceramic cup on top of the instrument to emulate solar energy absorption and vapor diffusion resistance of irrigated crops. Figure A.4 (Appendix A) shows the described setup of the atmometer for this study with a diffusion cover (# 54) to estimate alfalfa reference ET (ETgage, 2004).

3.2.3.2 Weather Station

The weather station computed the reference evapotranspiration (ET_o) using the FAO Penman-Monteith equation. ET_o can be calculated using meteorological data as follows (Allen *et al.*, 1998):

$$ET_o = \frac{0.408\Delta\left(R_n - G\right) + \gamma \dfrac{900}{T + 273} u_2\left(e_s - e_a\right)}{\Delta + \gamma\left(1 + 0.34u_2\right)} \qquad \text{(Eq.3.4)}$$

where ET_o is the reference evapotranspiration (mm day^{-1});

R_n is the net radiation at the crop surface (MJ m^2 day^{-1});

G is the soil heat flux density (MJ m^2 day^{-1});

T is the mean daily air temperature at 2 m height (°C);

u_2 is the wind speed at 2 m height (m s^{-1});

e_s is the saturation vapor pressure (kPa);

e_a is the actual vapor pressure (kPa);

$e_s - e_a$ is the saturation vapor pressure depletion (kPa);

Δ is the slope vapor pressure curve (kPa °C^{-1});

and γ is the psychrometric constant (kPa °C^{-1}).

$$e_s = \frac{e^o(T_{\max}) + e^o(T_{\min})}{2} \qquad \text{(Eq. 3.5)}$$

where $e^o(T_{min})$ is the saturation vapor pressure at daily minimum temperature (kPa); and $e^o(T_{max})$ is the saturation vapor pressure at daily maximum temperature (kPa).

According to Allen *et al.* (1998) the actual vapor pressure (e_a) can be derived from different approaches. In this case it was calculated from the relative humidity data as follows:

$$e_a = \frac{e^o(T_{\min})\frac{RH_{\max}}{100} + e^o(T_{\max})\frac{RH_{\min}}{100}}{2} \qquad \text{(Eq. 3.6)}$$

where RH_{max} is the maximum relative humidity (%); and RH_{min} is the minimum relative humidity (%).

$$\Delta = \frac{4098\left[0.6108\exp^{\left(\frac{17.27T}{T+237.3}\right)}\right]}{(T+237.3)^2} \qquad \text{(Eq. 3.7)}$$

where T is the air temperature (°C); and exp(..) = 2.7183 (base of natural logarithm) raised to the power (..).

$$\gamma = 0.665 \times 10^{-3} P \qquad \text{(Eq. 3.8)}$$

where P is the atmospheric pressure (kPa).

The weather station monitored air temperature and relative humidity, rainfall, solar radiation and, wind speed. The program in the CR10X datalogger (Campbell Scientific, Inc., Logan, UT) took readings every 15 minutes and a 24-hour reading. The program used this weather data to compute the reference evapotranspiration (ETo).

3.2.3.3 Arkansas Irrigation Scheduler

The Arkansas Irrigation Scheduler was used to schedule irrigations for each of the fields, and used an evapotranspiration algorithm determined by (Cahoon *et al*., 1990):

$$ET = (PAN)(MC)(0.86) \qquad \text{(Eq. 3.9)}$$

where ET is the daily evapotranspiration;

PAN is the daily pan evaporation;

MC is the modified crop coefficient.

For calculations in SI units the equation for pan evaporation is:

$$PAN = 25.4\ [A+B\ (1.8TMP+32)^2+C\ (1.8TMP+32)+D\ (DYL)] \qquad \text{(Eq. 3.10)}$$

where PAN is the daily class A pan evaporation (mm);

TMP is max daily temperature (°C);

DYL is the day length (hours);

A, B, C, D regression coefficients.

In this case the regression coefficients values used were for Calhoun, Louisiana where A = 0.612262; B = 0.000145; C = -0.020996; D = 0.025093.

The day length calculation was based on the day of the year and site latitude:

$$DEC = 0.40928\ [\sin(4.88835 + 0.017214 * I)] \qquad \text{(Eq. 3.11)}$$

$$DYL = 7.63947\ \{\cos^{-1}[-\tan(LAT) * \tan(DEC)]\} \qquad \text{(Eq. 3.12)}$$

where: DEC is the solar declination (radians)

LAT is the site latitude (radians), for Calhoon, Louisiana LAT = 0.56738 radians;

I is the day of the year.

The modified crop coefficient used to account for the wetness of the soil was determined by the following:

$$MC = CC + (1 - CC)\, SW \qquad \text{(Eq. 3.13)}$$

where MC is the modified crop coefficient;

CC = crop coefficient;

SW = soil surface wetness coefficient.

The crop coefficient (CC) was obtained from the curves developed by Stegman *et al.* (1977). For more details Stegman *et al.* (1977) may be consulted.

According to Vories (2007) the value of SW and CC was obtained with the algorithm presented in Figure A.5 (Appendix A).

3.2.3.4 Precipitation

Tipping buckets (automated rain gauges) measured the precipitation at Angelina Plantation. Five instruments were placed in the study area (Figure A1, A2 Appendix A) in order to increase accuracy of measurements and reduce the impact of spatial variability of rain. The instruments were installed far enough away from surrounding objects to ensure that there was no obstruction affecting the rainfall catch (Brooks *et al.*, 2003).

The gauges were placed on stands such that the funnel orifice was one meter (39.4 in) above the ground surface. Gauges were leveled to obtain accurate collections (Brooks *et al.*, 2003). Hobo event loggers connected to the tipping buckets recorded the precipitation measurements. The logger accumulated increments of 0.25 mm (0.01 in). In order to guarantee accurate measurements the weather technician of the Biological and Agricultural Engineering Department calibrated these instruments. This calibration was performed before the instruments were deployed to the field (January, 2005).

3.2.3.5 Watermarks

Watermarks are granular matrix sensors that measures soil moisture. The Watermark sensors operate on the same principle of electrical resistance as gypsum blocks (Shock *et al.*, 2005). According to Berrada *et al.* (2001) and Shock *et al.* (2005) developed a calibration equation for the Watermark sensor:

$$S = -\frac{(4.093 + 3.213R)}{(1 - 0.009733R - 0.01316T)} \qquad \text{(Eq. 3.14)}$$

where S is soil water potential (kPa);

R is electrical resistance (kΩ);

T is soil temperature (°C).

In this project Watermark sensors were installed in three fields (2-10, 2-11 and 2-12). The Watermark Monitor is a datalogger that allows seven Watermark sensors and one temperature probe to be connected to it. The sensors were installed mid-way in the row at the east and west sections of the field. The sensors were attached to a PVC pipe attached to protect the wires and to make the sensors easier to push into the ground. A metal rod with a same diameter as the sensor was used to create a hole for the sensor. Then the sensors were driven into the ground to depths of 0.15, 0.30, 0.45 and 0.61 m (6, 12, 18 and 24 in). Finally, the hole was backfilled with fine soil and lightly compacted to prevent formation of a preferential path for rain or irrigation water and easily reach the sensor (Shock *et al.*, 2005). One sensor was located at 0.15 m, two at 0.30, 0.45 and 0.61 m spaced 0.6 m (2 ft) from each other. The Watermark Monitor logged soil water tension values every 15 min. Table 3.3 gives a range of soil water tension measurements related to different soil conditions.

According to Berrada *et al.* (2001) and Shock *et al.* (2005) in heavy soils the Watermark sensor approximately read the following scale:

Table 3.3. Watermark readings for management purposes in heavy soils.

Soil condition	Reading (kPa)	Description
Saturation	0-10	Soil is saturated with water (natural saturation)
Field capacity	10-30	Soil is near field capacity
Range for irrigation	60-100	Average field soil water tension prior to irrigation
Wilting point	100-200	Dangerously dry soil

3.2.3.6 Flowmeters

Propeller type flowmeters (McCrometer, Hemet, CA) were used to record the discharge irrigation water into each field and to determine the flow rate during an irrigation event. The flowmeter used is a M0300 "bolt-on saddle" model mounted on a 300 mm diameter (12 in) PVC pipe with a maximum discharge rate of 0.16 m3/s (2500 gpm). The flowmeter has an instantaneous flowrate indicator and a straight-reading totalizer that registered the total discharge. Three straightening vanes were installed on the upstream side of the meter to reduce spiraling action of the water hitting the propeller (McCrometer, 2005). The pipe layout for the flowmeter is illustrated in Figure A.6 (Appendix A).

3.3 Meteorological Data Management

3.3.1 Crop Evapotranspiration Estimation

3.3.1.1 Atmometer Estimation

This process was previously explained in section 3.2.3.1 using equation 3.1.

3.3.1.2 Weather Station Estimation

The weather station method used the FAO Penman-Monteith equation (Eq. 3.1) to estimate grass reference evapotranspiration (ETo). This ETo values were multiplied by the crop coefficient (Kc) values for soybeans to obtain the crop evapotranspiration (ETc).

The values for Kc change with the development of the plant (Doorenbos and Kassam, 1979). These values for soybeans (Table 3.4) were obtained from the table Doorenbos developed for different crops. Weather data was required to choose the Kc values in this case wind speed and relative humidity. The Kc values were selected for conditions of low wind speed (WS < 5 m/s or 11.2 mi/h) and high relative humidity (RH > 70%).

Table 3.4. Assumed crop coefficient values under Angelina Plantation weather conditions during the 2006 irrigation season.

Crop	Crop development stages				
	Initial	Crop development	Mid-season	Late season	At harvest
Soybeans	0.3	0.7	1.0	0.7	0.4

3.3.1.3 Arkansas Irrigation Scheduler Estimation

This process was previously explained in section 3.2.3.3 using equation 3.9.

3.3.1.4 Data Quality Control

Data was subject to quality control (QC) procedures. The method used is similar to those recommended by Allen *et al.* (1998). This is the case of solar radiation (Figure 3.1) where data shows the comparison between observed values (R_s) and computed values (R_{so}). The weather station recorded the R_s values. The highest observed values for R_s should correspond to the "envelope" of calculated R_{so} values, showing the accuracy of the pyranometer. On occasions R_s may exceed the predicted R_{so} when reflection of radiation from nearby clouds happens during periods when no cloud cover the pyranometer (Allen *et al.*,1998). The values from Angelina Plantation follow the trend aforementioned what indicates that the pyranometer was working properly.

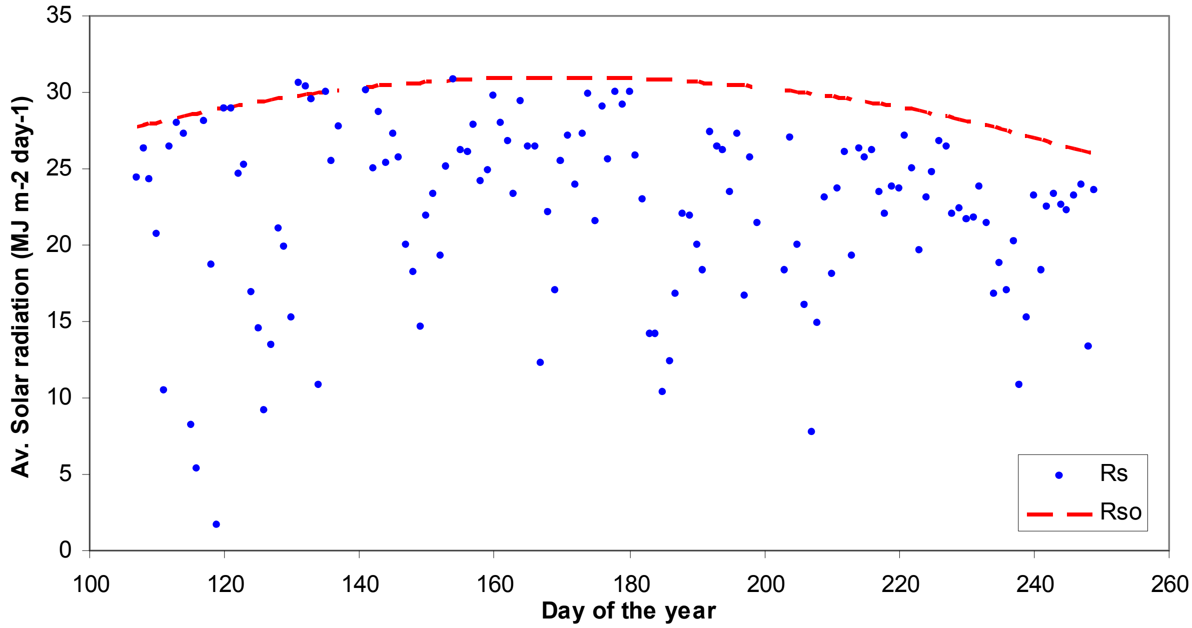

Figure 3.1. Quality control data for 24-hour calculation for solar radiation during 2006.

The equation used to determine R_{so} is described as follows (Allen *et al.*,1998):

$$R_{so} = (0.75 + 2 \text{ X10-5 } z)\, R_a \qquad \text{(Eq. 3.15)}$$

where: R_{so} is the short wave radiation on a clear-sky day (MJ m^{-2} day^{-1});

z is the station elevation(m);

R_a is the extraterrestrial radiation (MJ m^{-2} day^{-1}).

In this case the station elevation for Monterey, Louisiana was 10.3 m

$$R_a = \frac{24(60)}{\pi} G_{sc} d_r \left[\omega_s \sin(\varphi)\sin(\delta) + \cos(\varphi)\cos(\delta)\sin(\omega_s)\right] \qquad \text{(Eq. 3.16)}$$

where G_{sc} is solar constant = 0.0820 MJ m^{-2} min^{-1};

d_r is the inverse relative distance Earth-Sun;

ω_s is the sunset hour angle (rad);

φ is the latitude (rad);

δ is the solar declination (rad).

$$d_r = 1 + 0.033\cos\left(\frac{2\pi}{365}J\right) \quad \text{(Eq. 3.17)}$$

$$\delta = 0.409\sin\left(\frac{2\pi}{365}J - 1.39\right) \quad \text{(Eq. 3.18)}$$

where J is the number of the day in the year between 1 (January 1) and 365 or 366 (December 31)

$$\omega_s = \frac{\pi}{2} - \arctan\left[\frac{-\tan(\varphi)\tan(\delta)}{X^{0.5}}\right] \quad \text{(Eq. 3.19)}$$

where $X = 1 - [\tan(\varphi)]^2 [\tan(\delta)]^2$ and $X = 0.00001$ if $X \leq 0$.

In order to observe if tipping buckets (rain gauges) were recording properly, cumulative precipitation data was plotted. During the irrigation season gauge at field 2-20 did not record precipitation from August 20 until September 7, 2006 (Figure B.1, Appendix B). The zero values generated by the gauge were discarded.

In the case of relative humidity no other automated station was recording close to Angelina Plantation. Therefore, it was not possible to compare the daily relative humidity values to perform the quality control analysis (Fontenot, 2004).

3.3.1.5 Statistical Analysis

All the statistical analysis was performed using the PROC Mixed model from SAS. The analysis was a one-way analysis of variance (ANOVA) where the fields (2-9, 2-10, 2-11, 2-12, 2-19, 2-20) were the number of trials and the days of the analyzed period were the random effect. The three estimations methods (atmometer, weather station and Arkansas Irrigation Scheduler method) were analyzed all together to determine of there were significant differences in the crop evapotranspiration (ETc) estimates at a 95% confidence interval. The methods were analyzed together because more power was achieved.

3.3.2 Soil Moisture Monitoring

3.3.2.1 Watermarks

The process for the soil moisture monitoring using the Watermarks sensor was explained in section 3.2.3.5.

3.3.3 Irrigation Data Management

3.3.3.1 Irrigation Water Allocation

To irrigate the crops, water was pumped from four "on site" wells with flow rates ranging from 0.08 m^3/s to 0.1 m^3/s (1200 gpm to 1700 gpm) and powered by diesel engines. In addition, the location of these four wells determined the pumped water allocation for each of the seven fields analyzed; fields 2-8 and 2-10 shared one well; fields 2-9, 2-11 and 2-12 shared another well; fields 2-18 and 2-19 also shared one well. The only case where a field had their own well was field 2-20. Figure A.7 (Appendix A) illustrates the aforementioned distribution.

3.3.3.2 Irrigation Water Measurements

3.3.3.2.1 Inflow

Inflow measurements were measured by propeller type flowmeters described in section 3.2.3.6.

3.3.3.2.2 Outflow

The fields at Angelina Plantation had a particular design. It is important to mention that when field 2-10 was irrigated, the tailwater was also filling supply ditches on 2-11 through the east dropinlet after the water reached the end of the sloped basin. After irrigating field 2-11, water was drained into supply ditches in field 2-12 through the east and west dropinlets. Finally the water from field 2-12 was drained into a bayou after finishing its irrigation. Figure A.8 presents a graphical description of the outflow process.

3.3.3.3 Irrigation Scheduling

3.3.3.3.1 Arkansas Irrigation Scheduler

The Arkansas Irrigation Scheduler utilize a water balance approach to determine when irrigation is should be applied. The principle of this scheduler is the estimation of the soil moisture balance considering the soil moisture deficit (Cahoon *et al*., 1990). For surface irrigation programs the equation used is described as follows (Cahoon *et al*., 1990):

$$DEF(I) = DEF(I-1) - PPT(I) + ET(I) \quad \text{(Eq. 3.15)}$$

where DEF (I) is the soil moisture deficit on the Ith day of the year;

PPT (I) is the effective precipitation on the Ith day of the year;

ET (I) is the evapotranspiration for the Ith day of the year.

According to Vories (2007) the program assumed that the irrigation event was completed in a day, including the recession. The day after the irrigation the deficit (DEF) started to accumulate again. Regarding the effective precipitation, Vories (2007) says that the scheduler assumes that the crop was kept well watered. Then the program was going to warn the user to enter a smaller precipitation value in the case that increasing runoff was observed.

CHAPTER 4. RESULTS AND DISCUSSION

4.1 Meteorological Data Management

The meteorological conditions were recorded all year long by the portable weather station. However, the most important data collected for this study was during the irrigation season starting on July 1 and finishing on September 7. The month and season (irrigation) total values for rainfall and average daily temperatures throughout the irrigation season are presented in Table 4.1. According to USDA-SCS (1988) the growing season for this area falls within the months of April through September where the maximum precipitation occurs. The year 2005 received more rain during the irrigation season (July and August mainly) than 2006. In 2006 rainfall and temperature totals for the irrigation season were higher than the long-term average. For 2005 rainfall was lower than the long term total. It is important to mention that between the instruments used to collect the rainfall (tipping buckets) there were differences in the data recorded within short distances among the gauges. Figure B.1 (appendix B) illustrates this variability between gauges where only gauge at field 2-8 and the one at field 2-12 had a significant difference. These gauges were about 1345 meters (4412 feet) apart and presented a variation of almost 100 millimeters of rainfall at the end of the irrigation season.

Table 4.1. Average daily values of rainfall, daily temperature, relative humidity (RH), and wind speed (WS) for the irrigations seasons of 2005 and 2006.

	2005				2006				Historical	
	Rain (mm)	Temp. (°C)	RH (%)	WS (m/s)	Rain (mm)	Temp. (°C)	RH (%)	WS (m/s)	Rain[b] (mm)	Temp.[c] (°C)
July	165.4	27.0	74	1.3	50.3	28.7	70	1.4	113.3	27.4
August	67.8	29.6	69	1.1	87.9	29.3	68	1.3	100.3	27.0
September[a]	-	26.8	66	2.0	-	25.0	65	1.9	91.7	24.7

[a]Rainfall values for September are not available because the measurement correspond only to the first week of the month where there was no rain.
[b]Period of 1971-2000 was obtained from the Southern Climate Regional Center data base (no RH and WS available).
[c]Period 1965-1979 was obtained from the Concordia Parish soil survey.

The other gages at fields 2-10/2-11, 2-19 and 2-20 had some variation but it was not significant according to the one-way ANOVA analysis. Data logging errors or equipment maintenance problems could have caused the differences in rainfall.

4.1.1 Crop Coefficient Estimation

The crop coefficient (Kc) values were determined to associate the reference evapotranspiration (ETo) to crop evapotranspiration (ETc). The Kc values used in the weather station (WS) and the Arkansas Irrigation Scheduler (AIS) methods were determined according to the growth stage of the plant. The WS estimation used the Kc tabular values from Doorenbos and the AIS Kc values are from the Stegman *et al.* (1977) (Cahoon *et al.*, 1990). The estimated Kc values for the analyzed period are presented in Table B.1 (Appendix B). These estimated coefficients were used to construct Kc curves for the WS and the AIS methods presented on Figure 4.1.

The differences in the Kc curves were due to the different emergence dates and the Kc estimation procedure. The WS estimation procedure used the tabular crop coefficients for each growth stage that also considered the local climatic conditions for wind speed and relative humidity during 2006 (Table 4.1). The Kc values correspond to high relative humidity (RH > 70%) and low wind (WS < 5 m/s or 11.2 mi/h) conditions established by Doorenbos. The AIS estimation procedure used an algorithm (Figure A.5, Appendix A) that determined the Kc change point based on the age of the crop or also called days after emergence (DAE). The WS estimation shows a significant difference with the AIS estimation.

The values estimated for WS and field 2-20 (AIS-1) were graphed separately with emergence dates on May 5 and 12, 2006 respectively. The WS Kc curve (WS/Doorenbos) assumed as its emergence date the latest "normal" emergence date (05/05/2006) for soybeans (MG IV) according to Vories (2007). One curve represented fields 2-9, 2-10 and 2-11 (AIS-3) since they had the same emergence date (05/22/2006) and the same Kc values throughout the plant cycle. In addition, one curve showed fields 2-12 and 2-19 (AIS-2) because they had their emergence date on May 23, 2006 and the same crop coefficient values. Curves AIS-3 and AIS-2 were not significantly different. However, AIS-1 shows a significant difference with AIS-3 and AIS-2 where this discrepancy is related to the gap in emergence dates.

4.1.2 Crop Evapotranspiration Estimation

4.1.2.1 Atmometer Method

Crop evapotranspiration (ETc) was estimated using three different methods, namely: atmometer method (ETgage), weather station method and Arkansas Irrigation Scheduler method. The atmometer method was a direct field measurement estimation of ETc obtained with an instrument called the ETgage®. ETc values logged were from July 27 to September 7 of 2006 however, analyzed dates were from August 17 to September 7. These days represent continuous data logging not affected by wiring failure of the instrument. It was found that the values computed by the $ETg_{2\text{-}9}$ and the $ETg_{2\text{-}19}$ were the highest among the three methods used to estimate ETc. Also between the two atmometers there was a variation in the values logged yet not significant**.** It is important to mention that both atmometers were not placed inside the fields due to a management decision. $ETg_{2\text{-}9}$ was located outside of field 2-9 on its east edge and the $ETg_{2\text{-}19}$ was placed within the compound of a portable weather station on a grassed area. According to Fontenot (2004), the weather station should be located over a short grass area to ensure maximum clearance and full exposure to the weather elements. The $ETg_{2\text{-}9}$ was on an area surrounded mostly by short weeds mowed not as frequently as the weather station area ($ETg_{2\text{-}19}$). Consequently, most of the time $ETg_{2\text{-}9}$ had denser ground cover than $ETg_{2\text{-}19}$ since the weeds grew around the instrument with less maintenance. Lal and Shukla (2004) says that ground cover intercepts a considerable amount of solar radiation as a result, higher or lower soil temperature will depend on the portion of soil covered. Therefore, the denser ground cover in this particular case could imply a lower temperature near ETg_{2-9} compared to a higher temperature around ETg_{2-19}. The weather conditions starting on September 1 and until September 6 were characterized by no rain; warm weather with an average air temperature of 25°C (77°F); fairly high relative humidity close to 70%; and low wind speed (less than 5 m/s or 11 mph). Allen *et al.* (1998) says that the solar radiation, air temperature, relative humidity, and wind speed are the meteorological factors that influence the evapotranspiration (ET). Therefore, if high relative humidity conditions reduce the ET demand and low wind speed diminishes the ET rate we can infer that the air temperature was the driving factor for variations in the ETc estimated by the atmometers. Since the temperature around ETg_{2-19} was higher due to less ground cover this represents higher evapotranspiration potential than at ETg_{2-9}. This higher evapotranspiration potential is illustrated by the variation between ETgages (Figure 4.2)

4.1.2.2 Weather Station Method

The weather station method used the FAO Penman-Monteith equation to estimate grass reference evapotranspiration (ETo). The ETo estimation was done by substituting the measured components of FAO Penman-Monteith equation. ETo estimates were done beginning April 19 until September 6 and the weather parameters used for estimating ETo were minimum and maximum average air temperature and relative humidity, solar radiation, wind speed and precipitation. The estimated daily ETo values are presented in Figure B.2 (Appendix B). These ETo estimates were multiplied by the Doorenbos crop coefficient (Kc) to obtain the ETc. Even though the ETo value obtained was multiplied by Kc the result was still within a range of the response of the ETo value (Thomas, 2007). These ETc values were used as the reference to compare the three methods because the WS measurements correspond to the national standards for data collection according to Thomas (2007).

4.1.2.3 Arkansas Irrigation Scheduler Method

The Arkansas Irrigation Scheduler (AIS) method considered the six fields planted with soybeans to estimate ETc. The AIS used an algorithm to calculate ETo based on empirical interactions involving pan evaporation and climatological information (Cahoon *et al*., 1990). Then the ETc estimation was made multiplying the ETo by the modified crop coefficient (MC) based on Stegman *et al*. (1977) soybeans curves. These calculations were determined using long-term climatic records that apply for the humid mid-South region and in this case based on the Calhoun, LA location.

ETc estimates were done from May 12 to September 16. These estimates for the six AIS fields were obtained using the algorithm presented in Figure A.5 (Appendix A). In this method the highest estimates of ETc values were in field 2-10 and the lowest ones in field 2-20. These variations are illustrated in Figure 4.3. The AIS method inputs for the ETc estimation were maximum temperature, rainfall and irrigation. However, maximum temperature was the same for all fields since this value came from the weather station (single gauge). This consideration reduced the effect of the temperature variable in the ETc estimation leaving the variable effect to the rainfall. The increase in evaporation following rainfall affected the ETc estimation. Therefore, variations in the rainfall pattern among the six fields caused discrepancies in the ETc values.

4.1.3 Crop Evapotranspiration Estimates Comparison

Estimates for daily crop evapotranspiration (ETc) were done beginning August 17 to September 6, 2006 period where data collected was continuous for the three methods used. Figure 4.4 illustrates the variations of cumulative ETc approximations where the same letter (A and B) means no significant difference between estimation methods. The ETc estimation from the weather station was used as the reference among three methods compared: weather station

(WS), ETgage® or atmometer (ETg_{2-9} and ETg_{2-19}), and the Arkansas Irrigation Scheduler (AIS_{2-9}, AIS_{2-10}, AIS_{2-11}, AIS_{2-12}, AIS_{2-19}, and AIS_{2-20}). Table B.2 (Appendix B) present the ETc estimates for values corresponding to the 2006 irrigation season. The statistical analysis performed was a one-way analysis of variance that analyzed the three methods used to increase the power of the test (Freund and Wilson, 2003).

The WS estimates using the FAO Penman-Monteith equation ranged from 2.1 to 5.2 mm/day (0.08 to 0.2 in/day). According to Alam and Elliot (2003) the ETgage provides crop evapotranspiration estimates in agreement with the modified Penman equation estimates. The ETgage estimates at field 2-9 estimated values ranging 1.3 to 6.1 mm/day (0.05 to 0.24 in/day). In addition, ETgage on field 2-19 presented values varying from 1.5 to 6.4 mm/day (0.06 to 0.25 in/day). Comparing these ETc estimations from the WS with the ETgage® ones (ETg_{2-9} and ETg_{2-19}) there was no significant difference between them. This similarity is graphically shown in Figure 4.4.

Crop evapotranspiration approximations made by the AIS on the six soybean fields varied from 1.5 to 4.8 mm/day (0.06 to 0.2 in/day). Significant difference was observed between the AIS estimates and the WS where these last ones were higher throughout the period analyzed. Greater ETo values for the WS method (Figure B.2, Appendix B) from August 17 to September 6 resulted in these higher ETc values compared to the AIS estimates. In addition, the AIS assumption that rainfall was going to increase ETc due to higher evaporation from wet soil and plant surfaces led to differences in the ETc estimation. It appears that the variations in the rainfall pattern among the six fields (Figure B.1 Appendix B) were the driving factor for those differences in the AIS method.

As mentioned before the WS ETc estimation was used as a reference for comparing the three methods. The previous results suggest that the WS and the ETgage ETc estimations were more suitable for the conditions present at Angelina Plantation. The WS estimation method used the FAO Penman-Monteith equation. Since the WS ad ETgage estimates were similar these results suggest that the statement made by Alam and Elliot (2003) is true: ETgage ETc estimates are in agreement with the modified Penman estimations. The AIS estimation shows lower estimates than the WS estimates throughout the analyzed period.

In this comparison analysis tests were performed to determine whether the following assumptions for analysis of variance had been violated (Freund and Wilson, 2003):

- The residuals are normally distributed
- The observations are independent
- The variances are homogeneous

Normality was checked using the Shapiro-Wilk test (Proc UNIVARIATE) where a P of 0.052 told us we had normal data. In addition, the normal plot did not show any outliers. No trends in these tests for the three methods used indicated that assumptions were violated.

4.2 Irrigation Data Management

4.2.1 Irrigation Water Measurements

During the two-year irrigation period (2005 and 2006) at Angelina Plantation (Monterey, LA), measurements were taken from the beginning of July until the middle of September. The infield conditions were measured until irrigation practices were discontinued to prepare for the harvesting process. In 2005 four of the fields were planted with soybeans (2-9, 2-10, 2-11, 2-12), two with rice (2-18, 2-19) and one is in cotton (2-8). For the study period of 2006 six fields were planted with soybeans (2-9, 2-10, 2-11, 2-12, 2-19, 2-20) and one with cotton (2-8). Table 4.2 summarizes the field distribution for the two-year research project.

4.2.1.1 Inflow

The irrigation water pumped into the fields was measured using propeller flowmeters installed at the riser of each field. These inflow measurements were recorded during two irrigation seasons (2005 and 2006) to monitor water use. Water use during 2005 ranged from 109 mm (4 in) to 331 mm (13 in). In 2006 (Table 4.3) the water use varied from 152 mm (6 in) to 459 mm (18 in) with yields from 2906 to 4010 kg/ha.

For the 2006 irrigation season level field 2-9 was irrigated two times (June 22 and August 17) averaging two days to complete each irrigation. Six spin ditches ran across the field on a north-south direction with the purpose of helping with the water distribution and drainage. Perpendicular to the spin ditches a polyethylene tube was laid out to carry the irrigation water along the south edge of the field and distributed across the whole field. While irrigating sand bags and piles of dirt were used to plug the end of the spin ditches to force water movement along the plant rows (east-west direction). This non-standard technique did not have success because water washed the dirt piles and went over the sand bags.

Table 4.2. Fields used in the 2005-2006 level basin research project at Angelina Plantation.

Year	Field #	Net area (ha)[a]	Crop	Irrigation method
2005	2-8	10.5	Cotton	Level
	2-9	24.8	Soybeans	Level
	2-10	15.3	Soybeans	Sloped
	2-11	14.7	Soybeans	Level
	2-18	22.7	Rice	Level
	2-19	22.7	Rice	Sloped
2006	2-8	10.5	Cotton	Level
	2-9	24.8	Soybeans	Level
	2-10	15.3	Soybeans	Sloped
	2-11	14.7	Soybeans	Level
	2-12	23.6	Soybeans	Level
	2-19	22.7	Soybeans	Sloped
	2-20	25.0	Soybeans	Sloped

[a]Net planted area

In sloped field 2-10 irrigation took place three times (June 16, July 13, August 2) with an average completion time of 2.5 days. The field has a west-east slope (0.1%) and a north-south slope (0.3%). Polyethylene tube of 0.4 meters of diameter (15 inches) was placed along the north edge of the field perpendicular to the rows orientation. Tail water from this field was drained out to a side canal during the first irrigation but conveyed to field 2-11 during the second and third irrigations.

The three irrigation events in level field 2-11 took place June 16, July 17 and August 4. Each event was completed in approximately 30 hours. However, the third irrigation was incomplete due to rain. The supply polyethylene tube was placed along the south edge of the field parallel to the rows direction. Ten spin ditches spaced approximately 67 m (220 ft) ran on a north-south direction and these ditches were used to direct water across the field and along middles. In the first irrigation the north end of the spin ditches was blocked with sand bags with no success since water went over the top of the bags. According to Branch (2006) water was seeping out from the riser after the irrigation was finished. Since the this field did not have slope and the polyethylene tube was on the edge of the field (no side ditch acting to drain excess water), the parallel rows close to the tube stayed wet for an extra time. It was observed that these rows suffered due to waterlogging.

Level field 2-12 was irrigated completely only once on June 16 taking three days to be completed. The second attempt to irrigate this field on July 18 was stopped due to rain. Five spin ditches spaced approximately 67 m (220 ft) were placed on the east-west direction and one along the contouring edge of the field next to a bayou. Sandbags were used in this field with the same poor result as in the other fields. The low areas in the field showed yellowing plants due to extended wet periods (Branch, 2006).

Sloped field 2-19 was graded to 0.2% on a south-north direction. The polyethylene tube was installed on the south edge of the field and was used during three irrigation events (June 16, July 18, August 3). Each irrigation event was completed in three days. Two more irrigation events were started but then stopped because of rainfall. Field 2-20 also graded to 0.2% (south-north) and its polyethylene supply line was located on the south edge of the field. Two irrigations (June 9 and 25) were completed and two more were interrupted by rain. One complete event required four days.

The common denominator for all the irrigated fields was that they were irrigated in sets. Due to their large area and the pump flow rate limitation each field was divided into two or more irrigation sets. The sliding gates (max flow 0.002 m^3/s or 30 gpm) installed on the polyethylene tube allowed sets of 50 to 80 gates opened at the same time.

Table 4.3. Total irrigation applied for the irrigation seasons between July to September for 2005 and 2006.

			Irrigation 2005[a]		Irrigation 2006[a]			
Fields	Irrigation method	Net area (ha)	mm	in	mm	in	Yield[c] (kg/ha)	# of irrig.[b]
2-8	Level	10.5	229.0	9.0	459.0	18.0	*	
2-9	Level	24.8	136.0	5.5	184.0	7.0	2988.0	2
2-10	Sloped	15.3	n/a	n/a	232.0	9.0	3864.0	3
2-11	Level	14.7	109.0	4.0	275.0	11.0	3193.0	2
2-12	Level	23.6	-	-	152.0	6.0	3037.0	1
2-18	Level	22.7	331.0	13.0	-	-	-	-
2-19	Sloped	22.7	151.0	6.0	325.0	13.0	2906.0	3
2-20	Sloped	25.0	-	-	305.0	12.0	4010.0	2

[a]Fields with this symbol (-) were not instrumented for that irrigation season
[b]# of complete irrigations (not interrupted by rain)
[c]Data provided by the LSU AgCenter in Concordia Parish
*Not harvested by the end of the study

4.2.2 Irrigation Scheduling

4.2.2.1 Arkansas Irrigation Scheduler

The Arkansas Irrigation Scheduler (AIS) is a scheduling tool used to determine the date for the required irrigation events according to the program's water balance method (Eq. 3.15).

This approach assumed good management for all the fields with a common Maximum Allowed Depletion (MAD) of 50% or 50.8 mm (2 in) for soybeans. According to tabulated values from Keller and Bliesner (1990) this MAD is reasonable for deep-rooted row crops. In this study the role of this tool was to verify that plants were not drought stressed according to the previously mentioned parameter of 50% MAD. Figures B.3 to B.8 (Appendix B) shows the management of field 2-9 to 2-20 throughout the season according to the AIS.

It is important to note that the allowable depletion of 50.8 mm (dotted horizontal line) was the threshold value to determine whether to irrigate or not. According to AIS in fields 2-9 to 2-12 the deficit was lower than the MAD at the first irrigation of the season. Fields 2-19 and 2-20 were irrigated when the deficit reached the MAD. In contrast, all fields except for 2-20 significantly exceeded the MAD before their second irrigation. High deficit values recommended irrigation to avoid crop water stress. These scenarios suggest that the AIS is a scheduling tool but there is a local management component when the farmer may actually irrigate or not. However, by the end of the season the program showed in all fields that the MAD was exceeded because the irrigation practices were discontinued since the farmer was preparing for harvest.

According to Vories (2007), AIS program assumes that a surface irrigation will be completed in a day (including recession). Then the next day the deficit starts to accumulate again. To irrigate some of the fields it took more than one day. This means that the soil was at field capacity or close to it for more than one day, especially with Sharkey clay soil with high storage capacity (USDA-SCS, 1988). This assumption suggests that the deficit calculated by the AIS would be overestimating the actual conditions and calling for irrigation sooner. In addition, the fact that the AIS used the 50.8 mm (2 in) MAD throughout the season indicated that the crops were receiving more water at the end of crop cycle when water demand is lower. More water means more irrigation events and a similar increment increase in irrigations costs. Branch

(2006) says that irrigating with a higher MAD value according to the crop stage (maturity) implies higher water use per irrigation. However, there is also a reduction in the number of irrigation events throughout the season reducing the irrigation costs.

4.3 Soil-Water Data Management

4.3.1 Watermarks

Automated collection of soil-water tension data (Watermark® sensor) by the Watermark Monitor showed the soil's wetting-drying response throughout the irrigation season. The fields analyzed were 2-10, 2-11 and 2-12 where instrumentation was located. Data was collected from July 1 to September 7, 2006 every hour and downloaded from the datalogger (Watermark Monitor). Soil water tension was analyzed at depths of 0.15 m, 0.30 m, 0.46 m, and 0.61 m (6, 12, 18, and 24 inches). Each Watermark Monitor had a temperature probe for data compensation. However, this probe was replaced by an extra Watermark sensor later on the irrigation season (July 25, 2006). This action implies that the Watermarks readings were good but they were not absolute. The east and west locations were essentially two replications of soil water tension measurements at different positions in the field (Figure A.1 Appendix A). The response of the Watermark (WM) sensors was analyzed after irrigation or a large rainfall event.

The WM sensors response to irrigation in fields 2-10, 2-11 and 2-12 are presented in Figures B.9 to B.20 (Appendix B). Almost all sensors (east and west locations) at the four different depths responded effectively to the irrigation events. The reading at each one of the sensors went to zero kPa following the irrigation events. This saturated condition (0 kPa) is called "natural saturation" because not all the porous space is filled by water due to air space (Berrada *et al.*, 2001). Special attention was directed when the sensors were installed to ensure good soil-sensor contact. However, the Sharkey clay soil presents a considerable amount of shrinkage and cracking when drying (Allen, 1965). This characteristic of the soil inevitably can cause the soil-sensor contact to be lost or weakened. According to Shock *et al.* (2005) contact failures could cause high and erratic readings. This problem has a high incidence in heavy soils (Sharkey clay) and during the high water need period of the plant. We can infer that the high and varying readings shown in field 2-12 especially from July 22 until August 10 could be the result of soil-sensor contact problems (Figures B.17 to B.20, Appendix B). During this period there was not much rainfall (1.7 mm or 0.07 in) and no irrigation events that correspond with multiple fluctuations in soil water tension.

An important consideration is the response of the WM sensors to precipitation. This response was influenced by the portion of water stored in the soil profile. Dastane (1974) calls this stored portion effective precipitation (P_{eff}) and says that it is the useful or utilizable rainfall. From August 21 to the 27 there was no irrigation and it rained substantially during these days. The soil-water tension readings in fields 2-10, 2-11 and 2-12 were high (approximately 100 kPa) meaning low moisture content in the soil. According to Dastane (1974) initial moisture in the soil influences P_{eff} in a great manner. The amount of P_{eff} is higher in areas where there is a deficit of moisture in the soil. During that week the soil moisture condition (Figures B.9 to B.20, Appendix B) was starting to approach to the wilting point range where soil-water tension is between 100 and 200 kPa (41 and 39% moisture content). Allen (1965) found that Sharkey clay soils start cracking at 39.34% and as the soil dries out cracks become wider. Then we can infer that these cracks caused by deficit of soil moisture were going to increase the P_{eff}.

4.3.2 Performance of Sloped Basin and Level Basin

To analyze more critically the irrigation performance of the sloped and level fields, soil moisture tension data was inspected. As a first step to evaluate the data collected by the Watermark Monitor it was necessary to transform the collected soil moisture tension values into moisture content values. Romkens *et al.* (1986) obtained desorption curves for three different horizons (A_p 0-17.8 cm, A_1 17.8-43.2 cm and A_c 43.2-78.7 cm) for a Sharkey clay soil. Romkens used Sharkey pedons located on the St. Gabriel Research Station in Iberville Parish, Louisiana which is a similar soil to the Sharkey found at Angelina Plantation. Soil water content calibration curves were developed using a linear approximation to obtain the calibration equation for each depth (0.15 m, 0.30m, 0.46 m, and 0.61 m) shown in Figures B.21, B.22 and B.23 (Appendix B respectively). These new moisture content values were plotted for the irrigation season.

According to Board (2006) days to R5 (from VE to R5) are important for final yield because it sets the time limit for the crop achieving its vegetative mass (stem, leaves, petioles). The crop must have a certain mass of these to be in a range where it has optimal yield potential. Drought before R5 will be harmful to yield if it reduces crop mass below what it needs for optimal yield. Soybean is most prone to drought stress during the flowering and pod formation periods (R1-R5).

The evaluated period fell approximately in between the R1 and R7 growth stages. The first growth stage R1 is the beginning of bloom and R7 is the beginning of maturity. Keller and Bliesner (1990) says that roots extract 70% of the water in the first half of the root's total depth and the effective rooting depth for soybeans ranges from 0.6 m to 0.9 m depending on soil conditions. Because of the characteristics of the Sharkey clay soil (heavy clay) the shallower depth (0.6 m) was assumed for the effective root depth. From this assumption the total water available in the soil profile at a certain effective rooting depth was calculated using the relationships presented in Table 4.4. In this case for the total water (Field Capacity) the D_A is the water content (cm^3/cm^3) value at the depth where first Watermark sensor is located, being D_A the shallowest Watermark and D_D the deepest one.

Table 4.4. Relationships to determine the available water at the effective rooting depth.

Root depth (mm)	Effec. Root depth (mm)	Growth stage (date)	Total water Field Capacity-FC (mm)	Unavailable water Wilting Point-WP (mm)	Available water (mm)
500	350	R1 (Jul. 4 –Jul. 24)	D_A *225 + D_B *125	2.7*225+2.7*125 = 945	FC-WP
600	420	R5 (Jul. 24 – Sep. 7)	D_A*225+D_B*155+ D_C*40	2.7*225+2.7*155+ 2.7*40 = 1134	FC-WP
900	630	R7 (Sep. 7)	D_A*225+D_B*155+ D_C*160 +D_D*85	2.7*225+2.7*155+ 2.7*160+2.7*85 = 1687	FC-WP

Even though the total water available was calculated, it was necessary to determine the available water at the different effective rooting depths (Table 4.4) through the season shown according to the growth stages R1, R5 and R7 (Figures 4.5 and 4.6). Available water was the difference between the water content at field capacity and the capacity at wilting point. The wilting point value was an assumed average value of 27% of water content at 15 bars of pressure obtained from USDA-SCS (1988) and Allen (1965). This calculated available water content was compared throughout the entire season with the 50.8 cm management used by the Arkansas Irrigation Scheduler. Figures 4.3 and 4.4 shows the influence of irrigation through the season as related to the 50% MAD (50.8 mm or 2 in) represented by the dotted horizontal line. In both cases, the available water was above the MAD through the entire season. In addition, during the critical period from R1 until R5 there was enough water available for the plant. However, shortly after the beginning of R5 the available water curve shows a continuous peak in the level field. This sustained peak (green oval) implies an excess water condition. As mentioned before by Branch (2006) rows close to the tube on the level field stayed wet for an extra time with subsequent yellowing. Excess water in the soil could have waterlogged the plants. On the other hand, the sloped field does not show these sustained high water content values implying that the field drainage was moving excess water out properly. These potential waterlogging periods could be reflected in the yield for this level field. According to Linkemer (1995) when rainfall or flooding is maintained for more than 48 hours on soybeans there will be a reduction in the yield. Another factor that influenced the time that water was in the level field was the presence of sand bags to block selected spin ditches at the beginning of the irrigation event. This practice is a non-standard procedure implemented by the farm managers at Angelina Plantation. These spin ditches directed the flow of water in and out of smaller areas within the field because of the limitation of the water supply pumping system. Additional manual labor was required to move sandbags when the field was being drained. The presence of sandbags might have limited some field drainage and allowed extra time for the plants to be under water. This non-traditional practice applied at Angelina Plantation made the irrigation process more labor intensive.

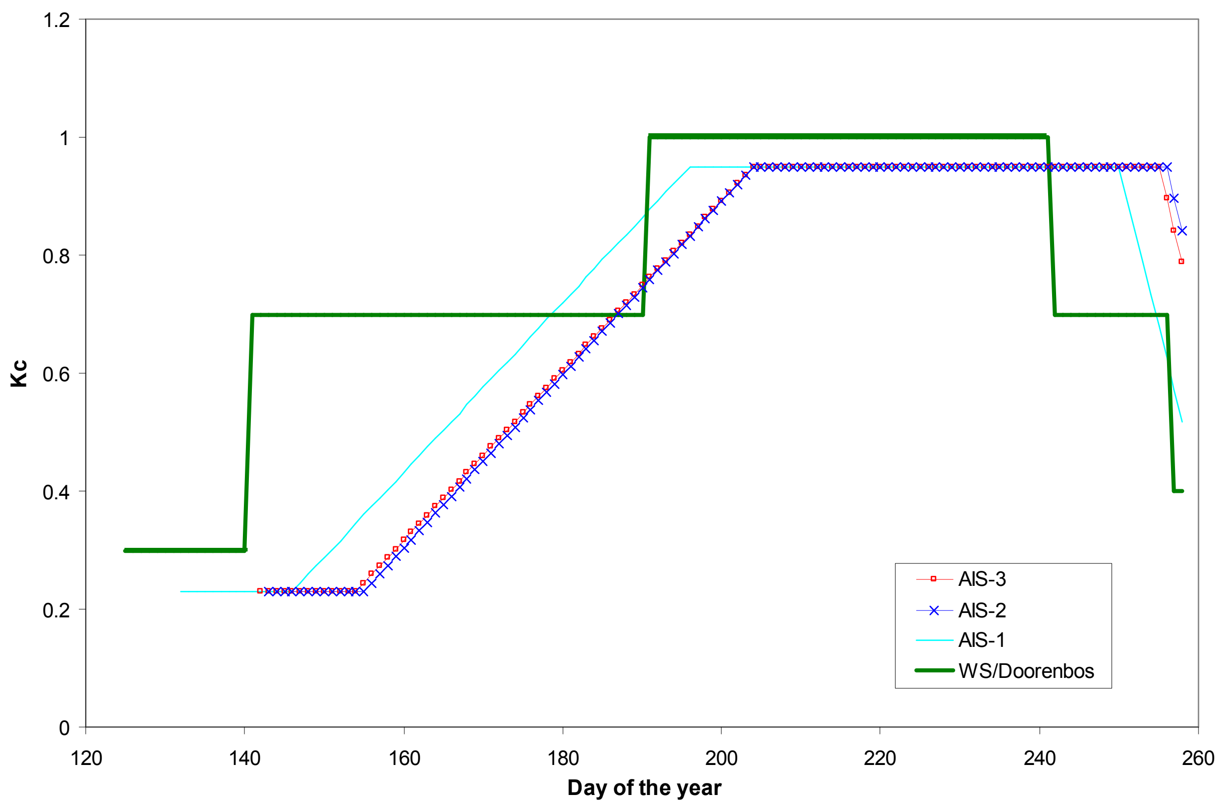

Figure 4.1. Constructed crop coefficient (Kc) values using values from Doorenbos (1979) and the Arkansas Irrigation Scheduler algorithm for the soybean fields during 2006.

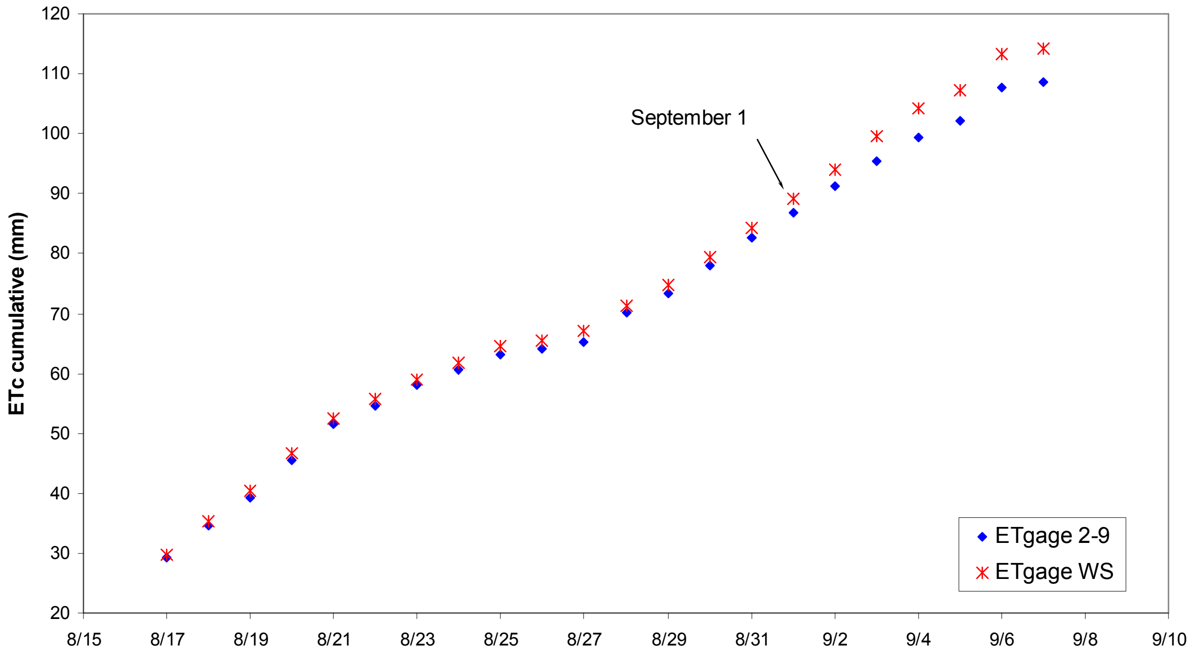

Figure 4.2. Crop evapotranspiration (ETc) estimations for the atmometer method from August 17 until September 7.

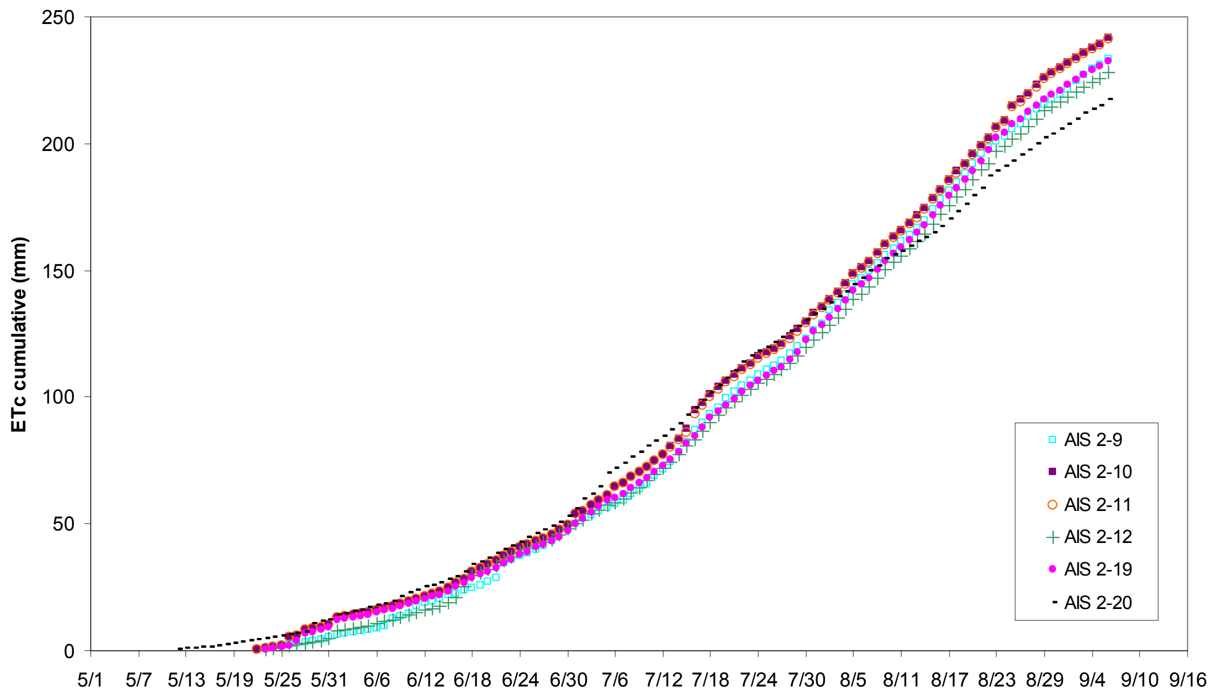

Figure 4.3 Arkansas Irrigation Scheduler (AIS) ETc estimation for six different fields during the 2006 irrigation season.

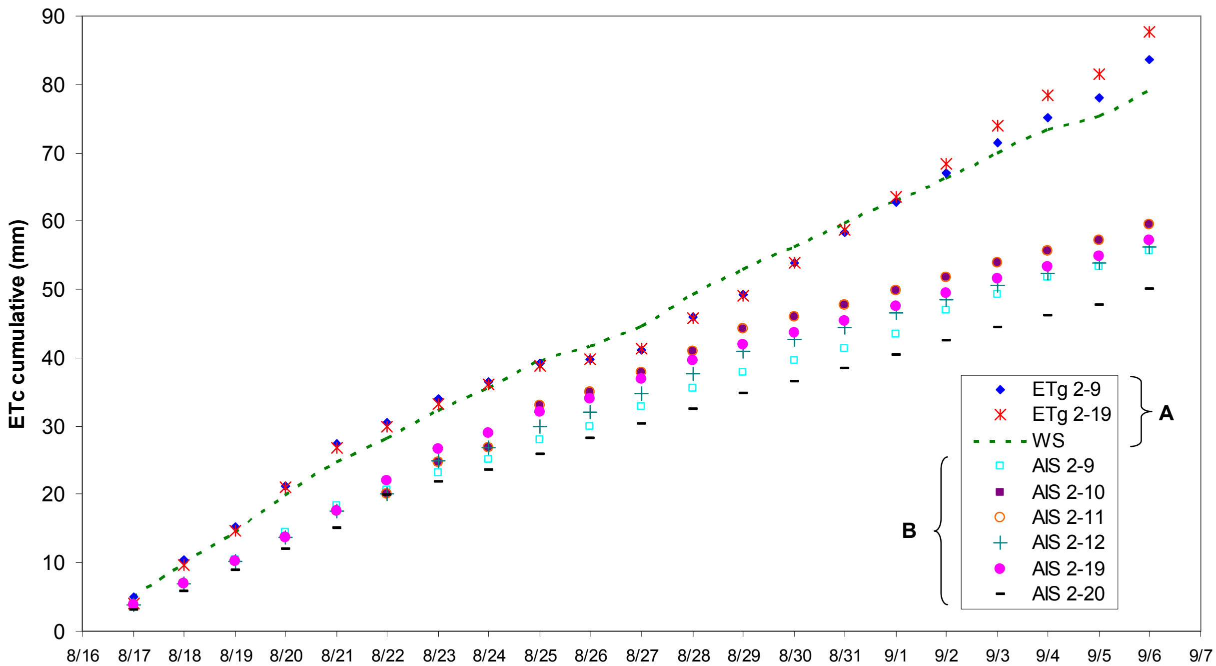

Figure 4.4. Cumulative crop evapotranspiration values (ETc) estimated by three different methods: atmometer or ETgage® (ETg), weather station (WS) and the Arkansas Irrigation Scheduler (AIS).

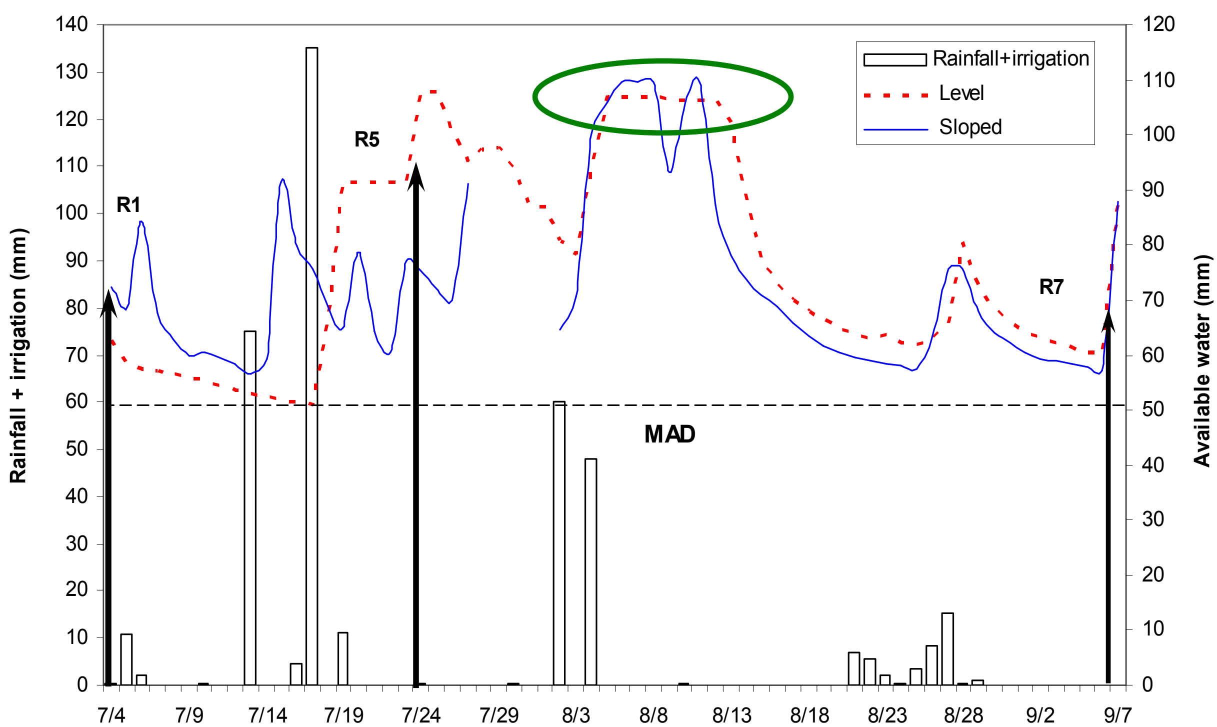

Figure 4.5. Available water content in relation to the maximum allowable depletion (MAD = 50.8mm) for different growth stages (R1, R5, R7) of soybeans during 2006 (east section of the level and sloped fields)

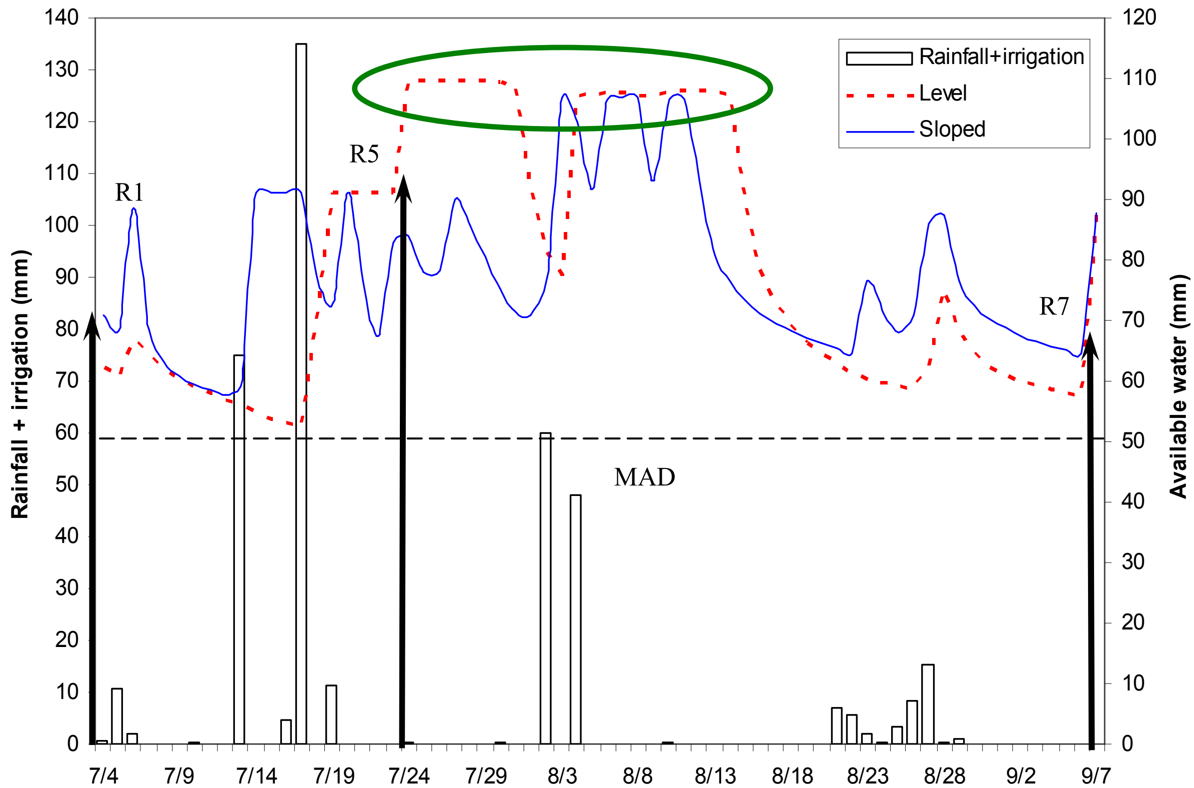

Figure 4.6. Available water content in relation to the maximum allowable depletion (MAD = 50.8mm) for different growth stages (R1, R5, R7) of soybeans during 2006 (west section of the level and sloped fields)

CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS

Crop evapotranspiration (ETc) estimates for soybeans were done during the growing season of 2006 at an agricultural site in Northeast Louisiana. Three different methods were compared, namely: atmometer method, weather station method and the Arkansas Irrigation Scheduler (AIS) method. The first two methods were based on the modified Penman (1963 Penman) and the FAO Penman-Monteith equations respectively. The University of Arkansas developed the third method. The goal was to compare these three methods using as a reference the weather station method. Results showed similar estimations by the weather station and atmometer methods and different estimates by the AIS approach. Variations between the WS method and the AIS method are associated with the ETo values used to obtain the ETc estimates. The WS method presented higher ETo values throughout the analysis period. In addition, the similarity of the estimated values by the atmometer to the ones from the weather station suggest that estimates based on the Penman family models are suitable for Angelina Plantation conditions.

Sloped and level basins were monitored during the irrigation seasons of 2005 and 2006. Water use measurements were recorded and the soil moisture conditions monitored. In 2006 two fields (one sloped, one leveled) were analyzed. Both cases performed adequately having enough available water for the crop throughout the season. However, the level basin had waterlogging problems. Non-standard irrigation procedures (sandbagging spin ditches) suggested a negative impact in the field drainage and made the irrigation process more labor intensive. Extra care is necessary to avoid waterlogging with level basins. Considerations like placing the polytube on the drained edge of the field (close to side ditch) could improve the ponding problems next to this tube. The fact that the spin ditches aided the distribution of water inside the field suggests the idea of reducing the distance between them (from 67 m or 220 ft to 60 m 200 ft).

The AIS is a good scheduling tool that accurately predicts when the crop needs irrigation. However, the results obtained at Angelina Plantation suggest that the farmer or irrigator programs irrigation events modified by farm requirements. Based on weather and soil conditions, and immediate needs the farmer or the irrigator will make the decision of when to irrigate. Even though the program recommends irrigation he will "play" with the rain forecast to reduce irrigation costs by holding back the irrigation if possible. An important idea is that throughout the irrigation season it is necessary to modify the Maximum Allowable Depletion (MAD) value according to the plant stage. The first stages of the plant will require more water but when the plant approaches maturity the water needs decrease. This consideration has the potential to reduce the number of irrigations during the season and consequently reduce the irrigation costs. However, irrigating at a higher MAD means higher water use per irrigation event.

For future studies, it is necessary to stress the importance of the instrumentation component. There is a critical need for high quality continuous readings to evaluate the irrigation techniques. The best way to achieve this goal is by monitoring on a daily basis all components of the study and keep manual records. On site support personnel are critical in order to accomplish this endeavor. Finally, it is very important to take into account the farm management component. When the farm where the study takes place is managed privately it is necessary to have a detailed plan where alternatives to the actual research procedure should be contemplated. These alternatives will help to "trouble shoot" any inconvenience during the time the fieldwork takes place for research purposes.

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APPENDIX A: INSTRUMENTATION AND FIELD LAYOUTS

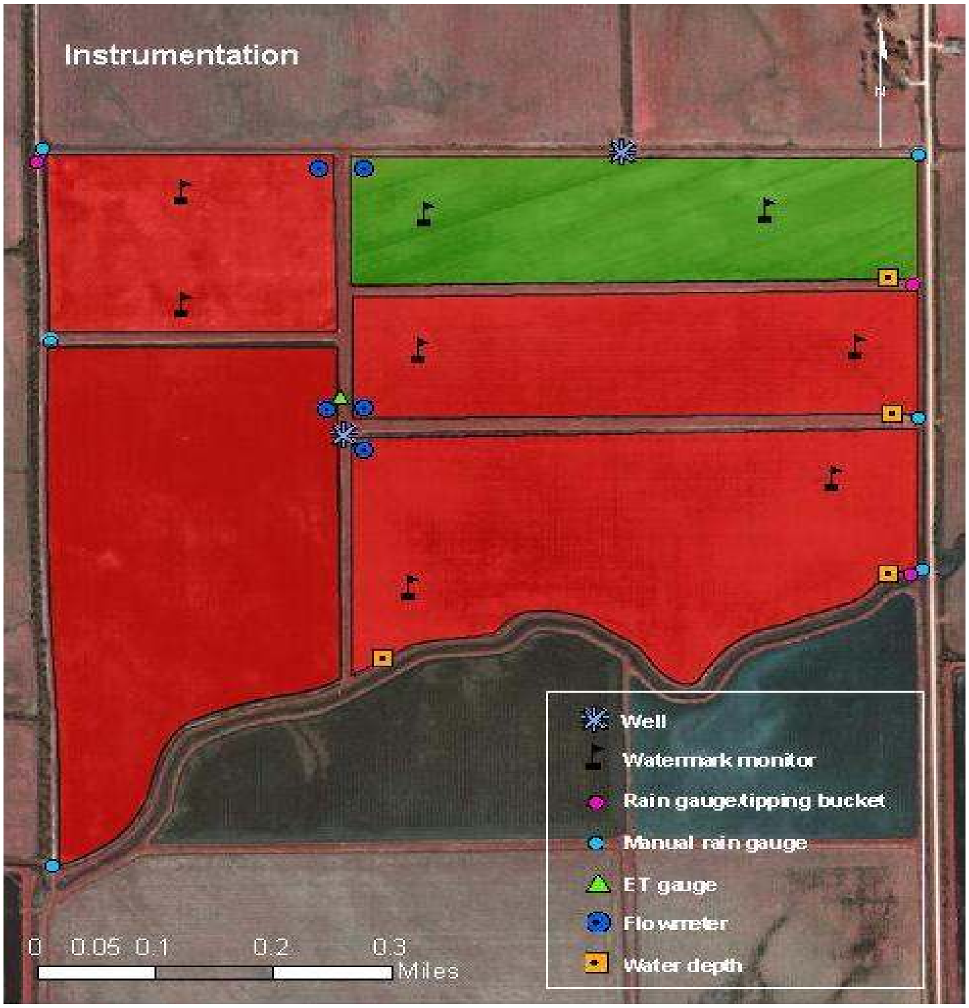


Figure A.1. Instrumentation layout for fields 2-8, 2-9, 2-10, 2-11, and 2-12 (western fields 2006). Level fields are in red and the sloped one in green.

Figure A.2. Instrumentation layout for fields 2-19 and 2-20 (eastern fields 2006).

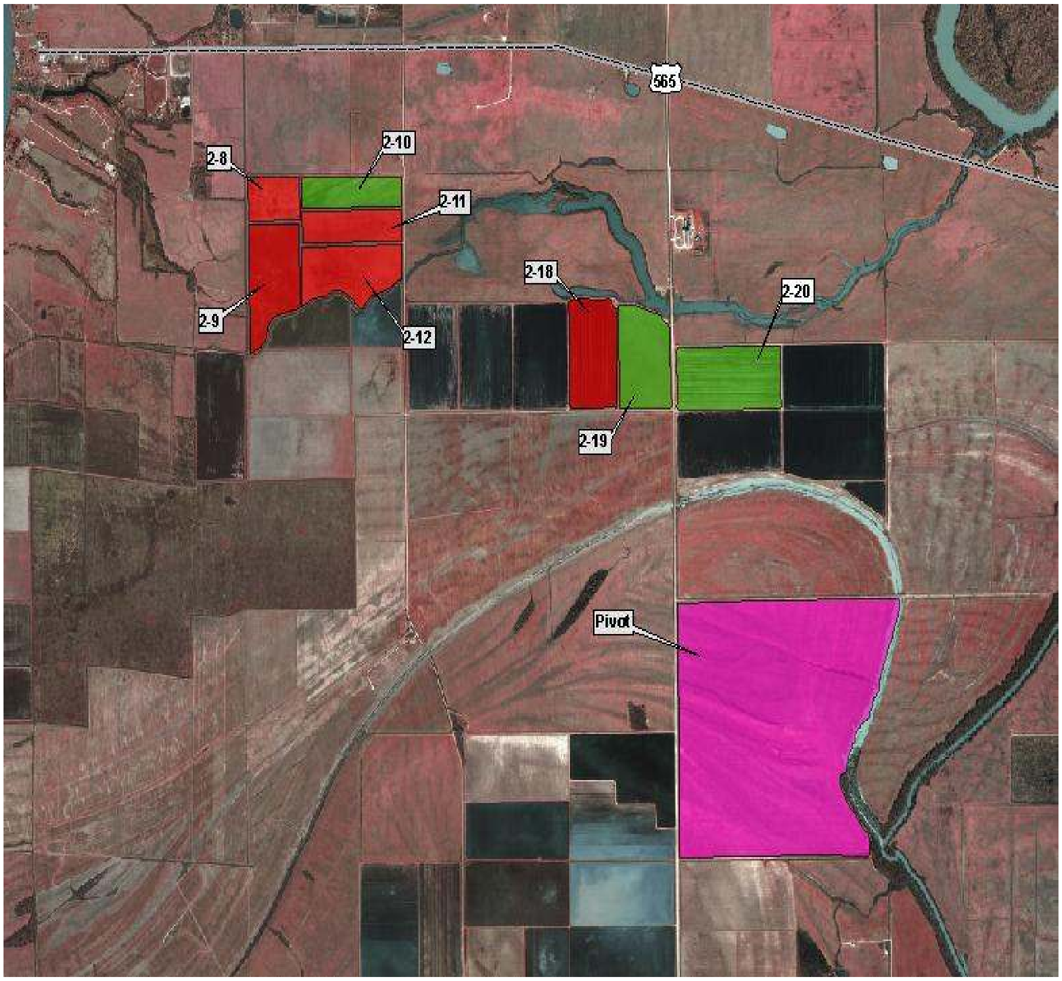


Figure A.3. Angelina Plantation layout for the 2005 and 2006 irrigation seasons.

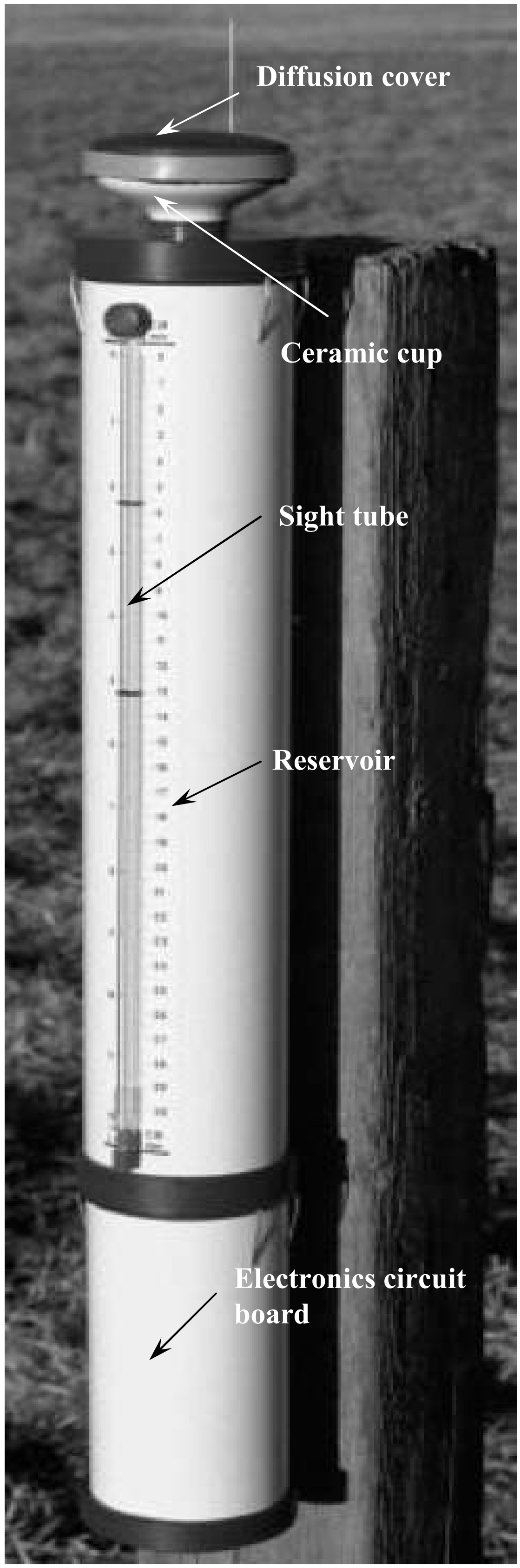
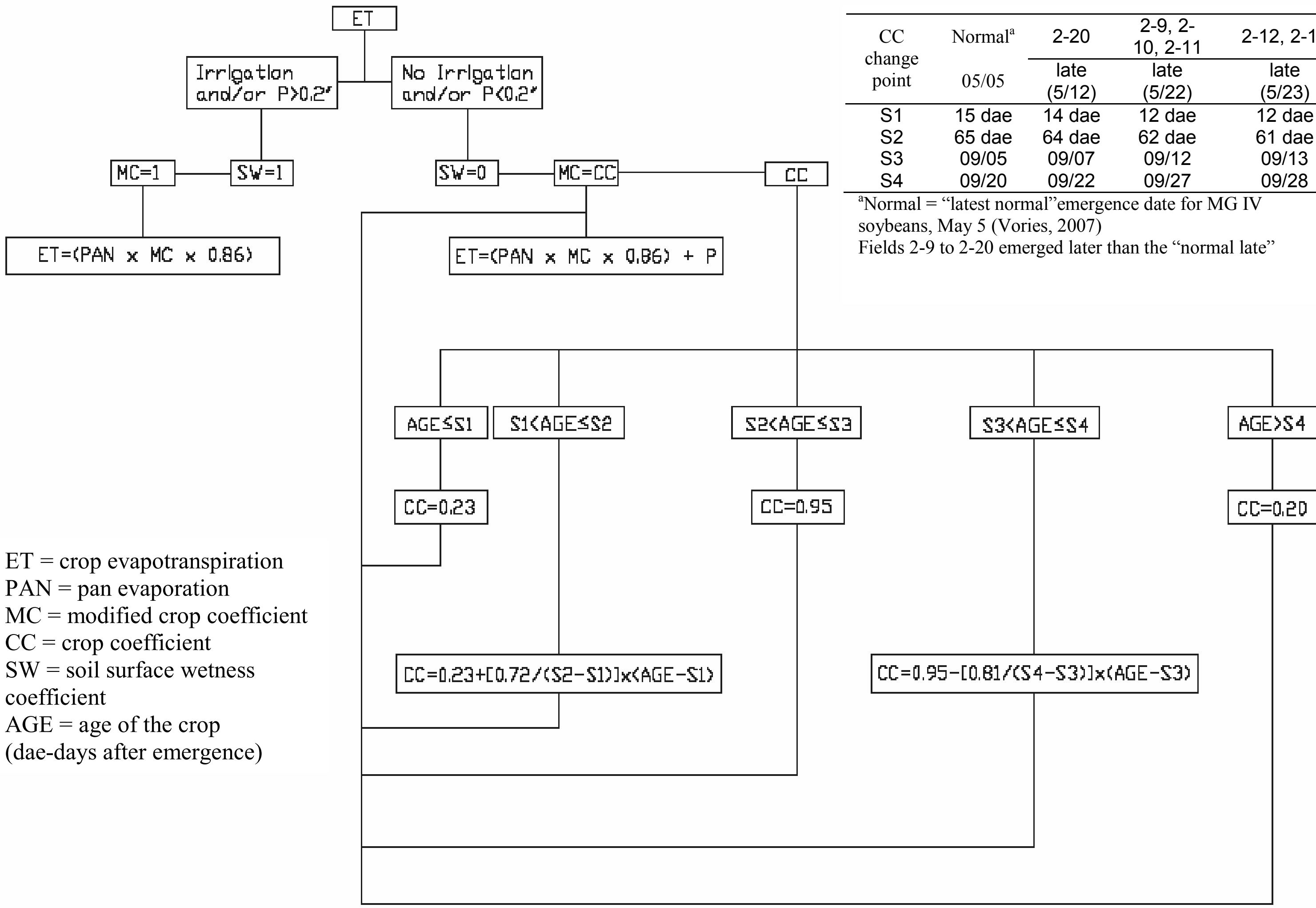


Figure A.4. Atmometer (ETgauge Model E) for evapotranspiration measurements.



CC change point	Normal[a]	2-20	2-9, 2-10, 2-11	2-12, 2-19
	05/05	late (5/12)	late (5/22)	late (5/23)
S1	15 dae	14 dae	12 dae	12 dae
S2	65 dae	64 dae	62 dae	61 dae
S3	09/05	09/07	09/12	09/13
S4	09/20	09/22	09/27	09/28

[a]Normal = "latest normal"emergence date for MG IV soybeans, May 5 (Vories, 2007)
Fields 2-9 to 2-20 emerged later than the "normal late"

ET = crop evapotranspiration
PAN = pan evaporation
MC = modified crop coefficient
CC = crop coefficient
SW = soil surface wetness coefficient
AGE = age of the crop (dae-days after emergence)

Figure A.5. Algorithm used by the Arkansas Irrigation Scheduler to determine the soil surface wetness coefficient (SW) and the crop coefficient (CC).

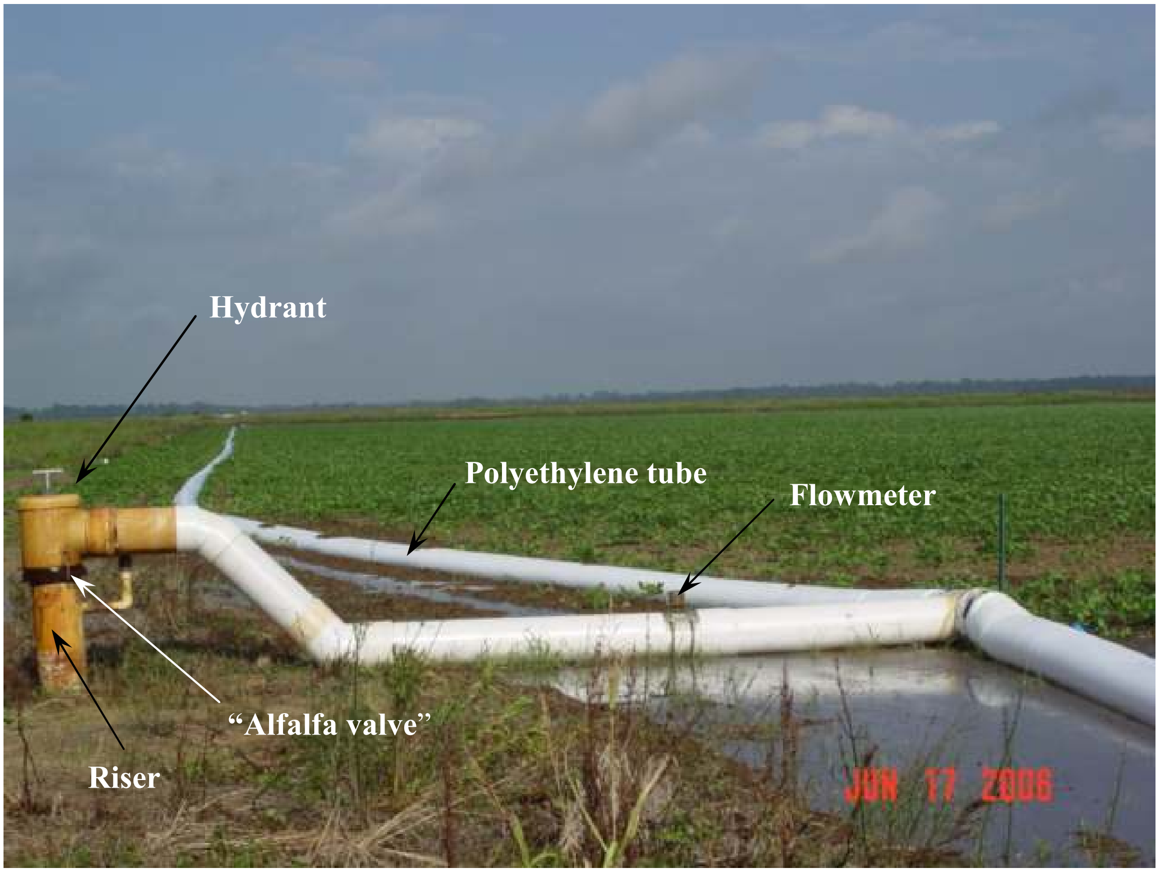


Figure A.6. Flowmeter used to record inflow of irrigation water and flowrate.

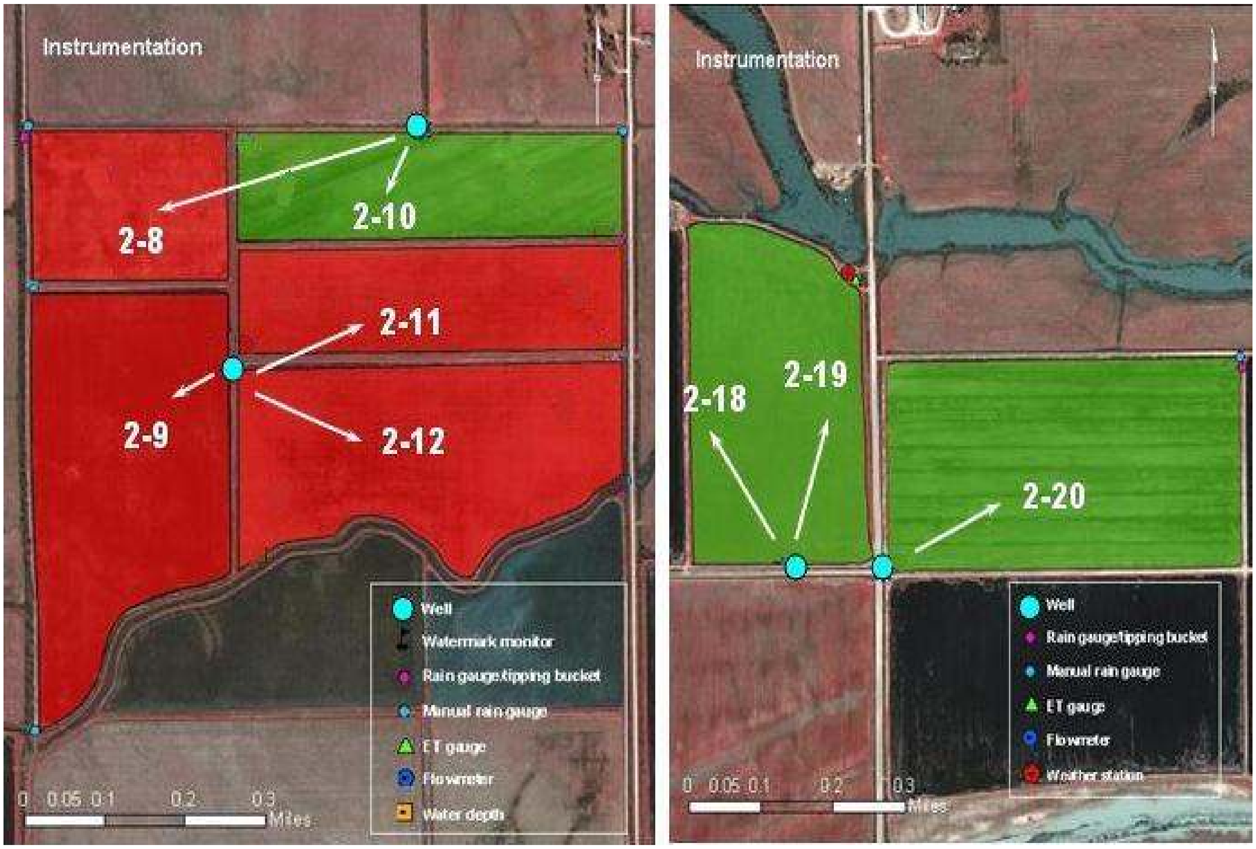


Figure A.7 Wells distribution and water allocation between fields at Angelina Plantation during 2006. Arrows indicate the fields served by each well.

Figure A.8. Outflow considerations for the irrigated fields (west section) during 2006 at Angelina Plantation. The blue arrows represent the outflow point from each field.
The white solid lines are the side ditches.

APPENDIX B: ANALYSIS OF RESULTS

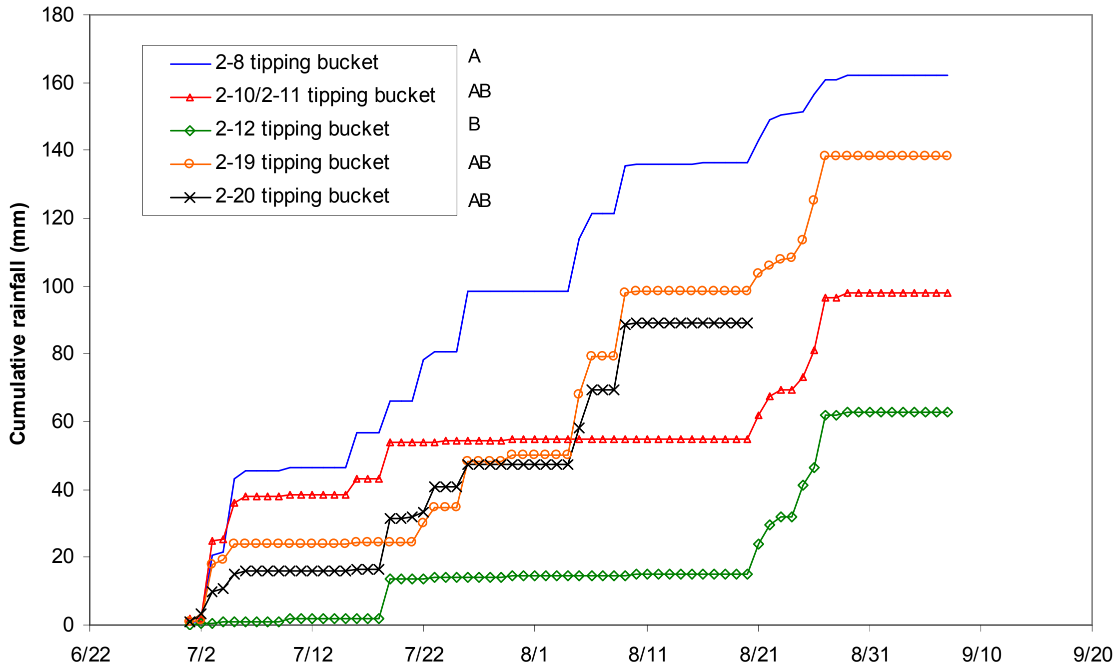


Figure B.1 Rainfall variability between tipping buckets during the 2006 irrigation season

Table B.1 Kc values for the Arkansas Irrigation Scheduler and the weather station/Doorenbos estimation methods from May 5 to September 15, 2006 (DOY = day of the year)

		Kc			
DOY	Date	AIS 2-9,2-10,2-11	AIS 2-12,2-19	AIS 2-20	Doorenbos
125	5-May				0.3
126	6-May				0.3
127	7-May				0.3
128	8-May				0.3
129	9-May				0.3
130	10-May				0.3
131	11-May				0.3
132	12-May			0.23	0.3
133	13-May			0.23	0.3
134	14-May			0.23	0.3
135	15-May			0.23	0.3
136	16-May			0.23	0.3
137	17-May			0.23	0.3
138	18-May			0.23	0.3
139	19-May			0.23	0.3
140	20-May			0.23	0.3
141	21-May			0.23	0.7
142	22-May	0.23		0.23	0.7
143	23-May	0.23	0.23	0.23	0.7
144	24-May	0.23	0.23	0.23	0.7
145	25-May	0.23	0.23	0.23	0.7
146	26-May	0.23	0.23	0.23	0.7
147	27-May	0.23	0.23	0.24	0.7
148	28-May	0.23	0.23	0.26	0.7
149	29-May	0.23	0.23	0.27	0.7
150	30-May	0.23	0.23	0.29	0.7
151	31-May	0.23	0.23	0.30	0.7
152	1-Jun	0.23	0.23	0.32	0.7
153	2-Jun	0.23	0.23	0.33	0.7
154	3-Jun	0.23	0.23	0.35	0.7
155	4-Jun	0.24	0.23	0.36	0.7
156	5-Jun	0.26	0.24	0.37	0.7
157	6-Jun	0.27	0.26	0.39	0.7
158	7-Jun	0.29	0.27	0.40	0.7
159	8-Jun	0.30	0.29	0.42	0.7
160	9-Jun	0.32	0.30	0.43	0.7
161	10-Jun	0.33	0.32	0.45	0.7
162	11-Jun	0.35	0.33	0.46	0.7
163	12-Jun	0.36	0.35	0.48	0.7
164	13-Jun	0.37	0.36	0.49	0.7
165	14-Jun	0.39	0.38	0.50	0.7
166	15-Jun	0.40	0.39	0.52	0.7
167	16-Jun	0.42	0.41	0.53	0.7
168	17-Jun	0.43	0.42	0.55	0.7
169	18-Jun	0.45	0.44	0.56	0.7

(Table continued)

170	19-Jun	0.46	0.45	0.58	0.7
171	20-Jun	0.47	0.47	0.59	0.7
172	21-Jun	0.49	0.48	0.60	0.7
173	22-Jun	0.50	0.49	0.62	0.7
174	23-Jun	0.52	0.51	0.63	0.7
175	24-Jun	0.53	0.52	0.65	0.7
176	25-Jun	0.55	0.54	0.66	0.7
177	26-Jun	0.56	0.55	0.68	0.7
178	27-Jun	0.58	0.57	0.69	0.7
179	28-Jun	0.59	0.58	0.71	0.7
180	29-Jun	0.60	0.60	0.72	0.7
181	30-Jun	0.62	0.61	0.73	0.7
182	1-Jul	0.63	0.63	0.75	0.7
183	2-Jul	0.65	0.64	0.76	0.7
184	3-Jul	0.66	0.66	0.78	0.7
185	4-Jul	0.68	0.67	0.79	0.7
186	5-Jul	0.69	0.69	0.81	0.7
187	6-Jul	0.71	0.70	0.82	0.7
188	7-Jul	0.72	0.71	0.84	0.7
189	8-Jul	0.73	0.73	0.85	0.7
190	9-Jul	0.75	0.74	0.86	0.7
191	10-Jul	0.76	0.76	0.88	1
192	11-Jul	0.78	0.77	0.89	1
193	12-Jul	0.79	0.79	0.91	1
194	13-Jul	0.81	0.80	0.92	1
195	14-Jul	0.82	0.82	0.94	1
196	15-Jul	0.83	0.83	0.95	1
197	16-Jul	0.85	0.85	0.95	1
198	17-Jul	0.86	0.86	0.95	1
199	18-Jul	0.88	0.88	0.95	1
200	19-Jul	0.89	0.89	0.95	1
201	20-Jul	0.91	0.91	0.95	1
202	21-Jul	0.92	0.92	0.95	1
203	22-Jul	0.94	0.94	0.95	1
204	23-Jul	0.95	0.95	0.95	1
205	24-Jul	0.95	0.95	0.95	1
206	25-Jul	0.95	0.95	0.95	1
207	26-Jul	0.95	0.95	0.95	1
208	27-Jul	0.95	0.95	0.95	1
209	28-Jul	0.95	0.95	0.95	1
210	29-Jul	0.95	0.95	0.95	1
211	30-Jul	0.95	0.95	0.95	1
212	31-Jul	0.95	0.95	0.95	1
213	1-Aug	0.95	0.95	0.95	1
214	2-Aug	0.95	0.95	0.95	1
215	3-Aug	0.95	0.95	0.95	1
216	4-Aug	0.95	0.95	0.95	1
217	5-Aug	0.95	0.95	0.95	1
218	6-Aug	0.95	0.95	0.95	1
219	7-Aug	0.95	0.95	0.95	1

(Table continued)

220	8-Aug	0.95	0.95	0.95	1
221	9-Aug	0.95	0.95	0.95	1
222	10-Aug	0.95	0.95	0.95	1
223	11-Aug	0.95	0.95	0.95	1
224	12-Aug	0.95	0.95	0.95	1
225	13-Aug	0.95	0.95	0.95	1
226	14-Aug	0.95	0.95	0.95	1
227	15-Aug	0.95	0.95	0.95	1
228	16-Aug	0.95	0.95	0.95	1
229	17-Aug	0.95	0.95	0.95	1
230	18-Aug	0.95	0.95	0.95	1
231	19-Aug	0.95	0.95	0.95	1
232	20-Aug	0.95	0.95	0.95	1
233	21-Aug	0.95	0.95	0.95	1
234	22-Aug	0.95	0.95	0.95	1
235	23-Aug	0.95	0.95	0.95	1
236	24-Aug	0.95	0.95	0.95	1
237	25-Aug	0.95	0.95	0.95	1
238	26-Aug	0.95	0.95	0.95	1
239	27-Aug	0.95	0.95	0.95	1
240	28-Aug	0.95	0.95	0.95	1
241	29-Aug	0.95	0.95	0.95	1
242	30-Aug	0.95	0.95	0.95	0.7
243	31-Aug	0.95	0.95	0.95	0.7
244	1-Sep	0.95	0.95	0.95	0.7
245	2-Sep	0.95	0.95	0.95	0.7
246	3-Sep	0.95	0.95	0.95	0.7
247	4-Sep	0.95	0.95	0.95	0.7
248	5-Sep	0.95	0.95	0.95	0.7
249	6-Sep	0.95	0.95	0.95	0.7
250	7-Sep	0.95	0.95	0.95	0.7
251	8-Sep	0.95	0.95	0.90	0.7
252	9-Sep	0.95	0.95	0.84	0.7
253	10-Sep	0.95	0.95	0.79	0.7
254	11-Sep	0.95	0.95	0.73	0.7
255	12-Sep	0.95	0.95	0.68	0.7
256	13-Sep	0.90	0.95	0.63	0.7
257	14-Sep	0.84	0.90	0.57	0.4
258	15-Sep	0.79	0.84	0.52	0.4

Table B.2. Daily crop evapotranspiration (ETc) estimated values calculated by three different methods at Angelina Plantation during August and September of 2006

Date	ETc (mm/day)								
	WS	ETg_{2-9}	ETg_{2-19}	AIS_{2-9}	AIS_{2-10}	AIS_{2-11}	AIS_{2-12}	AIS_{2-19}	AIS_{2-20}
8/17	5.0	5.1	4.1	3.8	3.8	3.8	3.8	3.8	3.0
8/18	4.8	5.3	5.6	3.0	3.0	3.0	3.0	3.0	2.8
8/19	4.8	4.8	5.1	3.6	3.3	3.3	3.3	3.3	3.0
8/20	5.2	6.1	6.4	4.1	3.6	3.6	3.6	3.6	3.0
8/21	4.9	6.1	5.8	3.8	3.8	3.8	3.8	3.8	3.0
8/22	3.5	3.0	3.0	2.3	2.5	2.5	2.5	4.6	4.8
8/23	3.9	3.6	3.3	2.5	4.6	4.6	4.8	4.6	2.0
8/24	3.4	2.5	2.8	2.0	2.3	2.3	2.0	2.3	1.8
8/25	4.0	2.5	2.8	2.8	6.1*	6.1*	3.0	3.0	2.3
8/26	2.1	0.8*	1.0*	2.0	2.0	2.0	2.0	2.0	2.3
8/27	3.0	1.3	1.5	2.8	2.8	2.8	2.8	2.8	2.0
8/28	4.6	4.8	4.3	2.8	3.0	3.0	2.8	2.8	2.3
8/29	3.7	3.3	3.3	2.3	3.3	3.3	3.3	2.3	2.3
8/30	3.2	4.6	4.8	1.8	1.8	1.8	1.8	1.8	1.8
8/31	3.4	4.6	4.8	1.8	1.8	1.8	1.8	1.8	1.8
9/1	3.3	4.3	4.8	2.0	2.0	2.0	2.0	2.0	2.0
9/2	3.2	4.3	4.8	3.6	2.0	2.0	2.0	2.0	2.0
9/3	3.6	4.3	5.6	2.3	2.0	2.0	2.0	2.0	2.0
9/4	3.4	3.8	4.6	2.5	1.8	1.8	1.8	1.8	1.8
9/5	2.1	2.8	3.0	1.5	1.5	1.5	1.5	1.5	1.5
9/6	3.8	5.6	6.1	2.3	2.3	2.3	2.3	2.3	2.3

*Values with an asterisk are outliers not considered in the statistical analysis

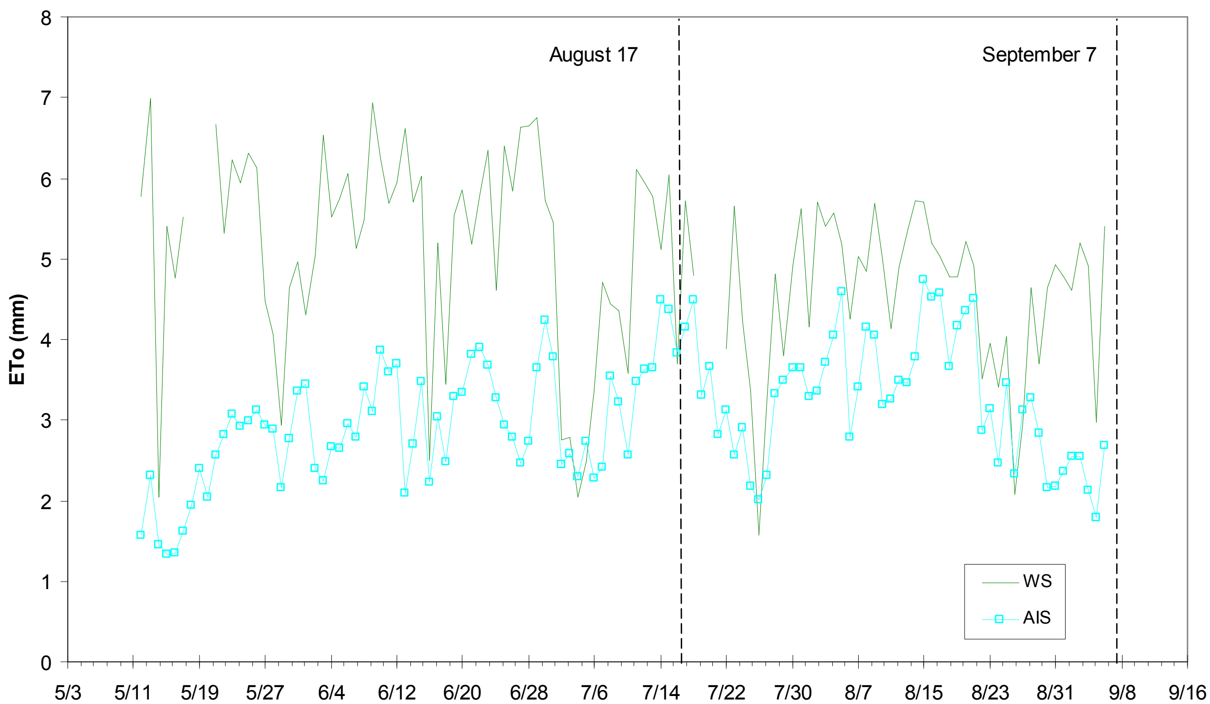


Figure B2. Reference evapotranspiration (ETo) estimation for the weather station (WS) and Arkansas Irrigation Scheduler (AIS) estimations for 2006.

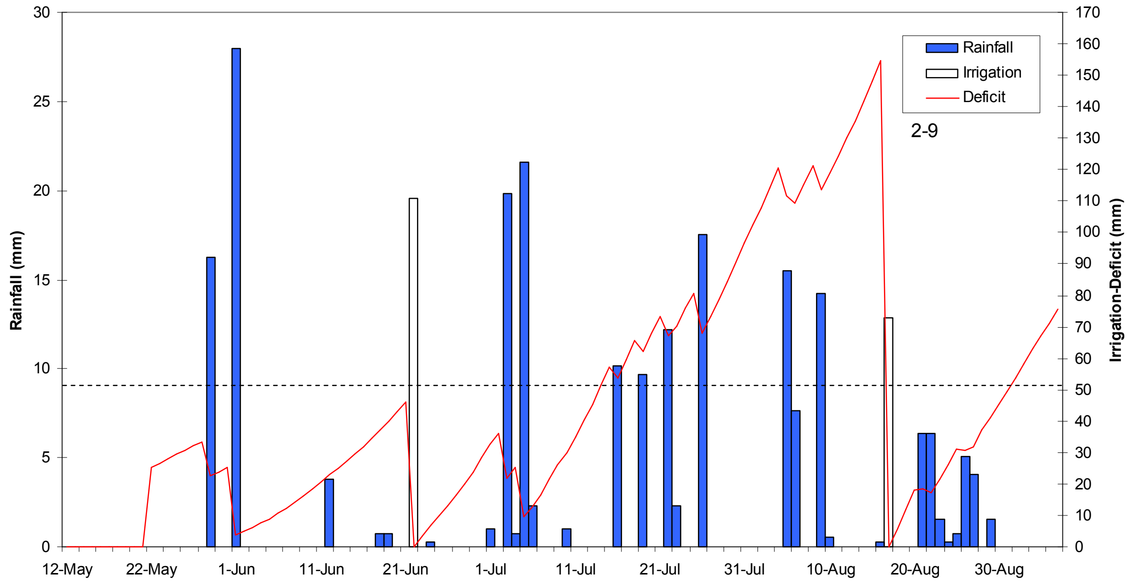


Figure B.3. Scheduling representation of the Arkansas Irrigation Scheduler throughout the season for field 2-9. The dotted line represents the Maximum Allowable Depletion (MAD = 50.8 mm)

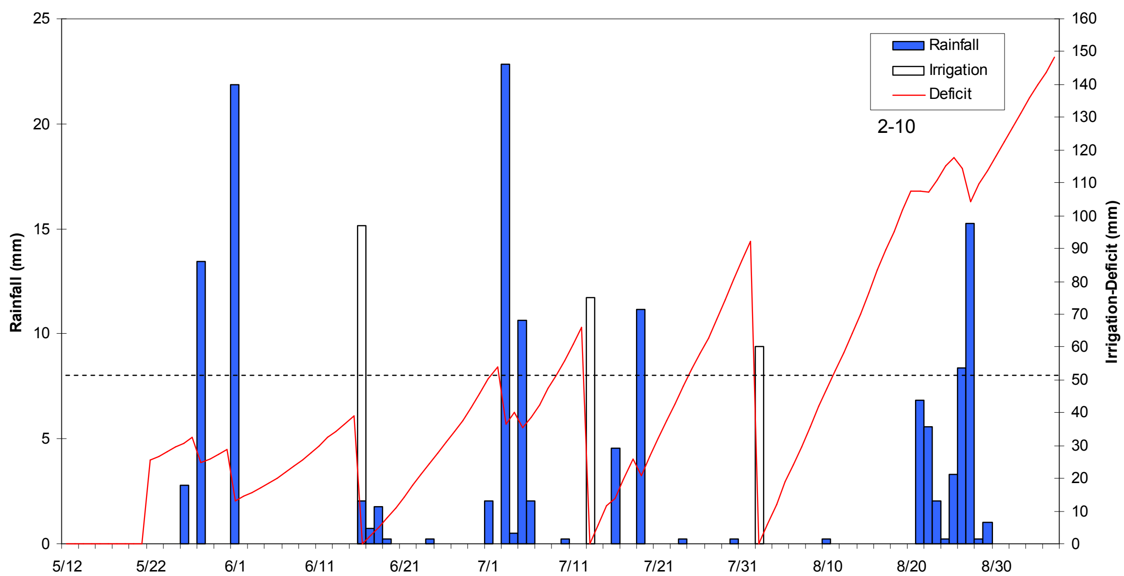


Figure B.4. Scheduling representation of the Arkansas Irrigation Scheduler throughout the season for field 2-10. The dotted line represents the Maximum Allowable Depletion (MAD = 50.8 mm)

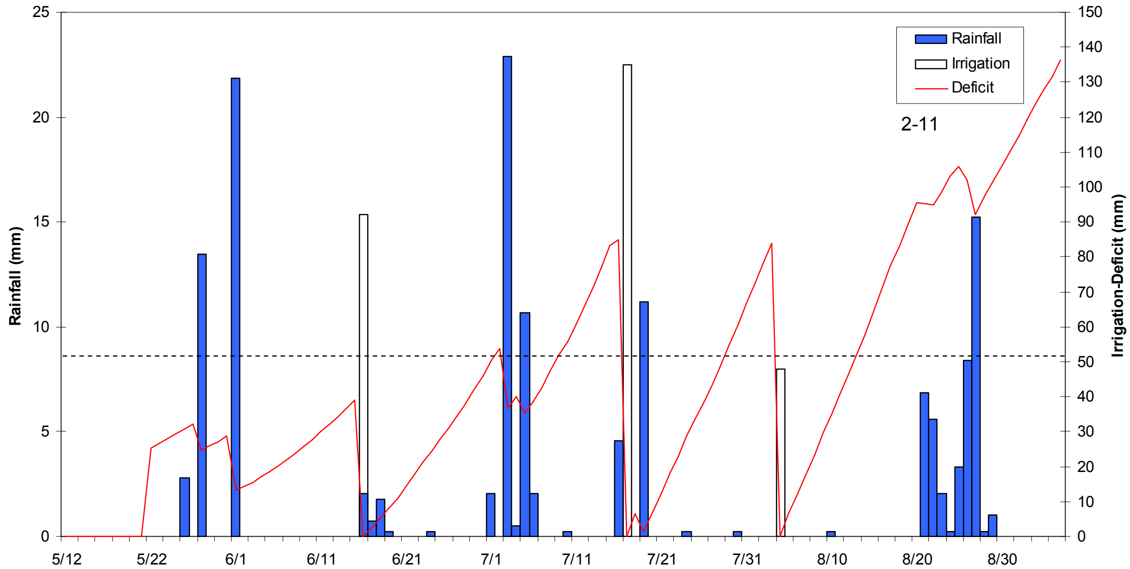


Figure B.5. Scheduling representation of the Arkansas Irrigation Scheduler throughout the season for field 2-11. The dotted line represents the Maximum Allowable Depletion (MAD = 50.8 mm)

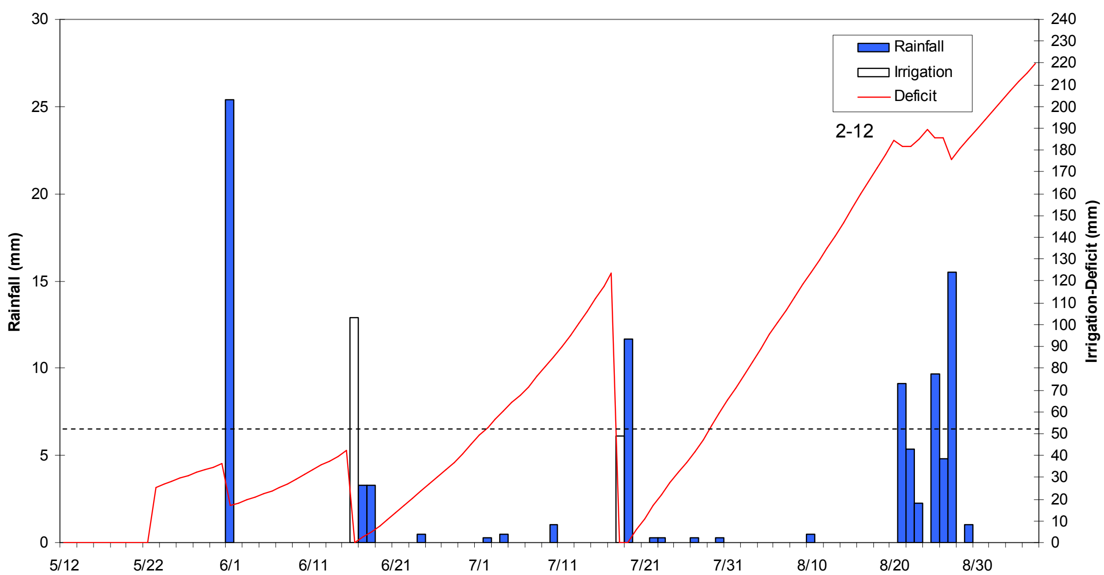


Figure B.6. Scheduling representation of the Arkansas Irrigation Scheduler throughout the season for field 2-12. The dotted line represents the Maximum Allowable Depletion (MAD = 50.8 mm)

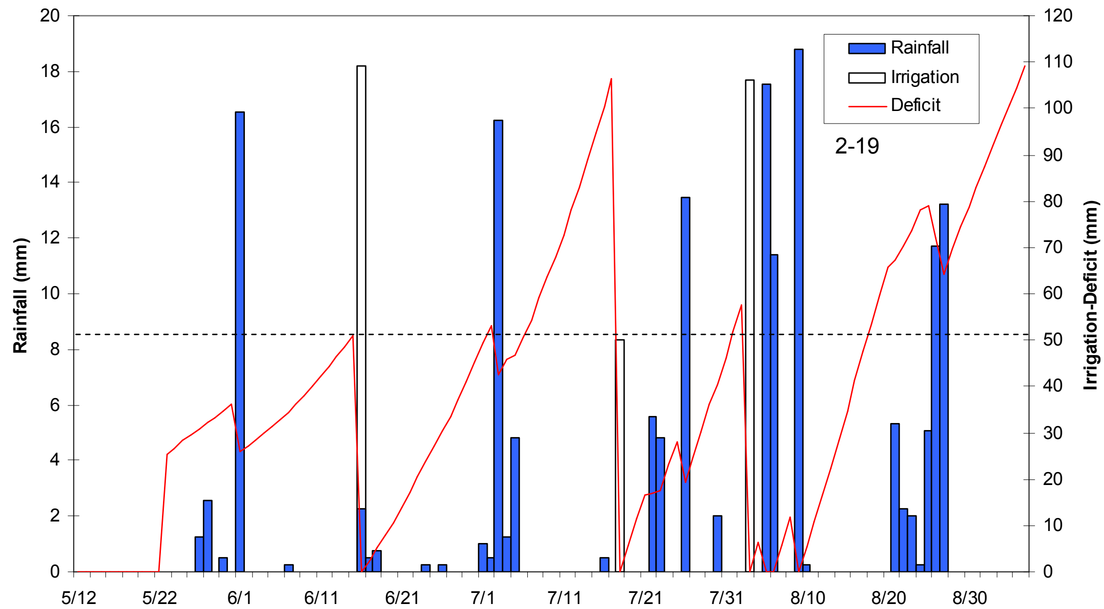


Figure B.7. Scheduling representation of the Arkansas Irrigation Scheduler throughout the season for field 2-19. The dotted line represents the Maximum Allowable Depletion (MAD = 50.8 mm)

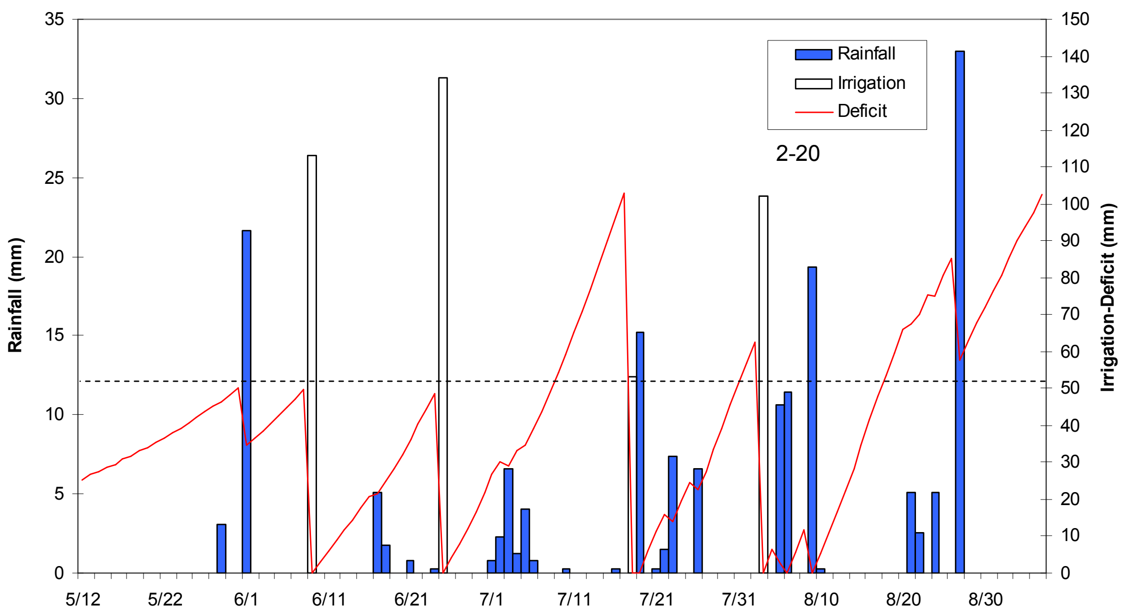


Figure B.8. Scheduling representation of the Arkansas Irrigation Scheduler throughout the season for field 2-20. The dotted line represents the Maximum Allowable Depletion (MAD = 50.8 mm)

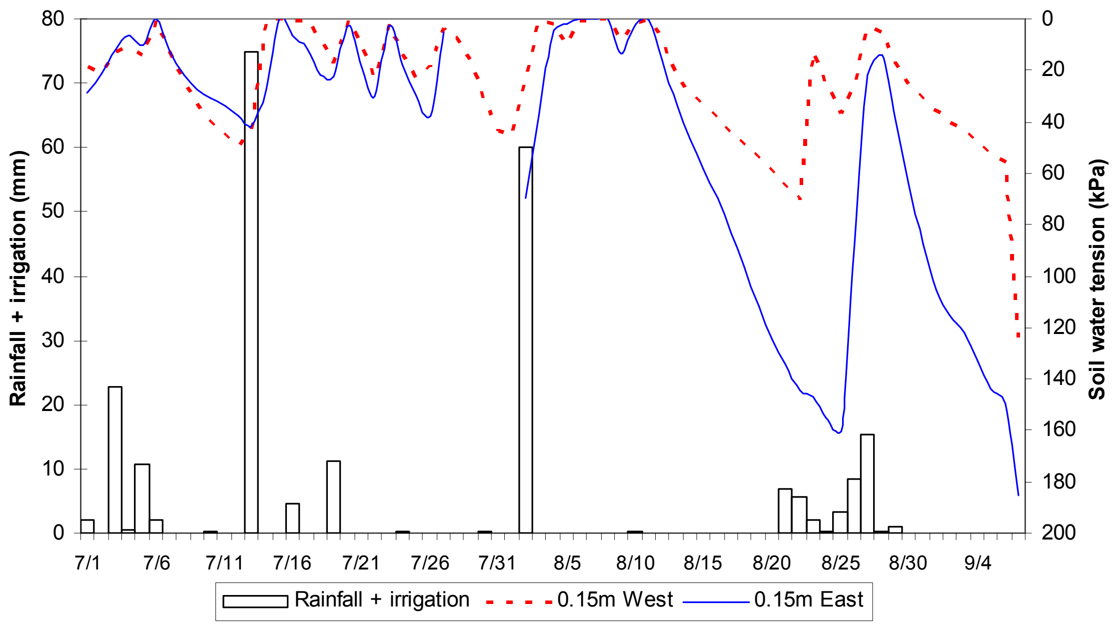


Figure B. 9. Watermark sensor response during an irrigation and rainfall events for watermarks at 0.15 meters depth in field 2-10 during 2006

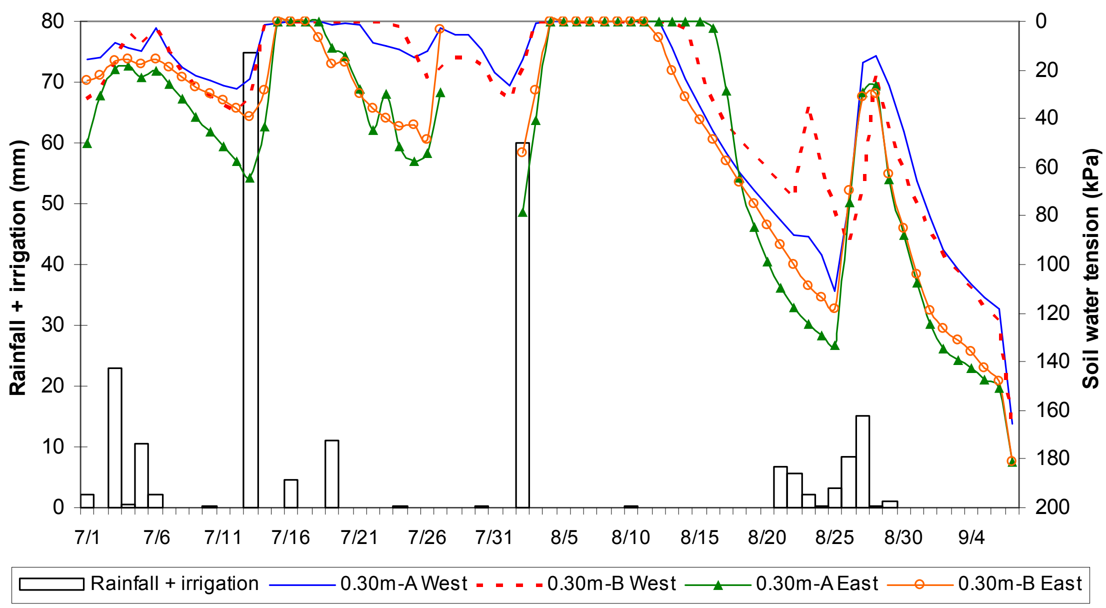


Figure B. 10. Watermark sensor response during an irrigation and rainfall events for watermarks at 0.30 meters depth in field 2-10 during 2006

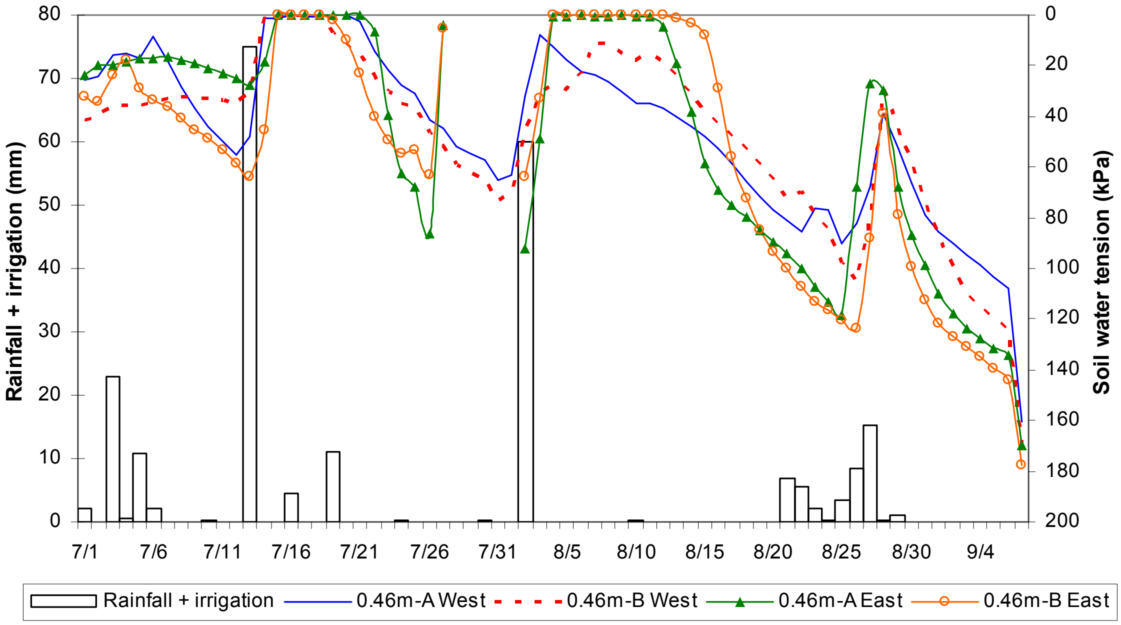


Figure B.11. Watermark sensor response during an irrigation and rainfall events for watermarks at 0.46 meters depth in field 2-10 during 2006

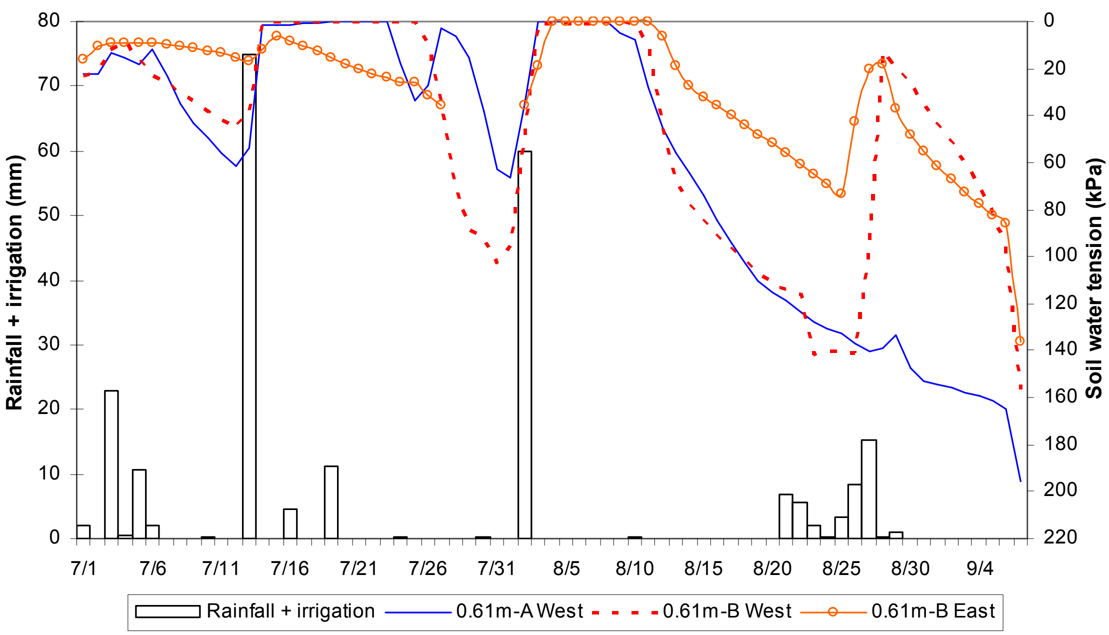


Figure B.12. Watermark sensor response during an irrigation and rainfall events for watermarks at 0.61 meters depth in field 2-10 during 2006

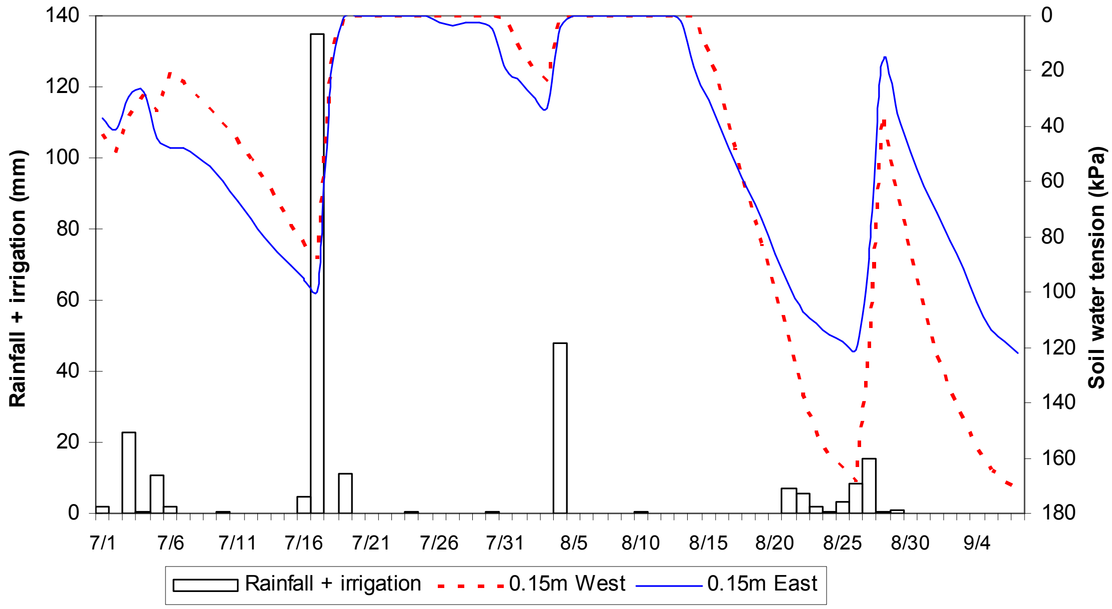


Figure B.13. Watermark sensor response during an irrigation and rainfall events for watermarks at 0.15 meters depth in field 2-11 during 2006

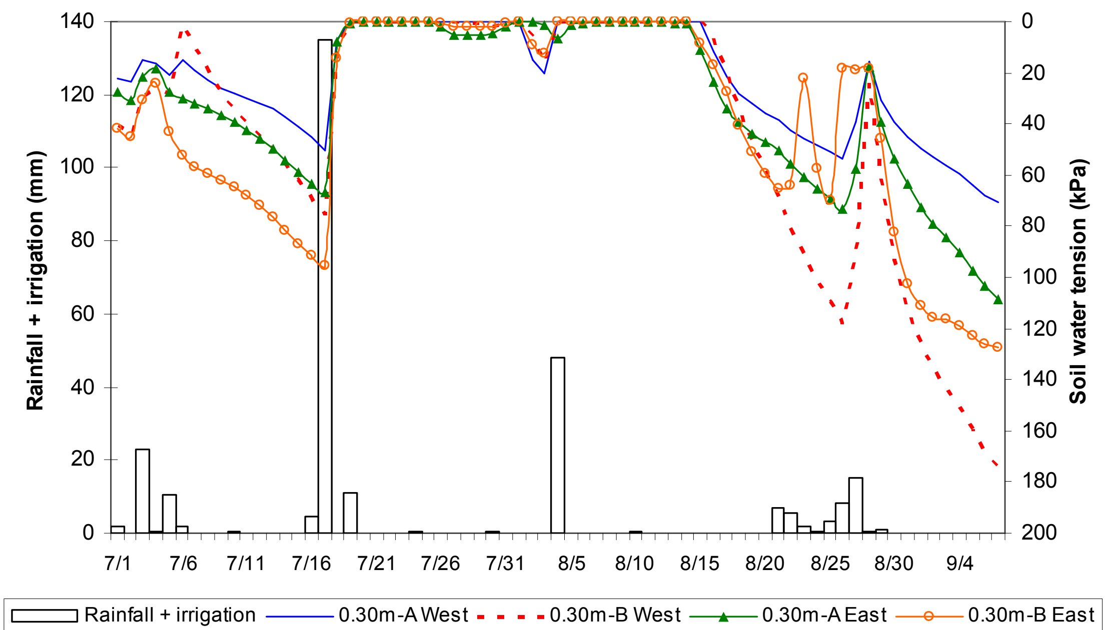


Figure B. 14. Watermark sensor response during an irrigation and rainfall events for watermarks at 0.30 meters depth in field 2-11during 2006

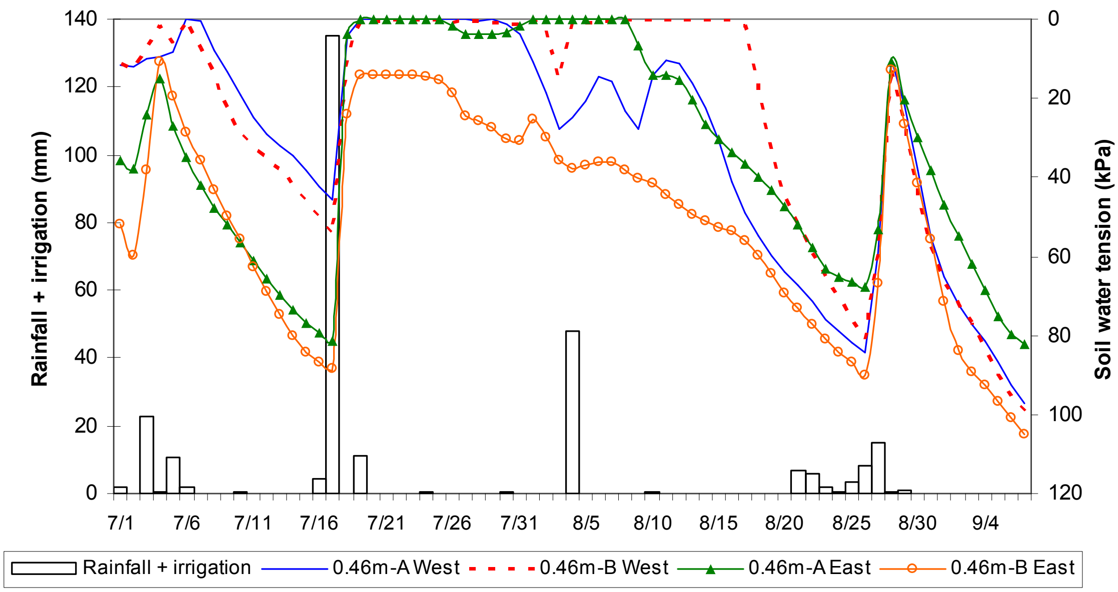


Figure B.15. Watermark sensor response during an irrigation and rainfall events for watermarks at 0.45 meters depth in field 2-11 during 2006

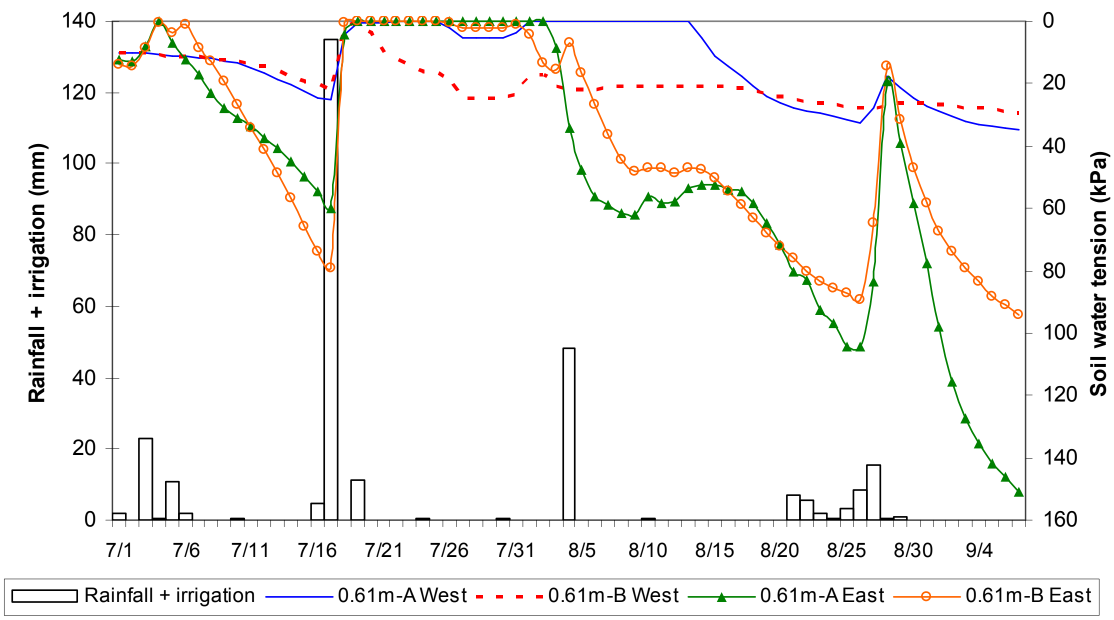


Figure B. 16. Watermark sensor response during an irrigation and rainfall events for watermarks at 0.61 meters depth in field 2-11 during 2006

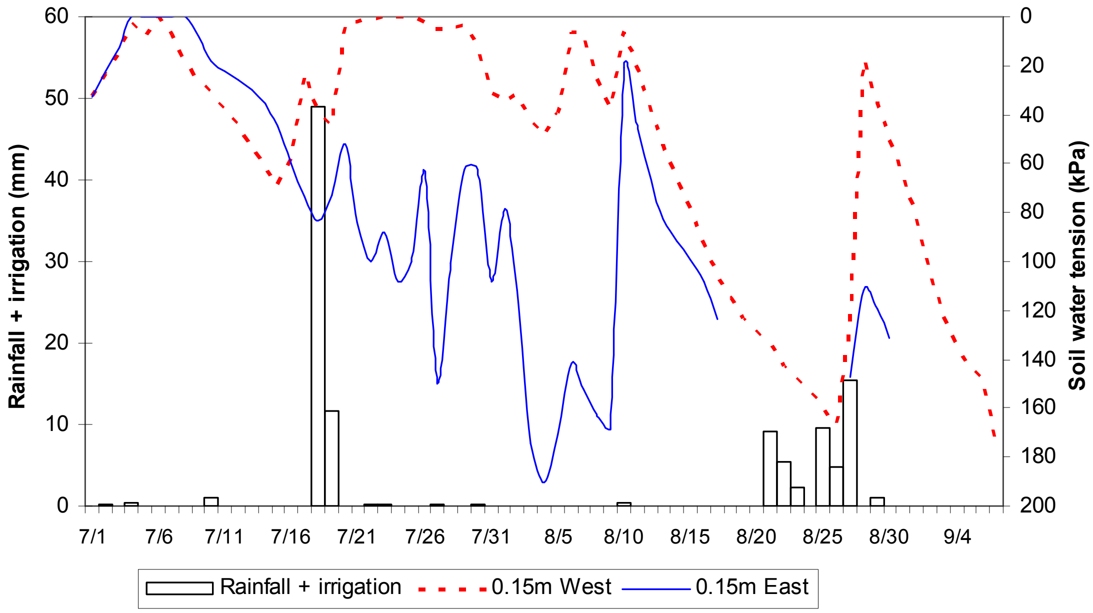


Figure B.17. Watermark sensor response during an irrigation and rainfall events for watermarks at 0.15 meters depth in field 2-12 during 2006

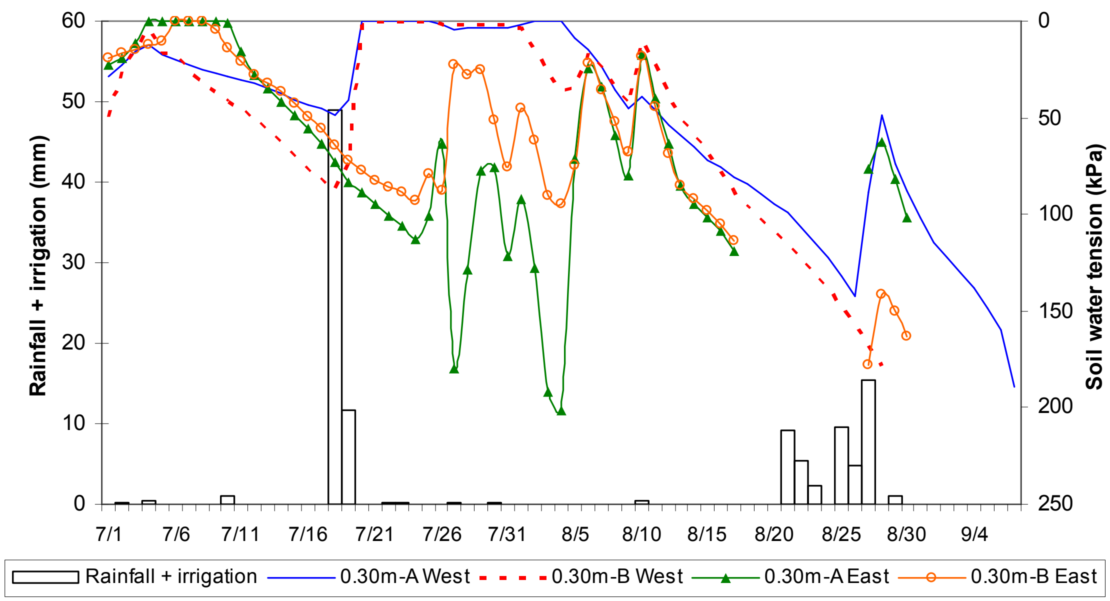


Figure B.18. Watermark sensor response during an irrigation and rainfall events for watermarks at 0.30 meters depth in field 2-12 during 2006

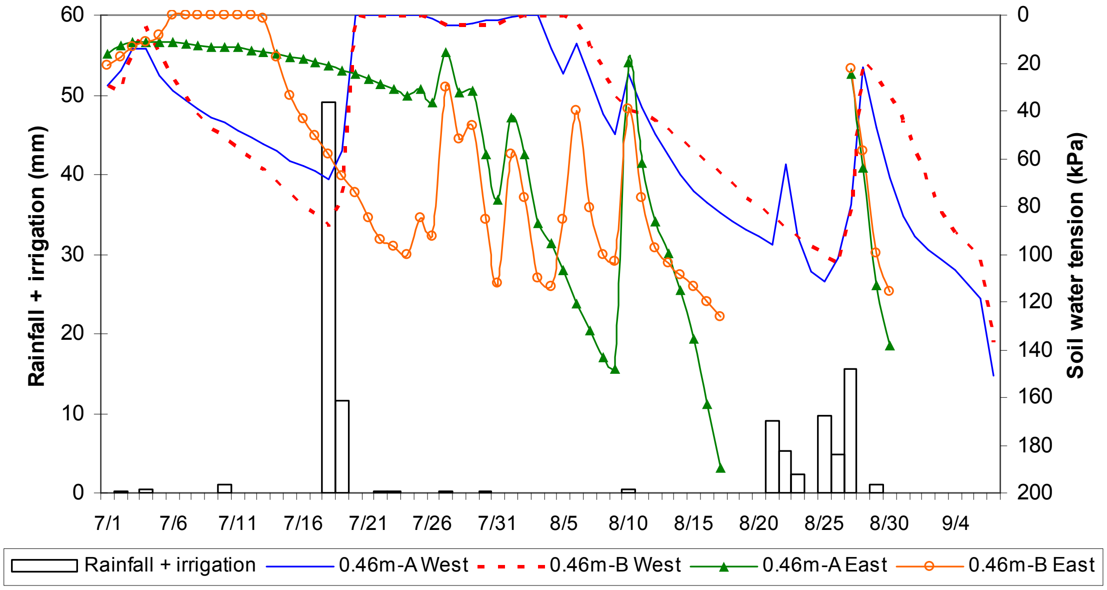


Figure B. 19. Watermark sensor response during an irrigation and rainfall events for watermarks at 0.46 meters depth in field 2-12 during 2006

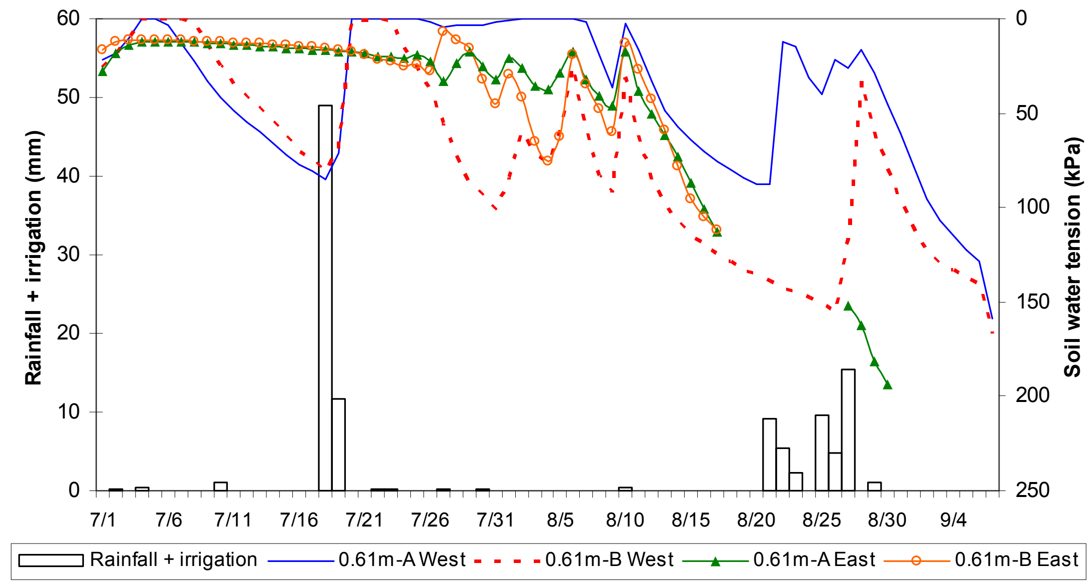


Figure B. 20. Watermark sensor response during an irrigation and rainfall events for watermarks at 0.61 meters depth in field 2-12 during 2006

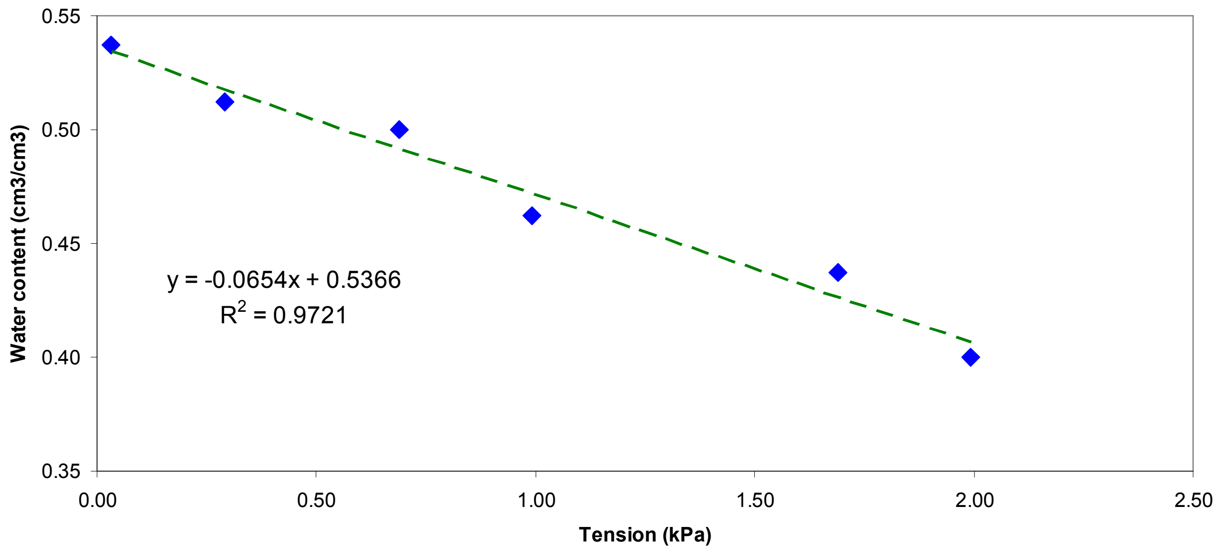


Figure B.21. Linear approximation and the calibration equation for 0.15 m Watermarks depth sensors based on Romkens *et al.* (1986) desorption curves for Louisiana Sharkey clay soil.

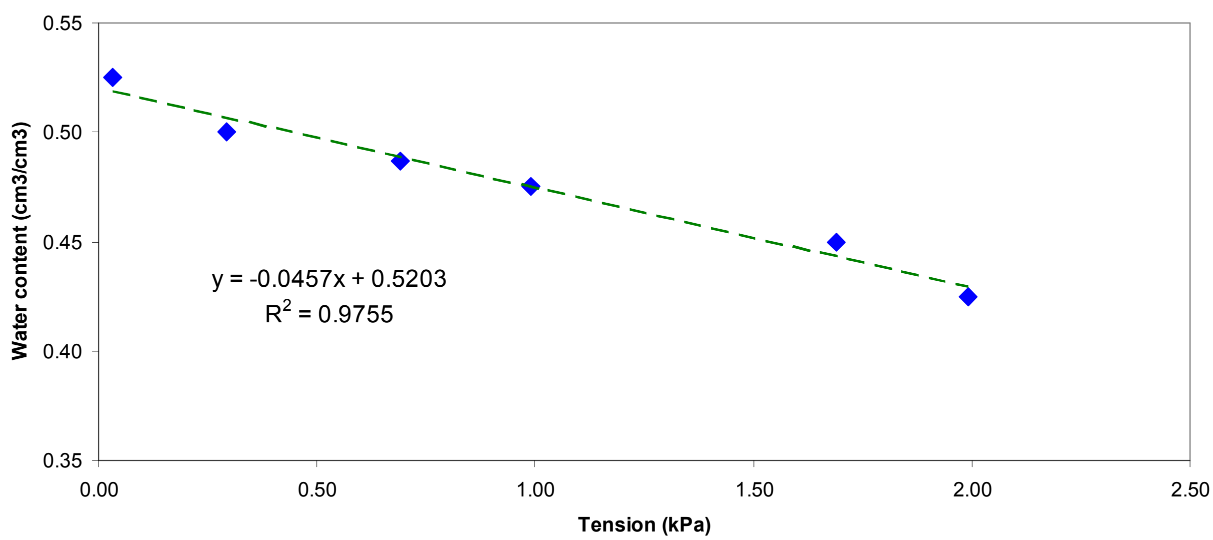


Figure B.22. Linear approximation and the calibration equation for 0.30 m Watermarks depth sensors based on Romkens *et al.* (1986) desorption curves for Louisiana Sharkey clay soil.

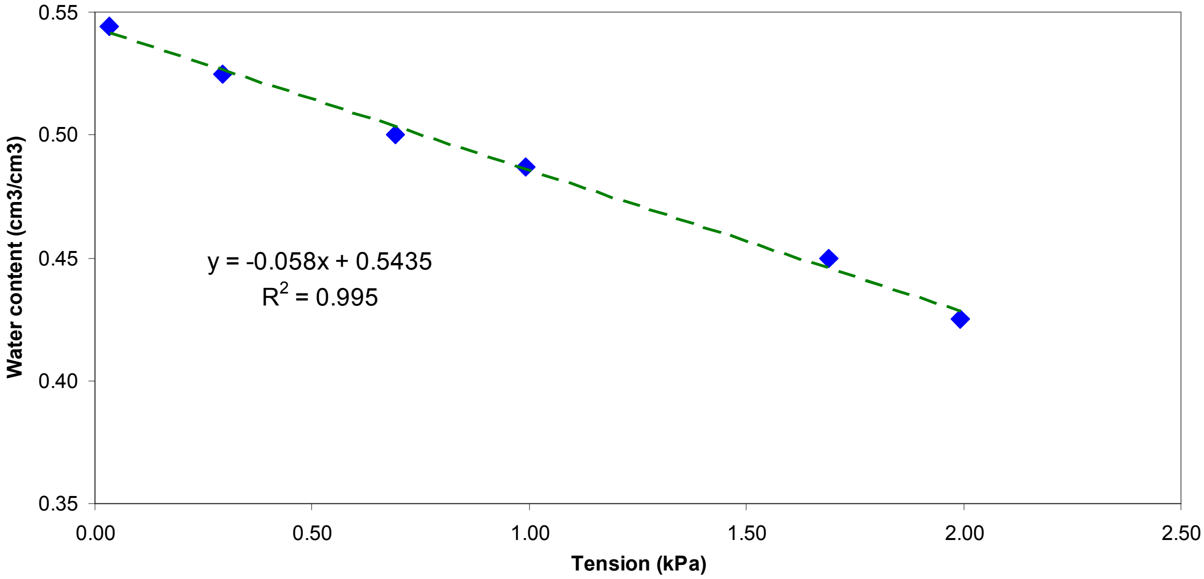


Figure B.23. Linear approximation and the calibration equation for 0.46 and 0.60 m Watermarks depths sensors based on Romkens *et al.* (1986) obtained desorption curves for Louisiana Sharkey clay soil.

VITA

Luis Rafael Ocampo Briceño was born to Mrs. Vyria Briceño and Mr. Nazario Ocampo on October 28, 1978, in San José, Costa Rica. He attended the Instituto Tecnológico de Costa Rica where he obtained a Bachelor of Science degree in agricultural engineering in 2004.

Later in August 2004, he enrolled in the graduate program offered by the Department of Biological and Agricultural Engineering at Louisiana State University in Baton Rouge, Louisiana. He will receive the degree of Master of Science in Biological and Agricultural Engineering majoring in water resources engineering in August 2007. He is planning to work in water resources engineering field after graduation and travel around the world.