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Evaluation of Smart Irrigation Controllers: Year 2011 Results

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EVALUATION OF SMART IRRIGATION CONTROLLERS:

YEAR 2011 RESULTS[1]

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SUMMARY

A smart controller testing facility was established by the Irrigation Technology Center at Texas A&M University in College Station in 2008 in order to evaluate their performance from an "end-user" point of view. The "end-user" is considered to be the landscape or irrigation professional (such as a Licensed Irrigator in Texas) installing the controller. Controllers are tested using the *Texas Virtual Landscape* which is composed of 6 different zones with varying plant materials, soil types and depths, and precipitation rates.

This report summaries the results from the 2011 evaluations. Nine controllers were evaluated over a 152 day period, from April 11 - May 29, 2011 and August 8 to November 20, 2011. Controller performance was analyzed for each seasonal period (spring, summer, fall). Controller performance is evaluated by comparison to the irrigation recommendation of the TexasET Network and Website (http://texaset.tamu.edu), as well as for *irrigation adequacy* in order to identify controllers which apply excessive and inadequate amounts of water.

Programing smart controllers for specific site conditions continues to be a problem. Only two (2) of the nine (9) controllers tested could be programmed directly with all the parameters needed to define each zone.

Total Irrigation Amounts

- When looking at seasonal irrigation amounts for the entire landscape, one (1) controller was within +/- 20% the recommendation of the TexasET Network for all six (6) stations during the Fall Evaluation Period
- Two (2) controllers applied more than ETo for all three (3) seasonal periods.
- Seven (7) controllers applied more than a simple ETc model (ETo x Kc, neglecting rainfall) for one or more seasons.

Adequacy Analysis

- No controllers were consistently able (across all 6 stations) to adequately meet the plant water requirements for any season.
- For all seasons combined, 51 stations (37%) showed adequate irrigations, 48 stations (35%) showed excessive irrigation amounts and 39 stations (28%) irrigated inadequately
- Four (4) controllers had five (5) stations that provided adequate amounts of water for one or more seasons.

Factors that could have caused over/under irrigation of landscapes are improper ETo calculations and insufficient accounting for rainfall. However, 2011 was a drought year with only 5.45 inches of rainfall. ET values recorded off the controllers were inconsistent and erratic throughout the study.

Based on 2011 performance, controllers with on-site sensors, generally performed better and more often irrigated closer to the recommendations of the TexasET Network than those controllers which have ETo sent to the controller. While water savings shows promise through the use of some smart irrigation controllers, excessive irrigation is still occurring under some landscape scenarios.

INTRODUCTION

The term *smart irrigation controller* is commonly used to refer to various types of controllers that have the capability to calculate and implement irrigation schedules automatically and without human intervention. Ideally, smart controllers are designed to use site specific information to produce irrigation schedules that closely match the day-to-day water use of plants and landscapes. In recent years, manufacturers have introduced a new generation of smart controllers which are being promoted for use in both residential and commercial landscape applications.

However, many questions exist about the performance, dependability and water savings benefits of smart controllers. Of particular concern in Texas is the complication imposed by rainfall. Average rainfall in the State varies from 56 inches in the southeast to less than eight inches in the western desert. In much of the State, significant rainfall commonly occurs during the primary landscape irrigation seasons. Some Texas cities and water purveyors are now mandating smart controllers. If these controllers are to become requirements across the state, then it is important that they be evaluated formally under Texas conditions.

CLASSIFICATION OF SMART CONTROLLERS

Smart controllers may be defined as irrigation system controllers that determine runtimes for individual stations (or "hydrozones") based on historic or real-time ETo and/or additional site specific data. We classify smart controllers into four (4) types (see Table 1): Historic ET, Sensor-based, ET, and Central Control.

Many controllers use ETo (potential evapotranspiration) as a basis for computing irrigation schedules in combination with a root-zone water balance. Various methods, climatic data and site factors are used to calculate this water balance. The parameters most commonly used include:

- ET (actual plant evapotranspiration)
- Rainfall
- Site properties (soil texture, root zone depth, water holding capacity)
- MAD (managed allowable depletion)

The IA SWAT committee has proposed an equation for calculating this water balance. For more information, see the IA's website: http://irrigation.org.

Table 1. Classification of smart controllers by the method used to determine plant water requirements in the calculation of runtimes.

Historic ET	Uses historical ET data from data stored in the controller
Sensor-Based	Uses one or more sensors (usually temperature and/or solar radiation) to adjust or to calculate ETo using an approximate method
ET	Real-time ETo (usually determined using a form of the Penman equation) is transmitted to the controller daily. Alternatively, the runtimes are calculated centrally based on ETo and then transmitted to the controller.
On-Site Weather Station (Central Control)	A controller or a computer which is connected to an on-site weather station equipped with senors that record temperature, relative humidity (or dew point temperature) wind speed and solar radiation for use in calculating ETo with a form of the Penman equation.

MATERIALS AND METHODS

Testing Equipment and Procedures

Two smart controller testing facilities have been established by the ITC at Texas A&M University in College Station: an indoor lab for testing ET-type controllers and an outdoor lab for sensor-based controllers. Basically, the controllers are connected to a data logger which records the start and stop times for each irrigation event and station (or hydrozone). This information is transferred to a database and used to determine total runtime and irrigation volume for each irrigation event. The data acquisition and analysis process is illustrated Figure A-1 . Additional information and photographs of the testing facilities are provided in the Appendix.

Smart Controllers

Nine (9) controllers were provided by manufacturers for the Year 2011 evaluations (Table 2). Each controller was assigned an ID for reporting purposes. Table 2 lists each controller's classification, communication method and on-site sensors, as applicable. The controllers were grouped by type for testing purposes

Table 2. The controller name, type, communication method, and sensors attached of the controllers evaluated in this study. All controllers were connected to a rain shut off device unless equipped with a rain gage.

Controller ID	Controller Name	Type	Communication Method	Sensors[1]	Rain Shutoff
A	ET Water	ET	Pager	None	✓
B	Rainbird ET Manager Cartridge	ET	Pager	Tipping Bucket Rain Gauge	
C	Hunter ET System	Sensor Based	None	Tipping Bucket Rain Gauge, Pyranometer, Temperature/ RH	
D	Hunter Solar Sync	Sensor Based	None	Pyranometer	✓
E	Rainbird ESP SMT	Sensor Based	None	Tipping Bucket Rain Gauge, Temperature	
F	Accurate WeatherSet	Sensor Based	None	Pyranometer	✓
G	Weathermatic Smartline	Sensor Based	None	Temperature	✓
H	Toro Intellisense	ET	Pager	None	✓
I	Irritrol Climate Logic	Sensor Based	None	Temperature, Solar Radiation	✓

Definition of Stations (Zones) for Testing

Each controller was assigned six stations, each station representing a virtual landscaped zone (Table 3). These zones are designed to represent the range in site conditions commonly found in Texas, and provide a range in soil conditions designed to evaluate controller performance in shallow and deep root zones (and low/high water holding capacities). Since we do not recommend that schedules be adjusted for the DU (distribution uniformity), the efficiency was set to 100% if allowed by the controller.

Programing the smart controllers according to these virtual landscapes proved to be problematical, as only two controllers (E and H) had programming options to set all the required parameters defining the landscape (see Table 4). It was impossible to see the actual values that two controllers used for each parameter or to determine how closely these followed the values of the virtual landscape.

One example of programming difficulty was entering root zone depth. Four of the nine controllers did not allow the user to enter the root zone depth (soil depth). Another example is entering landscapes plant information. Three of the controllers did not provide the user the ability to see and adjust the actual coefficient (0.6, 0.8, etc) that corresponds to the selected plant material (i.e., fescue, cool season grass, warm season turf, shrubs, etc.).

Thus, we programmed the controllers to match the virtual landscape as closely as was possible. Manufacturers were given the opportunity to review the programming, which two did. Five of the remaining manufacturers provided to us written recommendations/instructions for station programming, and one manufacturer trusted our judgement in controller programming.

Table 3. The Virtual Landscape which is representative of conditions commonly found in Texas.

	Station 1	**Station 2**	**Station 3**	**Station 4**	**Station 5**	**Station 6**
Plant Type	Flowers	Turf	Turf	Groundcover	Small Shrubs	Large Shrubs
Plant Coefficient (Kc)	0.8	0.6	0.6	0.5	0.5	0.3
Root Zone Depth (in)	3	4	4	6	12	20
Soil Type	Sand	Loam	Clay	Sand	Loam	Clay
MAD (%)	50	50	50	50	50	50
Adjustment Factor (Af)	1.0	0.8	0.6	0.5	0.7	0.5
Precipitation Rate (in/hr)	0.2	0.85	1.40	0.5	0.35	1.25
Slope (%)	0-1	0-1	0-1	0-1	0-1	0-1

Table 4. The parameters which the end user could set in each controller DIRECTLY identified by the letter "x."

Controller	**Soil Type**	**Root Zone Depth**	**MAD**	**Plant Type**	**Crop Coefficient**	**Adjustment Factor**	**Precipitation Rate**	**Zip Code or Location**	**Runtime**
A	X	X	X	X		X	X	X	
B[1]	-	-	-		X	-	-	X	X
C	X			X	X	X	X		
D[2]	-	-	-		-	-	-	X	X
E	X	X		X	X	X	X		
F[2]				X					X
G	X			X	X	X	X	X	
H	X	X	X	X	X	X	X	X	
I[2]	-	-	-		-	-	-	X	X

[1] Irrigation amount was set based on plant available water
[2] Controller was programmed for runtime and frequency at peak water demand (July).

Testing Period

The controllers were set up and allowed to run from April 11 to May 29, 2011 and from August 8 to November 20, 2011. Controller performance is reported over seasonal periods. For the purposes of this report, seasons are defined as follows:

- Spring: April 11 to May 29 (48 Days),
- Summer: August 8 to September 4 (28 Days),
- Fall: September 5-November 20 (76 Days).

ETo and Recommended Irrigation

ETo was computed from weather parameters measured at the Texas A&M University Golf Course in College Station, TX which is a part of the TexasET Network (http://TexasET.tamu.edu). The weather parameters were measured with a standard agricultural weather station (Campbell Scientific Inc) which records temperature, solar radiation, wind and relative humidity. ETo was computed using the standardized Penman-Monteith method.

TexasET and the Plant Water Requirement Calculator

In this report, smart controller irrigation volumes are compared to the recommendations of the TexasET Network and Website generated using the *Landscape Plant Water Requirement Calculator* (http://TexasET.tamu.edu) based on a weekly water balance. This is the method that is used in the weekly irrigation recommendations generated by TexasET for users that sign-up for automatic emails. The calculation uses the standard equation:

$$ETc = (ETo \times Kc \times Af) - Re \qquad \text{(Equation 1)}$$

where: ETc = irrigation requirement
ETo = reference evapotranspiration
Kc = crop coefficient
Af = adjustment factor
Re = effective rainfall

Due to the lack of scientifically derived crop coefficients for most landscape plants, we suggest that users classify plants into one of three categories based on their need for or ability to survive with frequent watering, occasional watering and natural rainfall. Suggested crop coefficients for each are shown in Table 5.

In addition to a Plant Coefficient, users have the option of applying an *Adjustment Factor*. This can be used to adjust the crop coefficient for various site specific factors such as microclimates, allowable stress, or desired plant quality. For most home sites, a *Normal Adjustment Factor* (0.6) is recommended in order to promote water conservation, while an adjustment factor of 1.0 is recommended for sports athletic turf. Table 6 gives the adjustment factor in terms of a plant quality factor.

A weekly irrigation recommendation was produced using equation (1) following the methodology discussed above. The Af used are shown in Table 3. Effective rainfall was calculated using the relationships shown in Table 7.

Table 5. Landscape Plant Water Requirements Calculator Coefficients

Plant Coefficients		**Example Plant Types**
Warm Season Turf	0.6	Bermuda, St Augustine, Buffalo, Zoysia, etc.
Cool Season Turf	0.8	Fescue, Rye, etc.
Frequent Watering	0.8	Annual Flowers
Occasional Watering	0.5	Perennial Flowers, Groundcover, Tender Woody Shrubs and Vines
Natural Rainfall	0.3	Tough Woody Shrubs and Vines and non-fruit Trees

Table 6. Adjustment Factors in terms of "Plant Quality Factors."

Maximum	1.0
High	0.8
Normal	0.6
Low	0.5
Minimum	0.4

Table 7. TexasET Effective Rainfall Calculator

Rainfall Increment	**% Effective**
0.0" to 0.1"	0%
0.1" to 1.0"	100%
1.0" to 2.0"	67%
Greater than 2"	0%

Irrigation Adequacy Analysis

The purpose of the irrigation adequacy analysis is to identify controllers which over or under irrigate landscapes. An uncertainty in calculating a water balance is effective rainfall, how much of rainfall is credited for use by the plant. Further complicating rainfall is the use and performance of rain shut off devices by smart controllers.

For this study we broadly define irrigation ***adequacy*** as the range between taking 80% credit for all rainfall and taking no credit for rainfall. These limits are defined as:

Extreme Upper Limit = ETo x Kc (eq. 2)
Adequacy Upper Limit = ETo x Kc x Af (eq. 3)
Adequacy Lower Limit = ETo x Kc x Af - Net (80%) Rainfall (eq. 4)
Extreme Lower = ETo x Kc x Af - Total Rainfall (eq. 5)

The adequacy upper limit is defined as the plant water requirement (eq. 3) without rainfall. Irrigation volumes greater than the upper limit are classified as ***excessive***. The adequacy lower limit is defined as the plant water requirements minus Net Rainfall (eq 4). The IA SWAT Protocol defines net rainfall as 80% of rainfall. Irrigation volumes below than the adequacy lower limit are classified as ***inadequate***.

For comparison purposes, extreme limits are defined by taking no credit for rainfall (upper) and total rainfall (lower). These limits are the maximum and minimum possible plant water requirements.

RESULTS

Results from the Year 2011 evaluation periods are summarized in Tables 9, 10 and 11 by season.

TexasET Comparisons

Controller performance during the Spring evaluation period (April 11-May 29, 2011) was generally poor.

Controllers Passing
None

Best Performers
Controller I had five stations that were within TexasET.
Controller A had four stations that were within TexasET.

Poor Performers
Controllers D and I produced irrigation volumes for the flowers zone in excess of ETo.
Controller B produced irrigation volumes in excess of ETc for four stations.
Seven controllers (B, C, D, E, F, G, H) did not produce irrigation volumes for any stations that were within TexasET.

Controller performance during the Summer evaluation period (August 8-September 4, 2011) was better.

Controllers Passing
None

Best Performers
Controller E had five stations that were within TexasET.
Controllers C, G and H had four stations that were within TexasET.

Poor Performers
Controllers D and I produced irrigation volumes in excess of ETo for two stations.
Controller D had six stations that were in excess of ETc.
Controller D did not produce any stations within TexasET.

Controller Performance during the Fall evaluation period (September 5-November 20, 2011) was generally poor.

Controllers Passing
Controller G

Best Performers
Controller B had four stations that were within TexasET.

Poor Performers
Controllers D and I produced irrigation volumes in excess of ETo.
Controllers D, C, E, F, H, and I produced irrigation volumes in excess of ETc.
Controller D had six stations that were in excess of ETc.

Tables 12-14 show the irrigation ***adequacy*** analysis for each station during the three seasonal periods. Irrigation adequacy distribution analysis results are shown in Table 15 over the study period and seasonally in Tables 16-18. Out of a total of 138 stations (all periods combined), 51 stations (37%) had adequate irrigations, 48 stations (35%) excessive irrigation amounts, and 39 stations (28%) irrigated inadequately. Controller performance appeared best during the Fall period with 55% of stations irrigated adequately. Three controllers (C, E and G) irrigated adequately 83% of the time.

Appendix B contains ET values recorded off controllers along with corresponding daily ETo and rainfall from the TexasET Network. Appendix C contains daily ET readings from controllers and the TexasET Network graphed with daily rainfall totals during the summer period (Figure C-1) and the fall period (Figure C-2). Controller ET values appeared erratic and inconsistent compared to TexasET throughout the study period; however all controllers consistently show decreases in ETo values during days which rainfall occurred.

Controller Problems

Four controllers experienced problems during the course of the study.

1. Controller A had a capacitor leak during the course of the study. This resulted in the controller software operating but not being able to turn valves on.

2. Controller C had a sensor module failure that was discovered during a routine check of controller status (power), the manufacturer was notified and a replacement was installed.

3. Although programmed and installed correctly, the Controller F failed to operate 4 out of the 6 programmed stations. The controller is currently being analyzed for a possible software or hardware malfunction.

4. Controller H experienced communication problems multiple times throughout the study. Controller alerts (beeping) occurred on at least 2 occasions during the evaluation period. The manufacturer was notified of the problem and a signal amplifier was installed on the controller. However, it was later determined that the problem was a result temporary poor signal service by the signal provider company in the testing area (a bad tower).

5. Controller D had a recall issued in late 2011 due to possible sensor malfunctions. As a result this model was discontinued and will be replaced with a newer for the 2012 year test.

Table 9. April 11- May 29, 2011 Performance. Irrigation amount (inches) applied for each controller station. Yellow denotes values within +/- 20 % of TexasET Recommendation.

Controller ID	Station 1	Station 2	Station 3	Station 4	Station 5	Station 6
A	4.97	3.77	2.99	2.11	2.63	2.5
B	9.23	5.65	4.18	2.99	3.83	5.33
C	3.66	2.30	1.10	1.05	1.16	0.55
D	12.11	7.66	6.00	3.84	5.13	2.49
E	5.49	3.12	1.73	1.31	1.67	0
F	5.58	NA	NA	NA	NA	1.87
G	5.26	2.33	1.85	1.29	1.58	0.58
H	4.27	2.39	1.66	1.27	1.53	0.65
I	12.25	3.70	2.69	1.83	2.73	1.30
Total ETo[1]	11.14					
Total Rainfall[2]	2.83					
TexasET Recommendation	7.09	4.00	3.01	2.07	2.92	1.26
Total ETc[3]	8.91	6.68	6.68	5.57	5.57	3.34

[1] Total ETo calculated using the standardized Penmen-Monteith method using weather data collected at the Texas A&M University Golf Course, College Station, Texas.

[2] Total Rainfall collected from TexasET Network Weather Station "TAMU Golf Course"

[3] Rainfall and Adjustment Factor not included in this calculation

Table 10. August 8 - September 4, 2011 Performance. Irrigation amount (inches) applied for each controller station. Yellow denotes values within +/- 20 % of TexasET Recommendation.

Controller ID	Station 1	Station 2	Station 3	Station 4	Station 5	Station 6
A	NA	NA	NA	NA	NA	NA
B	3.63	2.14	1.59	1.13	1.58	1.58
C	4.74	2.99	1.49	1.23	1.85	0.55
D	12.13	7.14	5.60	3.86	5.16	2.33
E	5.81	3.45	2.18	1.29	2.42	0
F	4.79	NA	NA	NA	NA	1.6
G	4.32	2.32	1.85	1.28	1.57	0.92
H	5.50	3.53	2.44	1.86	2.52	1.09
I	10.28	3.24	2.42	1.66	2.74	1.45
Total ETo[1]	7.05					
Total Rainfall[2]	0.34					
TexasET Recommendation	5.29	3.04	2.19	1.42	2.13	0.82
Total ETc[3]	5.64	4.23	4.23	3.53	3.53	2.12

[1] Total ETo calculated using the standardized Penmen-Monteith method using weather data collected at the Texas A&M University Golf Course, College Station, Texas.

[2] Total Rainfall collected from TexasET Network Weather Station "TAMU Golf Course"

[3] Rainfall and Adjustment Factor not included in this calculation

Table 11. September 5 - November 20, 2011 Performance. Irrigation amount (inches) applied for each controller station. Yellow denotes values within +/- 20 % of TexasET Recommendation.

Controller ID	Station 1	Station 2	Station 3	Station 4	Station 5	Station 6
A	NA	NA	NA	NA	NA	NA
B	6.05	2.93	2.17	1.55	0.76	0
C	10.13	5.02	3.18	2.36	3.01	1.11
D	23.17	13.01	10.20	6.72	8.99	4.21
E	9.65	5.16	2.91	1.72	2.43	0
F	9.00	NA	NA	NA	NA	3.40
G	7.11	3.11	2.47	1.71	2.10	0.87
H	9.01	5.57	3.85	2.92	3.97	1.71
I	13.00	4.82	4.00	2.08	4.31	1.46
Total ETo[1]	11.12					
Total Rainfall[2]	2.28					
TexasET Recommendation	6.64	3.65	2.56	1.73	2.48	1.04
Total ETc[3]	8.90	6.67	6.67	5.56	5.56	3.34

[1] Total ETo calculated using the standardized Penmen-Monteith method using weather data collected at the Texas A&M University Golf Course, College Station, Texas.

[2] Total Rainfall collected from TexasET Network Weather Station “TAMU Golf Course”

[3] Rainfall and Adjustment Factor not included in this calculation

SUMMARY AND CONCLUSIONS

Over the past five years since starting our "end-user" evaluation of smart controllers, we have seen improvement in their performance. However, the communication and software failures that were evident in our field surveys conducted in San Antonio in 2006 (Fipps, 2008) continue to be a problem for some controllers. In the past four years of bench testing, we have seen some reduction in excessive irrigation characteristic of a few controllers.

Our emphasis continues to be an "end-user" evaluation, how controllers preform as installed in the field. The "end-user" is defined as the landscape or irrigation contractor (such as a licensed irrigator in Texas) who installs and programs the controller.

Although the general performance of the controllers has gradually increased over the last four years, we continue to observe controllers irrigating in excess of ETc. Since ETc is defined as the ETo x Kc, it is the largest possible amount of water a plant will need if no rainfall occurs. This year, three controllers consistently irrigated in excess of ETc, even though over five inches of rainfall occurred during the study. The causes of such excessive irrigation volumes are likely due to improper ETo values and/or insufficient accounting for rainfall.

Three (3) controllers were equipped with tipping-bucket rain gauges which measure actual rainfall and six (6) controllers were equipped with rainfall shutoff sensors as required by Texas landscape irrigation regulations. Rainfall shutoff sensors detect the presence of rainfall and interrupt the irrigation event. During the 2011 evaluation period, below average rainfall occurred as the result of a historic drought. The spring period had the most rainfall (2.83 inches), and no major differences in performance observed between controllers using rain gauges and those using rainfall shutoff devices. This is in contrast to the 2010 study during which over 17 inches of rainfall occurred; and controllers using rain gauges applied irrigation amounts much closer to the recommendations of TexasET.

For a controller to pass our test, it would need to meet plant water requirements (TexasET Recommendations) for all six stations. Of the nine (9) controllers tested, none successfully passed the test during all three irrigation season. However, one controller passed for the fall irrigation season. Results over the last three (3) years have consistently shown that the majority of controllers over-irrigate (i.e., apply more water than is reasonably needed).

Generally, controllers with on-site sensors, performed better and more often irrigated closer to the recommendations of the TexasET Network than those controllers which have ET sent to the controller.

Current plans are to continue evaluation of controllers into the 2012 year. For the 2012 study, three controllers will be replaced with newer models to reflect upgrades in software or sensor technology. While water savings shows promise through the use of some smart irrigation controllers, excessive irrigation is still occurring under some landscape scenarios. Continued evaluation and work with the manufacturers is needed to fine tune these controllers even more to achieve as much water savings as possible.

Table 12. Irrigation adequacy during the Spring Period (April 11-May 29, 2011)

Controller	**Station 1**	**Station 2**	**Station 3**	**Station 4**	**Station 5**	**Station6**
A	Inadequate	Adequate	Adequate	Adequate	Adequate	Excessive
B	Excessive	Excessive	Excessive	Excessive	Adequate	Excessive
C	Inadequate	Inadequate	Inadequate	Adequate	Inadequate	Adequate
D	Excessive	Excessive	Excessive	Excessive	Excessive	Excessive
E	Inadequate	Adequate	Inadequate	Adequate	Adequate	Adequate
F	Inadequate	NA	NA	NA	NA	Excessive
G	Inadequate	Inadequate	Adequate	Adequate	Inadequate	Adequate
H	Inadequate	Inadequate	Inadequate	Adequate	Inadequate	Adequate
I	Excessive	Adequate	Adequate	Adequate	Adequate	Adequate

Table 13. Irrigation adequacy during the Summer Period (August 8-September 4, 2011)

Controller	**Station 1**	**Station 2**	**Station 3**	**Station 4**	**Station 5**	**Station6**
A	NA	NA	NA	NA	NA	NA
B	Inadequate	Inadequate	Inadequate	Inadequate	Inadequate	Excessive
C	Inadequate	Inadequate	Inadequate	Inadequate	Inadequate	Inadequate
D	Excessive	Excessive	Excessive	Excessive	Excessive	Excessive
E	Excessive	Excessive	Inadequate	Inadequate	Adequate	Inadequate
F	Inadequate	NA	NA	NA	NA	Excessive
G	Inadequate	Inadequate	Inadequate	Inadequate	Inadequate	Adequate
H	Adequate	Excessive	Adequate	Excessive	Excessive	Excessive
I	Excessive	Adequate	Adequate	Adequate	Excessive	Excessive

Table 14. Irrigation adequacy during the Fall Period (September 5-November 20, 2011)

Controller	**Station 1**	**Station 2**	**Station 3**	**Station 4**	**Station 5**	**Station6**
A	NA	NA	NA	NA	NA	NA
B	Inadequate	Inadequate	Adequate	Adequate	Inadequate	Adequate
C	Excessive	Adequate	Adequate	Adequate	Adequate	Adequate
D	Excessive	Excessive	Excessive	Excessive	Excessive	Excessive
E	Excessive	Adequate	Adequate	Adequate	Adequate	Adequate
F	Excessive	NA	NA	NA	NA	Excessive
G	Adequate	Inadequate	Adequate	Adequate	Adequate	Adequate
H	Excessive	Excessive	Adequate	Excessive	Excessive	Excessive
I	Excessive	Adequate	Adequate	Adequate	Excessive	Adequate

Table 15. Distribution of Station Adequacy, Inadequacy and Excess during the entire study.

	A[1]	**B**	**C**	**D**	**E**	**F**[1]	**G**	**H**	**I**	**%**
Adequate	4	4	7	0	10	0	9	5	12	37%
Inadequate	1	8	10	0	5	2	9	4	0	28%
Excessive	1	6	1	18	3	4	0	9	6	35%
% Adequate	NA	22%	39%	0%	56%	NA	50%	28%	67%	

[1] Controller A & F Performance based on only 6 stations

Table 16. Distribution of Station Adequacy, Inadequacy and Excess during the spring period.

	A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**%**
Adequate	4	1	2	0	4	NA	3	2	5	44%
Inadequate	1	0	4	0	2	NA	3	4	0	29%
Excessive	1	5	0	6	0	NA	0	0	1	27%
% Adequate	67%	17%	33%	0%	67%	NA	50%	33%	83%	

Table 17. Distribution of Station Adequacy, Inadequacy and Excess during the summer period.

	A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**%**
Adequate	NA	0	0	0	1	NA	1	2	3	17%
Inadequate	NA	5	6	0	3	NA	5	0	0	45%
Excessive	NA	1	0	6	2	NA	0	4	3	38%
% Adequate	NA	0%	0%	0%	17%	NA	17%	33%	50%	

Table 18. Distribution of Station Adequacy, Inadequacy and Excess during the fall period.

	A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**%**
Adequate	NA	3	5	0	5	NA	5	1	4	55%
Inadequate	NA	3	0	0	0	NA	1	0	0	9%
Excessive	NA	0	1	6	1	NA	0	5	2	36%
% Adequate	NA	50%	83%	0%	83%	NA	83%	17%	67%	

Appendix A

Figure A-1. System Set-Up and Data Flow

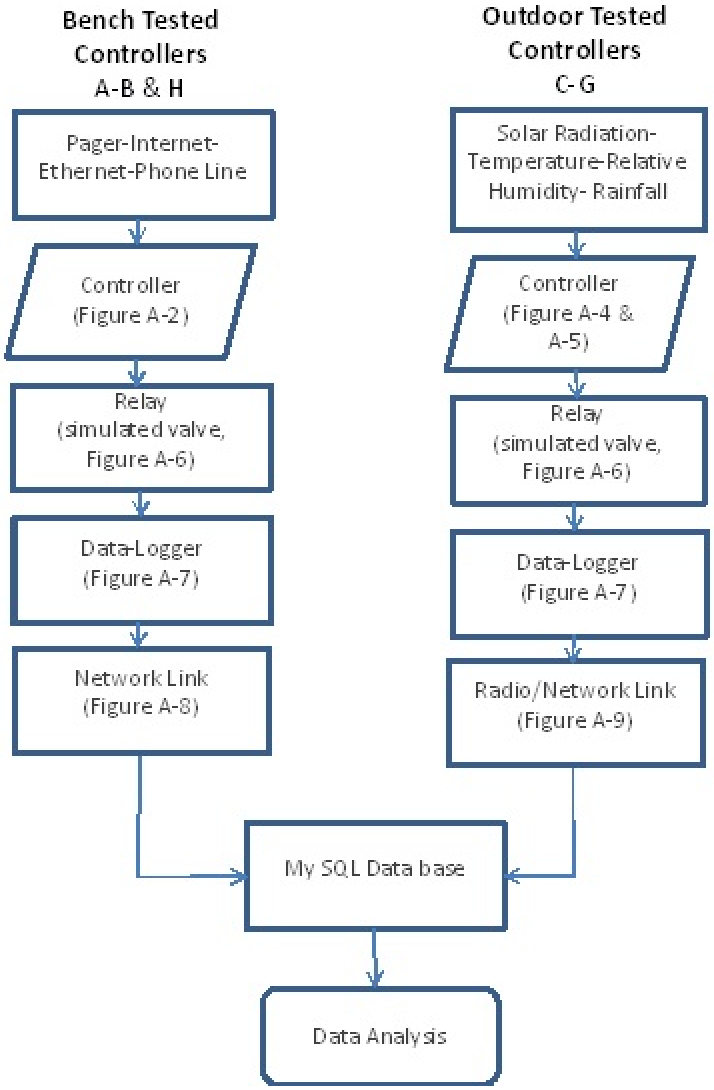


Figure A-2. Bench Tested Controllers

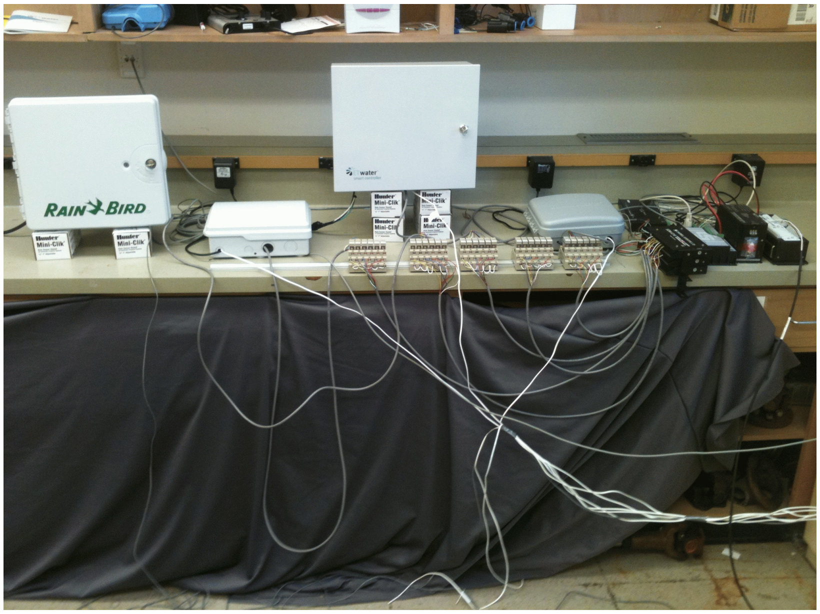


Figure A-3. Indoor Tested Controllers Rain Sensors

Figure A-4. Outdoor Tested Controllers

Figure A-5. Relays

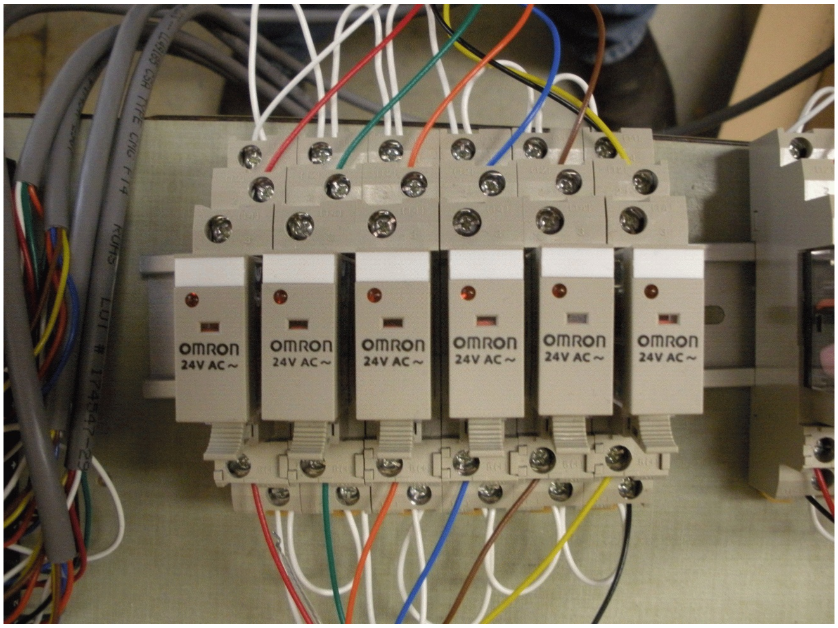


Figure A-6. Datalogger

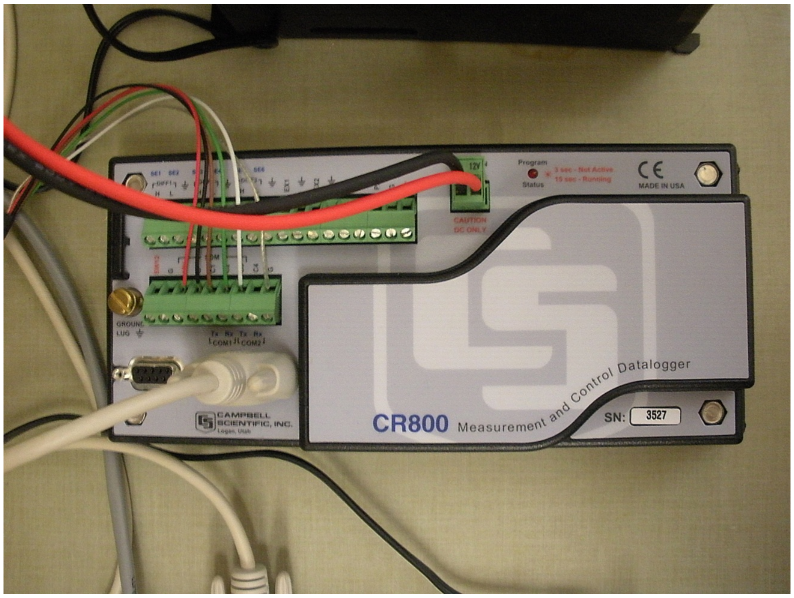


Figure A-7. Network Link

Figure A-8. Radio/Network Link

Appendix B

Table B-1. ET Values that were read off controllers and TexasET calculated ETo and measured rainfall.

Controller	ET Water	ET Manager	Hunter ET	Rainbird ESP	Toro	TexasET	Rainfall
8/1/2011				0.31		0.26	0
8/2/2011				0.29		0.28	0
8/3/2011	1.81	0.2		0.3	0.28	0.28	0
8/4/2011						0.29	0
8/5/2011						0.3	0
8/6/2011						0.27	0
8/7/2011						0.27	0
8/8/2011	1.86	0.21		0.28	0.3	0.31	0
8/9/2011			0.1	0.27	0.3	0.29	0
8/10/2011						0.3	0
8/11/2011						0.26	0
8/12/2011						0.29	0
8/13/2011						0.24	0
8/14/2011						0.24	0
8/15/2011	1.75	0.16	0.17	0.31	0.28	0.26	0
8/16/2011	1.74	0.2	0.18	0.26	0.28	0.28	0
8/17/2011	1.72	0.2	0.24	0.27	0.28	0.26	0
8/18/2011	1.71	0.19	0.22	0.28	0.28	0.26	0
8/19/2011			0.21	0.29	0.28	0.26	0
8/20/2011						0.27	0
8/21/2011						0.25	0
8/22/2011	1.8	0.17	0.18	0.28	0.28	0.23	0
8/23/2011	1.8	0.2	0.17	0.28	0.28	0.25	0
8/24/2011	1.8	0.18	0.19	0.28	0.27	0.24	0.17
8/25/2011	1.79	0.14	0.08	0.28	0.27	0.14	0.17
8/26/2011	1.74	0.2	0.11	0.25	0.23	0.24	0
8/27/2011						0.27	0
8/28/2011						0.22	0
8/29/2011						0.21	0
8/30/2011	1.78	0.17	0.17	0.28	0.27	0.26	0
8/31/2011	1.78	0.18	0.19	0.26	0.25	0.24	0
9/1/2011	1.71	0.17	0.18	0.25	0.25	0.18	0
9/2/2011	1.77	0.18	0.18	0.25	0.25	0.25	0
9/3/2011						0.27	0
9/4/2011						0.28	0
9/5/2011	1.64	0.18	0.16	0.24	0.34	0.24	0
9/6/2011	1.57	0.09	0.22	0.22	0.3	0.17	0
9/7/2011	1.54	0.12	0.24	0.28	0.26	0.18	0
9/8/2011	1.54	0.13	0.25	0.27	0.26	0.16	0

Table B-1, continued							
9/9/2011	1.54	0.09	0.26	0.26	0.25	0.17	0
9/10/2011						0.17	0
9/11/2011						0.2	0
9/12/2011	1.6	0.17	0.22	0.31	0.24	0.22	0
9/13/2011	1.65	0.15	0.25	0.28	0.26	0.26	0
9/14/2011	1.68	0.16	0.24	0.28	0.27	0.24	0
9/15/2011	1.67	0.2	0.19	0.25	0.27	0.15	0.02
9/16/2011	1.67	0.16	0.13	0.24	0.27	0.17	0
9/17/2011						0.17	0.01
9/18/2011						0.19	0
9/19/2011	1.5	0.17	0.12	0.2	0.07	0.14	1.24
9/20/2011	1.43	0.17	0.19	0.23	0.2	0.15	0
9/21/2011	1.38	0.14	0.18	0.24	0.2	0.17	0
9/22/2011	1.31	0.14	0.17	0.25	0.2	0.15	0
9/23/2011	1.27	0.12	0.14	0.22	0.21	0.17	0
9/24/2011						0.17	0
9/25/2011						0.27	0
9/26/2011	1.29	0.14	0.2	0.23	0.21	0.22	0.38
9/27/2011	1.34	0.17	0.17	0.23	0.22	0.18	0
9/28/2011	1.32	0.1	0.18	0.2	0.2	0.18	0
9/29/2011	1.34	0.09	0.18	0.23	0.22	0.2	0
9/30/2011	1.27	0.14	0.15	0.24	0.21	0.21	0
10/1/2011						0.14	0
10/2/2011						0.13	0
10/3/2011	1.28	0.18	0.18	0.2	0.19	0.13	0
10/4/2011	1.26	0.13	0.17	0.2	0.18	0.15	0
10/5/2011	1.27	0.1	0.17	0.18	0.18	0.18	0
10/6/2011	1.25	0.13	0.17	0.18	0.19	0.17	0
10/7/2011	1.22	0.13	0.11	0.17	0.19	0.16	0
10/8/2011						0.19	0
10/9/2011						0.05	0.84
10/10/2011						0.11	0
10/11/2011						0.12	0
10/12/2011	1.04	0.12	0.12	0.17	0.12	0.1	0
10/13/2011			0.13	0.16	0.12	0.14	0.02
10/14/2011		0.08				0.13	0
10/15/2011						0.13	0
10/16/2011						0.14	0
10/17/2011	1.05	0.11	0.12	0.12	0.21	0.15	0
10/18/2011	1.07	0.08	0.14	0.14	0.15	0.16	0
10/19/2011						0.16	0
10/20/2011						0.11	0

Table B-1 continued

10/21/2011						0.14	0
10/22/2011						0.15	0
10/23/2011						0.11	0
10/24/2011	0.94	0.07	0.09	0.09	0.15	0.1	0
10/25/2011	0.93	0.08	0.11	0.11	0.17	0.15	0
10/26/2011						0.15	0
10/27/2011	0.96	0.07	0.06	0.06	0.18	0.08	0.04
10/28/2011	0.93	0.06	0.03	0.03	0.18	0.07	0
10/29/2011						0.08	0
10/30/2011						0.08	0
10/31/2011	0.8	0.08	0.13	0.12	0.12	0.09	0
11/1/2011	0.79	0.08	0.13	0.12	0.12	0.14	0
11/2/2011	0.79	0.09	0.13	0.13	0.12	0.16	0
11/3/2011	0.79	0.07	0.14	0.14	0.12	0.12	0
11/4/2011	0.76	0.04	0.14	0.1	0.15	0.07	0
11/5/2011						0.12	0
11/6/2011						0.11	0
11/7/2011	0.79	0.09	0.05	0.12	0.07	0.11	0
11/8/2011	0.74	0.09	0.05	0.11	0.07	0.16	0
11/9/2011	0.74	0.09	0.11	0.13	0.07	0.1	0
11/10/2011	0.69	0.09	0.11	0.09	0.13	0.09	0
11/11/2011	0.7	0.14	0.14	0.1	0.13	0.13	0
11/12/2011						0.13	0
11/13/2011						0.15	0
11/14/2011	0.7	0.11	0.07	0.13	0.09	0.13	0
11/15/2011	0.69	0.11	0.03	0.13	0.08	0.04	0.23
11/16/2011	0.67		0.03	0.1	0.08	0.05	0
11/17/2011			0.12	0.1	0.08	0.11	0
11/18/2011			0.13	0.1	0.08	0.11	0
11/19/2011						0.1	0
11/20/2011						0.14	0

Appendix C

Figure C-1

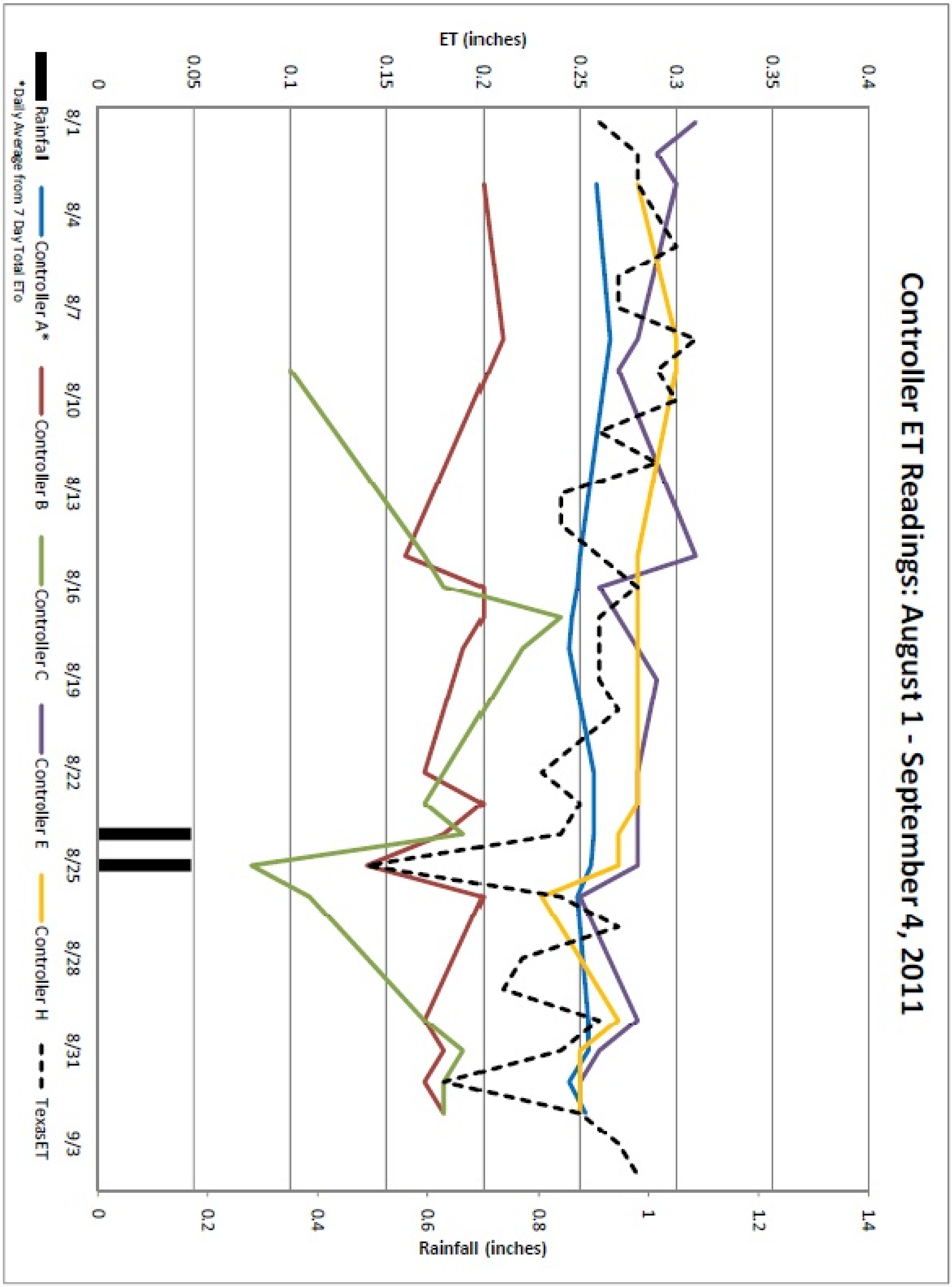
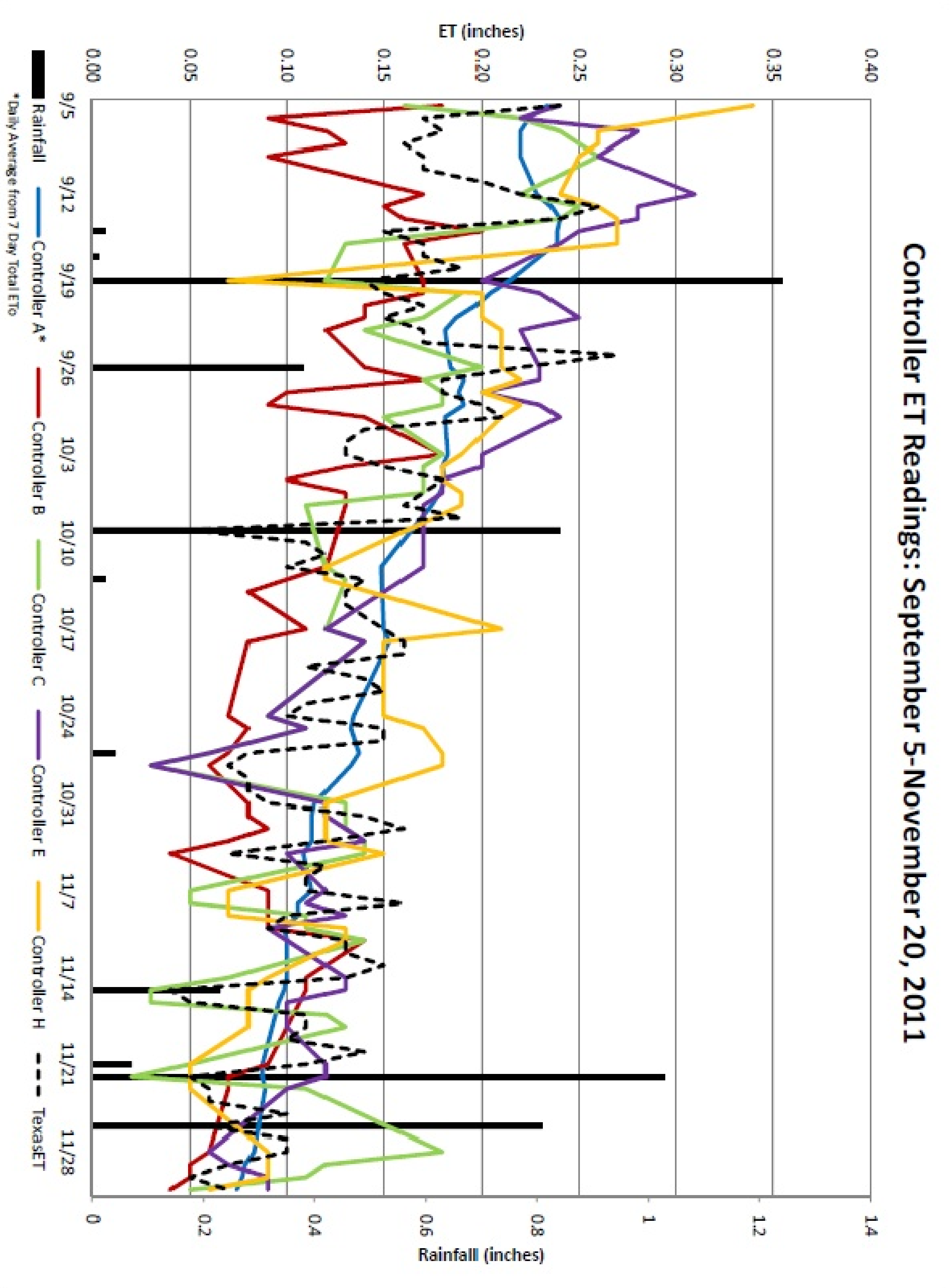


Figure C-2


Controller ET Readings: September 5-November 20, 2011
ET (inches)
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
Rainfall (inches)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
9/5
9/12
9/19
9/26
10/3
10/10
10/17
10/24
10/31
11/7
11/14
11/21
11/28
Rainfall
Controller A*
Controller B
Controller C
Controller E
Controller H
TexasET
*Daily Average from 7 Day Total ETo

Texas Water
Resources Institute
make every drop count

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