TR-443

EVALUATION OF SMART IRRIGATION CONTROLLERS:

YEAR 2012 RESULTS[1]

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SUMMARY

A smart controller testing facility was established 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 of the 2012 evaluations. Nine controllers were evaluated over a 216 day period, from April 30 – December 2, 2012. Controller performance was analyzed for each seasonal period (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% of the TexasET Network for all six (6) station during the Summer Evaluation Period.
- Two (2) controllers applied more than ETo for one (1) or both seasonal periods
- Four (4) controllers did not have any station apply +/-20% of TexasET Network Recommendations for one (1) or both seasonal periods.

Adequacy Analysis

- Seven (7) Controllers were able to (across all 6 stations) to adequately meet the plant water requirements for any season.
- One (1) controller consistently applied excessive amounts of irrigation for all six (6) stations for both seasonal periods.

Factors that could have caused over irrigation of landscape are improper ETo calculation and insufficient accounting for rainfall. The 2012 study received only 16.41 inches of rainfall compared to historical averages of 24.20 inches for the same time period. ET values recorded off the controllers were inconsistent throughout the study, often calculating ET values greater than 150% of weather station (TexasET Network) ET.

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 sensors 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 2012 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 gauge.

Controller ID	**Controller Name**	**Type**	**Communication Method**	**On-Site 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	-	Tipping Bucket Rain Gauge, Pyranometer, Temperature/ RH, Anemometer	
D	Hunter Solar Sync	Sensor Based	-	Pyranometer	□
E	Rainbird ESP SMT	Sensor Based	-	Tipping Bucket Rain Gauge, Temperature	
F	Accurate WeatherSet	Sensor Based	-	Pyranometer	□
G	Weathermatic Smartline	Sensor Based	-	Temperature	□
H	Toro Intellisense	ET	Pager	None	□
I	Irritrol Climate Logic	Sensor Based	-	Temperature, Solar Radiation	□

[1] Rain shut off sensors are not considered On-Site Sensors for ET Calculation or runtime adjustment

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 (with 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 three did. Five of the remaining manufacturers provided to us written recommendations/instructions for station programming, and one manufacturer trusted our judgment 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 run from April 30 to September 30 and from October 1 to December 2, 2012. Controller performance is reported over seasonal periods. For the purposes of this report, seasons are defined as follows:

- Summer: April 30 to September 30 (153 Days),
- Fall: October1 to December 2 (62 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) on a weekly basis. This weekly water balance approach is used for the weekly irrigation recommendations generated by TexasET for users that sign-up for automatic emails. The calculation uses the standard equation:

ETc = (ETo x Kc x Af) - Re (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, TexasET users have the option of applying an *Adjustment Factor*. This can be used to make adjustments for site 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.

For this study we broadly define irrigation ***adequacy*** as the range between taking 80% credit for all rainfall ($R_e = 0.8$) and taking no credit for rainfall ($R_e = 0$). 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 2012 evaluation periods are summarized in Tables 9, 10 and 11 by season.

TexasET Comparisons

Controller performance during the Summer evaluation period (April 30-September 30, 2012) was good.

Controllers Passing
Controller G had all six stations within the recommendations of TexasET

Good Performers
Controller B had five 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, F, H and I did not produce any stations within TexasET.

Controller Performance during the Fall evaluation period (October 1-December 2, 2012) was generally poor.

Controllers Passing
None

Best Performer
Controller C had three stations that were within TexasET.

Poor Performers
Controllers D produced irrigation volumes in excess of ETo.
Controllers D and F produced irrigation volumes in excess of ETc.
Controller B, D and H did not produce any stations within TexasET.

Tables 12-14 show the irrigation ***adequacy*** analysis for each station during the two seasonal periods. During the Summer period, four (4) controllers applied excessive amounts of irrigation for one or more stations with one (1) controller applying excessive amounts for all six (6) stations. Only three (3) controllers applied excessive amounts of irrigation during the Fall period, with one (1) controller applying excessive amounts for all six (6) station. No controllers during the study period applied inadequate amounts of irrigation.

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 entire evaluation period (Figure C-1) and as a percentage of daily ETo (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

Two controllers experienced problems during the course of the study.

1. Controller B had poor signal accuracy during the study dropping down as low as 17% at some times. The signal provider was notified and adjustments were made in the signal settings and an upgraded antenna was installed. Signal accuracy increased after adjustments.

2. 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 of temporary poor signal service by the signal provider company in the testing area (a bad tower).

Table 9. Entire Testing Period Performances. Irrigation amount (inches) applied for each controller station. Yellow denotes values within +/- 20 % of TexasET Recommendation. Red indicates values in excess of ETc.

Controller	Station 1	Station 2	Station 3	Station 4	Station 5	Station 6
A	26.79	16.66	12.51	11.21	10.50	7.50
B	24.75	13.35	9.70	6.93	8.44	3.55
C	19.31	9.11	5.29	5.10	5.27	0.57
D	68.32	43.52	33.46	20.89	27.96	13.91
E	30.18	16.97	8.90	4.85	7.39	0.00
F	28.72	24.54	27.81	10.18	16.29	10.46
G	22.49	13.02	9.76	6.62	9.47	3.73
H	27.89	17.87	12.40	9.41	12.78	5.53
I	60.31	20.42	15.04	9.32	13.67	6.38
Total ETo[1]	39.60					
Total Rain[2]	16.41					
Total ETc[3]	31.68	23.76	23.76	19.80	19.80	11.88
TexasET Recommendation	21.67	11.16	7.84	5.26	7.59	2.94

[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. Summer Performances. Irrigation amount (inches) applied for each controller station. Yellow denotes values within +/- 20 % of TexasET Recommendation. Red indicates values in excess of ETc						
Controller	Station 1	Station 2	Station 3	Station 4	Station 5	Station 6
A	22.00	14.28	10.83	9.28	9.45	7.50
B	20.33	10.55	7.65	5.46	6.20	3.55
C	15.67	7.59	4.58	4.13	4.68	0.57
D	55.31	35.11	26.90	16.72	22.35	11.19
E	25.92	14.66	7.80	4.60	6.60	0.00
F	24.90	18.70	22.91	8.44	13.51	8.67
G	18.50	10.54	7.90	5.46	7.66	2.94
H	23.69	15.18	10.53	7.99	10.86	4.70
I	56.47	17.92	13.33	8.23	12.72	5.66
Total ETo[1]	32.17					
Total Rain[2]	11.99					
Total ETc[3]	25.74	19.30	19.30	16.09	16.09	9.65
TexasET Recommendation	18.32	9.65	6.77	4.51	6.55	2.50

[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. Fall Performance. Irrigation amount (inches) applied for each controller station. Yellow denotes values within +/- 20 % of TexasET Recommendation. Red indicates values in excess of ETc.

Controller	Station 1	Station 2	Station 3	Station 4	Station 5	Station 6
A	4.80	2.38	1.68	1.92	1.05	0.00
B	4.41	2.80	2.06	1.47	2.24	0.00
C	3.64	1.53	0.71	0.97	0.59	0.00
D	13.01	8.42	6.56	4.17	5.61	2.72
E	4.26	2.31	1.10	0.25	0.79	0.00
F	3.82	5.84	4.90	1.74	2.78	1.79
G	3.99	2.49	1.86	1.16	1.81	0.79
H	4.20	2.69	1.87	1.42	1.93	0.83
I	3.83	2.50	1.71	1.08	0.95	0.72
Total ETo[1]	7.43					
Total Rain[2]	4.42					
Total ETc[3]	5.94	4.46	4.46	3.72	3.72	2.23
TexasET Recommendations	3.35	1.51	1.07	0.75	1.04	0.44

[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 12. Irrigation adequacy during the entire testing period (April 30-December 2, 2012)

Controller	Station 1	Station 2	Station 3	Station 4	Station 5	Station 6
A	Adequate	Adequate	Adequate	Adequate	Adequate	Adequate
B	Adequate	Adequate	Adequate	Adequate	Adequate	Adequate
C	Adequate	Adequate	Adequate	Adequate	Adequate	Adequate
D	Excessive	Excessive	Excessive	Excessive	Excessive	Excessive
E	Adequate	Adequate	Adequate	Adequate	Adequate	Adequate
F	Adequate	Excessive	Excessive	Adequate	Adequate	Adequate
G	Adequate	Adequate	Adequate	Adequate	Adequate	Adequate
H	Adequate	Adequate	Adequate	Adequate	Adequate	Adequate
I	Excessive	Adequate	Adequate	Adequate	Adequate	Adequate

Table 13. Irrigation adequacy during the Summer (April 30-September 30, 2012)

Controller	Station 1	Station 2	Station 3	Station 4	Station 5	Station 6
A	Adequate	Adequate	Adequate	Adequate	Adequate	Adequate
B	Adequate	Adequate	Adequate	Adequate	Adequate	Adequate
C	Adequate	Adequate	Adequate	Adequate	Adequate	Adequate
D	Excessive	Excessive	Excessive	Excessive	Excessive	Excessive
E	Excessive	Adequate	Adequate	Adequate	Adequate	Adequate
F	Adequate	Adequate	Excessive	Adequate	Adequate	Adequate
G	Adequate	Adequate	Adequate	Adequate	Adequate	Adequate
H	Adequate	Adequate	Adequate	Adequate	Adequate	Adequate
I	Excessive	Adequate	Adequate	Adequate	Adequate	Adequate

Table 14. Irrigation adequacy during the Fall (October 1-December 2, 2012)

Controller	Station 1	Station 2	Station 3	Station 4	Station 5	Station 6
A	Adequate	Adequate	Adequate	Adequate	Adequate	Adequate
B	Adequate	Adequate	Adequate	Adequate	Adequate	Adequate
C	Adequate	Adequate	Adequate	Adequate	Adequate	Adequate
D	Excessive	Excessive	Excessive	Excessive	Excessive	Excessive
E	Adequate	Adequate	Adequate	Adequate	Adequate	Adequate
F	Adequate	Excessive	Excessive	Adequate	Adequate	Adequate
G	Adequate	Adequate	Adequate	Adequate	Adequate	Adequate
H	Adequate	Adequate	Adequate	Adequate	Adequate	Adequate
I	Adequate	Adequate	Adequate	Adequate	Adequate	Adequate

DISCUSSION AND CONCLUSIONS

Over the past four 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 characteristics of 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, one controller consistently irrigated in excess of ETc, even though16.41 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 2012 evaluation period, below average rainfall occurred. The summer period had the most rainfall (11.99 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 both summer and fall seasons. However, one controller passed for the summer irrigation season. Results over the last four (4) years have consistently shown that some of the controllers over-irrigate (i.e., apply more water than is reasonably needed). This year, due to the amount of rainfall received during the study, no controller applied an inadequate amount of water compared to 2011 when six (6) controllers failed to meet minimum plant water requirements.

Generally, there was no difference in performance between controllers with on-site sensors and those controllers which have ET sent to the controller. Previous years evaluations had shown those controllers with on-site sensors to irrigate much closer to the recommendations of the TexasET Network.

Current plans are to continue evaluation of controllers into the 2013 year. 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.

Appendix A

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

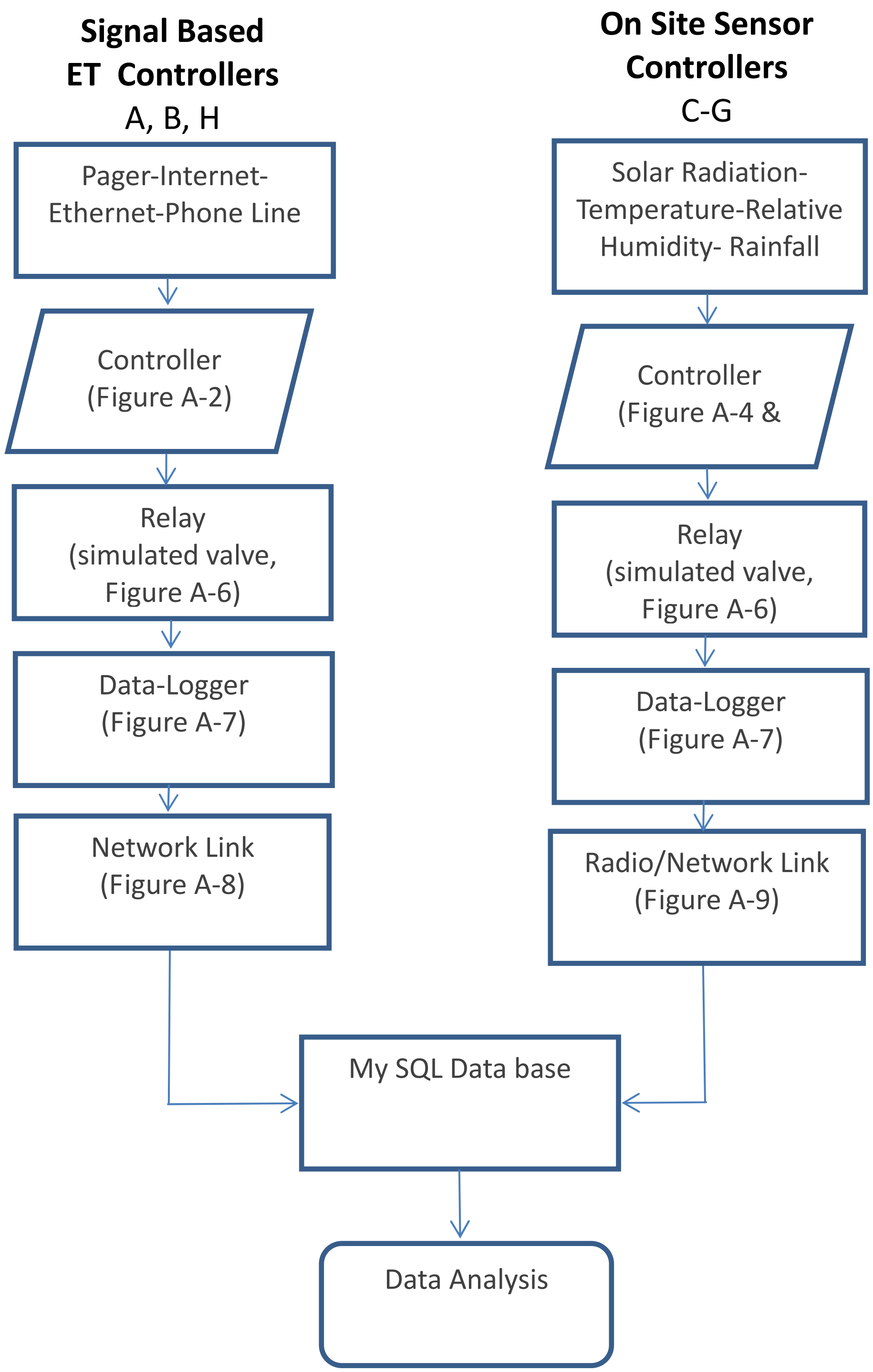


Figure A-2. Bench Tested Controllers

Figure A-3. Indoor Tested Controllers Rain Sensors

Figure A-4. Outdoor Tested Controllers

Figure A-5. Relays

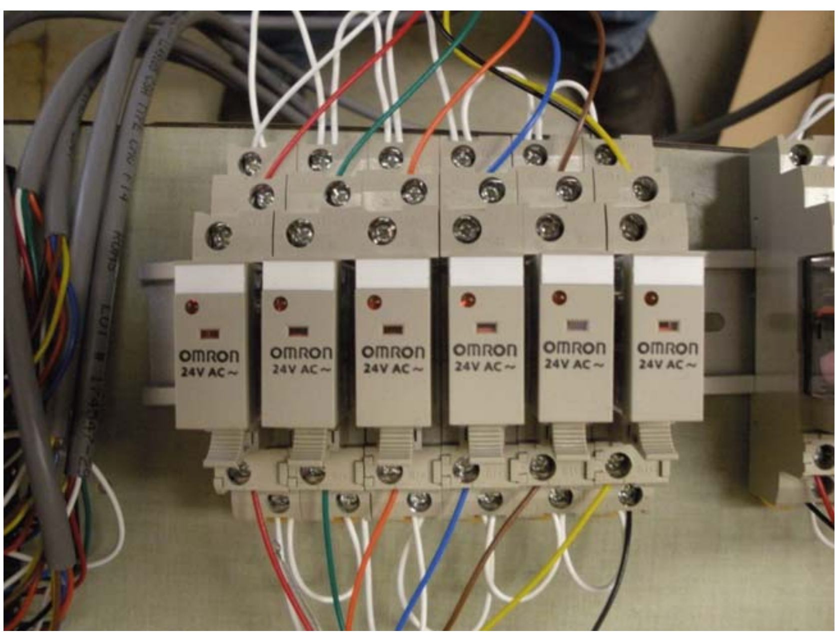


Figure A-6. Datalogger

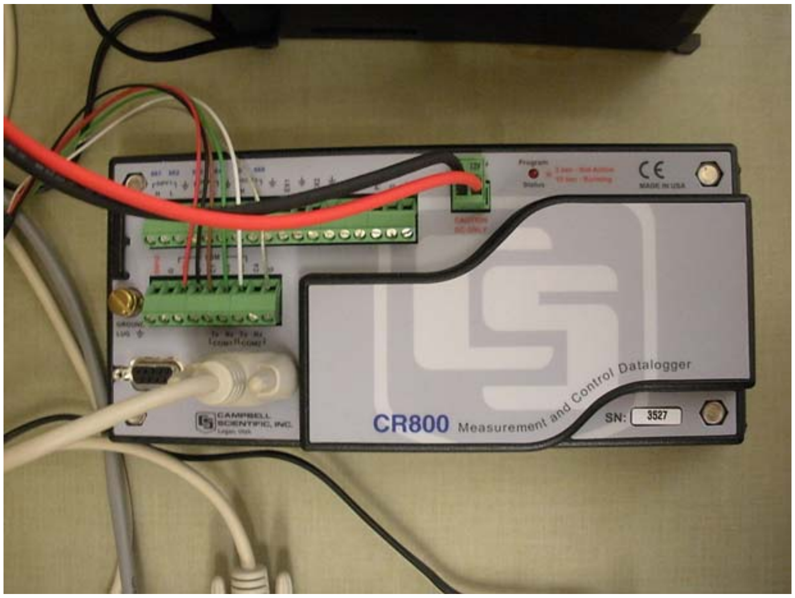


Figure A-7. Network Link

Figure A-8. Radio/Network Link

Appendix B

Date	ETWater	ETManager	Hunter ET	Rain Bird ESP SMT	Toro Intellisense	TexasET ETo	Rainfall
6/5/2012	0.23		0.11	0.24	0.31	0.21	0
6/6/2012	0.24	0.29	0.13	0.27	0.31	0.24	0
6/7/2012	0.24	0.22	0.11	0.26	0.31	0.26	0
6/11/2012			0.15	0.23	0.29	0.24	0
6/12/2012		0.23	0.14	0.24	0.29	0.29	0
6/13/2012	0.23		0.08	0.24	0.26	0.18	0.56
6/14/2012	0.23	0.23	0.11	0.24	0.26	0.19	0
6/18/2012	0.24	0.23	0.12	0.22	0.22	0.14	0
6/19/2012	0.24	0.23	0.1	0.22	0.22	0.24	0
6/20/2012	0.23	0.23	0.07	0.2	0.22	0.16	0.16
6/21/2012	0.22	0.23	0.09	0.22	0.23	0.19	0.36
6/25/2012	0.24	0.23	0.15	0.3	0.26	0.24	0
6/26/2012	0.25	0.23	0.17	0.32	0.26	0.25	0
6/27/2012	0.26	0.23	0.18	0.33	0.27	0.25	0
6/28/2012	0.27	0.2	0.13	0.3	0.29	0.25	0
7/2/2012	0.25	0.23	0.07	0.2	0.3	0.16	0.08
7/3/2012	0.24	0.23	0.09	0.24	0.3	0.23	0
7/5/2012	0.22	0.23	0.14	0.25	0.3	0.29	0
7/6/2012	0.23	0.2	0.15	0.26	0.3	0.26	0
7/9/2012	0.24	0.24	0.06	0.22	0.29	0.14	0.83
7/10/2012	0.24	0.15	0.08	0.26	0.2	0.19	0.13
7/11/2012	0.23	0.17	0.02	0.2	0.2	0.1	0.88
7/12/2012	0.22	0.19	0.05	0.17	0.17	0.1	0.03
7/16/2012	0.20		0.1	0.22	0.2	0.19	0
7/17/2012	0.20		0.13	0.24	0.26	0.23	0
7/18/2012	0.20		0.07	0.22	0.26	0.17	0
7/23/2012	0.23	0.21	0.14	0.22	0.25	0.22	0
7/24/2012	0.23	0.15	0.13	0.23	0.25	0.23	0
7/25/2012	0.23	0.13	0.11	0.24	0.26	0.22	0
8/14/2012	0.25	0.17	0.15	0.27	0.28	0.25	0
8/15/2012	0.25	0.24	0.2	0.26	0.28	0.3	0
8/16/2012	0.25	0.2	0.18	0.26	0.28	0.26	0
8/17/2012			0.14	0.26	0.28	0.27	0
8/20/2012			0.08	0.24	0.23	0.14	0.59
8/28/2012	0.21	0.12	0.11	0.22	0.28	0.14	0
8/29/2012	0.21	0.12	0.17	0.26	0.28	0.21	0
8/30/2012			0.18	0.24	0.28	0.25	0

8/31/2012	0.22		0.14	0.27	0.28	0.22	0
9/3/2012	0.22	0.17	0.15	0.24	0.23		
9/4/2012	0.23	0.18	0.16	0.25	0.23		
9/5/2012		0.15				0.32	0
9/13/2012			0.14	0.23	0.26	0.21	0
9/14/2012	0.20	0.2	0.01	0.18	0.19	0.12	0.11
9/25/2012		0.14	0.15	0.20	0.23	0.21	0
9/28/2012			0.08	0.19	0.23	0.14	0
10/1/2012				0.12	0.23	0.06	0.87
10/2/2012		0.11	0.11	0.17	0.16	0.18	0
10/4/2012			0.15	0.16	0.16	0.16	0
10/5/2012			0.12	0.17	0.16	0.19	0

Appendix C

Figure C-1

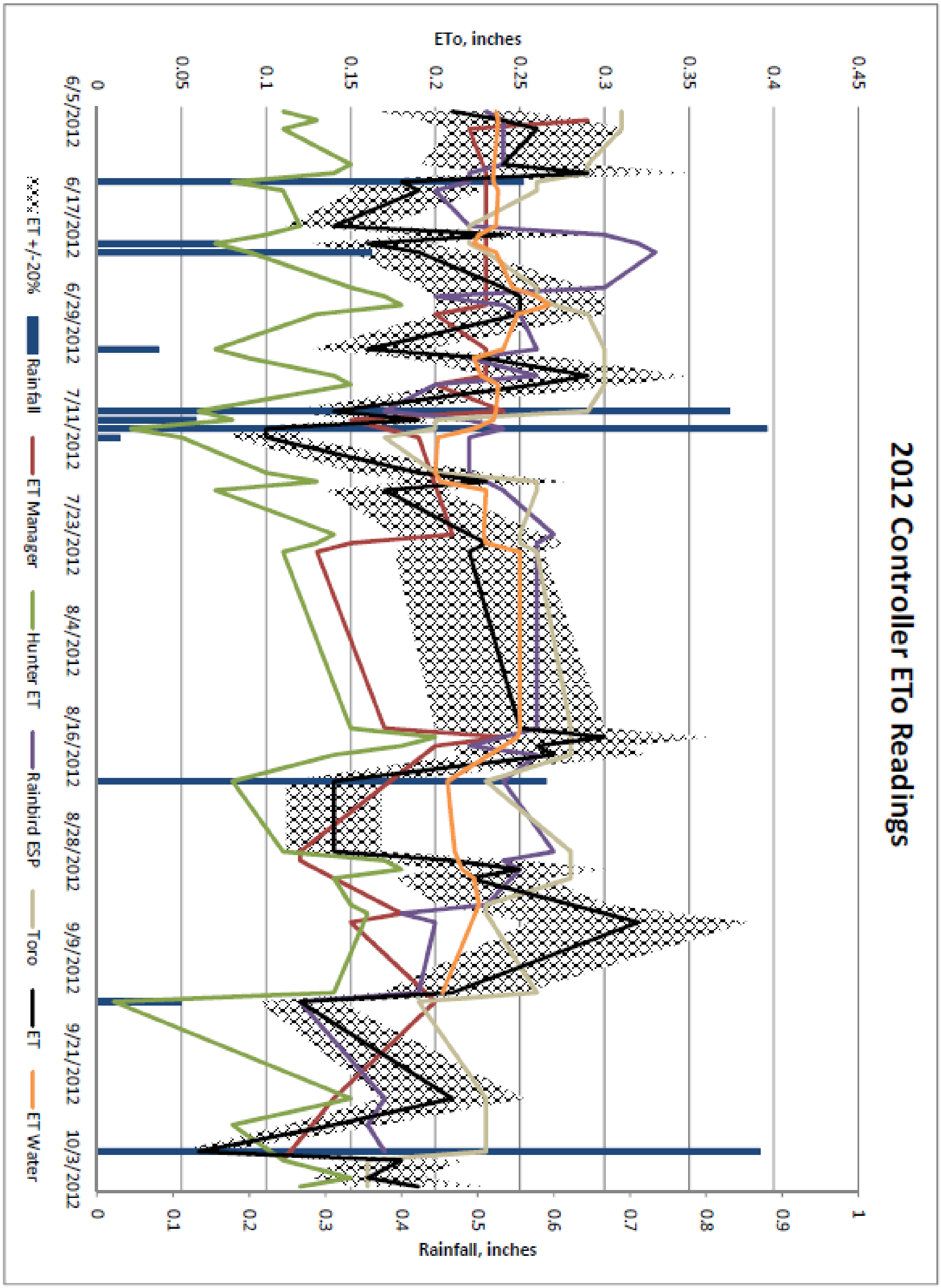
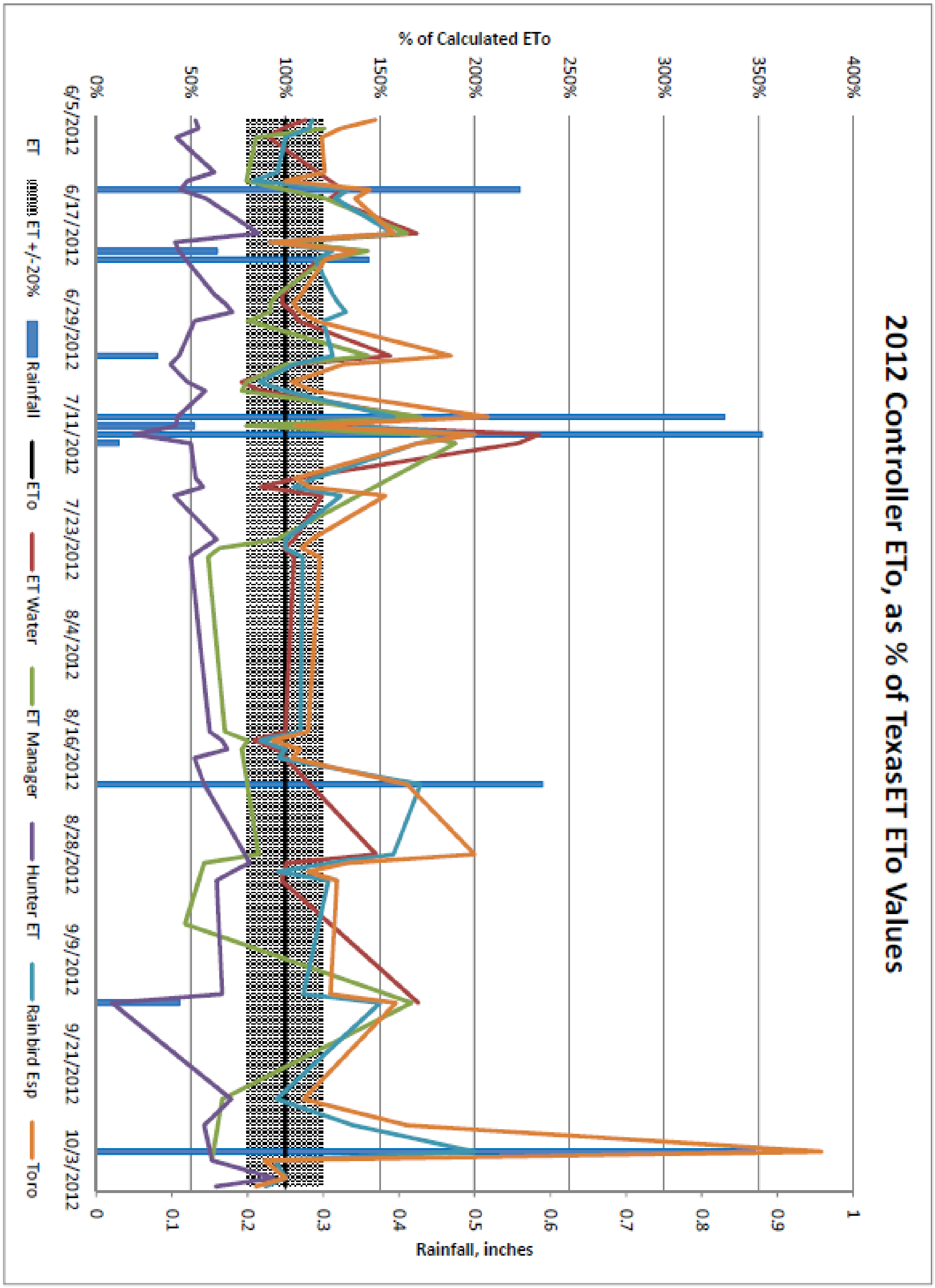


Figure C-2



2012 Controller ETo, as % of TexasET ETo Values
% of Calculated ETo
0%
50%
100%
150%
200%
250%
300%
350%
400%
6/5/2012
6/17/2012
6/29/2012
7/11/2012
7/23/2012
8/4/2012
8/16/2012
8/28/2012
9/9/2012
9/21/2012
10/3/2012
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Rainfall, inches
ET
ET +/-20%
Rainfall
ETo
ET Water
ET Manager
Hunter ET
Rainbird Esp
Toro

Texas Water
Resources Institute
make every drop count

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