Executive Summary

Soil moisture sensors have the potential to be useful tools in the efforts to manage urban water supplies. These inexpensive devices should be able to regulate irrigation of clock driven sprinkler systems in order to match actual applications to theoretical requirements based on actual plant water requirements. The three keys to success are: 1. having hardware which functions properly, and 2. having personnel who understand the equipment, and 3. providing them with the proper information to obtain the best results. Even though previous studies conducted by the City of Boulder have shown that at least one brand of sensors do, in fact, perform in the field as desired, there has been continued reluctance on the part of the entire irrigation industry to employ this technology. This is true from system designers to landscape contractors. The only parties who have shown a real interest in soil moisture sensors have been the owners and property managers, who hope to use them to reduce water bills. In the fall of 1996 the City of Boulder held a meeting with several property managers and landscape contractors who had been involved in the previous studies (the Users Group) in order to elicit their concerns over use of soil sensors.

At that meeting the major issues raised by the group involved uncertainty about the level of cost and effort required to operate a system of sensors, the long term reliability of the system, and the need to have a simple way to track the performance of irrigation systems to determine if the proper amount of water is being applied. The Users Group meeting led directly to the present study, and led the study team to focus on: the time and expense required to maintain irrigation systems equipped with the Watermark soil moisture sensors and Watermark Electronic Modules (WEM's); how these systems

performed after several years in the field, and how well the systems matched irrigation application to actual requirements.

The results of the study were encouraging: the time and cost for maintaining and operating the systems was nominal, the Watermark systems were found to be reliable after several years in the ground, and with minor exceptions, the sensor controlled sprinkler systems matched irrigation requirements very closely.

Maintaining the systems took an average of 6-7 minutes per WEM per week, or about ten staff hours per 100 WEM's per week. However, once systems are properly set, site visits may be spread out over periods of more than a week, thus reducing the required maintenance time. All 23 systems were installed during or prior to 1995 and remained operational with three exceptions. A homeowner severed the soil moisture sensor wire, one WEM had been stolen, and a second WEM was shorted out due to a faulty clock. Repairs were made in less than 15 minutes per job at a cost of about $9 for the severed wire and $130 for each WEM.

The total seasonal (April through September) theoretical irrigation water requirement was just over 28 inches (17.45 gallons per square foot) and the average actual application was approximately 21 inches (13 gpsf), or 76% of the theoretical requirement, while none of the owners complained about the quality of landscape. WEM's performed well, interrupting irrigation during periods of rain and allowing for the maximum application when needed. Once repairs were made and systems brought on line the only routine maintenance required was fine-tuning the WEM's.

In order to address the need for a better feedback mechanism for operators two simple irrigation scheduling tables were developed as part of this study. In addition, a more precise template for the WEM was also developed. Irrigation scheduling tables that allow the user to track system performance were created to give immediate feedback on how well the system matched the theoretical water requirement. Currently, the WEM's are labeled with a wet, dry and off region, which makes fine tuning difficult. A template that is installed behind the adjustment knob and calibrated every five degrees was used to keep track of WEM adjustments.

Introduction

Soil moisture sensors appeal to water planners and water systems analysts because they add an essential reality check to the typical clock driven irrigation system. It has been said that it makes no more sense to operate an irrigation system using only a clock than it would to operate a home furnace with a clock. No matter how closely one tried to model heating demands to historical seasonal or daily weather patterns the chances of the heat coming on when (and only when) it was needed would be small. The problem of scheduling furnace operation was first addressed by the use of simple thermostats. In an irrigation system, the soil moisture sensor is analogous to the thermostat. To push the analogy between irrigation and heating systems a bit further, one can consider the greater efficiencies, which can be achieved in a home heating system by linking a clock to the thermostat. Instead of the heat coming on whenever the temperature falls below the desired room temperature, the user can program the system to only come on certain days, or to use different minimum temperatures on weekdays vs. weekends or for sleeping times verses waking times.

An irrigation system with a good clock and a soil moisture sensor should, in theory, be able to duplicate the application efficiency of a more complex and expensive central control irrigation system. The users should be able to set a target soil moisture level with the sensor, and then use the clock to manage the basic schedule, including days of operations, start times, duration of irrigation and resting periods between applications. Under this type of operation the clock would be programmed for maximum day application (using several short cycles to avoid run-off) and the soil sensor would stop the system at the end of whatever cycle brought the soil moisture to the desired target level.

For a combination of reasons, despite their theoretical desirability, soil moisture sensors have yet to receive widespread acceptance by irrigation system operators. Concerns have been raised about their reliability, cost of installation and time requirements for operation and maintenance. In the fall of 1992, the City of Boulder, Colorado, Water Conservation Department began a long-term study of the performance of the Watermark soil moisture sensor system made by the Irrometer, Co of Riverside California. Under this program a number of sensors were installed in both public and private irrigation systems so that their performance could be tracked over time.

The present report adds to the previous reports, published by Aquacraft, Inc. and dated December 31, 1993 and January 18, 1995, in which the results of these studies in Boulder were published. In the 1993 study, data were presented on the performance of the Watermark soil moisture sensors and electronic switching modules (WEM's) in controlling the irrigation application of various irrigation timers. The previous studies showed that the soil moisture sensors and WEM's were successful in preventing irrigation when the desired soil moisture levels were met or exceeded. Also, the studies reported that the use of the soil moisture sensors allowed the actual irrigation application to match the theoretical application requirements well.

Even though the results of the previous studies have shown that the Watermark sensors do perform properly, and many homeowners' associations (who pay the water bills) were interested in using the technology, continued reluctance on the part of the irrigation maintenance companies was noted. The City of Boulder held a meeting with interested homeowners and contractors during the fall of 1996 to discuss the joint experience with soil sensors. This meeting showed that the contractors still were uncertain as to the reliability of the sensors, how to monitor their performance in the field, and how much man-power would be required to operate and maintain a system which included soil sensors. This meeting led to the City agreeing to support the present study. The focus of which was to address the three concerns raised at the soil sensor review meeting.

The goal of this project was to collect additional data on the performance of the WEM's and soil moisture sensors as well as detailed information on the investment of time and money required to manage and maintain the Watermark systems. In addition, irrigation scheduling tables were developed to be used by irrigators in the determination of daily water requirements.

Automatic irrigation systems are a convenient way for homeowners and landscape contractors to manage the application of water to vegetation. However, evidence suggests that automatic systems use more water annually than manual systems. The 1995 study concluded that homes in the Heatherwood neighborhood with sprinklers applied 24% more water per square foot than those with manual systems. The need for a way to keep the convenience of an automated system but to cut down on water application was evident. With the use of the Watermark soil moisture sensors and WEM's this task was accomplished. Clock driven irrigation systems were prevented from operating if the soil moisture levels were adequate to sustain the vegetation, preventing over watering. However, to be successful water conservation systems must be financially feasible, and require a reasonable time investment. A device that is affordable and easy to install, maintain, and monitor is necessary. If these requirements are met the systems lend themselves to mass application in the water conservation effort.

Description of Watermark System

The soil moisture sensors employed in this study were the Watermark Moisture Sensors coupled with the Watermark Electronic Module (WEM) manufactured by the Irrometer Co. of Riverside, CA. A schematic of the typical installation of the Watermark s shown in Figure 1. These are electrical resistance sensors in which the stainless steel electrodes are protected with both gypsum and granular silica media. They are manufactured with close tolerances in order to maximize their response consistency. The Watermark system uses two soil moisture sensors, which are wired in series and buried at a mid root depth, 6 to 8 inches apart. The sensors are connected to the WEM via a single two-strand wire. The WEM is wired to the irrigation clock/controller so that it can prevent irrigation when the soil is wet. The WEM receives 24V-ac power from the pump start/master valve terminal on the clock at the start of each irrigation cycle. The WEM measures the resistance across the soil moisture sensors, which varies with moisture conditions, and overrides the irrigation controller when soil moisture is above the user selected point by interrupting the field common. Soil moisture levels are selected by the user with the adjustment knob on the WEM. The WEM's used in this study are labeled only with DRY, WET and OFF positions. This made it difficult to keep track of previous settings when adjusting the WEM, so a template that is installed behind the adjustment knob was created. The template, shown in Figure 2, is marked every five degrees and the previous settings can be recorded and finer adjustments made on the WEM.

The Watermark system is available to the residential homeowner as well as contractors via pipe and irrigation supply houses. The product can be installed quickly and with minimal knowledge of wiring. When installing the sensors it is important to select an appropriate site. They must be installed in a location that is representative of the overall area to be controlled. Precautions should be taken not to place the sensors in areas prone the collection of runoff, such as the bottom of a hill, as well as areas that do not reflect the area being irrigated, for example, in the shade if most of the vegetation receives direct sunlight. Next, wire is run from the sensors to the WEM and the WEM is then wired to the clock.

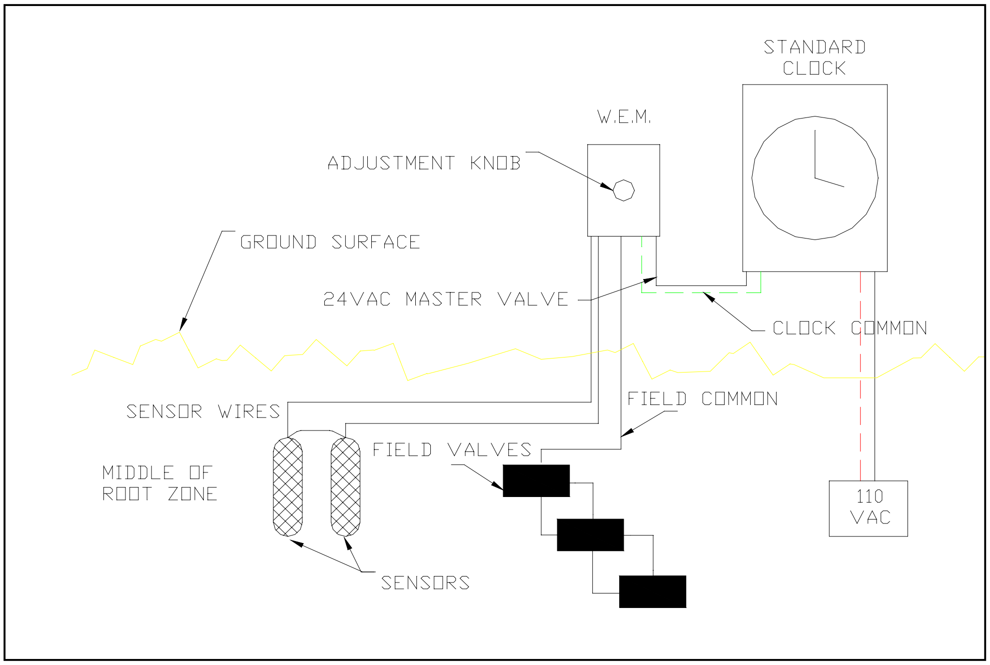

Figure 2: Schematic Layout of WEM System

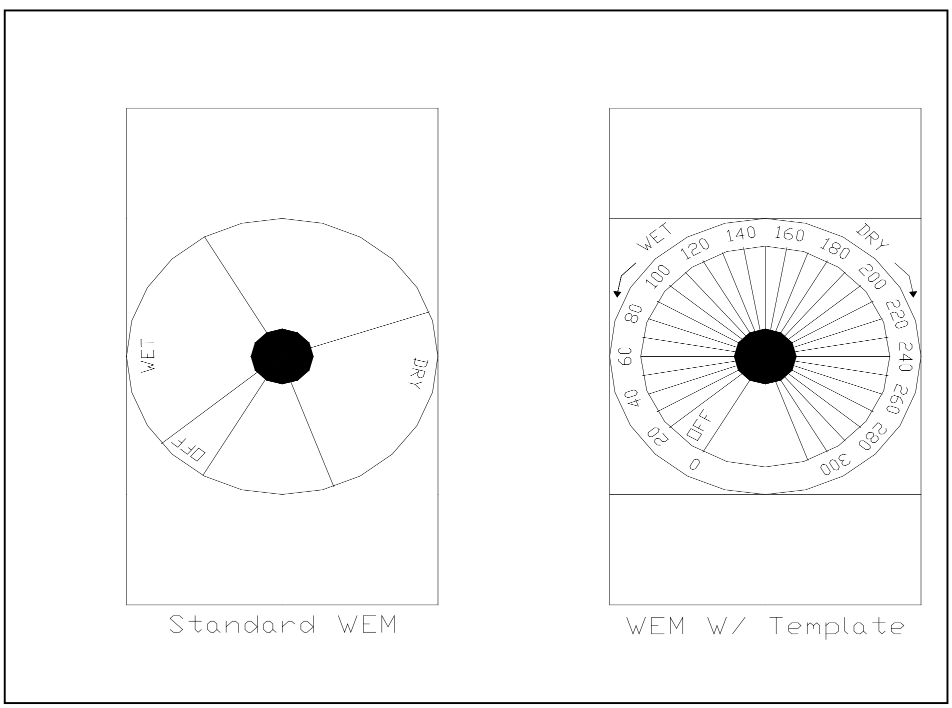

Figure 1: Modified WEM Face with Template

Once the soil moisture sensors are installed and the WEM is in place the consumer must find the appropriate dial setting for the WEM. When the soil has partially dried out, 3-4 days after irrigation such that it is just beginning to show some stress, the WEM is adjusted to the point where it is on the verge of calling for water. The irrigation clock is tuned off, and the WEM is gradually moved towards the wet end of the setting until irrigation is allowed. At this point it is moved slightly back to a dry setting. At this setting the system will be aligned so that the WEM is ready to call for water at the same time that the turf is ready to receive it. After this initial setting the vegetation will still need to be monitored and some fine tuning of the WEM may be necessary during routine maintenance.

When the appropriate WEM setting is found the irrigation timer is then set to come on everyday, or every other day. The zone times are set so that each zone will apply the maximum one or two day requirement. To avoid large surface runoff the application is broken down into several cycles so that application rates do not exceed infiltration rates of the soil. Once the system is set up in this manner it will not be necessary to reprogram the clock for seasonal demand variations. Furthermore, the system will also automatically respond to rainfall and temperature changes eliminating the need for daily programming during periods of rain. During routine maintenance, the WEM should be tested to ensure that it is working properly. Field checks are important because since the system is set to provide the maximum required application each time it comes on, any failure in the sensors would lead to significant over irrigation.

Procedures for 1997 Field Study

The fieldwork conducted for this study was aimed at collecting complete information about: 1. How well this group of sensors operated after being in the field for several years; 2. How frequently problems and errors occurred with the sensors; 3. The types of remedial actions which were required; and 4. The time and the cost required to operate and troubleshoot the system in the field. This is the information that appeared to be necessary to address the concerns of the Users Group expressed in the soil sensor review meeting.

The procedure for the 1997 study involved the following steps.

- A table was prepared listing all of the locations and contacts for all of the soil sensors that were installed in co-operation with the City from 1992 to 1996.
- All of the sensor locations were visited, and the owners/operators contacted so that a determination could be made as to which systems could be included in the study.
- Each system which was included was field checked and any necessary repairs were made (records were kept on all problems encountered and time spent).
- After start-up, each system was visited on a weekly basis to record water consumption and check the system for problems.
- Weather data were collected for calculation of local ET.
- Results were tabulated concerning both the hydrologic performance and time requirements for operating the system.

- In order to assist field personnel with monitoring the performance of their irrigation systems, simple tables were designed which allow users to track monthly or daily system performance.

Systems Included in 1997 Study

There were 23 sensor systems within Boulder that were monitored for this study. Two were installed on properties owned and maintained by the city, Elm Street Park and the Table Mesa site. Four were on residential properties, two in the Heatherwood neighborhood, one off Broadway and Alpine and the last off 28th Street and Jay Road. The remaining 17 sensors were installed in residential communities managed by CTB Services and maintained by two landscape contractors. Ten sensors were installed at the Winding Trail Village community at 28th Street and Winding Trail Drive and seven at the Willow Springs community on Iris and Juniper.

All the sensors and WEM's were installed during or prior to the 1995 study. As the first step in this study all the WEM's and soil moisture sensors were tested to see that they were in working order. One WEM at Winding Trail Village was not working and was replaced prior to data collection. A new WEM was installed at the Elm St. Park location because the WEM and irrigation timer had been vandalized. However the soil moisture sensors in both cases were found to be in good, working condition. Fifteen of the sensors had remained in the field for two years and were in good condition at the start of this study.

	Address of Installation	Year Installed	Irrigated Area (ft2)	Type of Irrigation Clock	Managed/Maintained By
Resident	4653 Kirkwood Ct.	1994	7120.8	Lawn Gene	Homeowner
	4736 Harwich St.	1994	11241	Richdel R416	Homeowner
	711 Alpine	1994	5929	Toro Freedom Four	Homeowner
	4313 Apple Wy.	1994	10466	Rainbird ESP 12	Homeowner
City	Elm Street Park	1992	10000	Rainbird ESP 6	City of Boulder - Streets
	Table Mesa Site	1992	1000	Richdel R414	City of Boulder - Streets
Willow Springs	2623 Juniper	1994	3341	Rainbird RC-7A	Contractor A
	2625 Juniper	1994	16913	Rainbird RC-7A	Contractor A
	2615 Juniper	1994		Buckner MT8	Contractor A
	2665 Juniper	1994	9005	Imperial Valet Timer	Contractor A
	2683 Juniper	1994	5691	Imperial Valet Timer	Contractor A
	2676 Juniper	1994	19690	Imperial Valet Timer	Contractor A
	2640 Juniper	1994	34618	Buckner MT8	Contractor A
Winding Trail Village	3877 Birchwood Ct.	1994	17487	Rainbird ESP 4	Contractor B
	3699 Roundtree Ct. (Top clock)	1994	15325	Imperial Valet Timer	Contractor B
	3699 Roundtree Ct. (Bottom clock)	1994	27718	Imperial Valet Timer	Contractor B
	3640 Roundtree Ct.	1994	9487	Rainbird ESP 4	Contractor B
	3753 Birchwood Dr.	1994	73000	Raindial	Contractor B
	3818 Northbrook Dr.	1994	84919	Imperial Valet Timer	Contractor B
	3834 Northbrook Dr.	1994	9226	Rainbird RC-7A	Contractor B
	3856 Northbrook Dr.	1994	29095	Buckner MT12	Contractor B
	2755 Winding Trail Dr.	1994	83035	Richdel 512PR	Contractor B
	2696 Winding Trail Dr.	1994	16796	Buckner MT12	Contractor B

Table 1: Sensor System Information

The WEM's were exposed to a variety of conditions. Three of the homeowners installed the WEM near their irrigation clocks in their basements. One homeowner had his installed in a splice box buried in the back yard. The remaining WEM's were all installed outside and while some were kept in the irrigation clock housing itself others were mounted in the open near the clock. At the Table Mesa site, the WEM was installed in 1992 and was mounted on a post, inside a small metal box. This was the oldest sensor of the group and while weathered worked fine throughout the study. One WEM at Willow Springs, two at Winding Trail Village and the one at Elm St. Park were all mounted outside the clock housing with no protection, that is they were exposed to direct sunlight and rain.

Establishment of Water Budget Models

In order to measure the performance of the systems we needed to have a standard against which their actual applications could be compared. The most reasonable value to use for this purpose was the weather based irrigation requirement based on net evapo-transpiration (net ET), which is the amount of water above rainfall that the vegetation requires to meet its metabolic requirements for maximum growth.

Net ET was calculated using local weather data , and the revised Blaney-Criddle method (SCS 1967). This method was chosen because it requires only temperature and precipitation data, which are the most readily available historic climate data. Soil moisture levels at each were expressed as the depth of water stored in the soil that is available for extraction by the vegetation. In the calculations this value was set at a maximum of 0.5 inches and was assumed to be at the maximum at the beginning of the irrigation season.

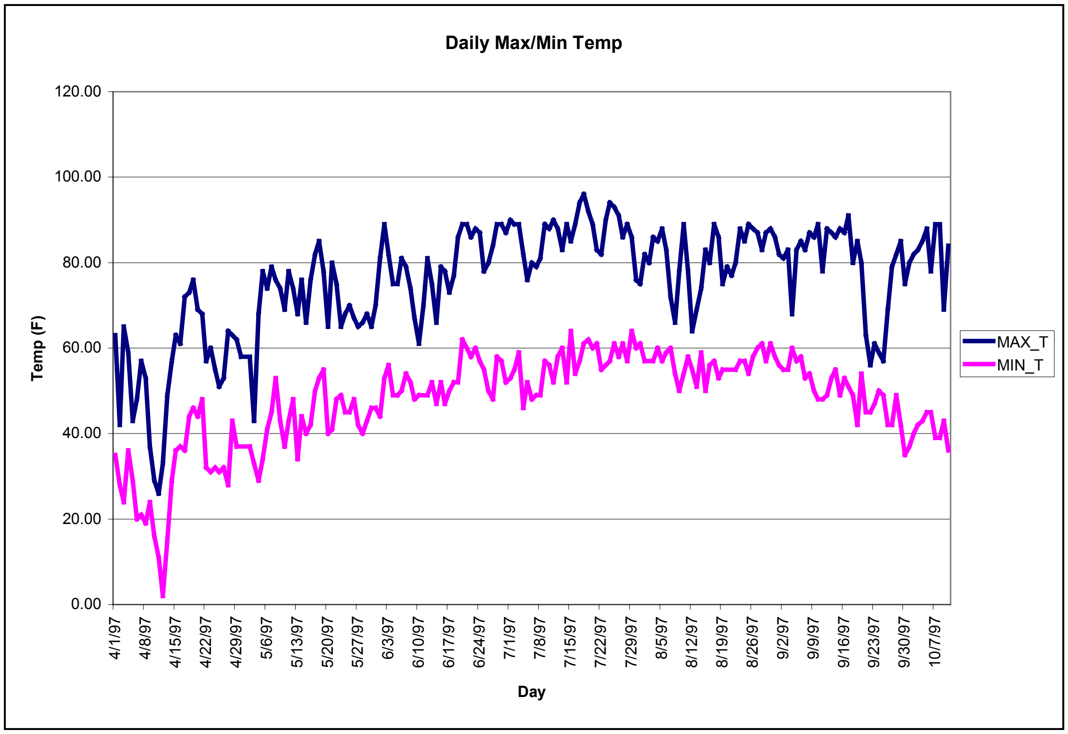

Figure 3: Daily Max/Min Temperature

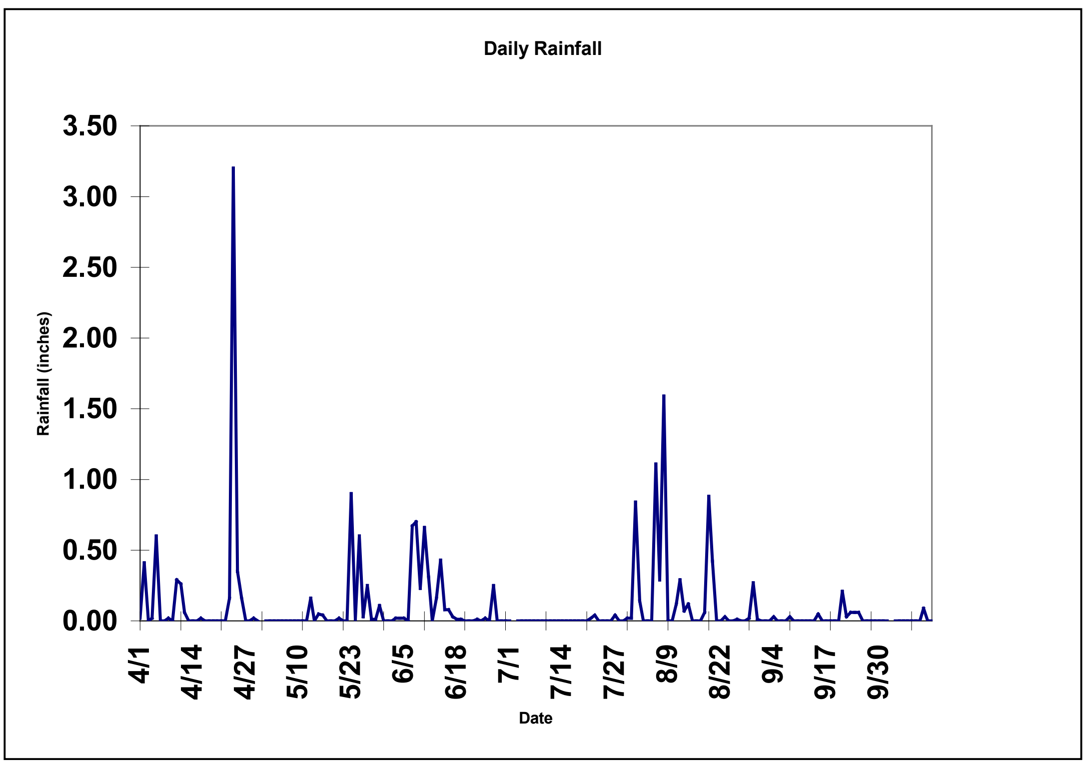

Figure 4: Daily Rainfall

The calculations were carried out using two spreadsheet models (please refer to Appendix C for examples). First, a model to calculate the net ET was developed. In this spreadsheet the daily temperature extremes and precipitation values, shown in Figures 3 and 4, were entered, and using the Blaney-Criddle method the net ET was calculated. From this the daily ET deficit, the amount of water that was removed from the soil by evapotranspiration, was determined. The daily ET deficit was conveyed to the second spreadsheet model via linked cells. In the second model the outdoor water usage was tracked, in gallons read from the meter, and converted into an application depth, in inches. Using the daily ET deficit from the first model and the irrigation application depth determined from field readings, the daily soil moisture value was calculated in the second model in checkbook balance fashion.

The theoretical irrigation requirement was determined in two steps. The daily net ET was first satisfied from soil moisture. As long as there was sufficient water stored in the soil (up to its estimated capacity of 0.5") no irrigation requirement was shown. When the soil moisture was depleted, however, the irrigation requirement was determined as the quotient of the daily net ET divided by the system irrigation efficiency.

In the second model, the theoretical irrigation water requirement and the actual irrigation application were tracked cumulatively and compared throughout the season. This was done for each water meter monitored. Results for each meter can be seen graphically in Appendix B. In this second model the assumed efficiency of the systems was 90%. This is a number typical to sprinkler application during non-daylight hours. Also, it was assumed that the systems had no leaks. System users reported no leaks in their respective systems and there was no evidence to indicate otherwise.

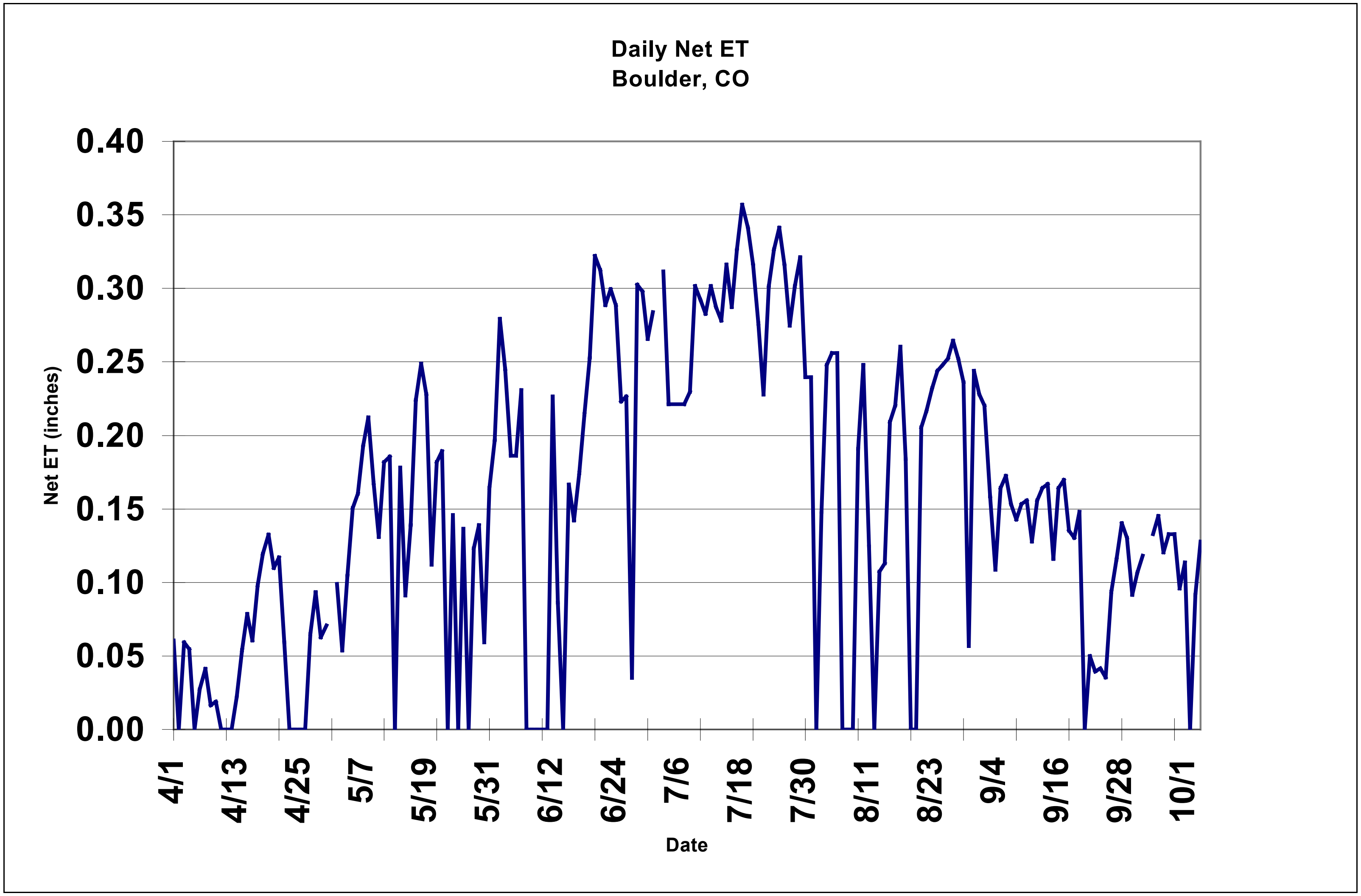

Figure 5: Daily Net ET

Field Visits and Data Collection

Each site was visited once a week to record data. Water use data were collected manually by reading gallons used on the water meter that monitored each clock. Where the meters provided domestic as well as irrigation water the meter's record was obtained through the city Utility Billing Office and the average winter water use was subtracted from the current meter reading to obtain the outdoor use. The volume of water applied was converted to a depth by dividing the volume applied, in cubic feet, by the irrigated area, in square feet. Irrigated areas were determined using aerial photos and AutoCAD drawings when available. The time required to test each WEM and any remedial action required was recorded as well as an assessment of the vegetation condition and any WEM adjustments made. Daily climate data, temperature extremes and precipitation, were obtained from a weather station located on the U. S. Department of Commerce grounds, at 27th Street and Broadway. The climate data were entered into the databases where the ET values and irrigation requirements were calculated.

Development of Irrigation Assessment Tables

During the User Group meeting during the fall of 1996 one of the major needs identified was for a simple way to evaluate how well any irrigation system (either with or without a sensor) is operating. Also, the users reported that this was especially important on systems that had sensors because they needed some feedback as to how well each system was performing. In order to meet this need a set of tables that allow for a comparison of actual irrigation application with the average theoretical irrigation requirement was developed as part of this study. The system allows the user to track the performance of the system on either a monthly or daily basis. In most cases monthly tracking should be adequate, but for larger or more complex systems daily tracking may be warranted. The tables are filled in by the users and will give them accurate data on how well their irrigation schedules match the theoretical application requirement or whether the vegetation is being over or under irrigated.

Two tables were developed; the first is based on a monthly time step and the second on a daily time step. Examples of both tables and the instructions for the tables explain each column and the calculation procedures are included in Appendix A of the report. In order to keep the system simple, both tables are dependent upon a number called the "Irrigation Factor". The Irrigation Factor is a number unique to each irrigated area and is determined by dividing 1604 by the irrigated area, in square feet. The number 1604 has the units inches-ft^2 /thousand gallons. When divided by the irrigated area in ft^2 the results is a factor with units of inches per thousand gallons. Using the Irrigation Factor, it is then easy to convert between gallons applied and inches applied as well as from theoretical inches to theoretical gallons of application.

The first table, the monthly time step, specifies a target application for the month. This target application is based on 85% of the average monthly ET based on Boulder climate data from 1900 to the present. The purpose of this table is simply to allow the user to quickly determine how much water should be applied to a given system in order to meet the *average* ET. In order to use the table the irrigator needs to first determine the area being irrigated by a specific system and the location of the water meter serving the system so that actual water use can be determined in the field. These basic pieces of information are essential and their collection, by themselves, will provide a significant step toward improved irrigation management. Once the Irrigation Factor for each parcel has been determined the users can convert from the target application, in inches, to target application, in thousands of gallons. The theoretical water application can then be compared with the actual application to see how well the two agree.

As mentioned above, the theoretical irrigation requirement is based on long-term averages (1900 – 1996), the actual application required for one specific season or month may be above or below the average. However, with the use of this table in conjunction with weather data published in the newspapers, the irrigators can judge whether a particular month or season was dryer or wetter than average and how well their actual application and scheduling coincides with the target application.

The second table, which is incremented on a daily time step, provides more accurate information, but it requires the user to record the daily maximum and minimum temperature and the daily precipitation. The table uses a monthly irrigation constant, which is a combination of ET and crop coefficients to calculate daily net ET via the Blaney-Criddle method. The net ET value is determined by subtracting the usable precipitation from the daily ET estimate. Useable precipitation is the amount of precipitation available to the vegetation, after abstractions, and for simplicity is taken as 80% of the actual precipitation for use in the table. The daily worksheet tracks soil moisture as the water in the soil available to be extracted by the vegetation. Based on the soil type found in this region the maximum soil moisture amount was determined to be 0.5 inches and for the purposes of the table the soil moisture is assumed to be at its maximum at the start of the irrigation season in April. The daily soil moisture value is determined by subtracting the net ET from the previous day's soil moisture. When the soil moisture value reaches zero or becomes negative it is time to irrigate. The required application depth is then calculated by subtracting the residual soil moisture from the target of 0.5 inches. Using the Irrigation Factor this depth can be converted to thousands of gallons.

The tables can be combined with a user monitored rain gage and thermometer installed on the irrigation site to produce more accurate results. Inexpensive rain gages and thermometers that record the daily temperature extremes can be purchased at hardware or electronics stores. Because of the significant spatial variability of Boulder's weather, data collected on site will increase the accuracy of the tables. If this is done it is important that the climate data be recorded everyday, as missing data or data from other sources will cause inaccuracies in the calculations.

These tables will allow the user to track performance of any irrigation system, but are intended specifically to provide feedback on performance of systems with soil moisture sensors. Even if the user simply determines the irrigated areas and reads the meter(s) on the first day of each month the accounting will provide confirmation of the irrigation system performance 6 or 7 times per season, which will either confirm it is working as desired, or will allow necessary adjustments to be made. In either case, the user will not have to guess about how well the scheduling is matching actual requirements.

Results of 1997 Study

The following section provides detailed results of the hydrologic and operational performance of the soil moistures systems included in this study. The body of the report contains summary information of the performance of all of the system. Details about each individual system are provided in Appendix B.

Irrigation Efficiency of Soil Sensors

The overall seasonal performance of the sensor controlled irrigation systems is summarized in Table 2. This table lists the actual applications for each site compared to the theoretical requirement for the period from April 1st to October 10th. During this period the requirement was 28.23" and the average application for the 23 sensor controlled systems was 21.35", which is 76% of the requirement. The maximum application was 124% at one of the Willow Springs sites, and the minimum application was 52% at one of the Winding Trails sites.

The seasonal results show that the systems were able to match long term applications to requirements, typically on the low side. It is very interesting to look at the short term results, especially the system's ability to prevent watering during times of excess rain, which can be seen in Figure 5 and Appendix B. Where the theoretical requirement curve flattens is an indication of little or no net ET (implying cool/rainy conditions), and where the actual application curve remains flat or increase in small increment the irrigation application rate is reduced.

There was considerable variation in performance. Some of this can be explained by differences between the irrigation sites and the weather station. The conditions at the sites certainly varied due to micro climate effects. At some sites there may have been more or less rain than at the weather station which would lead to an apparent disagreement between the sensors and the irrigation demands. Also, we were in the process of developing the irrigation guides during the study. If these had been available it would have been possible to make small adjustments to individual systems.

Table 2: Performance of Sensor Systems

	Address of Installation	Theoretical Requirement (inches)	Actual Application (inches)	% of Theoreical Requirement
Resident	4653 Kirkwood Ct.	28.23	15.35	54.39%
Resident	4736 Harwich St.	28.23	16.09	57.01%
Resident	711 Alpine	28.23	18.60	65.89%
Resident	4313 Apple Wy.	28.23	23.64	83.76%
City	Elm Street Park	28.23	16.23	57.51%
City	Table Mesa Site	28.23	19.52	69.14%
Willow Springs	2623 Juniper	28.23	21.00	74.40%
Willow Springs	2625 & 2615 Juniper	28.23	20.27	71.83%
Willow Springs	2665 Juniper	28.23	35.03	124.09%
Willow Springs	2683 Juniper	28.23	28.00	99.21%
Willow Springs	2676 Juniper	28.23	22.53	79.83%
Willow Springs	2640 Juniper	28.23	30.42	107.79%
Winding Trail Village	3877 Birchwood Ct.	28.23	14.73	52.18%
Winding Trail Village	3699 Roundtree Ct. (Top Clock)	28.23	15.63	55.38%
Winding Trail Village	3699 Roundtree Ct. (Bottom Clock)	28.23	27.83	98.60%
Winding Trail Village	3640 Roundtree Ct.	28.23	15.83	56.07%
Winding Trail Village	3753 Birchwood Dr.	28.23	14.68	52.01%
Winding Trail Village	3818 Northbrook Dr.	28.23	20.50	72.61%
Winding Trail Village	3834 Northbrook Dr.	28.23	19.80	70.16%
Winding Trail Village	3856 Northbrook Dr.	28.23	21.54	76.30%
Winding Trail Village	2755 Winding Trail Dr.	28.23	21.16	74.95%
Winding Trail Village	2696 Winding Trail Dr.	28.23	31.40	111.24%
	Average	28.23	21.35	75.65%

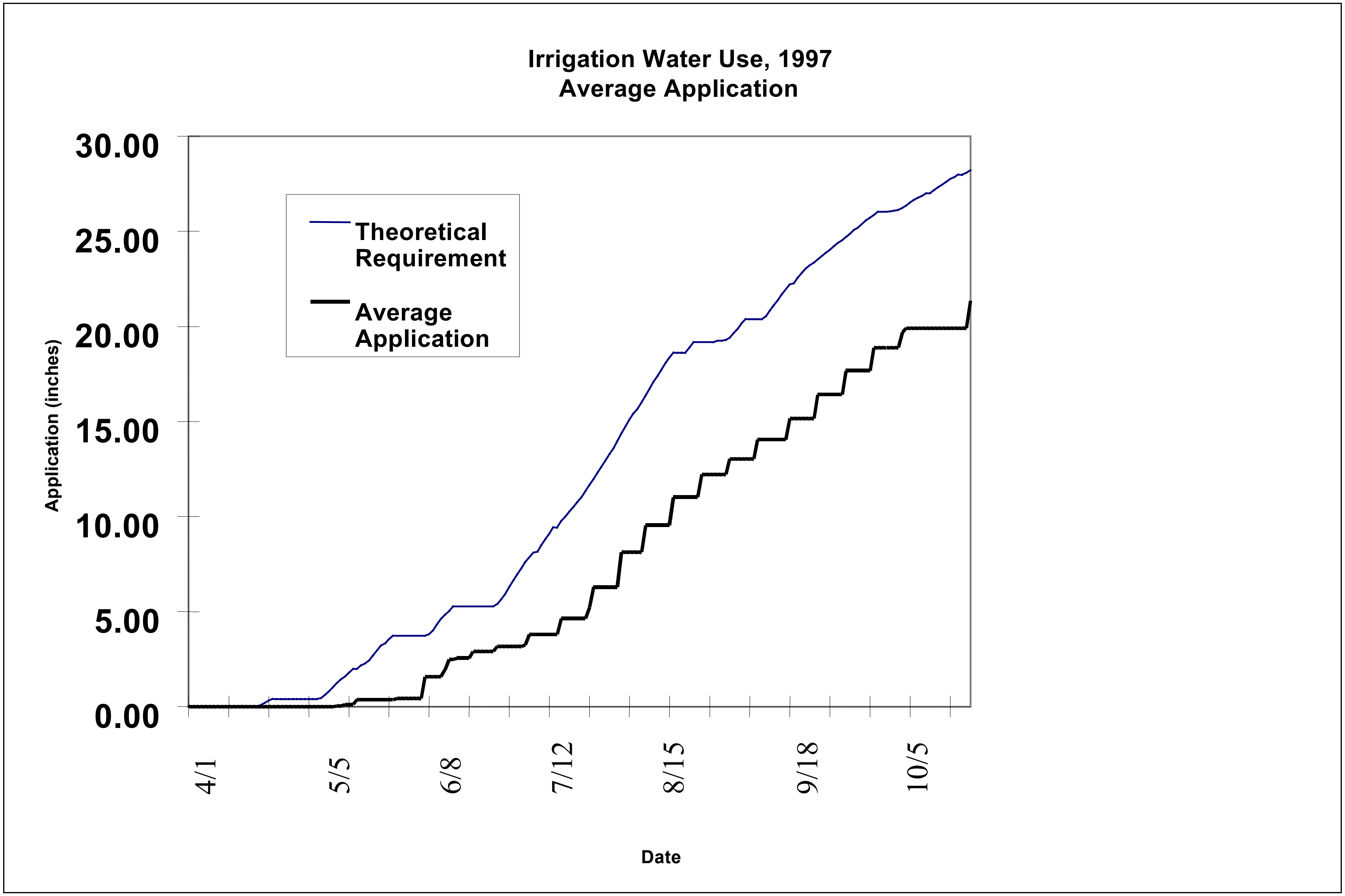

Figure 5: Theoretical Vs Average Application

Time and Money Requirements for Operating the System

This project was conducted by Joshua Scott, a graduate student at the University of Colorado. Prior to the start of the project he had little experience with irrigation timers and no experience with soil moisture sensors. After receiving initial orientation including reading the prior reports and the manufacturers instruction sheet, and visiting the sites with experienced personnel Joshua was left to his own devices to manage the system, collect the data and obtain help as needed. Our experience was that the time invested in becoming familiar with the systems was quite minimal. The operation of the different irrigation timers, the locations of sensors and how the WEM's are wired to the clocks took an average of 12 minutes per system to learn. A walkthrough at the largest site, Winding Trail Village, took about two hours, and included initiation on the hardware and a preliminary check to see that the WEM's and soil moisture sensors were working properly.

The time required to maintain a system that employed the Watermark system was tracked for this study. Site visits were made on a weekly basis and the time of arrival was recorded and then each sensor on the site was checked. The time the check began and the

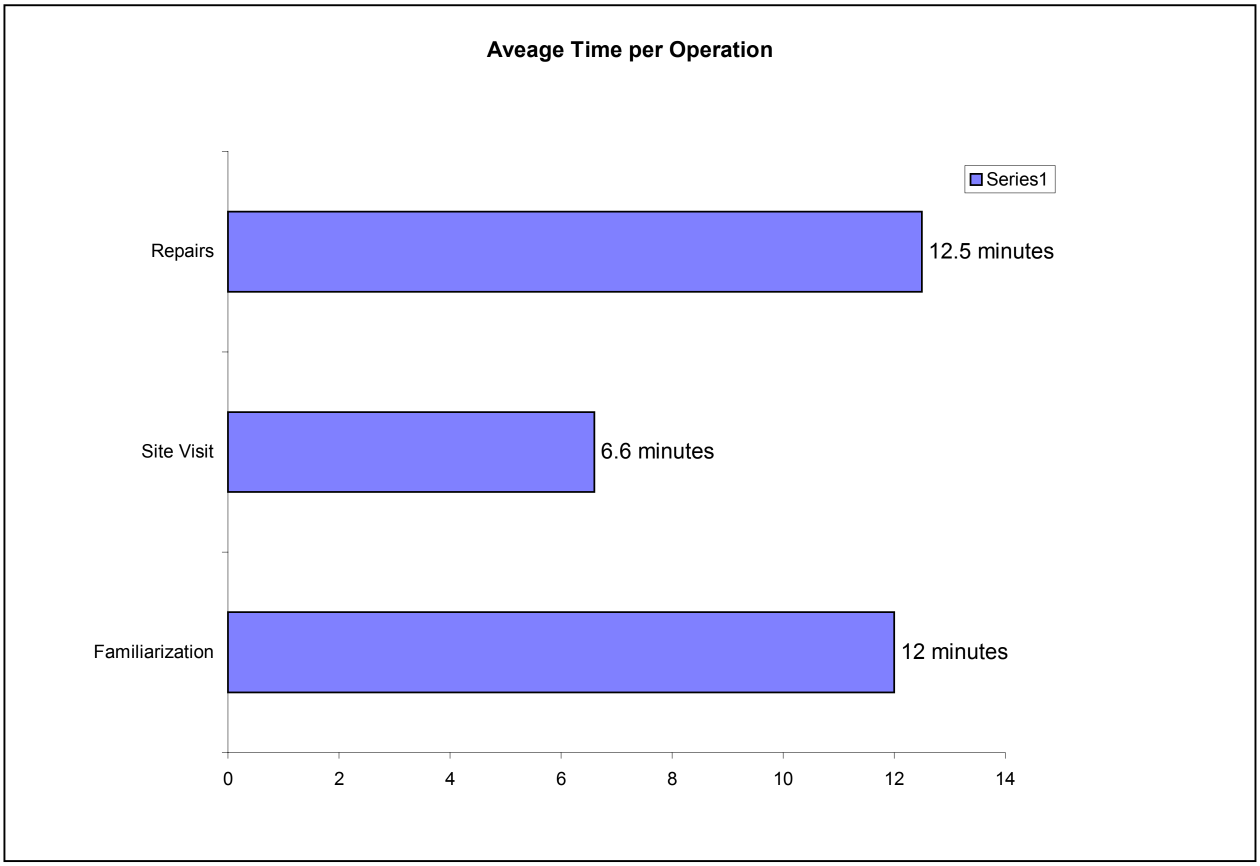

Figure 6: Operation Times

time it ended was recorded. The system check consisted of recording the water meter reading, noting the condition of the vegetation, irrigation days and times, and a check of the WEM and moisture sensors. First a visual inspection of the WEM was performed and the setting on the WEM dial was recorded. Then, to make sure the WEM and sensors were working, the WEM was turned to the DRY setting and the clock was manually turned on. When the WEM is in the extreme DRY setting it will override the clock and prevent irrigation. If this was preformed successfully the WEM was turned to the OFF position and the clock manually turned on, this allows for the sprinklers to come on and an inspection of the sprinkler system is done. If any broken sprinkler heads or other problems were noticed the contractor or homeowner was notified. With the system turned off any adjustments on the WEM were done and recorded at that time and the system was placed back in the automatic mode. To perform the system check as outlined took an average of about 6-7 minutes barring problems. Our experience indicates that an operator who is familiar with the Watermark system and the different clocks encountered could monitor many systems, at a rate of about ten man hours per 100 WEM's per week. This does not include travel time between sites, which would be required anyway as part of normal site checks. For this study a typical weekly round of site visits took approximately four hours, which included travel time (20 miles of driving) and a system check of 23 sensors.

During the course of this study there were very few system problems. Two WEM's needed replacing; one at the Elm Street mini park because of vandalism and the other on the Winding Trail Village property because the clock, which was replaced in May, had shorted out the WEM. One homeowner had replaced some pipe for the system and in doing so cut the wire from the sensors to the WEM. The wire was spliced back together and the system was operational for the start of data collection. These were problems that were corrected quickly and easily. Repairing the severed wire took only about 15 minutes to locate and repair while installing a new WEM was approximately a ten minute job.

It is quite noteworthy that no moisture sensors had to be replaced; which would have required extra time on the part of the system manager. Also, with the exception of the WEM's which was shorted out or stolen none of these control units needed replacement.

Costs for repair of the systems were modest. While the splicing job was inexpensive, about $9, a higher cost was associated with replacing the WEM's. The WEM's were purchased for $130 each. WEM's that fail in the field may be returned to Irrometer and if the failure was the result of a faulty WEM it will be replaced. In the first replacement the WEM had been stolen and in the second the WEM was damaged due to a problem with the irrigation clock so the cost burden was placed on the project. The total cost for repair and replacement of the 23 sensor system was approximately $270, but none of these costs can fairly be ascribed to problems with the sensor equipment, but are typical costs for dealing with theft and electrical problems in any irrigation system. Even if all of the costs were charged to the system the expected materials and repair costs would come to just under $12/unit per year. The labor time discussed above includes the time for repair and replacement.

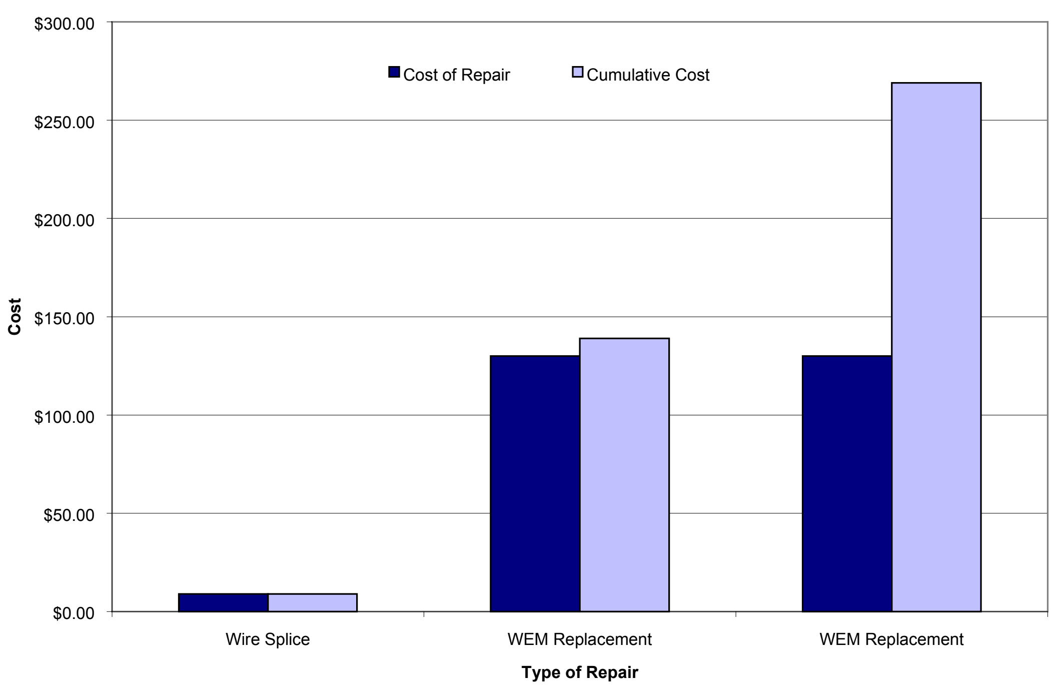

Figure 7: Repair Costs

This study confirmed our previous findings that the human factor continues to constitute the most important cause of potential failure in the system. We were dealing with two contractors: Contractor A and Contractor B. Contractor B, who was responsible for one of the two residential communities was the largest obstacle in this study. Contractor A, the contractor for the second residential property, was enthusiastic and cooperative about the study. However, Contractor B did not share his feelings and made his distrust of the sensors known from the start, but participated in the study primarily because the property management company directed him to do so. After the June rainfall he called to report that the sensors did not shut off the systems. In response the water use records, which showed that in fact no inappropriate irrigation had occurred were reviewed with him. Apparently, the success of the system in June did not convince him because during the rainy period in August he manually deactivated the timers for approximately six days without notifying the study team. While preliminary results showed that the systems were all performing at or below the theoretical requirement he was still not convinced of the value of the soil sensor system. Frequent meetings were necessary to show the results of the tracking and to keep him involved in the study. Much of this lack of trust in the sensors can be attributed to lack of immediate feedback. The contractor was unable to track the system performance himself and remained unconvinced. This is the reason behind the irrigation assessment tables; by providing immediate feedback of the system performance we hope that even the most skeptical contractor can be provided with the information needed to operate a sensor controlled system with confidence.

Conclusions and Discussion

This study reported on the time required to maintain, as well as the performance of, 23 Watermark soil moisture sensors and electronic switching modules (WEM's) in controlling various irrigation timers. All sensors were installed during or prior to 1994, four were used by homeowners, two by the city and seventeen by two independent contractors on larger residential properties. The performance of the systems was verified on a weekly basis by field inspections during which each unit was checked using the manufacturer's troubleshooting procedure. Durability of the systems exceeded expectations. Despite being in the field for several years only two WEM's needed to be replaced, for unrelated causes. In all cases the soil moisture sensors, the elements in direct contact with the ground, remained functional and did not need replacement.

Determination of the theoretical irrigation water requirement was accomplished by entering weather data into a spreadsheet model and then comparing it with the actual water application in a second, linked model. These models showed that the theoretical requirement during the study period was just over 28 inches and that on average the Watermark systems allowed approximately 21 inches, or 76% of the theoretical requirement, to be applied. This occurred despite the fact that each irrigation timer was programmed for maximum demand conditions, and set to run at least every other day. If any portion of the operation was cause for concern, we might consider the *low* application rates a problem, although we never received any complaints from property owners about the quality of the landscape. The sensors were limiting average applications to 76% of the theoretical requirement, but in some cases rates were down in the 50% range. While some of this variation may be explained by local weather conditions as the system progresses there appears to be a tendency for the sensors to withhold too much water. This should be addressed by using the tracking tables and making adjustments as necessary to the moisture level setting latter in the season.

The study showed that the time required to add soil moisture sensors to a group of irrigation timers was minimal. This study included weekly site visits during which a check of each system was performed. This system check took an average of 6-7 minutes per irrigation timer. Our experience leads us to estimate that Watermark systems can be monitored at a rate of about ten man hours per 100 WEM's per week (assuming weekly checks). Operators not familiar with the Watermark system can be initiated in less than 15 minutes. The wiring of WEM's to irrigation timers is easy to follow and understand and the interaction between the WEM's and soil moisture sensors can also be taught in minutes. Only three repairs were necessary and were remedied in a short amount of time and remedied at a total cost of $269; the average repair time was under 13 minutes. A contractor interested in installing and monitoring the Watermark system can accomplish this task with a minimum number of staff hours. During familiarization approximately 10 hours per week per 100 systems should be allowed. Once the systems are properly set we estimate the systems can be monitored using half the time, or 5 hours per week per 100 units. The average repair costs for a system of the age and condition found in this study was approximately $1200 per 100 units per year. The repairs will be primarily due to replacement of damaged or stolen WEM's.

The largest obstacle in this study was not equipment failure but skepticism on the part of one of the landscape contractors. One out of the two contractors did not trust the WEM's to interrupt the irrigation during rainy periods, despite being shown the water meter data which proved that the system had in deed been properly shut down. Frequent conversations with this contractor were necessary to ensure him that the systems were working properly and that they should remain on line.

The problem of distrust of the equipment had been previously noted, and was the reason that a set of irrigation scheduling tables was developed. These allow the user to track the performance of their irrigation systems on a monthly or daily basis for more immediate feedback. When used in conjunction with the Watermark system the contractors can determine weather the WEM has interrupted the irrigation cycle and if not then adjustments can be made. The irrigation scheduling tables stand on their own and can be used by any irrigator, regardless of weather they have soil moisture sensors installed or not. Irrigation performance can be tracked and compared to the theoretical requirements of the vegetation, allowing the users to determine if they are over or under watering.

As a further aide to operation of the system, a template for the WEM face was developed. The current WEM face is labeled with only wet and dry regions. This made it hard to keep track of the previous position of the WEM and how far to turn the adjustment knob when fine tuning the system. A template that is installed behind the adjustment knob and is marked every five degrees allowed the WEM positions to be noted and adjusted to wetter or drier positions more precisely. Templates can be installed quickly and easily and do not interfere with the operation of the system.

The ability of the WEM's to interrupt irrigation cycles during periods of rain was apparent in the data. This is particularly important on the properties managed by independent contractors where the contractors may be on site only once a week, or less.

This showed that the systems could be left for significant periods of time and if there were sufficient soil moisture available to the vegetation the WEM's would prevent irrigation. We believe that strictly from the operator's perspective, the time spent on installing and operating the soil moisture system will be more than compensated by the time saved in reprogramming and shutting off the systems in response to rain.

The soil moisture equipment used in this multi year study: the Watermark sensors and Watermark Electronic Module (WEM) proved themselves to be rugged and reliable. The WEM's remained in the field, exposed to a variety of weather conditions, and functioned properly after a 3 to 5 years. The soil moisture sensors, likewise, continued to operate properly after being in the soil for the same period of time.

The overall results of this study confirm the findings of the previous two studies:

1. The Watermark soil moisture sensors and WEM can automatically schedule irrigation applications at or under net ET requirements.
2. The equipment has operated for from 3 to 5 years without any failures in sensors, and with occasional WEM replacements needed for causes unrelated to the units themselves
3. The time required to operate the system is estimated at 10 hours per week per 100 units at start up and 5 hours per week for routine operation.
4. Costs for materials for replacements are estimated at $1200 per 100 units per year (this includes WEM replacement).

5. The use of the simple, monthly irrigation scheduling table presented in this report should greatly assist operators in tracking performance of the systems and, it is hoped, decrease their hesitancy to trust the technology.
6. The systems demonstrated that they routinely terminate irrigation after rainfall events, and keep it off until the soil dries out. This ability alone should justify the use of the sensors by irrigation managers who otherwise would have to travel to each site and manually shut of the clocks or, worse, allow the systems to irrigate in the rain.
7. Addition of soil moisture sensors, especially to systems with known high water use would greatly improve the efficiency of urban water use, and conserve potentially huge amounts of water.

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W. B. DeOreo, Lander, P., " Hard Data on Soil Moisture Sensor Performance: Summary of Soil Moisture Sensor Operations in Boulder, Colorado." Irrigation Association national meeting, Phoenix, AZ 1995

Aquacraft Water Engineering and Management, “Project Report: A Process Approach for Measuring Residential Water Use and Assessing Conservation Effectiveness”, Prepared for the City of Boulder, Office of Water Conservation, November 1994.

Cuenca, Richard H., *Irrigation System Design*, Prentice Hall, New Jersey, 1989.

Soil Conservation Service, Engineering Division, “Irrigation Water Requirements: Technical Release No. 21”, United States Department of Agriculture, April 1967.

Appendix A: Irrigation Scheduling Tables

The following tables allow for a comparison of actual irrigation application with the average theoretical irrigation requirement on a monthly time step. They were developed assuming a target application of 85% of the average evapotranspiration for the Denver Metro area of Colorado. If used outside this region, local climate data and ET values should be employed. The evapotranspiration was calculated using the Blaney-Criddle method with a crop coefficient for turf grass. These tables will give the user a sense of how well their irrigation scheduling follows the theoretical requirement; it should be noted that drought or inundation will cause extreme deficit or surplus when compared to the long term averages used in the tables. There are several tables that follow, use one table for each meter monitored.

1. Determine the number of irrigation clocks that are connected to the same water meter. Then calculate the area irrigated by each of these clocks and sum the areas to determine the total area of irrigation monitored by the meter. It may be helpful to record the meter location and number if many meters will be checked or if meters will be read by more than one person.
2. Calculate the Irrigation Factor for each meter. This is done by dividing 1604 by the area irrigated, in square feet. This factor, with units of inches per thousand gallon, will be used to determine the inches of water applied as well as the target application for the selected area.
3. The target application in thousands of gallons is simply the target application in inches divided by the Irrigation Factor. Enter the target application value into the table.
4. Take water meter readings at the beginning of the month and the end of the month. The actual gallons used is determined by subtracting the meter reading at the beginning of the month from the meter reading at the end of the month. Divide the actual gallons used by 1000 to get thousands of gallons used and enter this number into the table.
5. To determine the inches of application multiply the volume used, in thousands of gallons, by the Irrigation Factor. This can be compared to the target application for a particular month.

Average Monthly Rainfall (inches)

April	May	June	July	August	September
2.34	2.91	2.12	1.92	1.46	1.79

Helpful Conversion Factors

1 ft^3 = 7.48 gallons
1 acre = 43,560 ft^2
1 acre-ft = 325,851 gallons

Meter Number:__________________ Location:____________________________

Area:__________________________ Irrigation Factor:_______________________

Month	Target Application (inches)	Target Application (thou gal)	Actual Application (thou gal)	Actual Application (inches)
April	1.0			
May	2.8			
June	5.9			
July	7.4			
August	6.2			
September	2.9			
Total	26.2			

Meter Number:__________________ Location:____________________________

Area:__________________________ Irrigation Factor:_______________________

Month	Target Application (inches)	Target Application (thou gal)	Actual Application (thou gal)	Actual Application (inches)
April	1.0			
May	2.8			
June	5.9			
July	7.4			
August	6.2			
September	2.9			
Total	26.2			

Meter Number:____________________ Location:______________________________

Area:___________________________ Irrigation Factor:________________________

Month	Target Application (inches)	Target Application (thou gal)	Actual Application (thou gal)	Actual Application (inches)
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May	2.8			
June	5.9			
July	7.4			
August	6.2			
September	2.9			
Total	26.2			

Meter Number:____________________ Location:______________________________

Area:___________________________ Irrigation Factor:________________________

Month	Target Application (inches)	Target Application (thou gal)	Actual Application (thou gal)	Actual Application (inches)
April	1.0			
May	2.8			
June	5.9			
July	7.4			
August	6.2			
September	2.9			
Total	26.2			

Meter Number:____________________ Location:______________________________

Area:___________________________ Irrigation Factor:________________________

Month	Target Application (inches)	Target Application (thou gal)	Actual Application (thou gal)	Actual Application (inches)
April	1.0			
May	2.8			
June	5.9			
July	7.4			
August	6.2			
September	2.9			
Total	26.2			

The following tables allow for a comparison of actual irrigation application with the average theoretical irrigation requirement on a daily time step. They were developed assuming a target application of 85% of the average evapotranspiration for the Denver Metro area of Colorado. If used outside this region, local climate data and ET values should be employed. The evapotranspiration was calculated using the Blaney-Criddle method with a crop coefficient for turf grass. These tables will give the user a sense of how well their irrigation scheduling follows the theoretical requirement; it should be noted that drought or inundation will cause extreme deficit or surplus when compared to the long term averages used in the tables. For more accurate results the tables can be combined with a user monitored rain gage and thermometer installed on the irrigation site. Daily climate data, high and low temperatures and inches of precipitation, can be collected and used in the tables. If this is done it is important to record the observations daily as missing data or data from other sources can cause inaccuracies in the calculations.

First, determine the number of irrigation clocks that are connected to the same water meter. Then, calculate the area irrigated by each of the clocks and sum the areas to determine the total area of irrigation monitored by the meter. It may be helpful to record the meter location and number if many meters will be checked or if meters will be read by more than one person.

Monthly Constant - This number is already at the top of each monthly worksheet and is a factor used in the calculation of the evapotranspiration estimate.

Irrigation Factor - Calculate the Irrigation Factor for each meter; this factor will remain constant throughout the season. This is done by dividing 1604 by the area irrigated, in square feet. This factor, with units of inches per thousand gallons, will be used to determine the amount of water applied to the selected area.

$$\text{Irrigation Factor} = \frac{12 \text{ inches}}{1 \text{ ft}} \times \frac{1 \text{ ft}^3}{7.48 \text{ gallons}} \times \frac{1000 \text{ gallons}}{\text{thou gal}} \times \frac{1}{\text{Area, ft}^2}$$

$$\text{Irrigation Factor} = \frac{1604 \text{ inches-ft}^2}{\text{thou gal}} \times \frac{1}{\text{Area, ft}^2}$$

T max - Enter the high temperature for the day.

T min - Enter the low temperature for the day.

T ave - Calculate the average daily temperature. Sum the daily high and low and divide by two.

Precip - Enter the rain reported for the day in inches.

ET Calc I - Multiply monthly constant by the average temperature, T ave, and enter into the table.

ET Calc II- Multiply the average temperature, T ave, by 0.0173; then subtract 0.314 from this number and enter into the table.

ET - Calculate the daily evapotranspiration estimate, in inches, by multiplying the number entered in ET Calc I by the number entered in ET Calc II.

Useable Precip - To calculate the useable precipitation multiply the value in the Precip column by 0.8.

Net ET - Subtract the useable precipitation from the calculated ET value. A positive number indicates a daily deficit of water and irrigation may be necessary. A negative number indicates a daily surplus of water and therefore no irrigation is necessary.

Soil Moisture - This is the amount of water in the soil that is accessible to the plants. For the purposes of the worksheet it is assumed that the soil moisture at the beginning of the season is 0.5 inches. To calculate the soil moisture for the day subtract the current net ET value from the previous day's soil moisture value. When the soil moisture reaches zero or becomes negative it is time to irrigate. After irrigating, the soil moisture value will be set to 0.5 inches. The maximum amount of soil moisture that can be stored is 0.5 inches; for example, if it rains the day after irrigation a value of 0.5 inches should be entered for that day.

Required Application (inches) - When the value in the soil moisture column reaches zero or becomes negative subtract that number from 0.5 inches, this is the required application of water in inches. **** When subtracting a negative number the sign will change and the number will become positive: 5 - (-2) = 5 + 2 = 7.

Required Application (thou gal) - Divide the required application (inches) by the Irrigation Factor to determine the number of thousands of gallons that should be applied to the vegetation.

Actual Application (thou gal) - Subtract the meter reading at the beginning of the cycle from the meter reading at the end of the cycle and divide by 1000 to determine the actual number of thousands of gallons applied.

Actual Application (inches) - The actual application depth in inches is simply the actual application in thousands of gallons multiplied by the Irrigation Factor.

Average Monthly Rainfall (inches)

April	May	June	July	August	September
2.34	2.91	2.12	1.92	1.46	1.79

Helpful Conversion Factors

1 ft^3 = 7.48 gallons
1 acre = 43,560 ft^2
1 acre-ft = 325,851 gallons

Month: April

Meter # :__________________________ Location:___________________________ Irrigated Area:________________________

Monthly Constant: .0029 Irrigation Factor:_____________________

Day	T max	T min	T ave	Precip	ET Calc I	ET Calc II	ET	Useable Precip (Precip * 0.8)	Net ET	Soil Moisture (inches)	Required Application (inches)	Required Application (thou gal)	Actual Application (thou gal)	Actual Application (inches)
-	-	-	-	-	-	-	-	-	-	0.5	-	-	-	-
1														
2														
3														
4														
5														
6														
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Month: May

Meter # :__________________________ Location:___________________________ Irrigated Area:_______________________

Monthly Constant: .0041 Irrigation Factor:

Day	T max	T min	T ave	Precip	ET Calc I	ET Calc II	ET	Useable Precip (Precip * 0.8)	Net ET	Soil Moisture (inches)	Required Application (inches)	Required Application (thou gal)	Actual Application (thou gal)	Actual Application (inches)
1														
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5														
6														
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30														
31														

Month: June

Meter # :__________________________ Location:___________________________ Irrigated Area:_______________________

Monthly Constant: .0043 Irrigation Factor:

Day	T max	T min	T ave	Precip	ET Calc I	ET Calc II	ET	Useable Precip (Precip * 0.8)	Net ET	Soil Moisture (inches)	Required Application (inches)	Required Application (thou gal)	Actual Application (thou gal)	Actual Application (inches)
1														
2														
3														
4														
5														
6														
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Month: July

Meter # :__________________________ Location:___________________________ Irrigated Area:_______________________

Monthly Constant: .0044 Irrigation Factor:

Day	T max	T min	T ave	Precip	ET Calc I	ET Calc II	ET	Useable Precip (Precip * 0.8)	Net ET	Soil Moisture (inches)	Required Application (inches)	Required Application (thou gal)	Actual Application (thou gal)	Actual Application (inches)
1														
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Month: August

Meter # :__________________________ Location:___________________________ Irrigated Area:_______________________

Monthly Constant: .0038 Irrigation Factor:

Day	T max	T min	T ave	Precip	ET Calc I	ET Calc II	ET	Useable Precip (Precip * 0.8)	Net ET	Soil Moisture (inches)	Required Application (inches)	Required Application (thou gal)	Actual Application (thou gal)	Actual Application (inches)
1														
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5														
6														
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Month: September

Meter # :___________________________ Location:____________________________ Irrigated Area:________________________

Monthly Constant: .0026 Irrigation Factor:

Day	T max	T min	T ave	Precip	ET Calc I	ET Calc II	ET	Useable Precip (Precip * 0.8)	Net ET	Soil Moisture (inches)	Required Application (inches)	Required Application (thou gal)	Actual Application (thou gal)	Actual Application (inches)
1														
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5														
6														
7														
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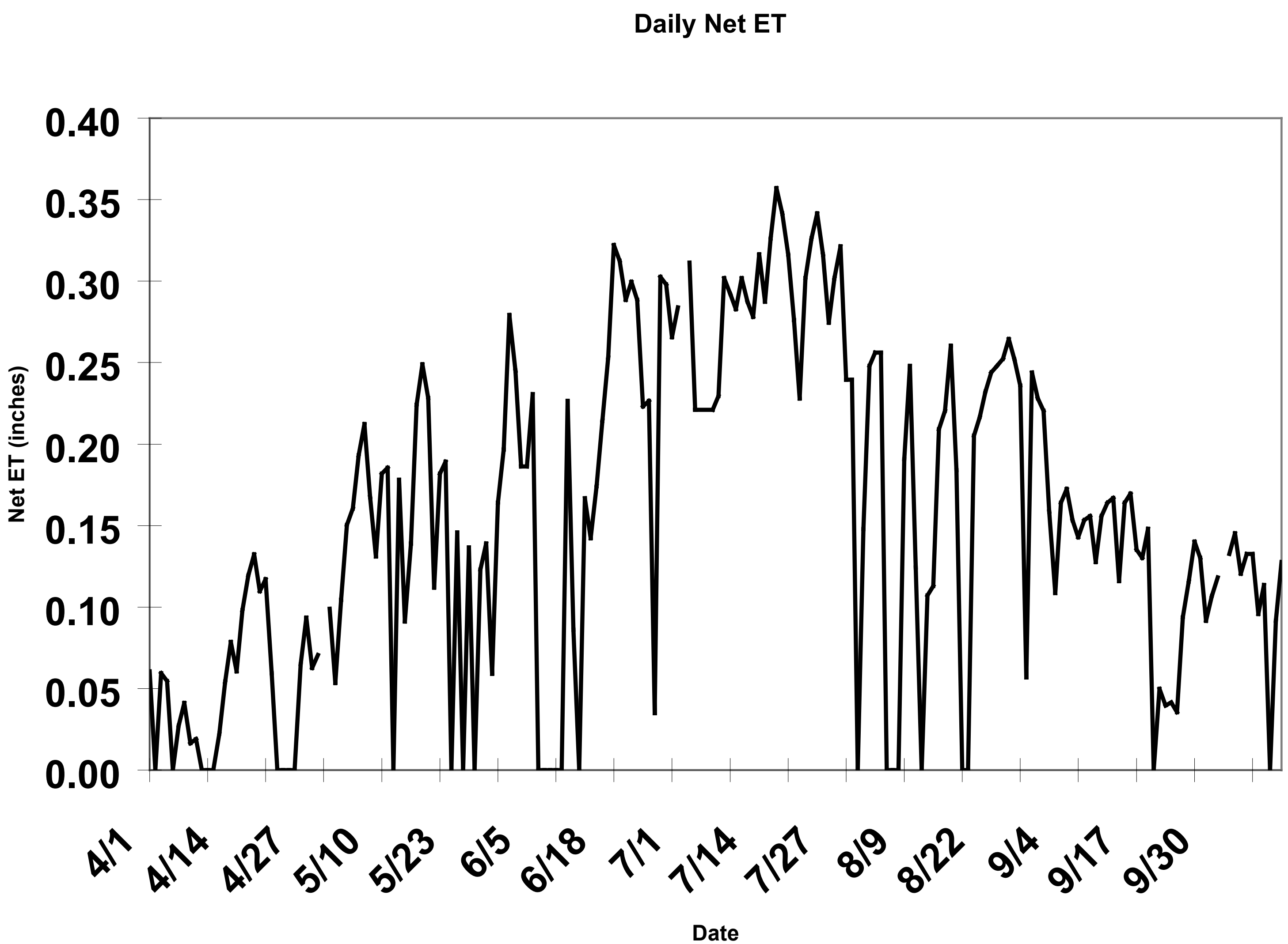
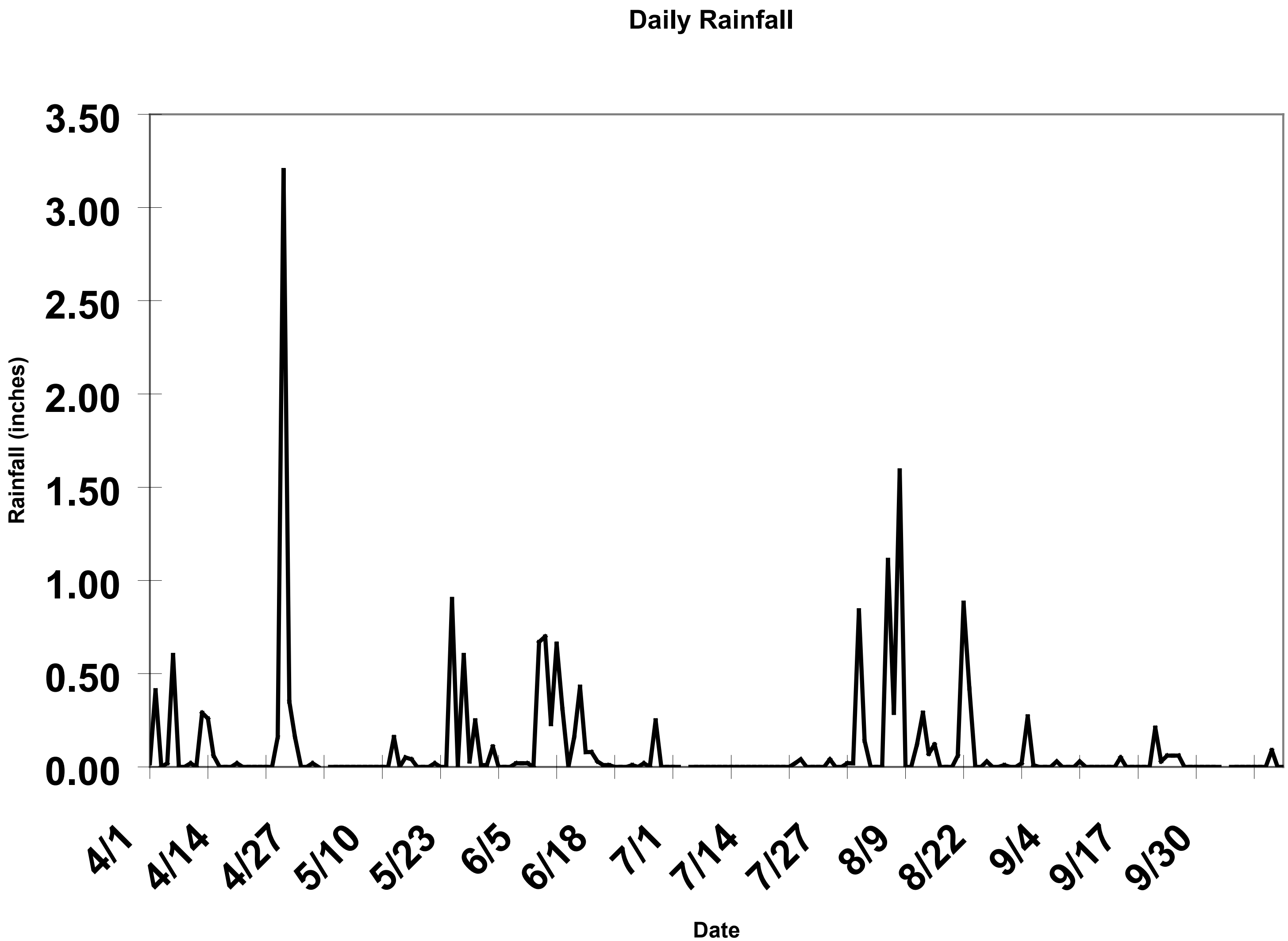
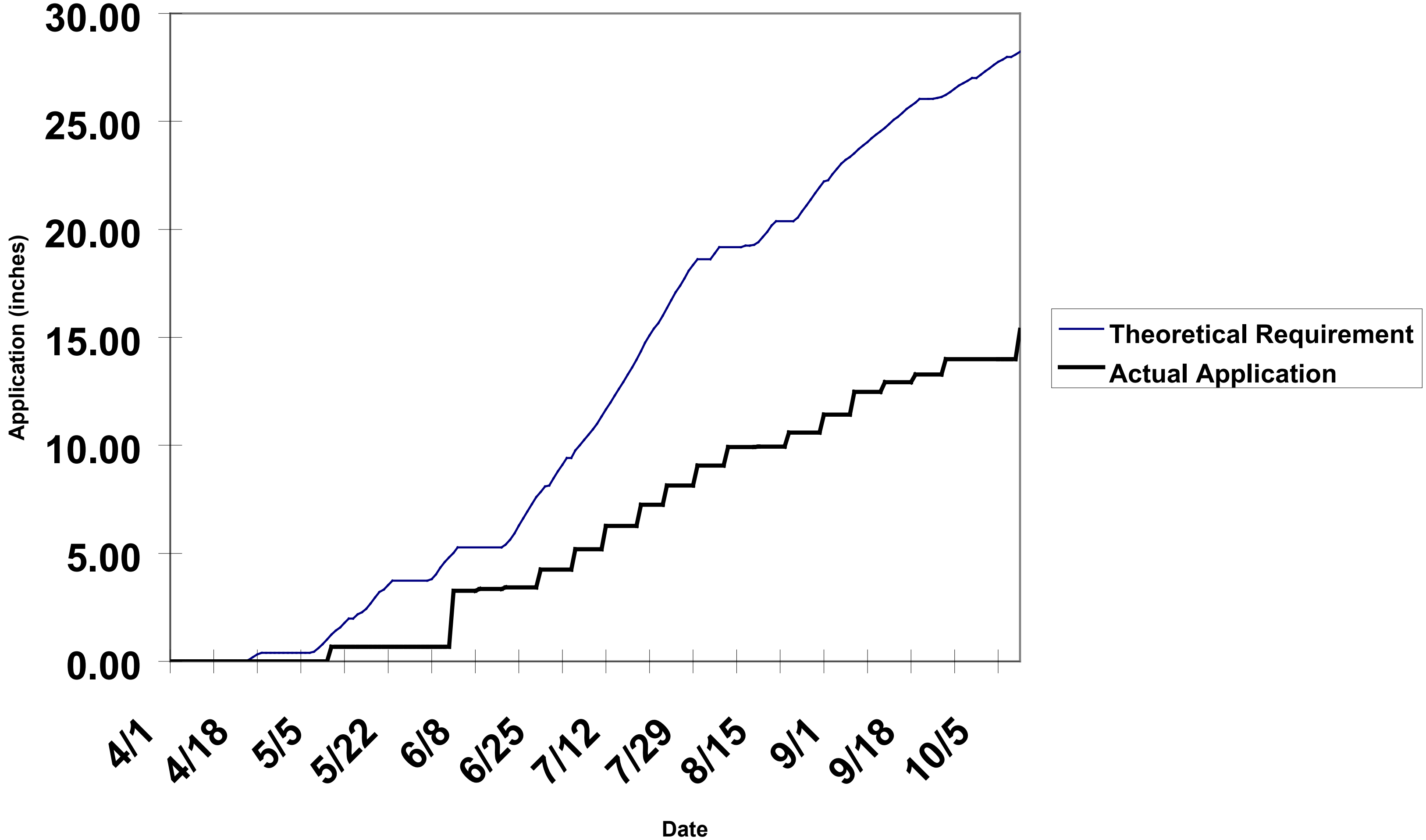
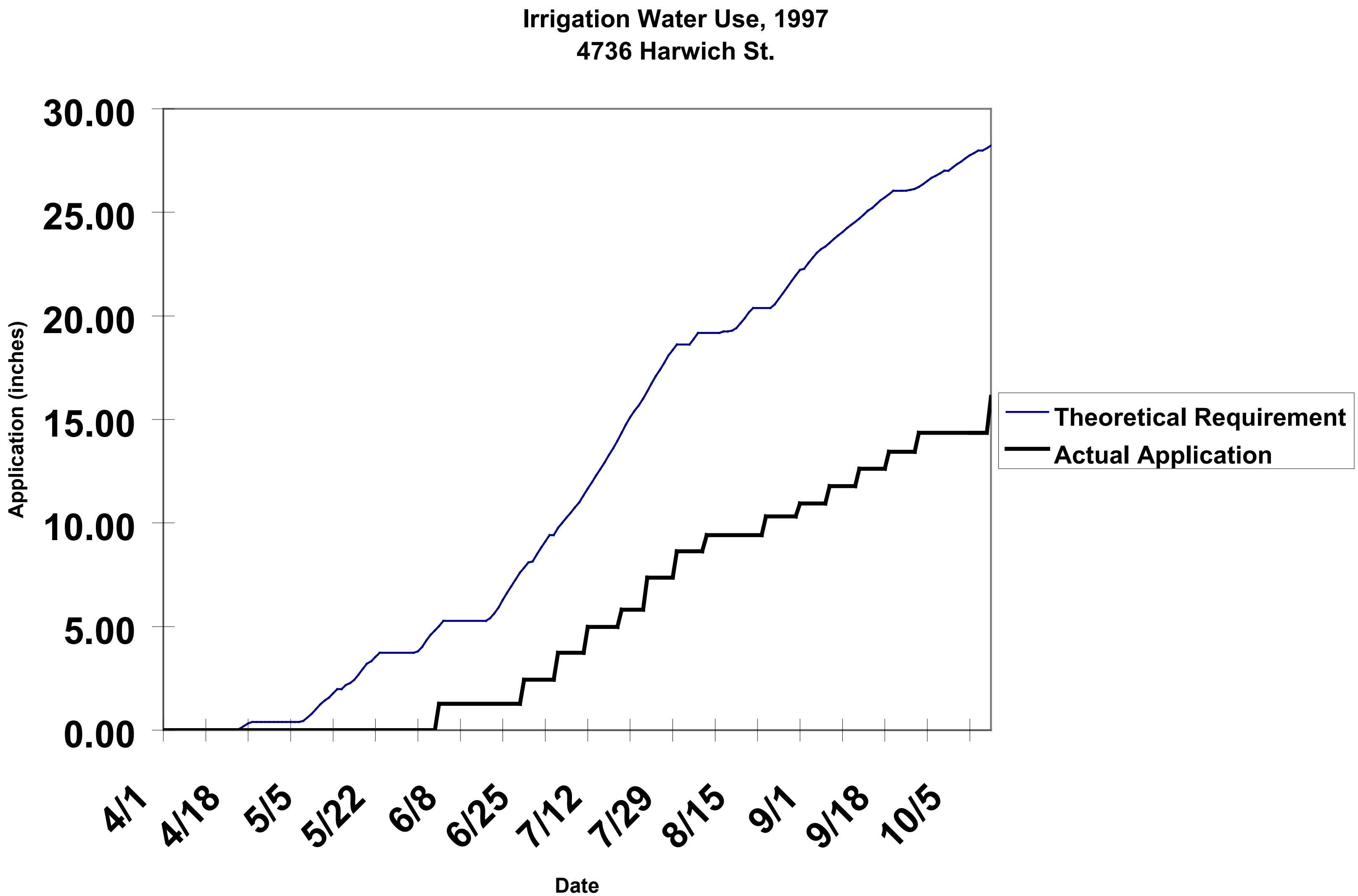
Appendix B: Rainfall, Net ET and Irrigation Water Use Graphs


Daily Net ET
Net ET (inches)
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
4/1
4/14
4/27
5/10
5/23
6/5
6/18
7/1
7/14
7/27
8/9
8/22
9/4
9/17
9/30
Date

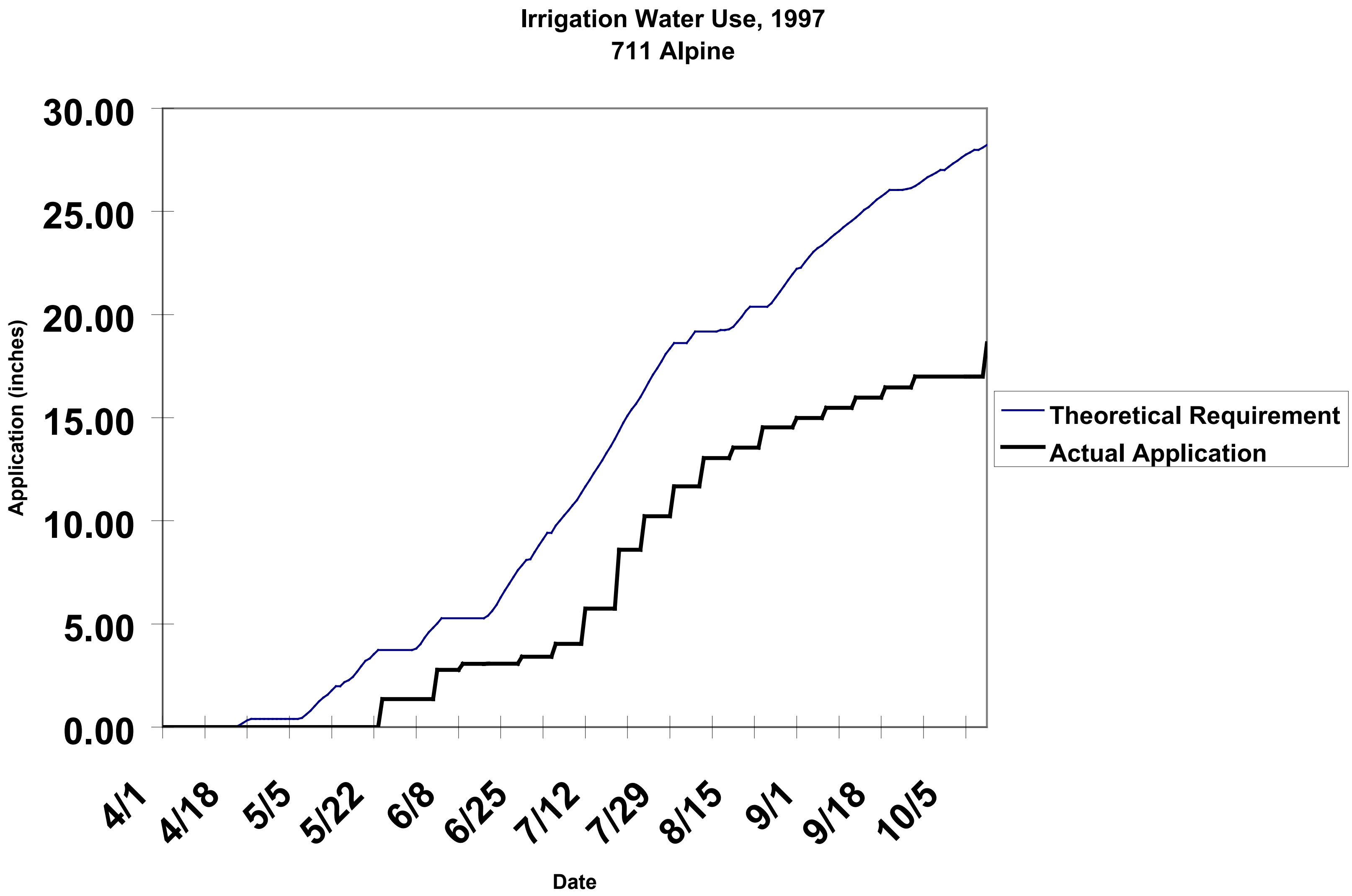

Daily Rainfall
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
Rainfall (inches)
4/1
4/14
4/27
5/10
5/23
6/5
6/18
7/1
7/14
7/27
8/9
8/22
9/4
9/17
9/30
Date

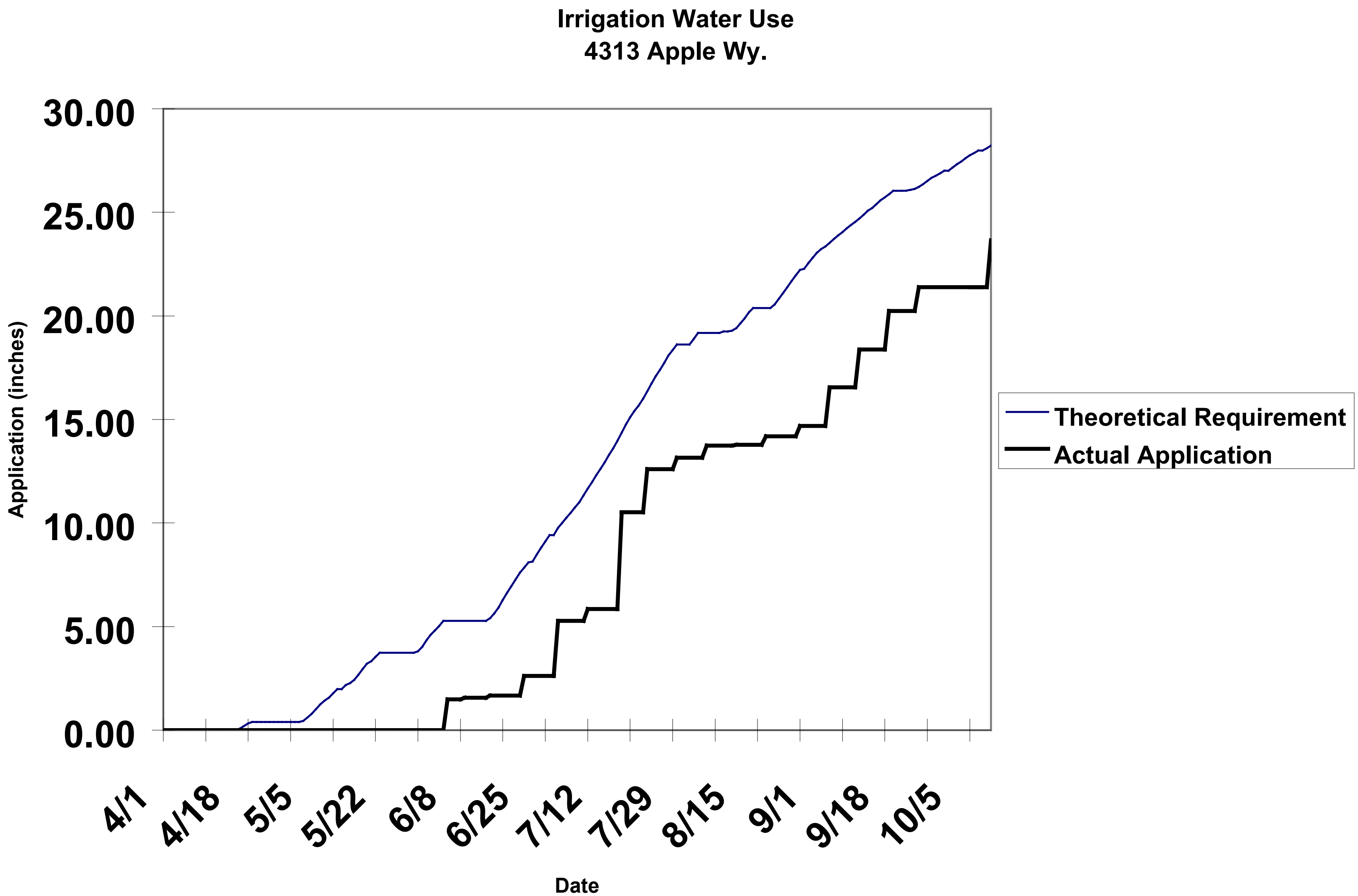
Irrigation Water Use, 1997
4653 Kirkwood Ct.

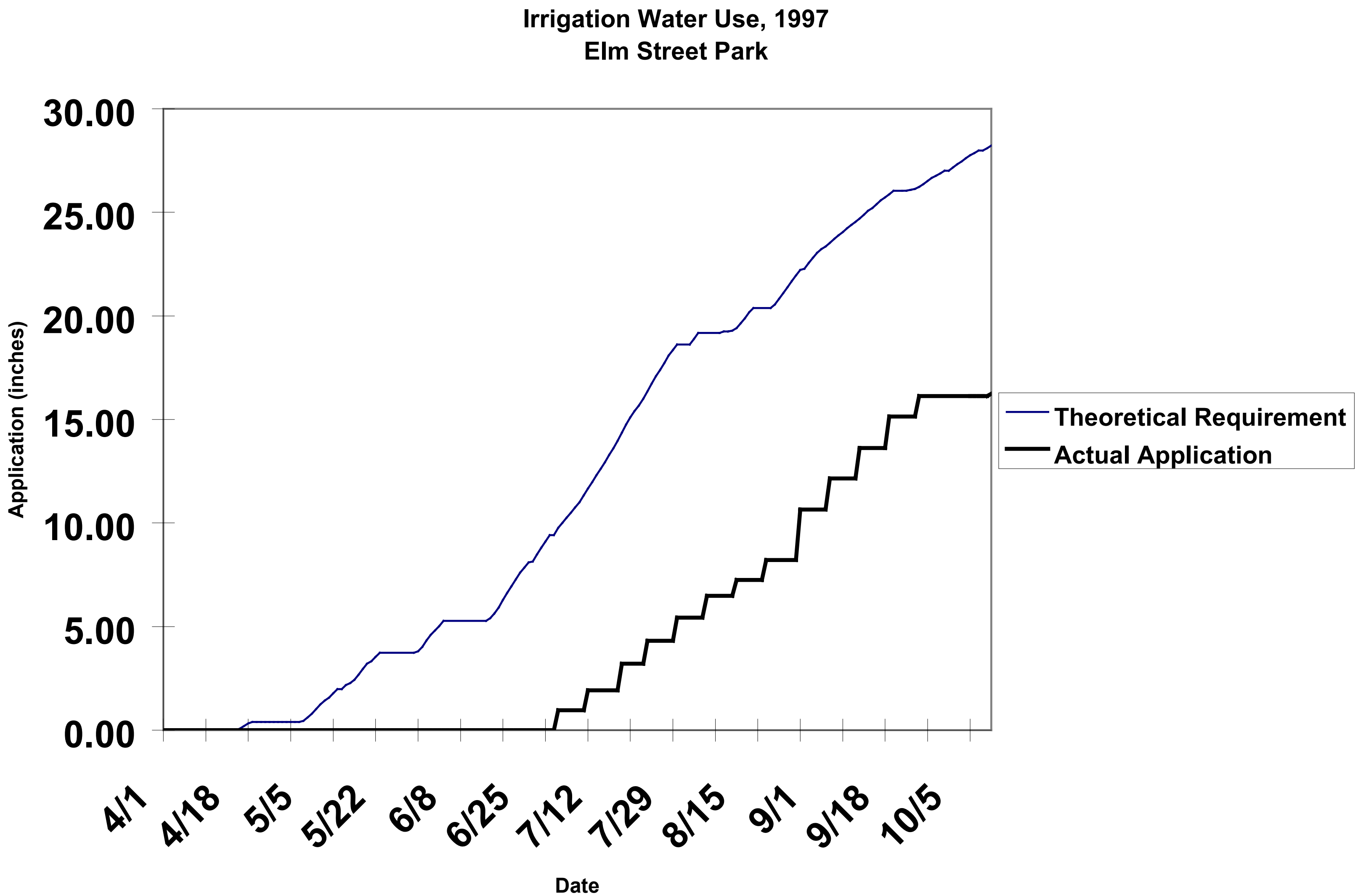


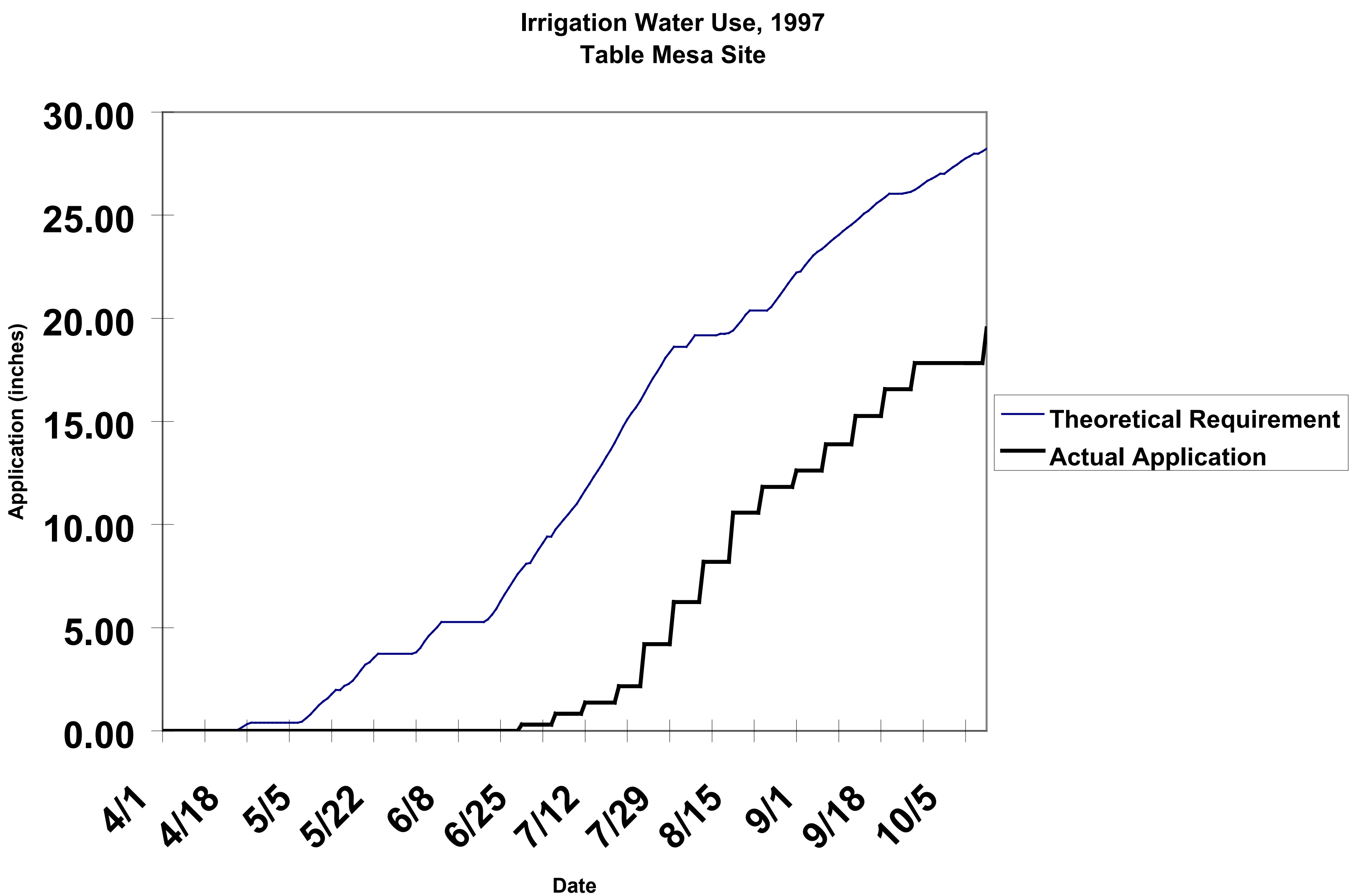


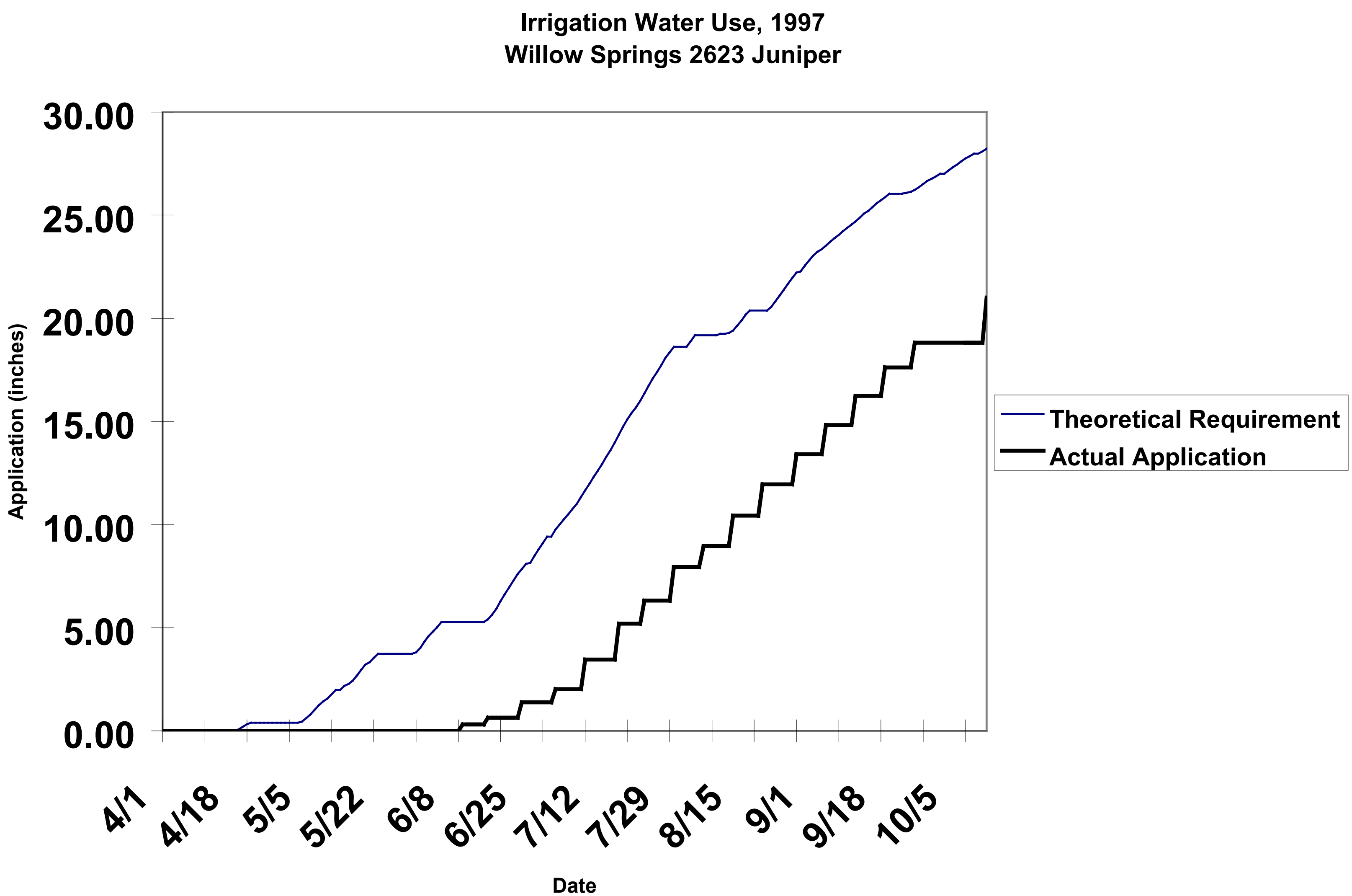
Irrigation Water Use, 1997
4736 Harwich St.
30.00
25.00
20.00
15.00
10.00
5.00
0.00
Application (inches)
4/1
4/18
5/5
5/22
6/8
6/25
7/12
7/29
8/15
9/1
9/18
10/5
Date
Theoretical Requirement
Actual Application

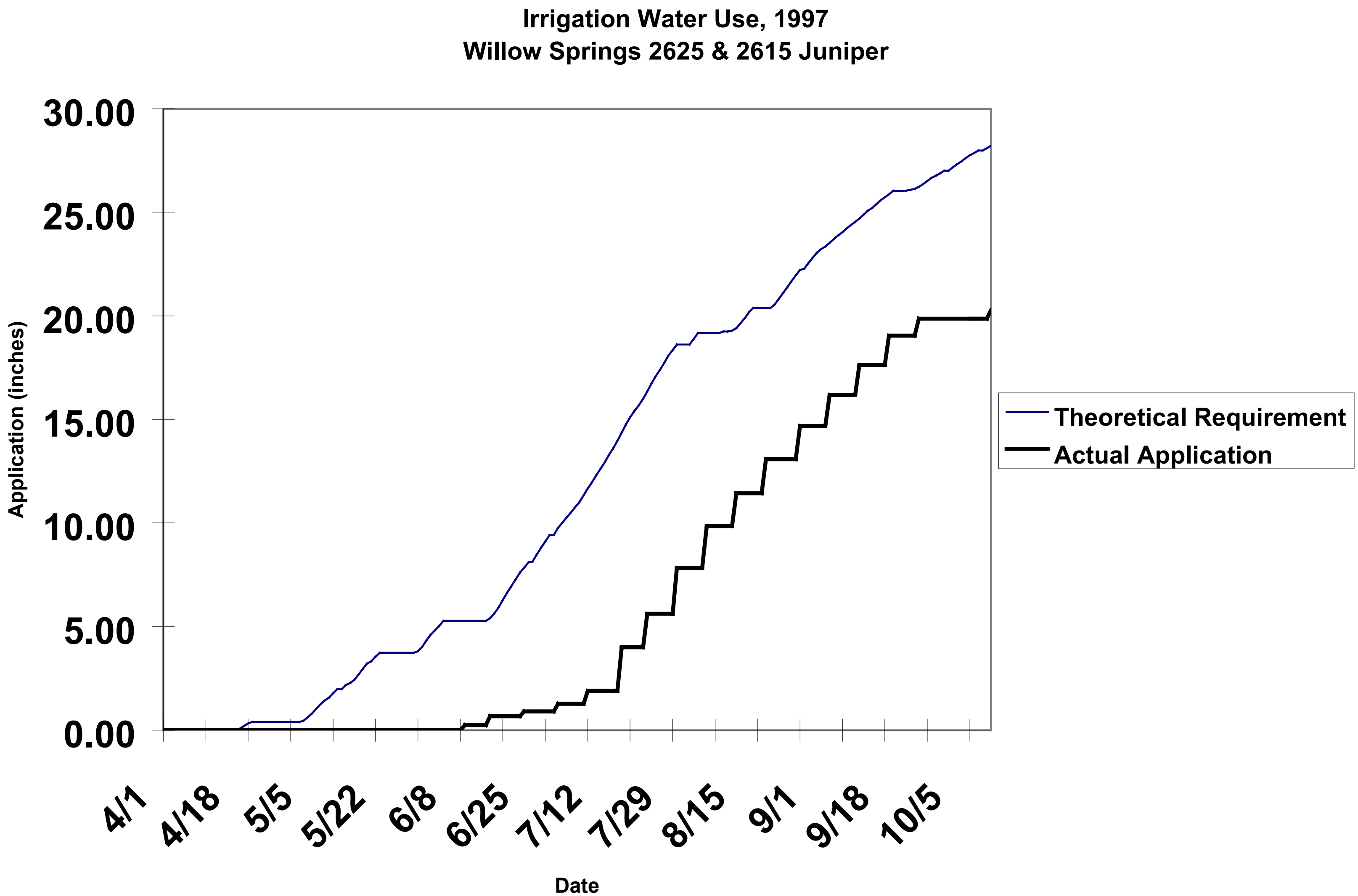

Irrigation Water Use, 1997
711 Alpine
30.00
25.00
20.00
15.00
10.00
5.00
0.00
Application (inches)
4/1
4/18
5/5
5/22
6/8
6/25
7/12
7/29
8/15
9/1
9/18
10/5
Date
Theoretical Requirement
Actual Application

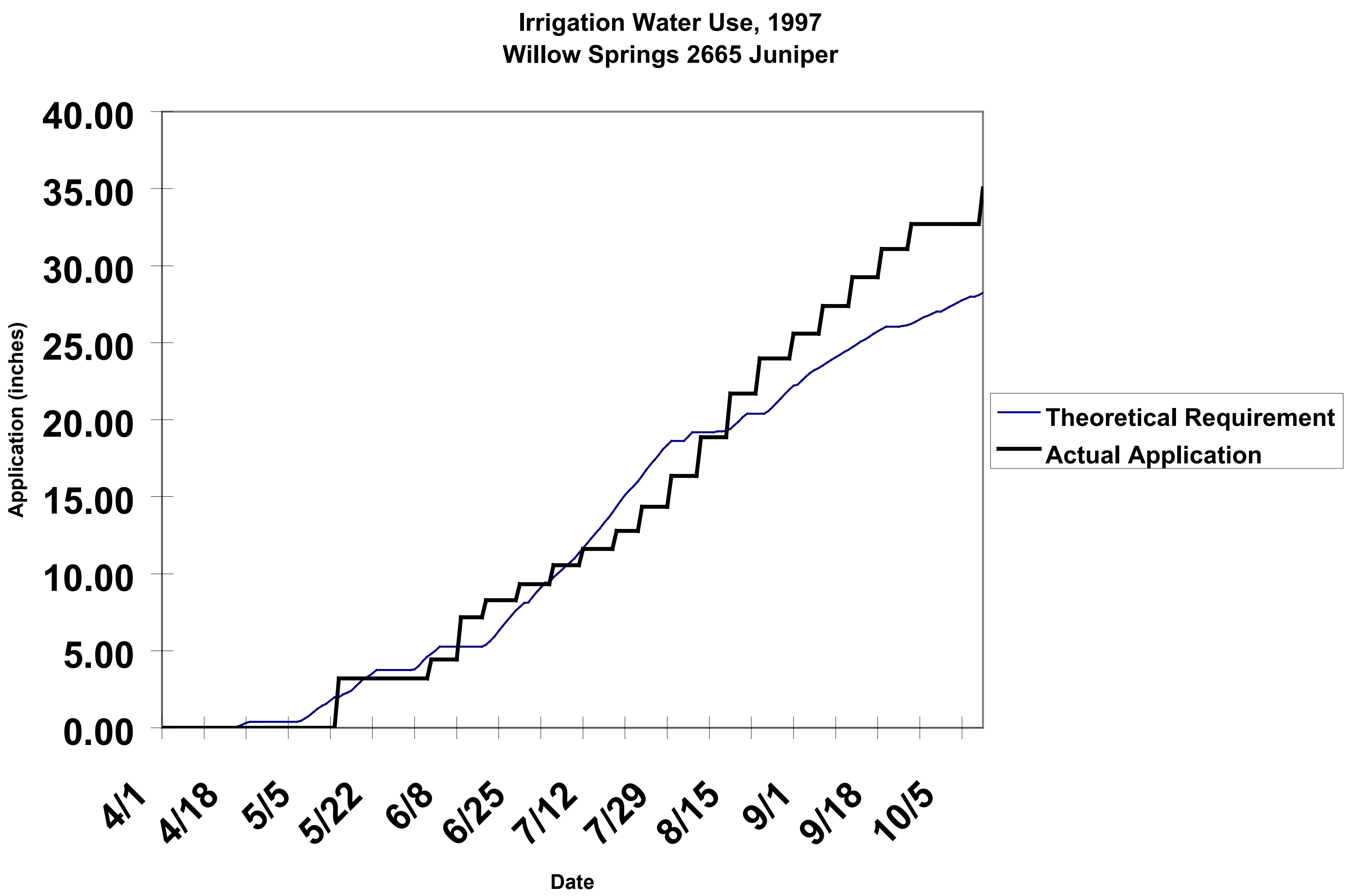

Irrigation Water Use
4313 Apple Wy.
30.00
25.00
20.00
15.00
10.00
5.00
0.00
Application (inches)
4/1
4/18
5/5
5/22
6/8
6/25
7/12
7/29
8/15
9/1
9/18
10/5
Date
Theoretical Requirement
Actual Application

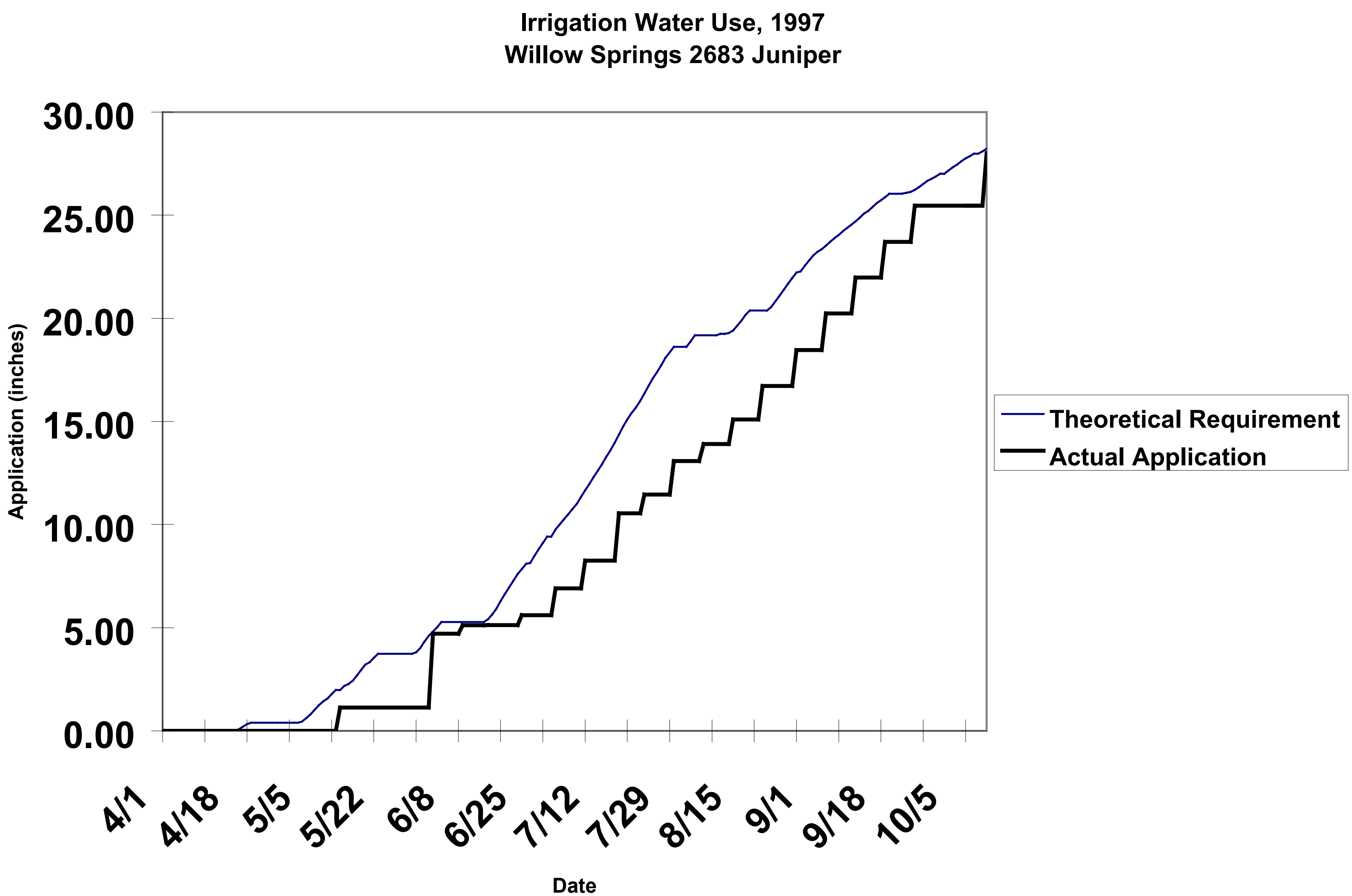

Irrigation Water Use, 1997
Elm Street Park
30.00
25.00
20.00
15.00
10.00
5.00
0.00
Application (inches)
4/1
4/18
5/5
5/22
6/8
6/25
7/12
7/29
8/15
9/1
9/18
10/5
Date
Theoretical Requirement
Actual Application


Irrigation Water Use, 1997
Table Mesa Site
30.00
25.00
20.00
15.00
10.00
5.00
0.00
Application (inches)
4/1
4/18
5/5
5/22
6/8
6/25
7/12
7/29
8/15
9/1
9/18
10/5
Date
Theoretical Requirement
Actual Application

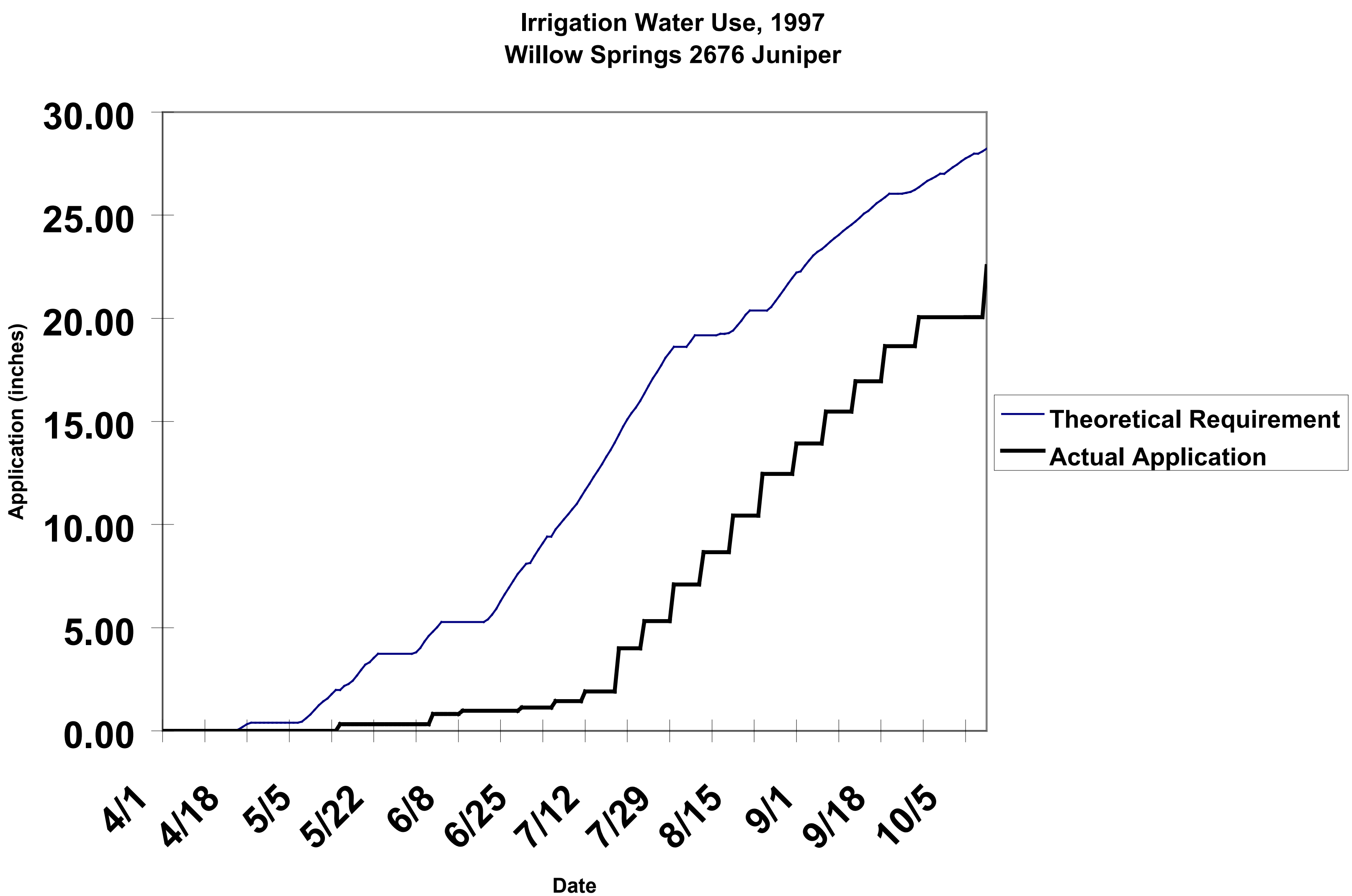

Irrigation Water Use, 1997
Willow Springs 2623 Juniper
Application (inches)
30.00
25.00
20.00
15.00
10.00
5.00
0.00
4/1
4/18
5/5
5/22
6/8
6/25
7/12
7/29
8/15
9/1
9/18
10/5
Date
Theoretical Requirement
Actual Application


Irrigation Water Use, 1997
Willow Springs 2625 & 2615 Juniper
30.00
25.00
20.00
15.00
10.00
5.00
0.00
Application (inches)
4/1
4/18
5/5
5/22
6/8
6/25
7/12
7/29
8/15
9/1
9/18
10/5
Date
Theoretical Requirement
Actual Application

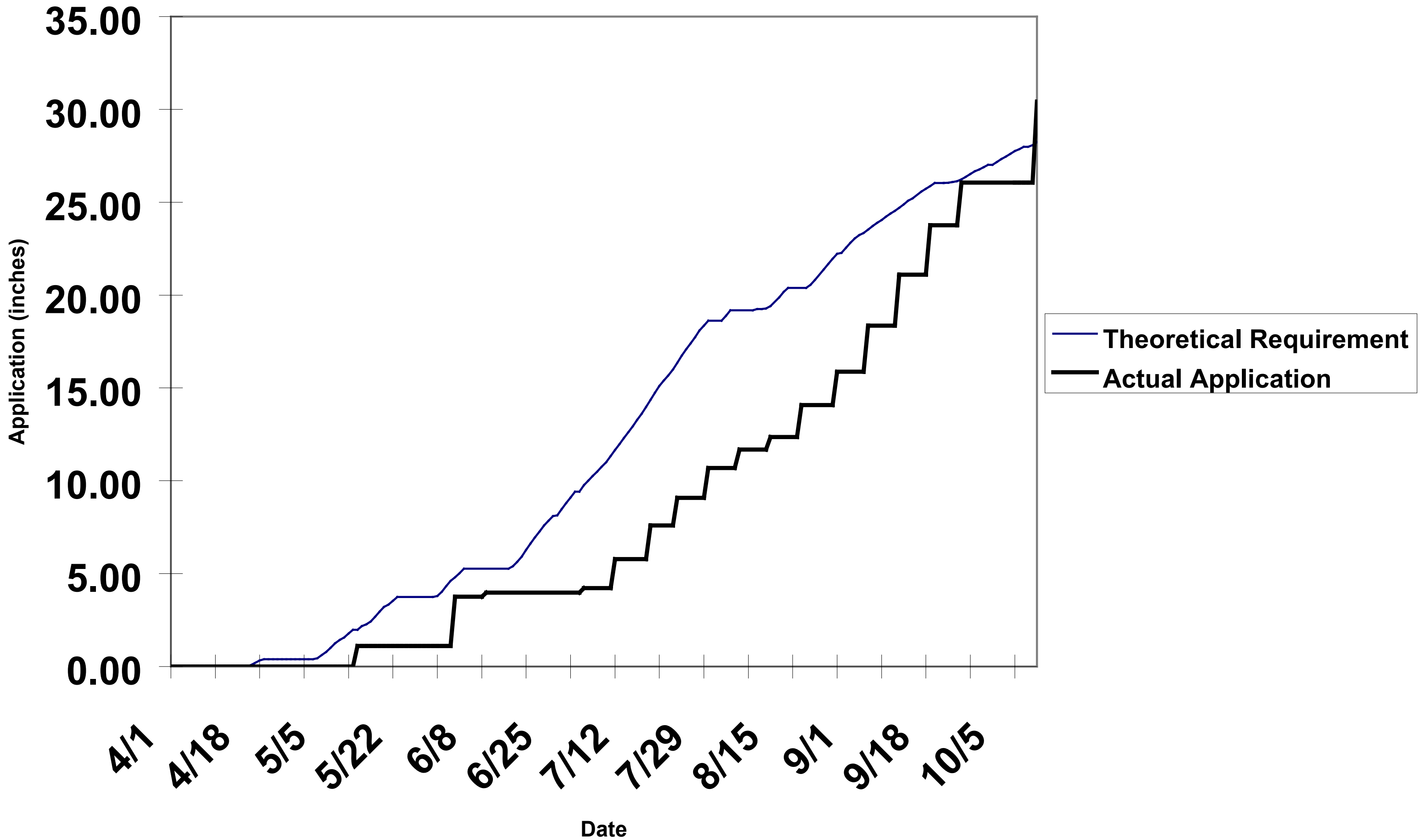

Irrigation Water Use, 1997
Willow Springs 2665 Juniper
40.00
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0.00
Application (inches)
4/1
4/18
5/5
5/22
6/8
6/25
7/12
7/29
8/15
9/1
9/18
10/5
Date
Theoretical Requirement
Actual Application

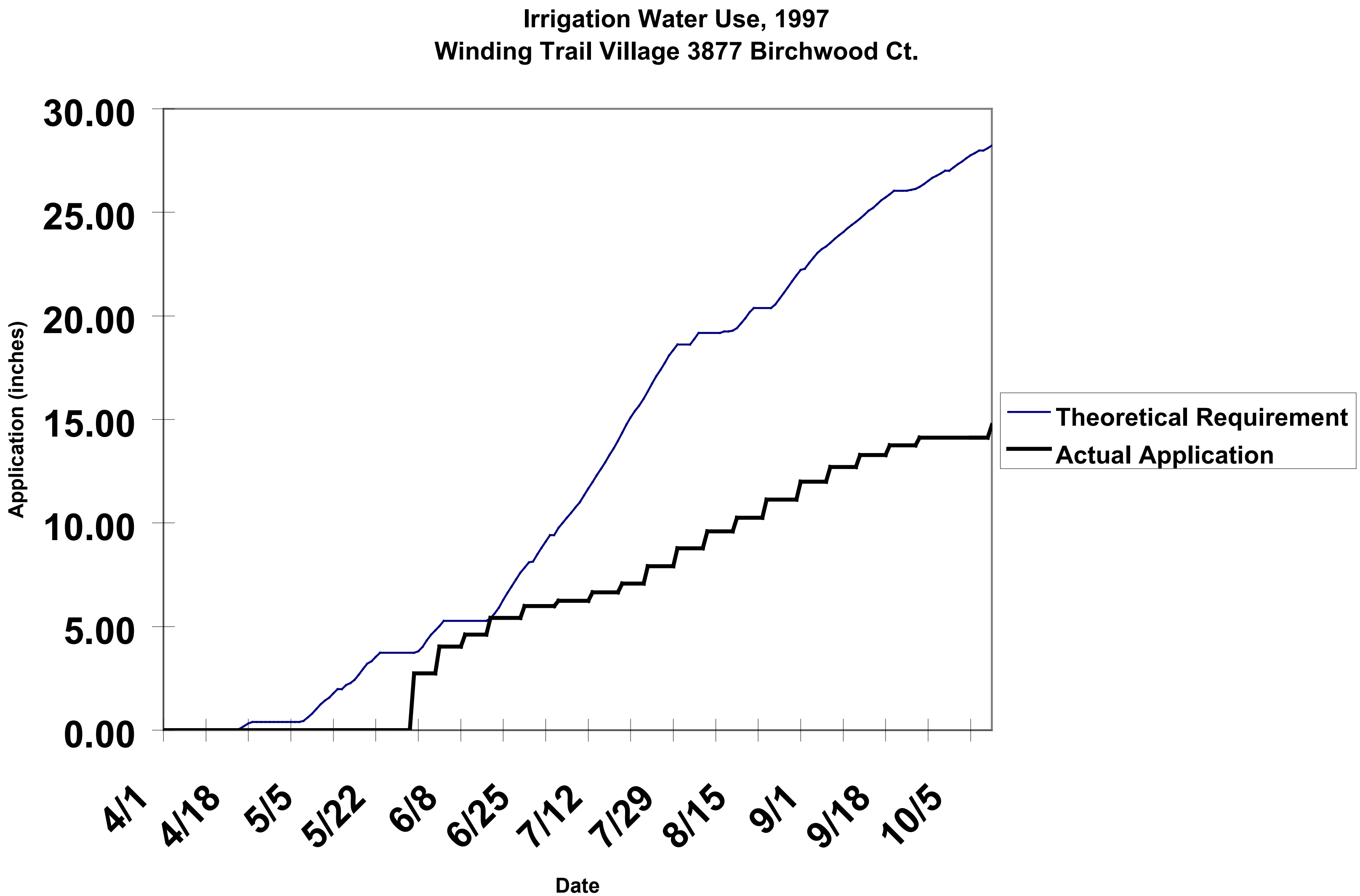


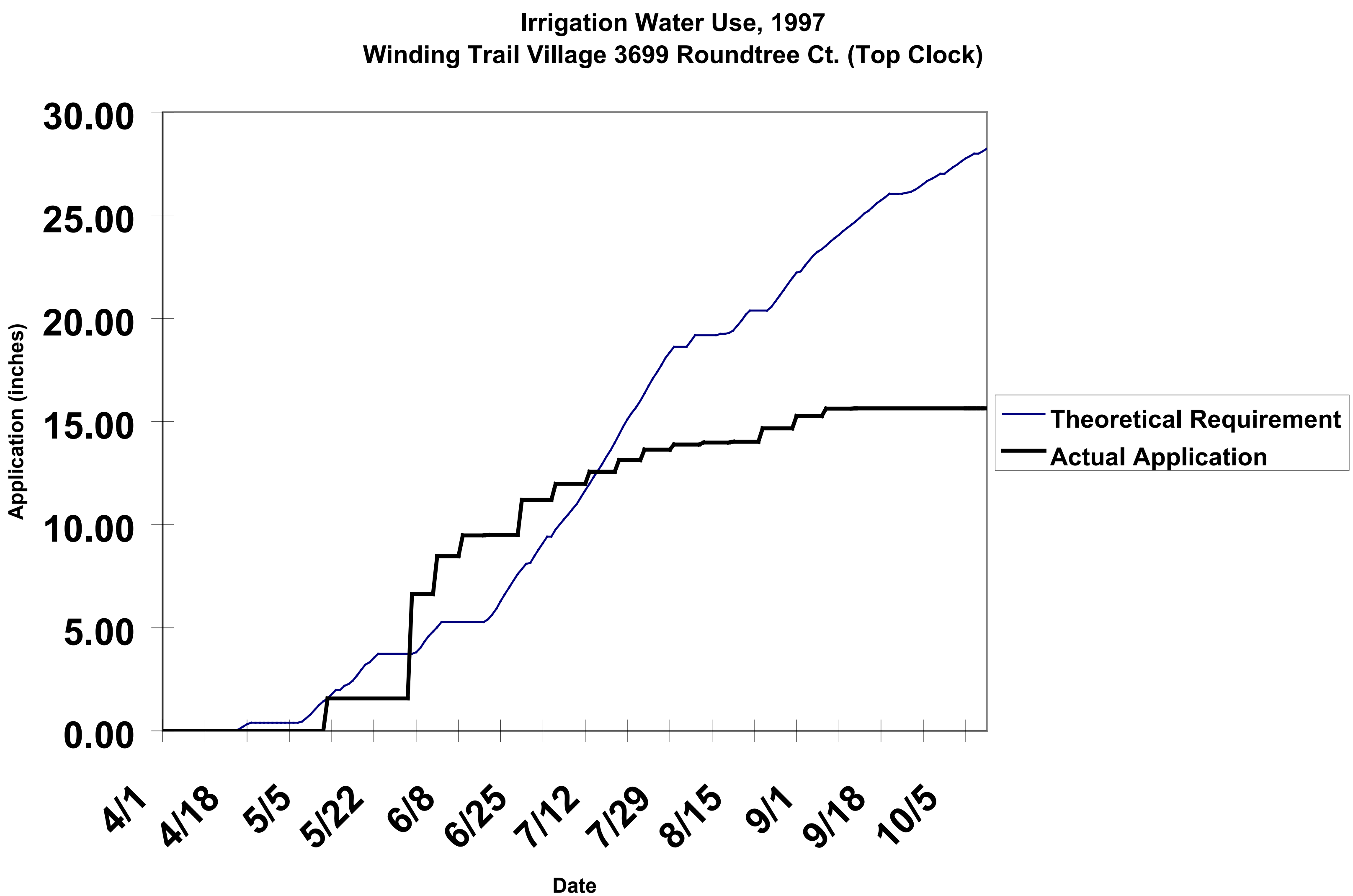
Irrigation Water Use, 1997
Willow Springs 2683 Juniper
30.00
25.00
20.00
15.00
10.00
5.00
0.00
Application (inches)
4/1
4/18
5/5
5/22
6/8
6/25
7/12
7/29
8/15
9/1
9/18
10/5
Date
Theoretical Requirement
Actual Application

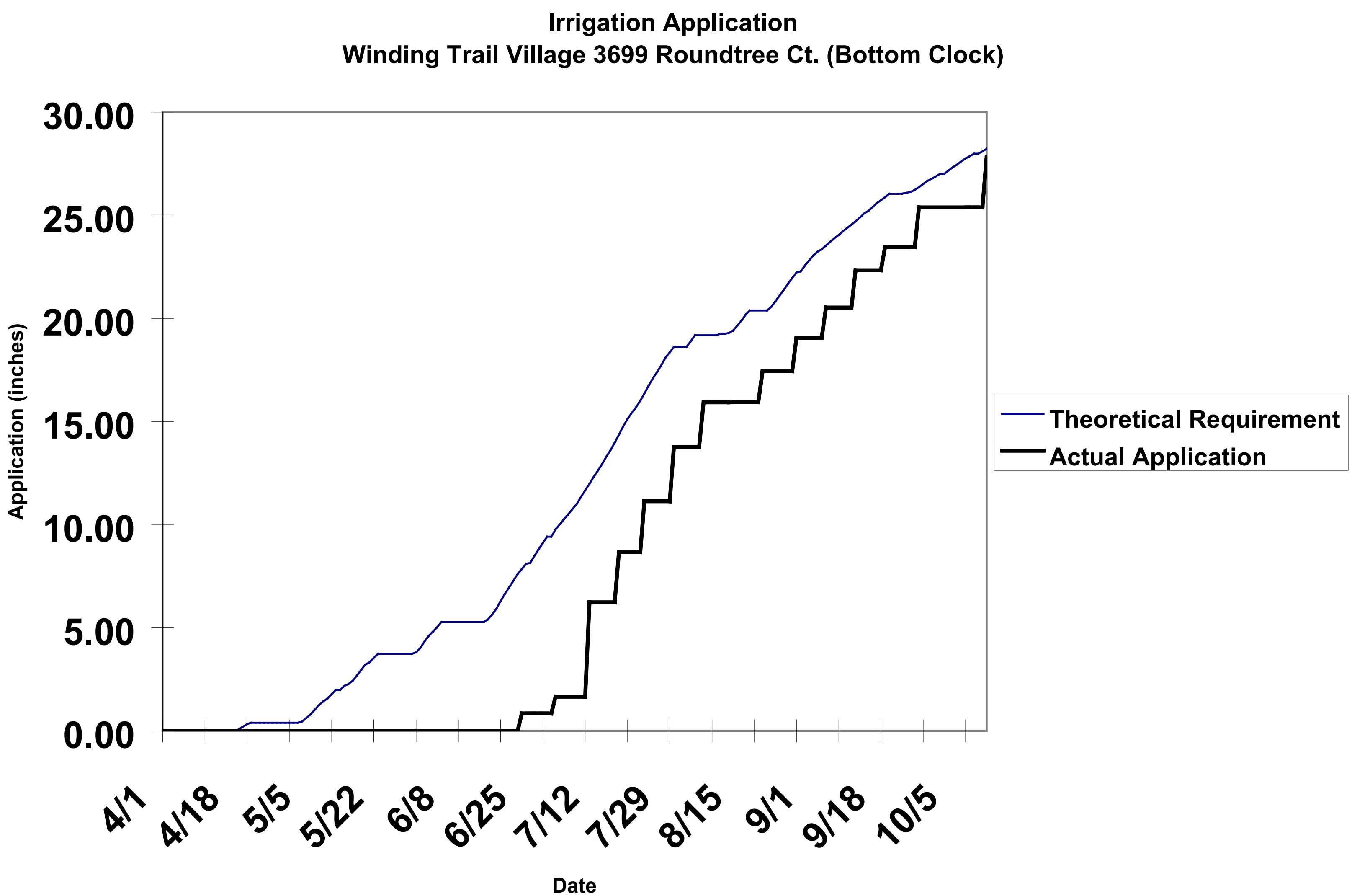

Irrigation Water Use, 1997
Willow Springs 2676 Juniper
30.00
25.00
20.00
15.00
10.00
5.00
0.00
Application (inches)
4/1
4/18
5/5
5/22
6/8
6/25
7/12
7/29
8/15
9/1
9/18
10/5
Date
Theoretical Requirement
Actual Application

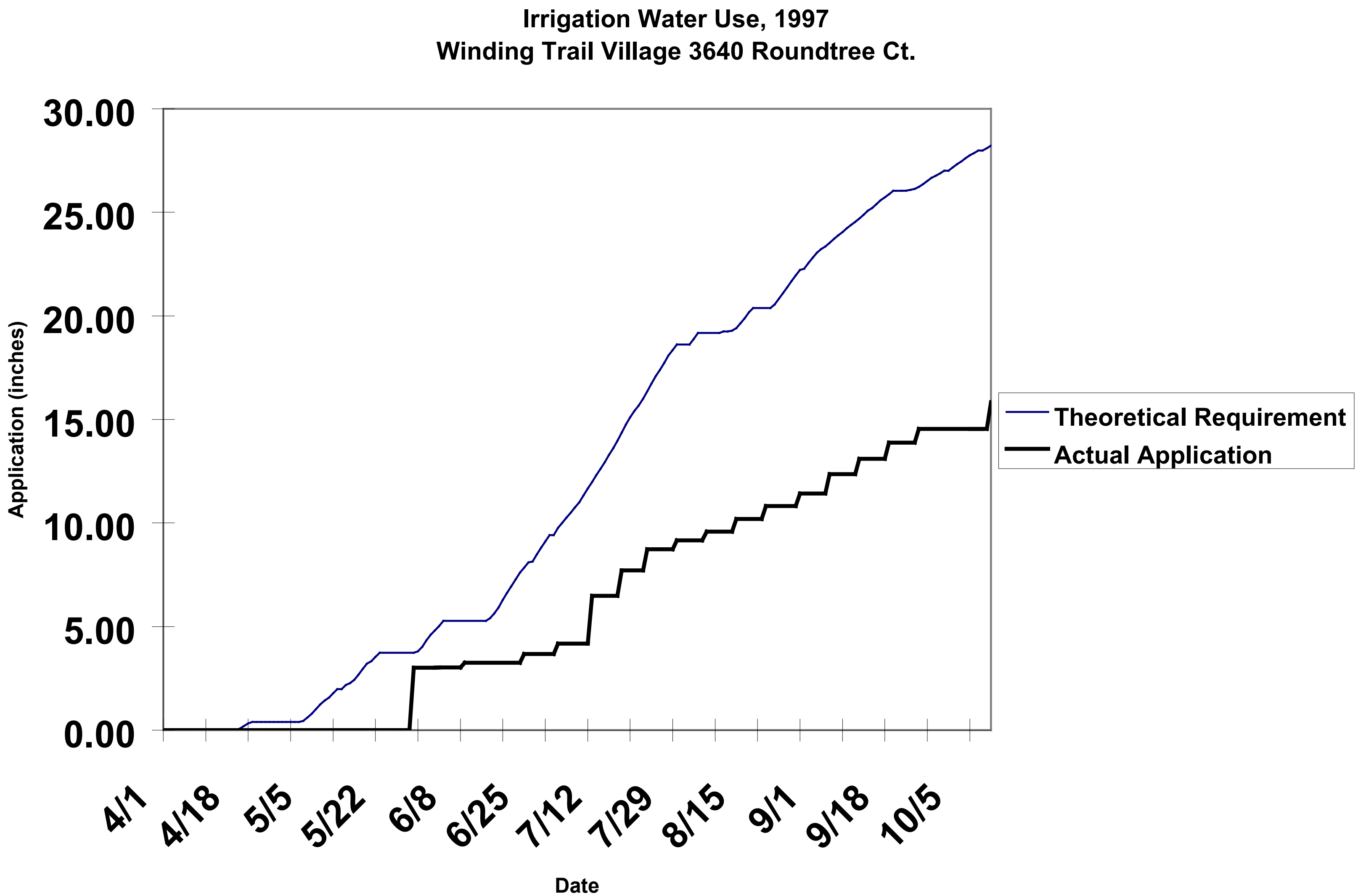
Irrigation Water Use, 1997
Willow Springs 2640 Juniper

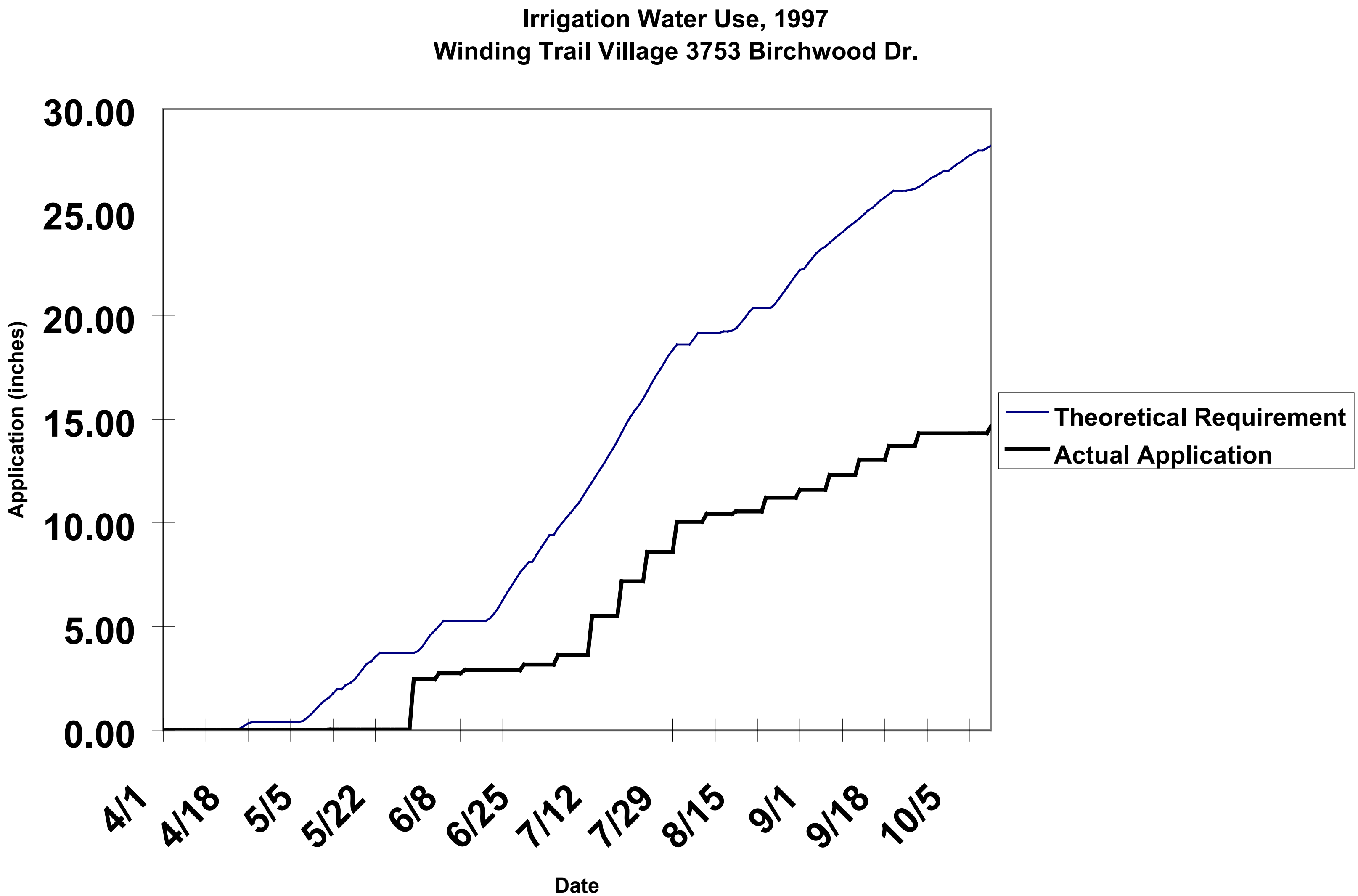


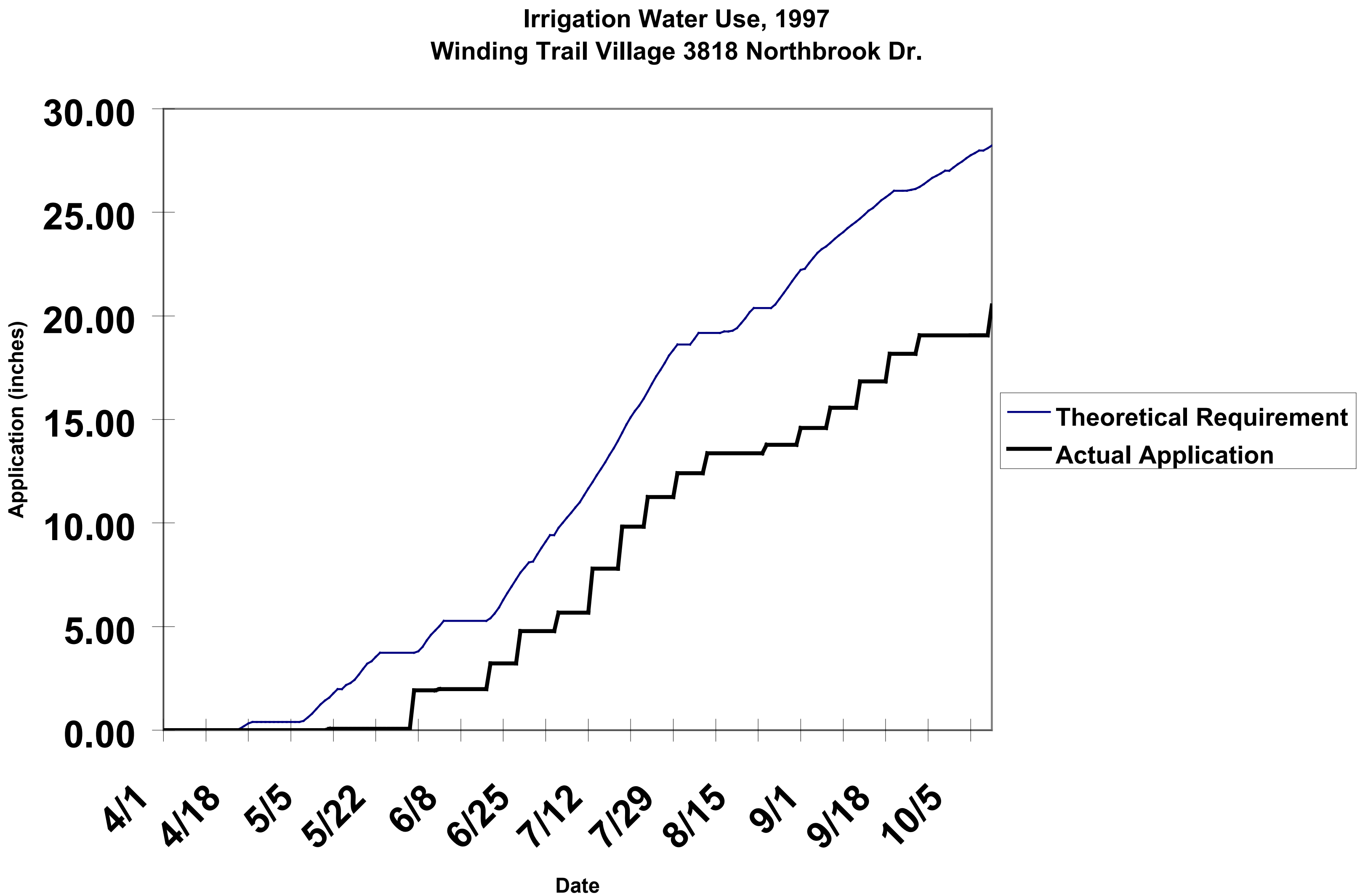

Irrigation Water Use, 1997
Winding Trail Village 3877 Birchwood Ct.
30.00
25.00
20.00
15.00
10.00
5.00
0.00
Application (inches)
4/1
4/18
5/5
5/22
6/8
6/25
7/12
7/29
8/15
9/1
9/18
10/5
Date
Theoretical Requirement
Actual Application

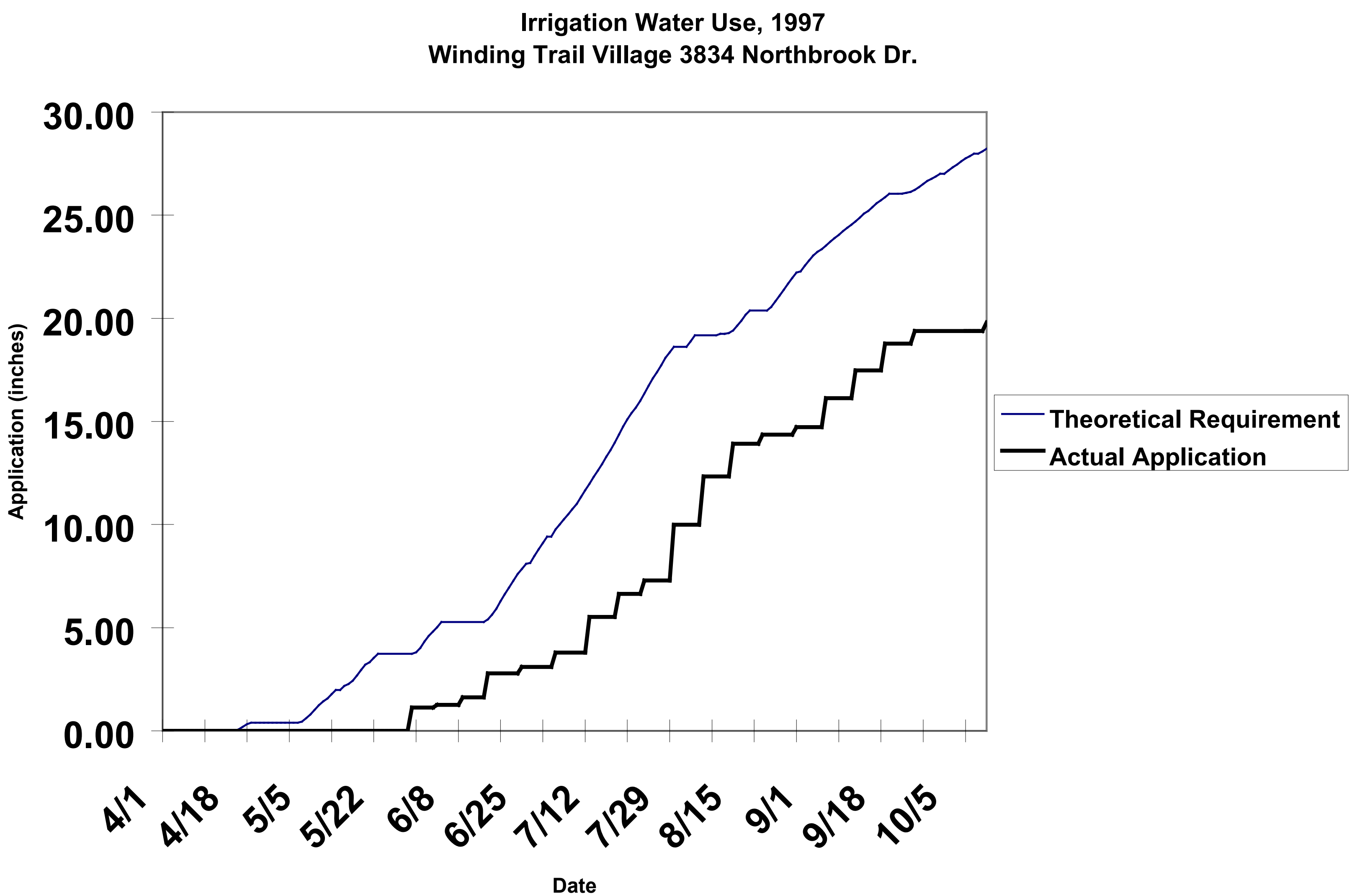

Irrigation Water Use, 1997
Winding Trail Village 3699 Roundtree Ct. (Top Clock)
30.00
25.00
20.00
15.00
10.00
5.00
0.00
Application (inches)
4/1
4/18
5/5
5/22
6/8
6/25
7/12
7/29
8/15
9/1
9/18
10/5
Date
Theoretical Requirement
Actual Application


Irrigation Application
Winding Trail Village 3699 Roundtree Ct. (Bottom Clock)
30.00
25.00
20.00
15.00
10.00
5.00
0.00
Application (inches)
4/1
4/18
5/5
5/22
6/8
6/25
7/12
7/29
8/15
9/1
9/18
10/5
Date
Theoretical Requirement
Actual Application

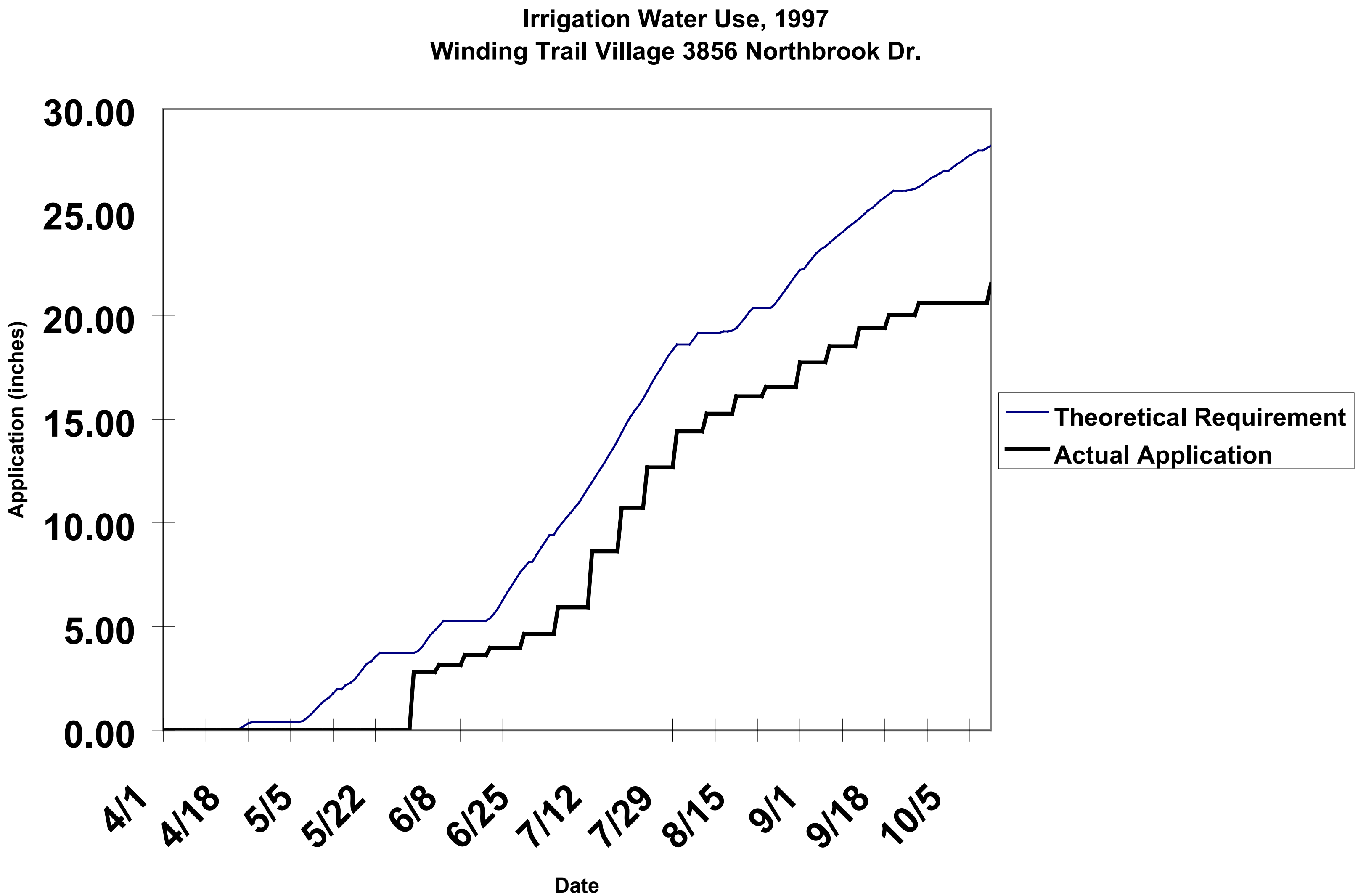

Irrigation Water Use, 1997
Winding Trail Village 3640 Roundtree Ct.
30.00
25.00
20.00
15.00
10.00
5.00
0.00
Application (inches)
4/1
4/18
5/5
5/22
6/8
6/25
7/12
7/29
8/15
9/1
9/18
10/5
Date
Theoretical Requirement
Actual Application


Irrigation Water Use, 1997
Winding Trail Village 3753 Birchwood Dr.
30.00
25.00
20.00
15.00
10.00
5.00
0.00
Application (inches)
4/1
4/18
5/5
5/22
6/8
6/25
7/12
7/29
8/15
9/1
9/18
10/5
Date
Theoretical Requirement
Actual Application

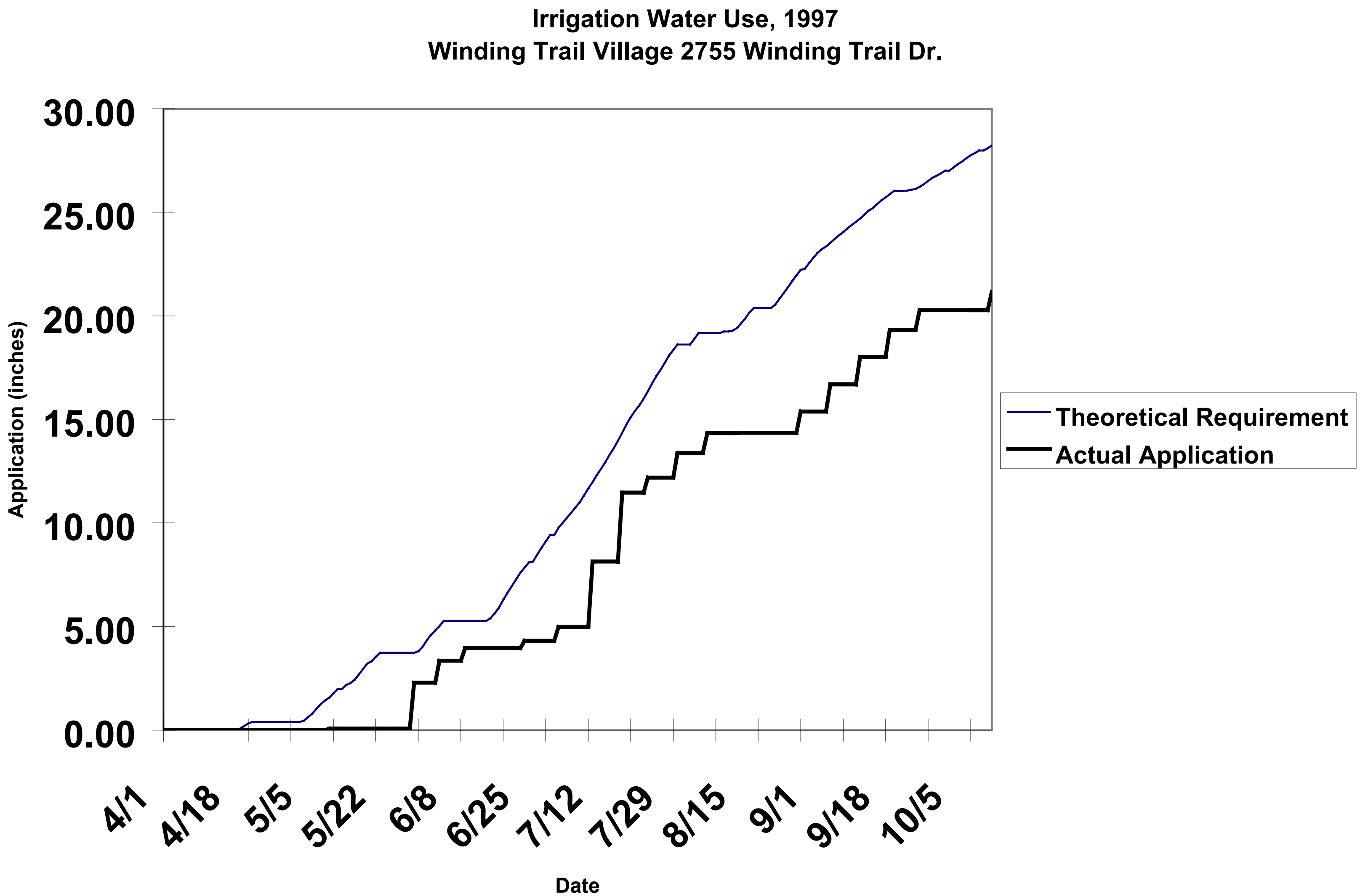

Irrigation Water Use, 1997
Winding Trail Village 3818 Northbrook Dr.
30.00
25.00
20.00
15.00
10.00
5.00
0.00
Application (inches)
4/1
4/18
5/5
5/22
6/8
6/25
7/12
7/29
8/15
9/1
9/18
10/5
Date
Theoretical Requirement
Actual Application



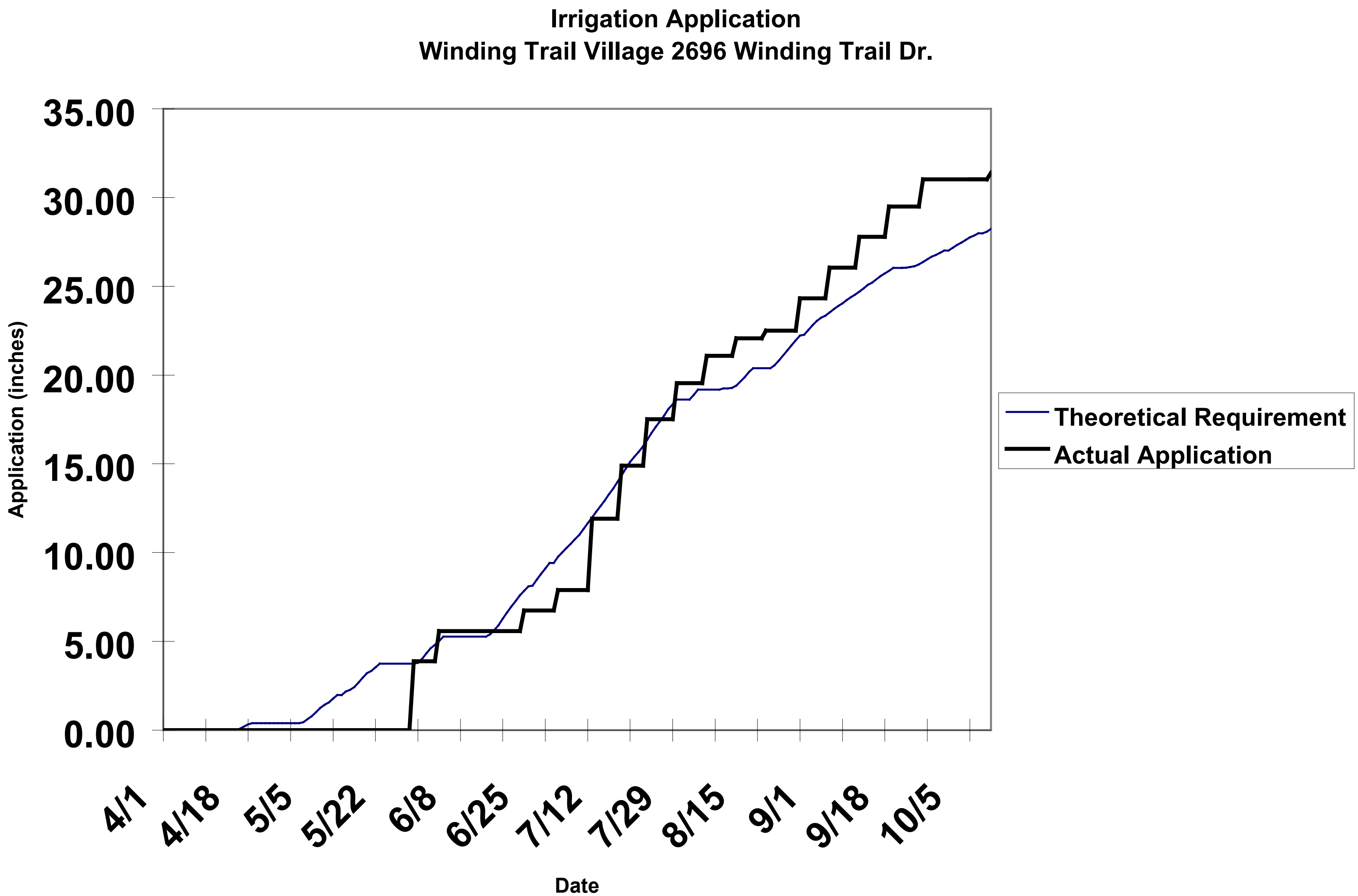
Irrigation Water Use, 1997
Winding Trail Village 3834 Northbrook Dr.
30.00
25.00
20.00
15.00
10.00
5.00
0.00
Application (inches)
4/1
4/18
5/5
5/22
6/8
6/25
7/12
7/29
8/15
9/1
9/18
10/5
Date
Theoretical Requirement
Actual Application

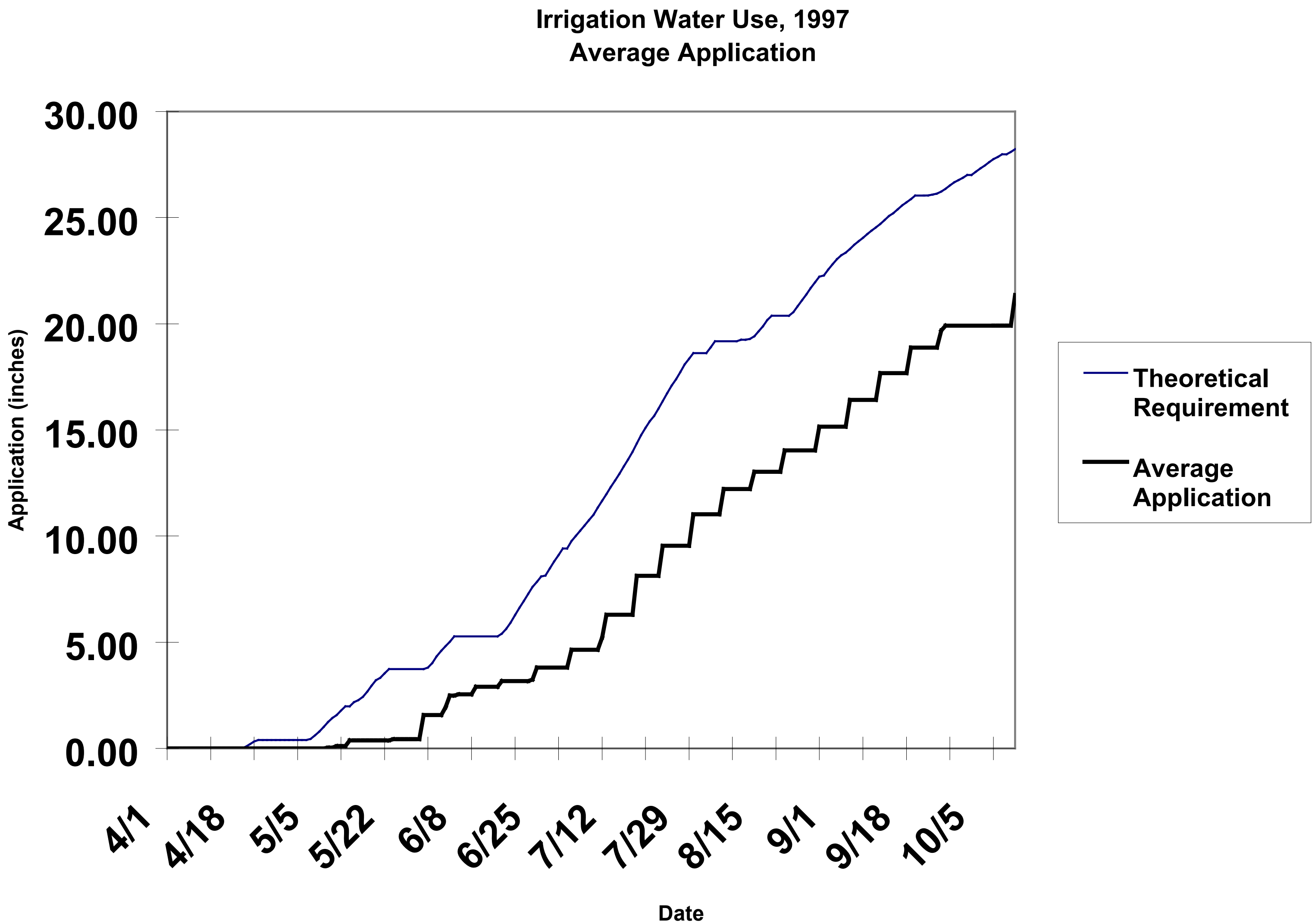


Irrigation Water Use, 1997
Winding Trail Village 3856 Northbrook Dr.
30.00
25.00
20.00
15.00
10.00
5.00
0.00
Application (inches)
4/1
4/18
5/5
5/22
6/8
6/25
7/12
7/29
8/15
9/1
9/18
10/5
Date
Theoretical Requirement
Actual Application



Irrigation Water Use, 1997
Winding Trail Village 2755 Winding Trail Dr.
30.00
25.00
20.00
15.00
10.00
5.00
0.00
Application (inches)
4/1
4/18
5/5
5/22
6/8
6/25
7/12
7/29
8/15
9/1
9/18
10/5
Date
Theoretical Requirement
Actual Application


Irrigation Application
Winding Trail Village 2696 Winding Trail Dr.
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0.00
Application (inches)
4/1
4/18
5/5
5/22
6/8
6/25
7/12
7/29
8/15
9/1
9/18
10/5
Date
Theoretical Requirement
Actual Application


Irrigation Water Use, 1997
Average Application
30.00
25.00
20.00
15.00
10.00
5.00
0.00
Application (inches)
4/1
4/18
5/5
5/22
6/8
6/25
7/12
7/29
8/15
9/1
9/18
10/5
Date
Theoretical Requirement
Average Application

Appendix C: Spreadsheet Model Examples

Boulder Soil Sensor 1997

WORKSHEET FOR CALCULATING DAILY ET
USING MODIFIED BLANEY CRIDDLE

Totals (inches):		
	SUMMER RAIN=	18.43
	SUMMER ET =	28.49

MONTH	PCNT DAYLIGHT	MONTH	K(C)	TOTAL PCP	MEAN TEMP	NET ET
4	0.0893	April	1.00	5.59	42.82	1.42
5	0.1001	May	1.25	2.19	57.18	4.20
6	0.1009	June	1.30	3.71	66.40	5.54
7	0.1022	July	1.30	1.12	71.40	8.28
8	0.0955	August	1.20	5.29	68.85	5.24
9	0.0839	September	0.95	0.53	63.72	3.75
						28.43

MONTH	DAY	MAX_T	MIN_T	DAILY RAIN	MEAN_T	CU FACTR	K(T)	K	GROSS ET	CUMLTV GROSS ET	NET ET	EXCESS RAIN	DAILY ET DEFICIT	CUMULTV ET DEF
4	1	63.00	35.00	0.02	49.00	0.14	0.53	0.53	0.08	0.08	0.06	0.00	0.06	0.00
4	2	42.00	28.00	0.41	35.00	0.10	0.29	0.29	0.03	0.11	-0.30	0.30	0.00	0.00
4	3	65.00	24.00	0.00	44.50	0.13	0.46	0.46	0.06	0.17	0.06	0.00	0.06	0.06
4	4	59.00	36.00	0.02	47.50	0.14	0.51	0.51	0.07	0.24	0.05	0.00	0.05	0.11
4	5	43.00	29.00	0.60	36.00	0.11	0.31	0.31	0.03	0.27	-0.45	0.45	0.00	0.11
4	6	48.00	20.00	0.00	34.00	0.10	0.27	0.27	0.03	0.30	0.03	0.00	0.03	0.14
4	7	57.00	21.00	0.00	39.00	0.11	0.36	0.36	0.04	0.34	0.04	0.00	0.04	0.18
4	8	53.00	19.00	0.02	36.00	0.11	0.31	0.31	0.03	0.37	0.02	0.00	0.02	0.20
4	9	37.00	24.00	0.00	30.50	0.09	0.21	0.21	0.02	0.39	0.02	0.00	0.02	0.22
4	10	29.00	16.00	0.29	22.50	0.07	0.08	0.08	0.00	0.39	-0.23	0.23	0.00	0.22

IRRIGATION APPLICATION VS REQUIREMENT DATABASE				
IRRIGATED AREA	0.13	ACRES	5691	SF
MAX AVAIL SOIL MOISTURE			0.5	INCHES
ESTIMATED SYSTEM LEAKAGE (GPD)	RATE1		0	GPD

IRRIGATION EFFICIENCY = 0.9

MONTH	DAY	IRRIGATION USE---> START-->	DATE 4/1/97	LOGGER FLOW (GAL)	METER READINGS (GALLONS)	METER READING (GALLONS)	EST LEAKAGE	IRRIG APP (GAL)	IRRIGATION APPLICATION (CF)	(FT)	(IN)	RUNTOT IRR APP	CUMTIV IRR APP	EXCESS RAIN	DAILY ET DEFICIT	CUMTIV ET DEFICIT	START SOIL STORAGE	SOIL WATER USE	ENDING SOIL STORAGE	IRRIG WATER REQUIR-EMENT
													0.00							
4	1				731000	0	0	0	0	0.00	0.00	0.00	0.39	0.00	0.10	1.52	0.50	0.10	0.11	0.00
4	2				731000	0	0	0	0	0.00	0.00	0.00	0.39	0.00	0.05	1.57	0.11	0.05	0.06	0.00
4	3				731000	0	0	0	0	0.00	0.00	0.00	0.45	0.00	0.10	1.68	0.06	0.06	0.00	0.05
4	4				731000	0	0	0	0	0.00	0.00	0.00	0.61	0.00	0.15	1.83	0.00	0.00	0.00	0.17
4	5				731000	0	0	0	0	0.00	0.00	0.00	0.79	0.00	0.16	1.99	0.00	0.00	0.00	0.18
4	6				731000	0	0	0	0	0.00	0.00	0.00	1.01	0.00	0.19	2.18	0.00	0.00	0.00	0.21
4	7				731000	0	0	0	0	0.00	0.00	0.00	1.24	0.00	0.21	2.40	0.00	0.00	0.00	0.24
4	8				731000	0	0	0	0	0.00	0.00	0.00	1.43	0.00	0.17	2.56	0.00	0.00	0.00	0.19
4	9				731000	0	0	0	0	0.00	0.00	0.00	1.57	0.00	0.13	2.69	0.00	0.00	0.00	0.15
4	10				731000	0	0	0	0	0.00	0.00	0.00	1.77	0.00	0.18	2.88	0.00	0.00	0.00	0.20
4	11				731000	0	0	0	0	0.00	0.00	0.00	1.98	0.00	0.19	3.06	0.00	0.00	0.00	0.21
4	12				749000	18000	0	18000	2406	0.27	3.21	3.21	1.98	0.01	0.00	3.06	0.00	0.00	0.01	0.00
4	13				749000	0	0	0	0	0.00	0.00	3.21	2.17	0.00	0.18	3.24	0.01	0.01	0.00	0.19
4	14	APRIL			749000	0	0	0	0	0.00	0.00	3.21	2.23	0.00	0.05	3.29	0.00	0.00	0.00	0.06