Using Relative Humidity as a Control Parameter for Programming Supplemental Irrigation

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ABSTRACT:
The applicability of using relative humidity (RH) as a parameter for controlling supplemental irrigation of landscaping turf is explored. This economical water-saving technique is intended primarily for the small-plot irrigator. For the many western sites studied, the RH-controlled system is shown to be effective. For these sites internet databases often can provide the detailed weather information required for determining both the potential and the limitations of this irrigation-control approach. Strong correlation is demonstrated between accessed portions of the continuous RH trace and the daily evapotranspiration data that is generally accepted as the best indicator of plant-watering needs. Management of water application includes the quantity of water applied, the daily timing of the irrigation sequence, the length of the total irrigation cycle, the ideal time of day for measuring RH for the control parameter, and the differences of climatological zone types and local soil conditions. Different zone types may require different control strategies.

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Major Findings

Foremost, this study is based on the applicability of evapotranspiration (ET) data for determining supplemental irrigation requirements. A unique use of relative humidity (RH) as a control parameter for regulating scheduled supplemental irrigation produces the following results. The bases for these conclusions constitute the text of this report.

- **RH-controlled interruption of regular application of supplemental irrigation water significantly reduces excess watering for periods of low need while yet satisfying the extended dryer periods.**
- **RH control systems measure the ambient RH and compare it to a set value (RH set-point) above which normally scheduled irrigation is curtailed for that particular period (e.g. daily).**
- **Combining a matrix of ET data with selected weather parameters (RH and precipitation) for a moderately lengthy period provides a minimal database for evaluating the applicability of RH-controlled irrigation interruption.**
- **Year to year, dry-period ET values are more consistent (predictable) than "average" monthly rainfall.**
- **Most large western cities have local or nearby sites that provide the required ET and weather data for establishing RH-based control parameters.**
- **Generally predictable diurnal (24-hour) RH variation shows that the more stable periods over time for measuring RH are early morning (~maximum RH) and early afternoon (~minimum RH).**
- **For effective irrigation control, the selected RH parameter (e.g., maximum or minimum RH) must strongly correlate with the daily changes in ET and precipitation values, and also must have enough variability to serve as a control parameter.**
- **From the generated database for a selected geographical region, the optimum time of day for making the RH-control measurement (RH set-point) is determinable.**
- **Control of irrigation by selecting an instantaneous RH set-pointvalue from a 24-hr period suggests:**
  - **a) Arid, high-altitude regions could use maximum RH.**
  - **b) Semiarid and moist regions make better use of minimum RH.**
- **For many days at all sites, because of regular diurnal temperature variation the maximum and minimum RH levels usually occur near 0600 hours and 1800 hours respectively.**
- **Fixed time-of-day RH measurements are a simple and economic means of effecting irrigation control for the small-plot user.**
- **For arid and semiarid regions, summer rainfall timing and to a lesser degree the geographical movement of weather systems, upset the diurnal regularity of the RH trace — especially the timing of the maximum RH. Maximum RH often occurs in rainy afternoon periods, and assumed sinusoidal regularity of the diurnal RH trace may lead to erroneous results.**
- **Agricultural ET databases generally include raw data from which effectiveness of irrigation control using RH measured at a fixed time of day can be closely assessed.**
- **Small-plot irrigators for whom the ambient RH normally changes little over a brief total irrigation cycle (a few hours) can use real-time RH-control. "Real-time" implies that ambient RH is continuously being compared to the RH set-point during the irrigation cycle.**
- **Large-area irrigators considerably improve irrigation efficiency by "locking in" the optimal RH set-point control parameter (maximum, minimum, or fixed-time RH) for the entire irrigation cycle.**
- **With morning irrigation usually advised for turf health and water savings, small-plot users also may opt to lock in an evening (~minimum) RH measurement for scheduling irrigation the following morning.**

Hardware and methods described in this report are protected by U.S. Patent No. 6,145.755.

Background and Introduction

The agricultural-industry-accepted standard that indicates plant-watering needs is evapotranspiration (ET), a calculated empirical parameter that accumulates the effects of solar radiation, wind, temperature, and relative humidity (RH). The units of ET are inches (or mm) of water per selected time period. For predicting the monthly needs of a particular region, the daily ET values for the same month over many years are simply summed for each year and the results averaged. Likewise, for each month, the precipitation is summed and combined with the calculated monthly ET value to advise the "normal" amount of supplemental irrigation for that month for the general area. Ideally, the applied irrigation water makes up the difference between the monthly accumulations of ET and precipitation, and shows little variation from year to year. Although most small-plot irrigators are advised to use projected monthly averages for setting the amount of applied water, year to year variations in both monthly rainfall and ET accumulations often cause over-watering or, less frequently, under-watering. The examples and arguments included in this paper validate the use of RH-controlled irrigation. Controlling irrigation with measured RH effects automatic daily water-application adjustments that can offset these varying weather-parameter distributions. The approaches and results presented herein are based on my full acceptance of ET as the best indicator of continually varying plant-watering needs. The main thrust of the paper is to show a strong correlation between the daily varying values of ET and a selected portion of the continuous RH trace. While I do not claim global applicability for these results, my studies show that most arid and semiarid regions can benefit considerably by using the proposed irrigation-control systems. Such sites are typically those for which supplemental irrigation constitutes an appreciable fraction of the turf water needs, i.e., sites for which potential savings from improving irrigation efficiency are appreciable.

The varying requirements for supplemental water needed over the irrigation season typically are represented by bell-shaped curves that for most sites peak during the June-July period. Adjustments to the applied-water needs based on such curves attempt to accommodate historically predictable seasonal changes, but do not address daily ET fluctuations periodically caused by intermittent rain or high humidity. Unfortunately, year-to-year variations that illustrate dramatic regional departures of rainfall from annual norms are commonplace. Any system or method that purports to economize the application of irrigation water must be able to sense and accommodate both seasonal and daily excursions of precipitation and ET from historical norms. The proposed RH-controlled irrigation system is shown to do precisely that for several different climatological zones of the western United States. The full potential and limitations of an RH-controlled irrigation system will be realized only when similar ET/RH correlation studies include all areas that routinely require supplemental irrigation.

Control of irrigation by sensed atmospheric RH initiated with the introduction of the Weathermiser® in the late 1900s[1]. For arid, high-altitude sites such as Tucson and Albuquerque that require relatively brief (a few hours) early morning watering, this simple device has proved very effective for reducing excess watering. While being a simple and reliable device however, it functions only as a "real-time" controller which limits its widespread applicability. These limitations involve regions where the RH correlation with ET is different from that of arid, high-altitude sites. They also concern irrigation systems for which lengthy watering cycles (greater than a few hours) are required. For such applications, the ambient RH variations that naturally occur during the irrigation cycle may force an uneven application of water — some irrigation stations at the site will be watered while others won't. Because of the generally consistent diurnal RH variation, this irregularity likely will be repeated, i.e., the same stations may be shorted the following day(s). Another significant disadvantage is that "real-time" control, by definitation, is not compatible with sites for which the RH control parameter is to be measured at a

[1] The Weathermiser is an irrigation-system adjunct that in real time senses RH for overriding (interrupting) the normally scheduled irrigation sequence. It was patented by Al Caprio of Albuquerque, NM on December 1998 and holds U.S. Patent 5,853,122. It includes an adjustable RH set-point such that if the sensed (ambient) RH is above the set-point, the electrical circuit to the irrigation valve(s) is interrupted, thus preventing irrigation until such time that the ambient RH again drops below the set-point during a scheduled irrigation cycle.

time other than during actual irrigation period. The ideal time for measuring the RH for most climatological regions is not during the typically recommended early morning watering period.
My improved control system likewise uses RH as the control parameter that similarly directs the interruption of the time-scheduled supplemental irrigation. But the new system also includes a time-delay option such that the optimal RH control signal is preserved and remains effective until the entire irrigation cycle is completed. This system modification greatly expands the geographical regions for which RH can be used as an effective parameter for conserving irrigation water. My studies show that for most arid or semiarid climatological regions that benefit from regular summer thunderstorms, minimum RH shows much better correlation with daily ET variations than maximum RH. This conclusion implies that for all such regions, a "real-time" control system based on ambient RH measurements requires irrigation in the hot afternoons (during which time minimum RH usually occurs) rather than the usually recommended cooler morning period.

Discussions that involve natural phenomena such as weather-related topics are necessarily complex and invariably incomplete. I assume moderate proficiency of the reader in the topics presented. The technical discussions are directed toward researchers, professional irrigators and consultants, as well as knowledgeable private users. However, I attempt to maintain sufficient simplicity in the technical discussions so that anyone with moderate scientific acumen can follow the logic. Accordingly, I must briefly define several concepts and parameters that will be "old hat" for irrigation professionals. To shorten the body of the report, highlighted words in the following text will have definitions and/or expanded discussions in appendices.

How Irrigation Needs are Determined

Most states with agricultural bases that substantially contribute to their economy provide seasonal real-time weather data to growers so that they can efficiently schedule the irrigation of commercial crops. Some regions provide this information only to fee-paying members, but many others provide free access to such data. Generally this information is in the form of tabulated daily weather parameters and reference evapotranspiration (ETo) calculations. These empirical ET values constitute the industry-accepted standard for establishing crop-irrigation requirements. The ET calculations typically integrate weather conditions over a specified period of time and involve four continuously recorded parameters: temperature, RH, solar radiation, and wind. These parameters are forwarded to a central computing station from a network of automated recording sites dispersed throughout the growing region. Sometimes, the nearest recording station of the agricultural network is close enough to a metropolitan area to accurately model its ET behavior. For example Ft. Lupton, CO information (from CoAgMet[2]) approximates the behavior of Denver; and Spencer, OK information (from the Oklahoma Cooperative Extension Service) approximates the behavior of Oklahoma City. Both of these weather-recording sites are about 15 miles from the city cores.

For assessing plant-watering needs, a single value (reference ET or ETo) is calculated on a daily basis for each field site. The user (or service provider) then adjusts this value by a crop factor (Tc) for the specific crop of interest. For the purposes of this paper the crop is cool-season turf grass that has a Tc of 0.8 to be applied to the ETo. For warmer regions, warm-season turf grass with a crop factor of 0.6 often is preferred[3] because of the 25% lower water usage. Increasingly, more populous states and some metropolitan areas such as Denver also provide local ET data for urban users during the turf irrigation season. I use urban data for local site-behavior comparisons, but the data-set completeness (e.g., including ETo and daily maximum and/or minimum RH together with continuous or hourly RH values) required for optimizing the RH-set-point selection usually is available from only the agricultural sites. I urge non-agricultural users to access these ET/weather data sets. They are generally understandable and straightforward in their applicability for home use. At the very least they

[2] Colorado Agricultural Meteorological Network.
[3] Various sources recommend slightly different crop factors for the same crop. They also may base the ET calculation on different crops and different algorithms. I am not promoting any particular ET value or crop factor; for the purposes of this study they are all very similar and result in the same overall conclusions.

should be used as the basis upon which irrigation scheduling (timing and water-application quantity) is initially set up and seasonally adjusted. They also provide the data sets for establishing the RH set-point values for controlling supplemental irrigation in the examples included herein.

Estimates of annual supplemental water for "normal years" combine the historical turf needs (ET) with historical precipitation records on a month-by-month basis for the irrigation season. Supplemental water needs for turf grass vary widely from region to region depending on the four parameters cited for calculating the ETo as well as the seasonal rainfall timing and quantity, and local topography and soil conditions. Ideally, local annual "monsoons" coincide with the irrigation season, but this is not always the case. In addition, individual rainfalls during the irrigation season may not be totally effective in reducing the supplemental irrigation because they are too intense to be absorbed, or because saturated soil or a sloped surface contributes to high runoff. In a natural process called the water budget method soil can "bank" several days of needed moisture. Turf-watering needs estimated for a specific local region include some or all of these factors. Table 1 projects annual applied water needs of cool-season grasses for selected western cities.[4, 5] The applied-water values of Table 1 sometimes are termed "water deficit."

Table 1. Applied-water requirements for cool-season grasses (inches/yr.)

Flagstaff, AZ	31.2	Reno, NV	36.4
Phoenix, AZ	76.7	Las Vegas, NV	55.9
Tucson, AZ	71.5	Santa Fe, NM	31.2
Sacramento, CA	39.0	Albuquerque, NM	39.0
San Francisco, CA	27.3	Bismark, ND	19.5
Los Angeles, CA	62.4	Oklahoma City, OK	26.0
Denver, CO	28.6	Portland, OR	24.7
Boise, ID	35.1	Sioux Falls, SD	24.7
Kansas City, KS	23.4	Dallas, TX	37.7
St Louis, MO	23.4	San Antonio, TX	49.4
Missoula, MT	20.8	Houston, TX	28.6
Omaha, NB	26.0	Salt Lake City, UT	31.2

Note in Table 1 that the turf irrigation requirements for arid, high-desert Albuquerque approximate those of both Sacramento and Dallas, both lower and much more humid regions. The supplemental needs are similar despite the fact that the average annual rainfall accumulations of these three cities are about 8.9 inches, 17.5 inches, and 33.7 inches respectively. The major climatological difference between Albuquerque and Sacramento is the timing of the rainfall; Albuquerque's rain occurs mostly in the summer while Sacramento's occurs in the winter (non-irrigation) period. The Dallas disparity has a different basis. Dallas average temperatures are consistently higher than those of Albuquerque, and ET values are particularly sensitive to high temperature. However considerably more rainfall and higher humidity reduces Dallas's applied water needs by either offsetting or lowering the ET values.

The annual and monthly ET calculations together with historical rainfall data constitute the database for <u>initially</u> programming irrigation schedules. However, historical weather-data averages are inadequate for scheduling application of agricultural crop water because occasional annual rainfall variations of more than 50% are not uncommon. Additional irrigation adjustments are imperative. The same must hold for turf irrigation. The major factor affecting differing annual water requirements for a selected site is the variation

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[4]Because of the more readily available gratis meteorological/ET data in the west, I restrict the scope of my initial studies to western states. However, the overall conclusions likely are applicable to most eastern areas.

[5] A more complete list of U.S. cities is accessed on web site: www.waterwiser.org. This site is a valuable resource for information concerning water conservation.

and timing of precipitation. If the irrigation-control system can accommodate this unpredictable variation it approaches the balance needed to assure acceptable turf health together with irrigation economy.

Creating an irrigation schedule

Creating an irrigation schedule starts with the examination of ETo and precipitation data for the selected region. Turf-referenced ETo values represent the moisture that the turf can absorb for maximum growth. Averaged monthly data are represented by the typically bell-shaped curves shown in Figure 1 for several cities. This figure also includes single-year data: 1997 for Denver, and 1998 for Albuquerque. These two single-year inclusions clearly depart from the typically smooth, symmetrical, bell-shaped curves and demonstrate the need for irrigation control beyond the predicted average seasonal requirements. ETo data, of itself, is not sufficient for irrigation-scheduling purposes. ETo needs to be offset by effective rainfall. Effective rainfall is the rainfall accumulated during the irrigation season less the amount lost to runoff and deep-soil percolation. For most well-grassed sites, percolation is usually low. For level turf plots, a stand of healthy grass reduces runoff for all but exceptionally heavy downpours. The Table 1 list of annual applied-water requirements considers these factors, i.e., on a monthly basis ETo is first adjusted for the crop factor (0.8 for cool-season turf grass), and then offset for historical normal effective rainfall. The monthly needs are accumulated to produce the tabulated ETo-referenced turf water-usage requirements in Table 1.

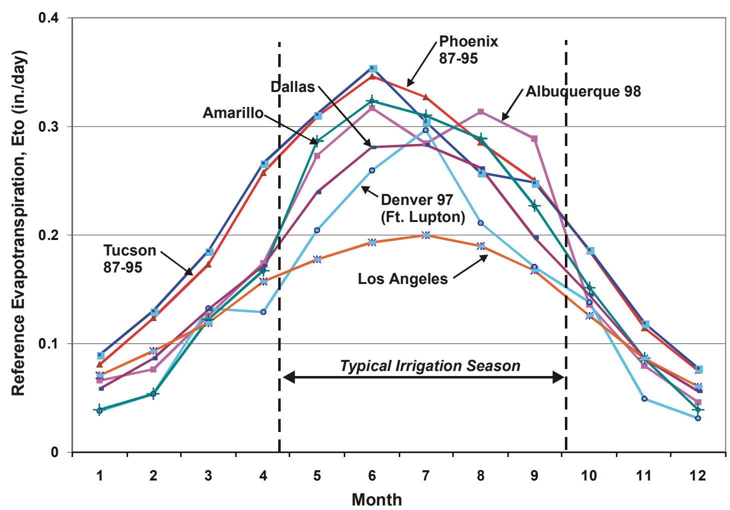


Figure 1. Monthly evapotranspiration (ETo) for several western cities

The calculated monthly ETo values of Figure 1 are not used unaltered by irrigation schedulers. A single ETo value[6] may be used for many different agricultural crops. A turf crop factor (Tc) modifies the calculated ETo value as mentioned earlier (Tc = 0.8 for cool-season grass). The individual curves of Figure 1 are modified for actual crop needs similar to the example shown in Figure 2. ETo values are first adjusted by crop factor into ET values applicable to turf grass. The reduced ETo value (ET) represents the total amount of water that healthy cool-season turf grass with a height of about 4 inches and a well-developed root system can absorb to produce maximum growth. The graphed data[7] of Figure 2 combine ET and rainfall values for each month of an averaged 30-year span for College Station, Texas. The author of this data assumes an across-the-board

[6] Since historically, ETo values were calculated for agricultural crops, ET data are not necessarily based on our reference crop of cool-season grass. The reader is advised to closely examine information from the various ET sources. The reference crop usually will be specified.
[7] Extracted from Richard L. Duble, "Water Management of Turfgrass," Texas A & M University (TAMU). This excellent comprehensive discussion paper is available in the TAMU website.

25% loss of precipitation to runoff[8]. Thus for his model, effective rainfall is only 75% of the actual. The monthly difference between ET and effective rainfall values represents the water deficit (green curve), the supplemental water to be applied on a monthly basis. The averaging of many years of such data produces the generally smooth bell-shaped ET curves of Figure 1. However, as noted earlier, single-year ET traces can exhibit dramatic excursions from the usual smooth curves.

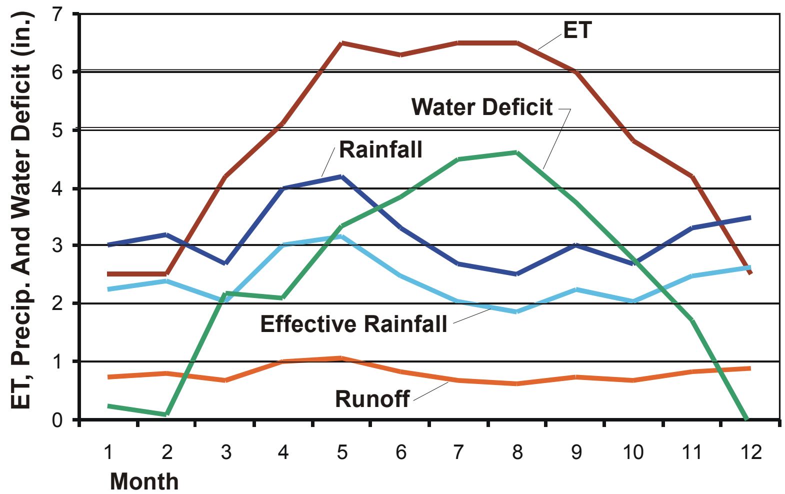


Figure 2. Water deficit for College Station, TX (30-year average)

Ideally moist soil conditions and maximum turf growth are implied in the ET curve of Figure 2. Generally, however, turf growers do not desire maximum growth of turf grass. Most users desire to minimize irrigation and mowing frequency while maintaining an acceptable appearance of their lawn. In addition to the turf or crop factor, a second multiplier is used to further reduce the applied water. This parameter is called allowable stress (AS) and represents the appearance of the turf that is acceptable to the user. Allowable stress factors range from about 1.0 for turf with no stress (e.g., golf greens) to 0.4 for highly stressed (discolored) turf. A common AS selection from this range might be a value of 0.6 that represents the appearance of sod in well-managed public parks. Multiplying the raw ETo values by both the crop factor and the allowable stress factor provides the modified ET value that represents the actual need of the turf as determined by the user, and which is then offset by effective rainfall to calculate the required irrigation supplement. The irrigation supplement together with effective precipitation matches the loss of turf moisture due to evaporation and transpiration. In the included performance models, I modify the ETo values for a cool-season grass crop factor of 0.8 and a stress factor of ~0.6. These combined factors reduce the actual ET values for cool-weather turf grass to ~50% of the reference ETo values. Using different values for the individual ETo adjustment multipliers will not invalidate the techniques and conclusions — the numerical results may vary, but the overall irrigation-control logic based on RH measurements remains valid.

Most irrigation systems, especially those employing sprinklers, apply water unevenly. A really balanced sprinkler system will have a system efficiency of perhaps 80% while poorer systems drop to 50% or even lower. To protect minimally irrigated areas, the supplemental water values calculated above must be divided by the irrigation system efficiency to schedule the total water to be applied. Since this correction is site specific, it is not considered in the following calculations of turf watering need. I also ignore runoff as being largely site specific. Its effects, while not included in the numerical calculations, are considered after the data matrices that illustrate control performance have been created.

[8] This high (for the author) value may be caused by intense Texas rainfall, often exceeding several inches for a single storm. Summer thunderstorms produce most of the offsetting precipitation.

Control of Irrigation for Daily Weather Variations

Annual data provides the basis for initially programming the irrigation water for monthly or daily application. However, the programmed "normal" irrigation should be updated daily by some means to account for sporadic periods of rain and high humidity. At present, to avoid "watering in the rain" timer-programmed watering sequences for residences or other small-plots typically are interrupted by hit-or-miss manual intervention. While ET calculations are sometimes provided on a daily basis to urban small-plot irrigators, to effectively use this data manual intervention is again required. Professional irrigation schemes use costly irrigation controllers interactively connected with computerized data centers that integrate daily weather and ET data for a broad area of coverage. These controllers automatically make watering adjustments based on the conditions of the site at which the weather data is taken. Unfortunately, for climatological regions that receive their summer rainfall mainly from thunderstorms, irrigation-site conditions may differ radically on a day-to-day basis from those even at a nearby measurement station.

The crux of this paper is that for several different climatological regions, a strong correlation of some portion of the continuous RH trace with daily excursions of the ET trace indicates that near-real-time, responsive, efficient, hands-off irrigation control is feasible even for small plots. RH comparisons made by an inexpensive sensor (humidistat) included in the irrigation system's control circuit adjust the applied water (scheduled on historical averages) to the plant's actual daily varying needs. This new control option eliminates the inconsistency of manual intervention, bypasses the cost and suspect areal applicability of the high-tech approach, and yet provides an effective, economical, automatic or hands-off solution to over-watering. Furthermore, the proposed system has the unique advantage of being irrigation-site specific; it is little concerned with weather conditions perhaps fifteen miles away at the weather station. This latter advantage is particularly important for geographical regions for which the rainfall during the irrigation season is mainly from thunderstorms. The areal inconsistency of such rainfall is well recognized.

In its simplest real-time RH-control configuration, a humidistat is internally coupled to an integral electrical switch such that whenever the ambient RH is above a user-selected RH set-point the electrical switch remains open. The humidistat includes a means for varying the RH set-point. The user manually selects the value of the RH set-point, and whenever the sensed ambient RH is greater than the set-point no irrigation can occur because the open-switch condition prevents the valves from operating. The irrigation-system architecture shown in Figure 3 is that presented by the Caprio patent. The humidistat is installed in series with the common return wire from each of several sprinkler valves. In the usual system configuration, the irrigation valves use a single or common return wire in their circuit. Although my newly proposed RH-controlled irrigation-system configuration includes time-delay functions for optimizing the system's water-conservation efficiency, the basic action of interrupting the timer-controlled watering cycles is analogous.

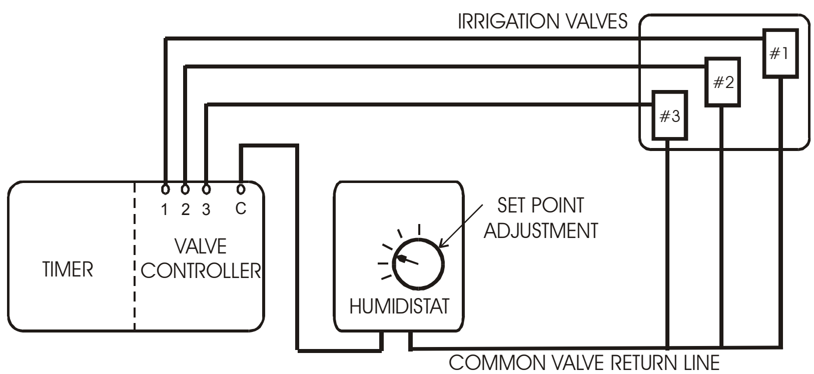


Figure 3. Humidistat interrupter installed in "real-time" control circuit

The proposed new hardware systems and database usage should raise users' and water suppliers' expectations for better performing irrigation systems. The forgoing and following discussions, however, do not imply a diminished need for irrigation professionals. On the contrary, for properly installed and programmed irrigation systems, the new methods permit professionals to offer improved water savings to small-plot users at affordable prices. I fully realize that most such users will not ponder the detailed technical intricacies that yield the general conclusions presented herein. However they will use the results when the advantages are verified and publicized by trusted sources. Especially for the small-plot irrigator, the control schemes and logic that determine the RH set-point should be straightforward and easily applied. Accordingly, my goal is to minimize RH-control adjustments. Ideally a single unchanging site-specific RH set-point value can be calculated that is effective for the entire irrigation season. I show that this goal has been realized for sites from several different meteorological regions.

Regional Climatological Difference

Regional climatological differences require different approaches to controlling irrigation with sensed RH. In order for any sensed parameter to provide effective control, the variation of the parameter must be broad enough to permit the selected sensor (humidistat) to provide a meaningful measurement. Even more important, the selected control parameter must show good correlation with variations in the target parameter — ET in our discussion. I use tabulated daily entries of selected parameters for an entire month to calculate the effectiveness of competing RH-control schemes. I convert such to a graphical format to allow rapid visual appraisal of the results. The general format for information presentation is that shown in Figure 4.

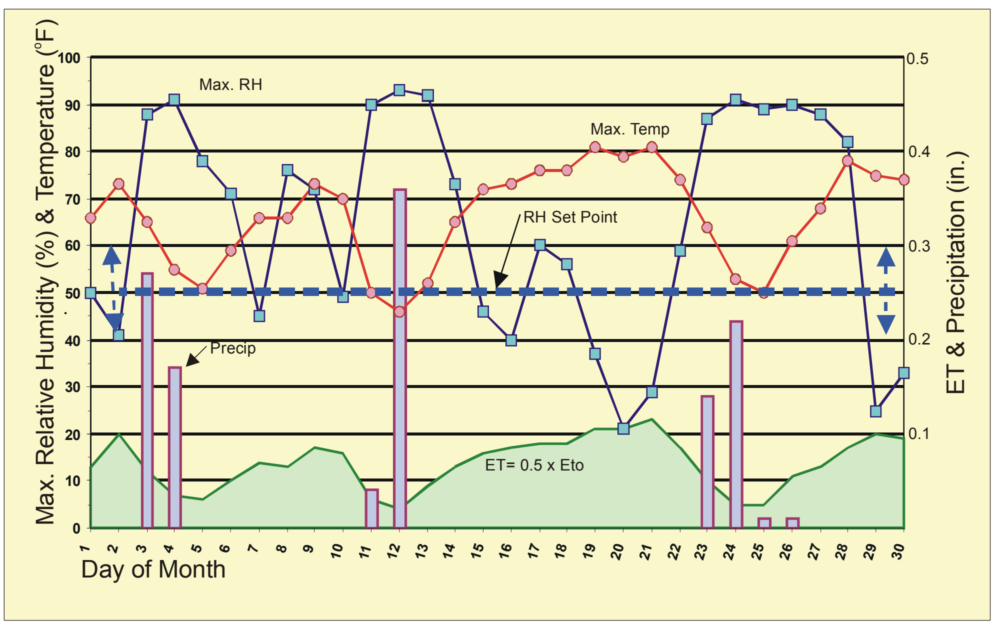


Figure 4. Albuquerque Daily Weather/ET History (April 1997)

The solid green area representing the evapotranspiration (ET) trace in this figure is bounded by 0.5 times the daily ETo as described earlier. To keep the chart simple, only the maximum RH trace is included in this data grouping since it is an acceptable control parameter for this arid site and is better adapted for using real-time control. The daily maximum RH charted is the highest instantaneous value of RH measured for the 24-hour period regardless of the time of day at which it occurred. Note that the ET trace and the daily precipitation columns are plotted to the same scale (indicated on the right-hand vertical axis). The daily variations of ET are considerable (~ 4:1), as is usual when appreciable sporadic rainfall occurs. This observation underscores the need for coordinated daily irrigation control.

Ignoring runoff as negligible, the accumulated daily ET and precipitation values for the month are 2.06 inches and 1.22 inches respectively resulting in a monthly water deficit of 0.84 inches. I set the daily water-application level to be near the peaks of the ET entries (averaged over many years) to always satisfy lengthy dry periods. This water-application amount is higher than recommended by many irrigation professionals because their water-application settings usually attempt to compensate for historical (average) rainfall. Because year-to-year precipitation is markedly inconsistent, I adjust for the rainfall on a real-time daily basis rather than historical basis. The dry-period ET values (peaks) are much more constant year after year, and thus the water-application value based on these periods will be reasonably consistent for the same month of any year for this site. I select a water application level of 0.08 inches per day accumulating to a total (if not interrupted) of 2.40 inches for the month. However, dividing the monthly water deficit by the application per day (0.84/0.08) yields only 10.5 days for which watering should occur. April having 30 days, the difference is 19.5 no-water days (nwd) to be selected by the control system.

Now consider the RH set-point to be a horizontal line spanning the entire chart. It represents a fixed value of RH for the entire month. Move this "set-point" line up or down until 10 or 11 of the daily maximum RH data points are on or below the line. A position near 50% (dashed blue line in Figure 4) meets this stipulation. Only for those days where the RH trace is below the set-point line will irrigation be allowed. An astute observer will note that an RH set-point similarly can be made to match the water deficit for any particular month if, like in our example, the set-point selection is made after the fact. What is promising, however, is that for many prior or subsequent years for April in Albuquerque, the same results prove valid, i.e., the ideal RH set-point remains nearly constant. In fact, multi-year studies are the optimal method for establishing both the monthly watering rate and the RH set-point. Many similar examples constitute the bases for my conclusions.

Refer again to Figure 4 for some important observations. First, note that the ET trace is mirrored by the maximum temperature trace. Also, the temperature and RH traces are generally reversed mirror images. These observations satisfy our intuition that higher temperatures and lower RH are consistent with increased watering needs. RH and temperatures values are not independant from each other. (Having demonstrated these relationships, temperature will not be included in subsequent illustrations.) The more important observation in Figure 4 is the relationship of the maximum RH trace with the ET trace. The curves show an inverse relationship: the higher the RH trace, the lower the ET trace. This behavior is especially pronounced for the three rainy periods — the major peaks of the maximum RH trace match the timing of the troughs of the ET trace. Also, it does not require actual precipitation to lower the ET trace; often high humidity suffices. Observe the ET values for the 13th and 25th through 28th. The first day has no rain and the second period received only a trace. It is not uncommon for an RH-controlled system to stop irrigation a day or two before the actual onset of rain because of increased RH (and accompanying lowered ET) preceeding the rainfall.

Another significant observation of Figure 4 is that the "water-day" periods allowed by the RH-controlled system (i.e., those days whose maximum RH value is below the set-point level) generally correspond to the periods of higher ET, that is to say, the sequential days with the greater needs for supplemental water. However, it is not necessary to precisely match the ET needs on a day-by-day basis. This topic is pursued in detail on several of the irrigation web sites, but such details are not relevent to the main thrust of this paper. The essential result is that soil has the capability to bank a few to several days of moisture. The banking capacity is generally site specific, and depends on several variables including location, meteorological conditions, pre-existing soil moisture, time of year, the turf crop, and the soil type and topography. A typical summer carry-over period for fully moist loamy soil might span three to six days. Our goal for use of RH-controlled irrigation is to match turf-moisture needs over a moderately lengthy time period.

In the preceding example we assumed that daily maximum RH provided our control parameter. We now consider the daily variation in RH. The continuous daily RH trace typically varies in roughly sinuisoidal fashion as shown in Figure 5. This graph shows slightly smoothed traces of the continuous RH values for two consecutive days from Ft. Lupton, CO. This trace is not a record of water content in the atmosphere. In fact, the actual amount of moisture in the atmosphere typically remains fairly constant over a "normal" 24-hour period while the instantaneous RH values fluctuate considerably, especially for high-altitude regions. The causitive factor of RH fluctuation is diurnal temperature variation usually peaking at about 4:00 or 5:00 pm and reaching its low at about 5:00 or 6:00 am. Considering the inverse RH/temperature relationship noted earlier, we would expect that the maximum RH level normally occurs in early morning, while the minimum RH level occurs in early evening. This is precisely what most often happens. While similar data for other sites may show greater or less peak-to-peak variation than the curve shown in Figure 5, the argument made in the preceeding paragraph universally holds true. Early morning typically yields the highest RH values while afternoon yields the lowest RH values. Only the occurrence of summer storms, passage of frontal systems or squall lines, and other moisture-generating phenomena upset this regular behavior. Their effect on RH behavior will be examined later.

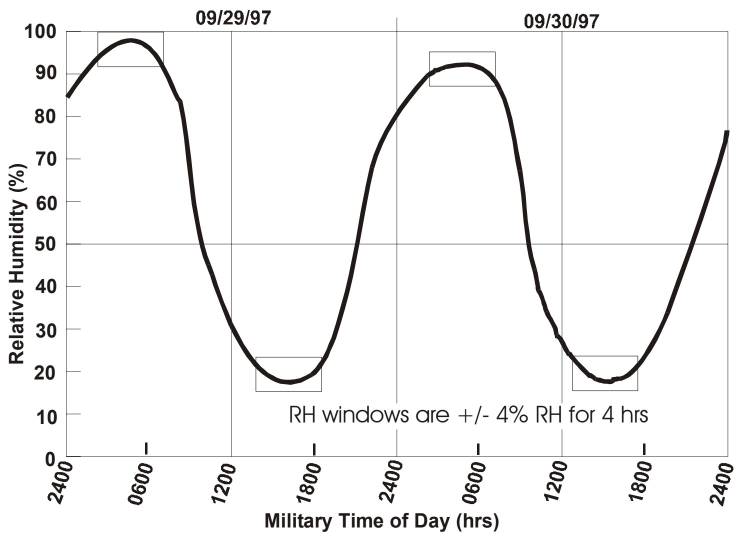


Figure 5. Continuous RH trace for two successive days

The RH trace in Figure 5 also illustrates that at the peaks and lulls of the RH trace the instantaneous RH values are fairly constant for several hours, i.e., they are not particularly sensitive to RH measurement timing at these positions. Conversely, the extremely steep slopes of the traces between the peaks and valleys indicate that RH values from these regions are extremely sensitive to measurement time. This observation of typical RH behavior is important because irrigation programmers already include a clock, the simplest and most economical means for timing the comparison of the ambient RH with the humidistat's set-point. Simply select a fixed time of day that corresponds to a flatter portion on the RH curves. Stations producing daily ET information usually include maximum and/or minimum RH. Based on availability of this data, as well as the fact that the maximum and/or minimum RH values usually change little for several hours, I restrict selection of irrigation-control parameters to periods of either the maximum or minimum RH.

Figure 6 shows the continually changing RH trace for an entire month (August) at Ft. Lupton, CO. At first glance, this raw trace looks very irregular, but the time-axis has been compressed ~15 times relative to Figure 5. I include Figure 6 to illustrate the predictable regularity of diurnal variation of RH for longer periods of time. This lengthier trace also encompasses several rainy periods that upset the diurnal RH regularity. For example, the rain accumulated from the 4th through the 6th exceeded 1.7 inches and the minimum RH levels during and following this period increased significantly implying generally high average

RH throughout this entire rainy period. A second rainy period was the 09th through the 13th with similar RH increase noted. The third rainy period was from the 17th to the 18th. All three rainy periods have have strong correlations with selected portions (minimum RH) of the continuous RH trace spanning this month. Since a thorough understanding of atmospheric RH variation is vital to assessing the nuances of the proposed RH control of irrigation, Appendix II includes an expanded discussion of this topic.

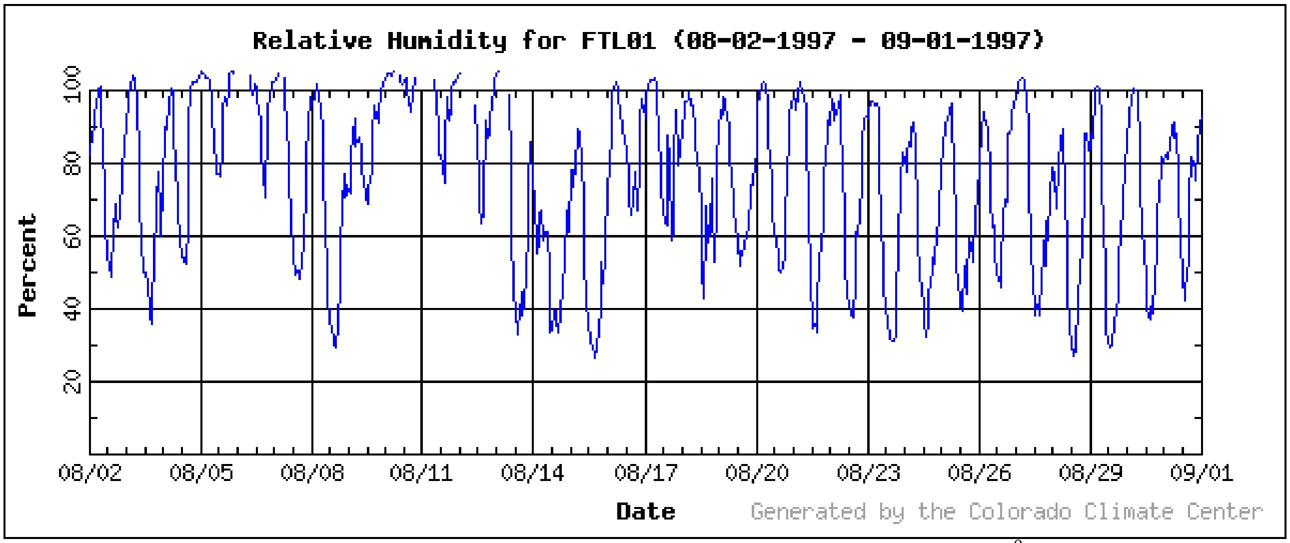


Figure 6. Continuous RH trace for Ft. Lupton, September 1997[9]

This continuous graphical RH trace allows determinination of precisely when an RH set-point is actually exceeded (on a minute-to-minute basis) for uncertain situations when the tabulated RH value is very close to the set-point. This uncertainty arises because some stations list the RH values averaged for each one-hour period thus masking both the maximum and minimum extremes. These stations typically calculate an ET value for each hour and then sum them over the 24-hour period to arrive at the daily ET value. As a result neither a "true" maximum or minimum RH is provided. Data-user judgement must consider these factors. If the graphed data of Figure 6 is greatly expanded along the time axis, the actual sensed RH value at any selected instantaneous time can be extracted. Because of the previous discussions about how tabulated hourly RH entries are often calculated (averaged), similar graphical presentations of RH vs. time, if available, may be the only means of fixing an absolute ambient RH value to a precise time of day. Likewise, this graphical data can establish the actual time of day at which the maximum or minimum RH occurs. Some stations include this information in their raw digital format for presenting daily data. In any event, I caution the reader to determine how the data provider generates tabulated RH values.

We examined an arid site (Albuquerque) postulating maximum RH as our control parameter in Figure 4. We now examine another arid site (Tucson — September, 1999) in Figure 7. Because of regularly higher temperature, Tucson's ET values are generally greater than those of Albuquerque. Dry months indicate fairly consistant ET requirements with minimal need of irrigation interruption. For the included weather-history examples, I have deliberately selected months that have relatively more rainfall. With the data included in Figure 7 we compare effectiveness of irrigation control using either maximum or minimum RH entries for establishing the set-point. To accommodate the drier periods in Figure 7 the irrigation application rate is 0.13 in./day. The daily ET values sum to 3.32 inches. The accumulated precipitation is 1.44 in. resulting in a water deficit of 1.88 inches. However, the last day of the preceding month (August) had a

[9] The data shown are extracted directly from the CoAgMet (Colorado Agricultural Meteorological Network) website material. This site provides unusually complete year-round ET and weather data summaries primarily for agricultural purposes. Although slightly north of Denver, the completeness of the data sets makes this site a better source for fixing RH-controlled irrigation behavior for Denver than the less complete local data sets available from Denver Water.

rainfall of 0.71 inches with a carryover into September of about three or four additional no-water days. All things considered, the deficit equates to about 12 days that need irrigation. For using maximum RH as the control parameter, the RH set-point (dashed blue horizontal line) is adjusted to about 83%. There are 12 days for which the maximum RH is below this set-point. Likewise, for minimum RH the set-point is ~18-19%. This latter set-point value introduces the use of "minimum RH" as the control parameter.

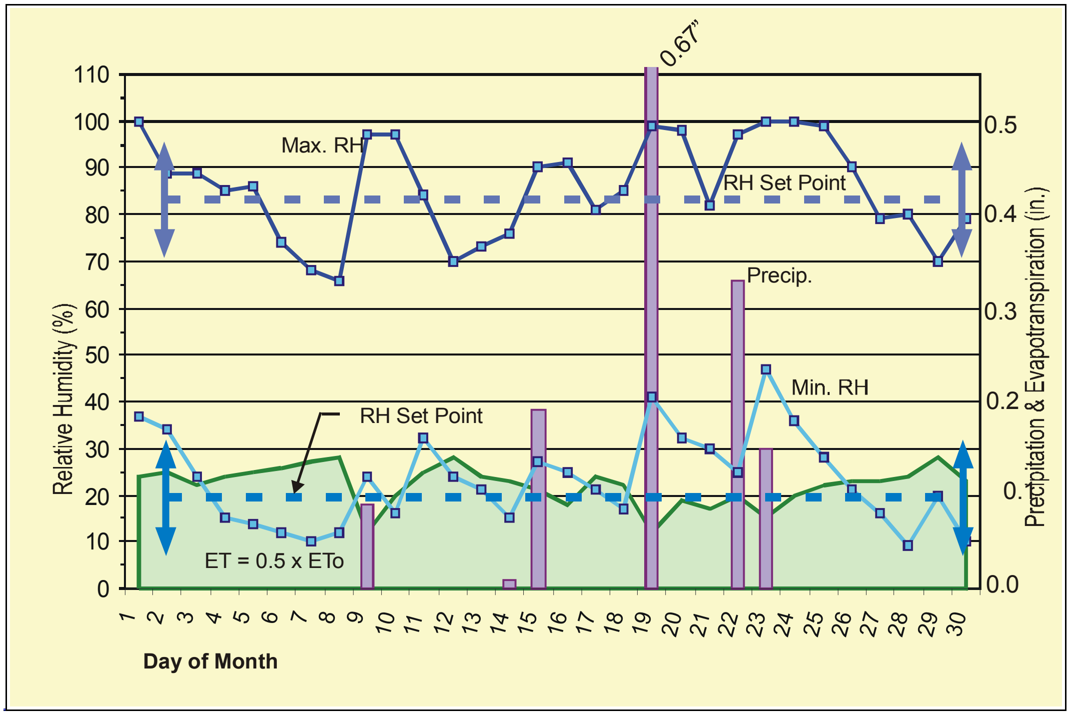


Figure 7. Tucson daily weather/ET history (September 1999).

Figure 8 duplicates and expands the data set of Figure 7 and allows comparison of all competing RH entries that are candidate control parameters for the modeled irrigation control system. Figure 8 presents graphical interpretation of the each of six selected RH values available from some agricultural data providers. For Tucson, the Arizona Meteorological Service (AZMET) data provides all of the discussed RH parameters. The dark blue traces of Figure 8 duplicate the instantaneous maximum and minimum RH curves of Figure 7. They are the true instantaneous maximum and minimum RH values listed for each day. The light blue traces are the maximum and minimum of the RH values from averaged hourly data entries for each day. These daily RH entries are the maximum and minimum of the 24 values averaged over each hourly period, e.g., the 0200-hr value averages the RH occurring between 0100 and 0200 hrs. While one of the 24 RH entries for hourly listings of each day is close to the instantaneous maximum or minimum RH value, by definition the instantaneous RH values listed for a particular day always bound the hourly-averaged values. The orange traces are the hourly-averaged value for the listed fixed time for each day of the month. The times selected are the "normal" time near which the maximum and minimum diurnal RH values commonly occur. It is this third option that is more compatible with existing irrigation-programmer systems.

For an irrigation study that adopts hourly-averaged maximum RH (upper light blue trace in Figure 8) to model as the control parameter, for this particular month the RH control point can be lowered 4% (from 83% to 79%) to produce the same number of no-water days. However, there are now five days that have RH matching or within a few percent of this new RH set-point value. These near matches with hourly-averaged RH entries, as mentioned earlier, introduce uncertainty as to what the actual ambient RH is at the instant of measurement. Typically daily RH entry values within about 3-4% of the RH set-point are assigned this uncertainty. More importantly, for a fixed-time-of-day RH comparison, the ambient RH at the precise time selected for making the measurement, rather than either of the tabulated “maximum RH” entries of the daily record controls the irrigation logic. We next compare control by these various parameters.

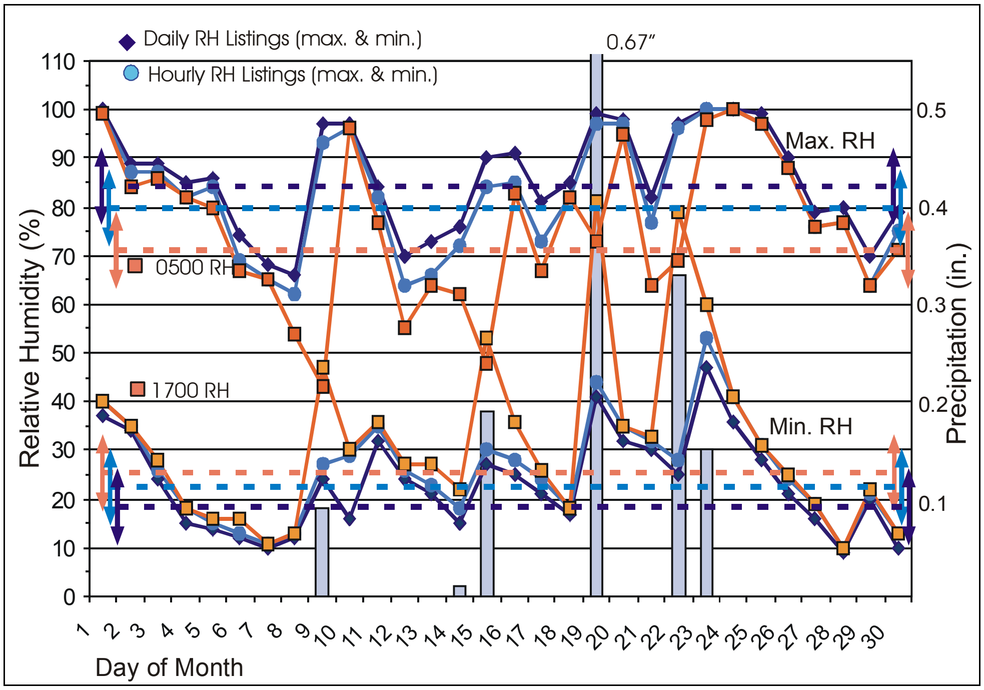


Figure 8. Tucson Daily RH Value Comparisons (September 1999)

Recall that I earlier proposed that the “maximum RH” measurement be made at a fixed time of day expected to correlate with minimum daily temperature (for most sites ~6:00 am), and hopefully approximating the instant at which RH is maximum. The orange traces in Figure 8 are the hourly averaged 0500-hr (assumed to approximate maximum RH) and 1700-hr (assumed to approximate minimum RH) values for the precise times used by the humidistat to make the decision on whether or not to irrigate. For also accommodating a “real-time” control-system modeling response, I select a time slightly earlier than the expected maximum RH peak of 6:00 am; opting for 5:00 am to center a two-hour watering period around the actual 6:00 am peak. The 1700-hr readings also precede the historical time of maximum daily temperature by about one hour. This time-offset approach is geared toward evaluating “real-time” RH control for which we need the RH to remain fairly constant for the duration of watering cycle (perhaps several hours).

None of the hourly-averaged entries (light blue or orange traces) are instantaneous values. At any instant of time within the listed hour these entries have uncertainties from the tabulated value typically of a few percent. This uncertainty is observed in Figure 8 by comparing the light blue and dark blue traces for typically dry periods. Within the two sets of three matched traces, the individual RH traces show clear differences recalling my caveat to determine the precise definition of the RH data being availed. With this illustration the daily instantaneous maximum RH value can be compared to the hourly-averaged “maximum RH” entry and the RH value tabulated for 0500 hours for the same data set.

For all dry days the daily instantaneous maximum or minimum RH (dark blue traces) and the hourly-averaged maximum or minimum RH (light blue traces) are very close, varying by a few percent or less. The fixed-time values (orange traces — 0500 hours or 1700 hours) also closely mimic the other maximum or minimum RH traces for the dryer periods. However rainfall dramatically upsets this regularity, especially for the 1700-hour RH values. The reason for these excursions is the usual daily timing of the rainfall together with rapid RH increase. If the rain could be programmed to fall at 0500 hours, the three curves would merge. In reality, rainfall and accompanying high RH on many summer and fall days occurs in the afternoon or evening. The 1700-hour RH trace clearly illustrates this behavior. For every rainy day or period in Figure 8, the 1700-hour RH value represents an appreciable increase above either of the two “minimum RH” listings for that day. There are four days where the 1700-hour RH is actually higher than the 0500 RH. From this observation alone (and confirmed by the tabulated hourly precipitation data), we assess mostly afternoon rainfall. A consequence of this observation is that for this site the 1700-hour RH value is an even more effectual parameter than “minimum RH” for correlating with precipitation and the accompanying ET-trace behavior.

With the expanded data bases like that shown Figure 8, I establish an RH set-point (at either morning or afternoon) for a fixed-time control system that controls the number of allowed irrigation days as well as by using any of the maximum or minimum RH values tabulated for each day. I adopt fixed-time ambient RH measurements that usually approximate the other RH entries for both of the times that are candidates for RH control. The selected-time hourly RH values are tabulated for the entire month (the orange-colored traces). However, these values listed in the raw hourly format also are averaged over the previous one-hour period. As observed in Figure 8, the tabulated hourly “maximum” and “minimum” RH values for most dry days closely approach either the maximum and minimum instantaneous values that likely were made during the same hour. The fixed-time error introduced by averaging any one-hour period of continuous RH data should usually be within the same few percent.

In the current example, to allow 12 watering days the RH set-point for the 0500-hr measurement will be ~71%; for the 1700-hour measurement it will be ~27%. Regardless of timing, the irrigation system functions the same — for all days at which the ambient RH is above the set-point at the time of the measurement, irrigation is prevented. The set-point values calculated for the fixed-time RH measurements of 71% (~ maximum RH, 0500 hours) and 27% (~ minimum RH, 1700 hours) compare with similar set-point values estimated for instantaneous RH (absolute maximum and minimum) from Figure 7 of ~83% and ~18% respectively, i.e., roughly a 10% inward adjustment in both cases. For maximum RH, the adjustment is downward; for minimum RH it is upward. The potential value of this adjustment is that it probably can be applied to weather data sets that do not include RH data as complete as that used in these examples.

Using the fixed-time tabulated hourly RH values from the raw database offers superior control while using an ultra-simple timer-controlled irrigation system. However the compact data listing that includes absolute maximum and minimum RH for each day is more available and also much easier to manipulate in the models for deriving the RH set-point. The latter consideration is important when acknowledging the multitude of sites to be studied, together with the fact that the raw hourly data required for the fixed-time analyses is available for only limited agricultural sites. This dilemma suggests only two solutions. If the actual (instantaneous) maximum or minimum daily RH values are to be used, a control-circuit logic must be developed that can accumulate continuously monitored RH data for a 24-hour period and extract the maximum and/or minimum RH values for control purposes. Modern integrated circuits can be designed to accomplish this task inexpensively if they are made in quantity; however the output from the humidistat must now be digital. Alternatively, perhaps an RH correlation for both morning and evening fixed times can be estimated from maximum and minimum instantaneous RH values recorded for each site in like manner to that of the previous example. Regardless of the RV value being compared, the ambient RH comparison (to the set-point) results in a simple go/no-go logic instruction to be used or retained by the irrigation programmer. For this arid site the 1700-hr RH measurements show excellent correlation with precipitation and ET. In this single-month example we also determined that both fixed-time RH set-point levels could derive from the daily instantaneous maximum or minimum RH data by adjusting (inward) the resulting set-point levels by about 10% for fixed-time control. Although fixing the set-point values should consider many years of RH data from the same month for this site, perhaps the ~10 % correction is valid for many months of every year. Possibly a simple approach that correlates these results for each site on a statistical basis can be realized.

To evaluate this idea, individual plots similar to Figure 8 were created for June through September for the consecutive years 1997 through 2000 for Tucson. In Table 2 the target values (bold numerals in the first row) for no-water days (**nwd**) were established by the techniques presented earlier. Set-points based on both the maximum instantaneous RH or its 0500-hour surrogate (yellow highlight) require RH set-point-value changes in mid season for the most economical irrigation control. A single-value set-point for 0500 measurements (blue highlight) averages the two earlier settings but shows some performance degradation. Although not necessarily expected for this arid region, the minimum RH (not listed in Table 2) and its 1700-hour surrogate correlate even better with the target **nwd**s. Additionally, use of the 1700-hr RH set-point comparisons does not require a set-point change during the irrigation season. For this site the simplest scheme for the humidistat-controlled irrigation system makes the RH measurement at 1700 hours and shows exceptional correlation with the target **nwd**s. The 1700-hr RH values (lowest row in Table 2) allow selection of a constant set-point of ~30% for the entire 4-year study period. Compare the number of controlled no-water days in this last row with the target **nwd** values in the first row.

Table 2. Correlation of various irrigation-control schemes with target **nwd** values for Tucson

	June (0.19"/day				July (0.18"/day				Aug. (0.14"/day				Sept. (0.13"/day			
	1997	1998	1999	2000	1997	1998	1999	2000	1997	1998	1999	2000	1997	1998	1999	2000
Target **nwd**	**0**	**0**	**0**	**21.5**	**4.6**	**25.6**	**31**	**7.1**	**17.5**	**19.5**	**19**	**21.6**	**20.2**	**9.8**	**16.5**	**5.8**
Max RH SP=72%	1	1	0	13	9	25	29	12								
Max RH SP=82%									17	23	22	22	21	10	19	9
0500 RH SP=62%	1-2	0	0	11	6	23-26	22-24	8-10								
0500 RH SP=72%									14-21	20-23	15-21	15-17	19-22	11-12	17-19	9-10
0500 RH SP=67%	0-1	0	0	10-11	2-6	19-23	24-26	9-10	23-28	23-27	20-24	17-19	23-27	12-17	19-23-	12-13
1700 RH SP=30%	0-1	0	0	9-10	3-6	16-18	23-26	3-4	19-28	17-24	12-17	12-19	16-21	5-8	12-16	1-2

NOTES:
1. Daily water application is based on ~maximum daily ETs for the month.
2. ET = 0.5 x ETo. Assumes turf factor = 0.8; allowable stress ~ 0.6.
3. Target no-water-days (**nwd**) = no. days per month less (ΣET – Precipitation) / daily water application. Runoff reductions not included.
4. Target no-water-days (**nwd**) in red should be reduced for heavy rainfall runoff. Local soil conditions are involved.
5. AZMET hourly RH entry is average for the previous 60 minutes.
6. Uncertainty of RH-controlled **nwd** entries in the body of the table occurs when the (averaged) hourly RH entries are within a few percent of the RH set-point.

The variation in required water application over this period is appreciable as evinced by the dissimilar entries for target no-water-days for each month. In spite of this, the modeled RH-controlled irrigation system shows remarkable correlation with watering needs on both daily and monthly bases. Because of its control-circuit simplicity and hands-off consistency, I would opt for the 1700-hr RH control scheme for this site. While hourly-averaged minimum RH values do not exhibit extensive variation from instantaneous RH levels, the 1700-hr values show considerable departures from both (see Figure 8) as well as exceptionally strong correlation with precipitation, both of which promote the 1700-hr RH measurement as a good control-parameter option. In fact the 1700-hr RH values show much better correlation with ET needs and precipitation irregularity than the minimum RH entries. However, for the simple proposed timer/humidistat irrigation-control scheme to be proved broadly effective for conserving irrigation water at other sites, comparable studies that are based on other similarly complete RH data sets are needed. Unfortunately, databases that include ready access to similarly complete information are limited, and this shortcoming suggests the need of an alternative approach for evaluating fixed-time RH measurements in our control system. Shortly I will reinvestigate a simple method that shows promise for estimating the effectiveness of fixed-time control systems using only the more commonly available RH data.

Thus far I have examined monthly climatological detail for only arid sites (Albuquerque and Tucson). Either maximum or minimum RH (or their timed "surrogates) have been shown to effectively balance controlled irrigation for these sites. Let's look at another type of climatological zone in semiarid Denver. Denver, like Tucson, has progressive municipal water-conservation programs and likewise benefits from summer monsoons. However it usually has higher RH levels and typically more rain. Figure 9 presents data for a representative summer month. (The data is actually from Ft. Lupton, a nearby CoAgMet agricultural station.) The month was selected to demonstrate both dry- and wet-period behavior. The first observation is that the maximum RH is consistently high and doesn't show much variation. Like for the continuous RH trace shown earlier for September at this site as Figure 6, only a few days have maximum RH excursions below 85% likely precluding use of this parameter for irrigation control for June in Denver — there simply isn't enough variability. Consistently high morning-RH levels synchronize with many days for which dew is observed, a regular occurrence in Denver for the entire May-September irrigation season, and further suggests that maximum RH would be a poor irrigation-control parameter. However, the minimum-RH trace exhibits considerable variation and, as shown in Figure 9, seems well correlated with precipitation. We therefore opt for irrigation control using only minimum RH or 1700-hr RH for our set-point comparisons.

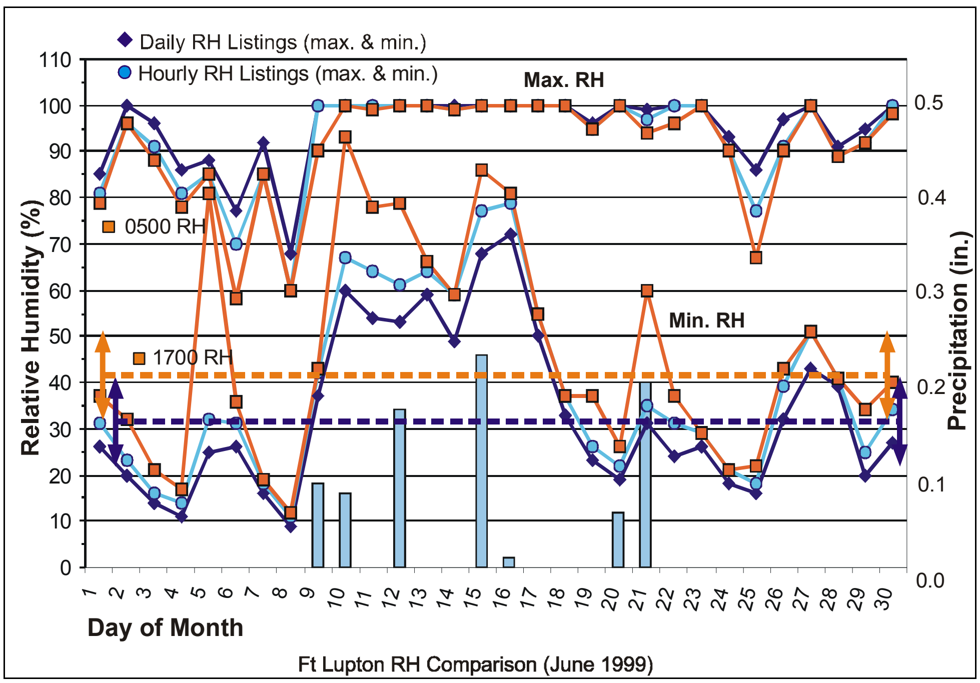


Figure 9. June, 1999 Daily RH Comparisons for Denver (Ft. Lupton)

Calculating the daily water application similar to the previous examples (0.16 in./day for June although I have omitted the ET trace in Figure 9), we estimate the number of no-water days for the month: 12. As stated previously, we opt for the 1700-hr RH comparison as the candidate control parameter. For this single month of Figure 9, the corresponding 1700-hr (fixed-time) set-point should be about 42%. Eleven to fourteen "no-water" days result. The uncertainty of the number of days again arises because the (averaged) 1700-hr RH values on several days (9,th, 26,th 28,th and 30th) are within a few percent of the selected set-point value. Similar to the Tucson example, multi-year and multi-month extension of the data set suggests an approximately 40% RH set-point level for the entire irrigation season. However, this set-point value is applicable only for this site, and only when the RH measurement is made near 1700 hours[10]. Referring again to Figure 9, note the excellent correlation of the no-water days with the rainy periods.

Similar to the Tucson example that compares 1700-hr set-point values (lower orange trace) with those based on instantaneous minimum daily RH entries (lower dark blue trace), the correction applied is again ~10% to convert minimum RH set-points to 1700 RH set-points. For example, to get the 12 no-water days calculated for this month, the instantaneous minimum-RH trace indicates a set-point of 33% while the 1700 RH trace indicates a set-point of ~42%. The magnitude of this correction seems fairly consistent for these two sites (one arid, one semiarid). However, other sites need comparable studies to establish the universality of this correction.

Also, like for Tucson, when using the 1700-hour RH comparisons, a unchanging set-point for the entire irrigation season provides excellent correlation to fluctuating water needs indicated by the ET trace. Table 3 shows four years of data for Denver spanning May through August. The target "no-water-day" (**nwd**) values again are shown by the bold numerals in the upper row. Only the minimum RH and 1700-hour RH correlations with the monthly target **nwd**s are shown. The italicized numerals below the set-point **nwd** entries are the monthly deviation from the target **nwd** days. Red entries indicate over watering; blue entries indicate shortages. Both italicized entries assume that the average value of the listed monthly **nwd** uncertainty span is the appropriate value to compare with the target value.

Table 3. Correlation of RH control effectiveness for Denver (Ft. Lupton)

	May (0125"/day)				June (0160"/day)				July (0.160"/day)				August (0.120"/day			
	1997	1998	1999	2000	1997	1998	1999	2000	1997	1998	1999	2000	1997	1998	1999	2000
Tgt nwd	**13.4**	**15.8**	**15.5**	**21.1**	**21.8**	**8.2**	**11.6**	**11.9**	**19.1**	**18.1**	**15.9**	**10.2**	**23.9**	**12.1**	**26.4**	**17.6**
Min RH SP=30%	15	12	16	12	17	12	14	11	12	20	19	7	22	17	21	15
	1.6	*3.8*	*1.5*	*9.1*	*4.8*	*3.8*	*2.4*	*0.9*	*7.1*	*1.9*	*3.1*	*3.2*	*1.9*	*4.9*	*5.4*	*2.6*
1700 RH SP=40%	18-21	11-16	16-21	9-12	19-22	12-16	13-19	10-13	11-16	19-22	18-23	7-11	22-28	18-21	18-24	18-21
	6.1	*2.3*	*3.0*	*10.6*	*1.3*	*5.8*	*4.4*	*0.4*	*5.5*	*2.4*	*4.6*	*1.2*	*1.1*	*7.4*	*3.4*	*1.9*

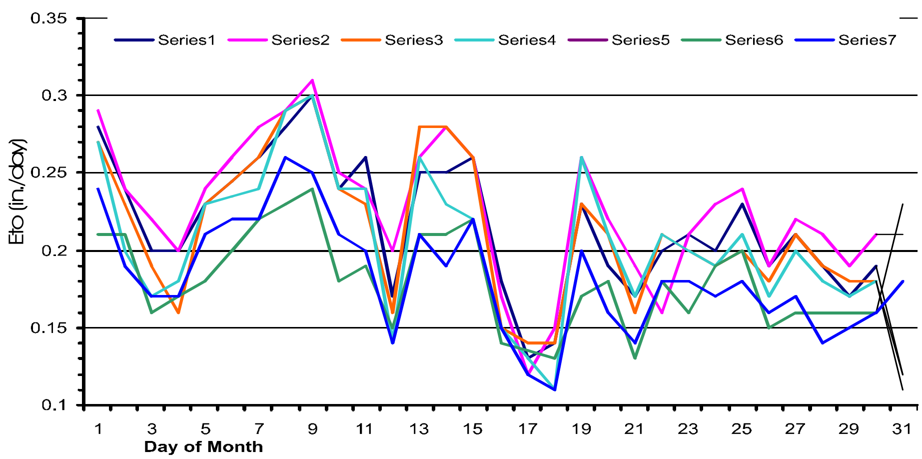
NOTES:
1. Daily water application (title headers) is based on ~maximum daily ETs for the month.
2. ET = 0.5 x ETo. Assumes turf factor = 0.8; allowable stress ~ 0.6.
3. Target no-water-days (**nwd**) = number of days in month less (ΣET – ΣPrecipitation) / daily water application for that month. Runoff reductions not included.
4. Target no-water-days (**nwd**) in red should be reduced for heavy rainfall runoff. Local soil conditions and topography are involved.
5. CoAgMet hourly RH entry is average for the previous 60 minutes.
6. Uncertainty of RH-controlled **nwd** entries in the 1700-hr table entries occurs when the (averaged) hourly RH entries are within a few percent of the RH set-point.
7. Italicized entries are monthly over-watering (red) or under-watering (blue) accumulations.

The accumulation of the **nwd** deviations over the four-month irrigation-season study period for any year can roughly evaluate the long-term effectiveness of the proposed control system. The ideal accumulation is zero. For example, with the 1700-hr set-point fixed at 40%, the 1997 irrigation season shows monthly deviations of +6.1 days (May), -1.3 days (June), -5.5 days (July), and +1.1 days (August), resulting in a seasonal deviation of only +0.4 days relative to the accumulated target "no-water days." The other three years have seasonal **nwd** deviations accumulation of +12.7 days for 1998, +8.6 days for 1999, and –10.3 days for 2000.

[10] The better time might be 1630 hrs for the 1700-hour RH listing since the 1700-hour listing is the average RH from 1600 hours to 1700 hours. Although the RH measured at the mid-hr likely is closer to the reported value than either of the end values, this subtlety is beyond the scope of the present study.

Assuredly the sod would be healthy even for the year 1998 that shows a moderate irrigation deficit. The fact that no corrections have been made to account for the high run-off days (target **nwd**s in red) probably skews the performance predictions conservatively downward. Nevertheless, the correlation to the desired target values is again remarkable, especially when considering that the RH set-point is the same for the entire irrigation season and for all four years of the study period.

Earlier I touted the advantage of the RH control system being site specific. I then used a site somewhat remote from Denver (~15 miles) to establish a control system for metropolitan Denver. This apparent contradiction is countered by assessing that the overall RH control behavior for these two sites will be predictable. While the input values of RH, precipitation, and ET might be considerably different, the overall control response within this geographical region should be similar. Figure 10 compares ETo traces for August, 2000 from seven different sites in the metropolitan Denver region. This information is extracted from the user-accessible Denver Water ET web site. Also listed is the accumulated precipitation for this month. Note the considerable variation (spanning a factor of greater than 3 times) in this latter parameter, at least for these August entries.



1. 56th Ave. Pump 4.79"
2. Lonetree Pump 3.83"
3. Marston Water 2.62"
4. Moffat Water 1.34"
5. Aurora North Satellite 1.62"
6. Aurora Tierra Park 2.45"
7. I-25 mousetrap 3.79"

Figure 10. ETo and precipitation comparisons for multiple Denver stations for August, 2000

The substantial differences noted for parameters from these sites, all within the greater Denver region, support the earlier assertion that a single weather station cannot effectively serve a large geographical area with daily data entries for RH, ET, and precipitation. Comparisons of similar data from four widely dispersed stations in metropolitan Albuquerque show similar results. Intuitively we know that while the applied water may be comparable over longer periods for all of these sites, the precipitation differences for these Denver stations during the selected month must result in considerable differences of the directed "no-water days" for individual stations. The limited Denver Water database does not allow a detailed study similar to those presented earlier. The essential conclusion however, is that each Denver site has a distinctive behavior, and local irrigation control would be better served by using the local data set. This site-specific behavior is a distinct advantage for the on-site RH-controlled irrigation system.

I have examined many other locales, some with considerably lesser data bases, and am encouraged that for most sites RH-controlled irrigation can lead to substantial matching of irrigation-needs for both extended wet and dry periods. The more difficult sites for establishing RH control set-points involve areas that have persistently high average RH. However these sites have comparatively low ET requirements and, unless also accompanied by persistent high temperature that elevates the ET values, turf in such sites is minimally irrigated if at all, i.e., the potential for significant water savings is low. Accordingly, most of my study sites are those that are classified as arid or semiarid. Acceptance of RH as an effective control parameter for balancing irrigation for these selected sites should lead to other marginal areas being studied, perhaps by universities or extension programs that now, to a large degree, already provide most of the ET and weather data on which my studies are based.

Conclusions

The technical results of the study are summarized in the Findings Section at the beginning of this report. In order to emphasize the potential effectiveness of RH control of irrigation systems, I have consciously ignored the hardware needed for modifying existing irrigation systems. My rationale is that the potential irrigation economies can be confidently verified by utilizing existing meteorological/ET databases such as are demonstrated in the included system-performance models. My patent (U.S. Patent No. 6,145,755) discloses several schemes for synthesizing commercial humidistat-control hardware into some existing irrigation-programmer systems to provide the necessary RH-comparison signal lock-in and time delays. These component arrangements introduce into timer-controlled irrigation systems such electronic devices as latching relays and time-delay relays as are detailed in the text and drawings of the referenced patent. A block diagram showing the essence of the new RH-controlled irrigation system is extracted from that document as Figure 13. I include this schematic in the report primarily for those who may not accept my professed results that are based solely on the database studies. Such users can avail the referenced schemes to inexpensively demonstrate proof-of-concept results.

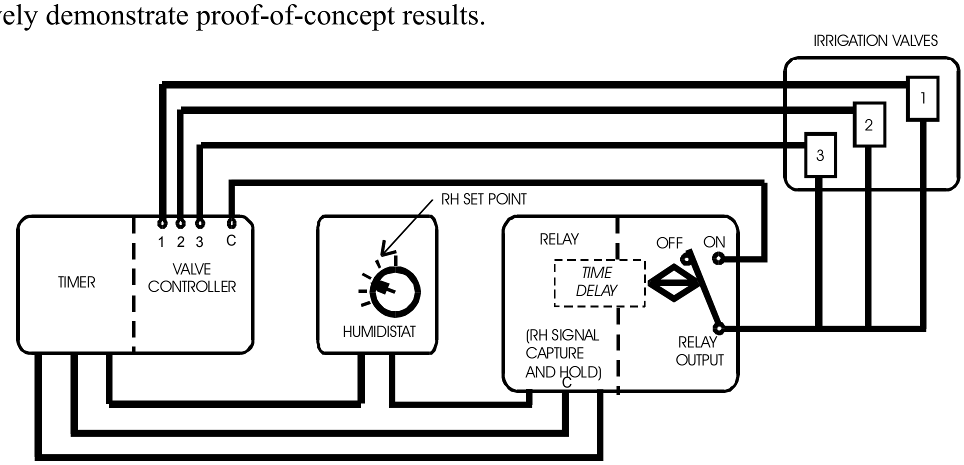


Figure 13. Schematic of irrigation-control system with RH sensor and time delay

Regarding commercial hardware integration in general, I concluded in the early phases of my study that in order for the proposed RH-control schemes to be widely used, the timer-programmer itself should be modified. It should include the option of setting a selectable time for making the RH comparison, and also include the means of holding the irrigation-control command until the entire following irrigation cycle has been initiated and completed. Only the humidistat would be a distinct, remote component of the irrigation-system programmer. I became convinced that only this approach would simplify the system hardware sufficiently to encourage widespread application of the proposed RH-controlled irrigation schemes.

APPENDIX I. Definition of Terms

allowable stress (AS) parameter defining the minimum acceptable grass appearance controlled by the soil water content.
cool-season grass grass appropriate for moderate to harsh winters; typically bluegrass, rye, bentgrass, and fescue.

crop evapotranspiration (ET) parameter indicating plant-water needs that combines transpiration and evaporation. For cool-season grasses the quantities of moisture converted by transpiration and evapotranspiration are roughly equivalent.
dew point temperature at which moisture begins to condense from an air mass.
effective rainfall precipitation that contributes to turf crop needs; i.e., that which can be stored in the root zone.
evaporation change of state from a liquid phase to a gas phase (e.g., from soil to atmosphere).
irrigation cycle time period encompassing the complete irrigation process — for our purposes this period includes all of the irrigation stations (sprinklers) being controlled by the programmer.
irrigation schedule timing sequence that specifies the days to irrigate, the time of day to initiate the irrigation cycle, and the valve operation-periods for each sequential station.
irrigation station single or multiple irrigation-valve grouping operated by a dedicated control signal from the timer
latching relay basically an electrically controlled on/off switch. A latching relay receives an electrical signal, operates the switch, and retains the switch position until the relay receives a second electrical signal that reverses the switch position.
manual intervention manual timer/programmer manipulation that overrides the preset timing sequence of an irrigation programmer. Many commercial irrigation programmers have a "water-saver" setting that allows the user to temporarily cancel the programmed watering sequence. The operator must be on site and must remember to reset the timer for normally scheduled irrigation.
no-water-days (nwd) days for which high ambient RH (low ET) indicates that scheduled water application is not required.
percolation liquid water filtering down into the deep soil. For our purposes deep percolation is water that penetrates to the soil beneath the root zone and is therefore not available to offset plant evapotranspiration.
potential evapotranspiration (ETo) a crop-need parameter calculated for a reference crop. The ETo generally represents the amount of water that the reference crop can use to produce maximum growth.
real-time control irrigation control for which the RH control parameter is continually monitored for allowing/interrupting the ongoing irrigation. If the ambient RH changes across the RH set-point during the irrigation cycle, some stations will irrigate; others will not.
reference evapotranspiration (ETo) another term for potential evapotranspiration.
relative humidity (RH) ratio (in percentage) of water that a volume of air contains compared to the amount of water that it could contain if it were fully saturated (RH = 100%).
RH set-point user-selected, fixed-RH setting on the humidistat controller. For all occurrences of higher ambient RH at the time of measurement irrigation is prevented.
runoff rainfall lost from the soil because it cannot be absorbed for various reasons, e.g., the rain is too intense or the soil is already saturated.
saturated soil soil that holds all the near-surface water that it is capable of holding.
soil moisture-holding capacity the amount of water that the root zone of the turf is capable of holding when fully "charged" or saturated. For typical grassed soils this value is from 0.4 to 0.7 inches.
solar radiation essentially the sun's energy received by the crop. This parameter can be measured by radiometers, but many stations estimate the reported parameter based on integrating clear/cloudy sky conditions. Especially for arid regions, this latter method provides satisfactory results for calculating ETo.
stress factor user-determined parameter that reduces water usage based on an acceptable turf appearance (see also turf quality). Applied when maximum crop growth is not essential
turf quality parameter selected by the user to control the appearance of the turf. Values typically range from 0.4 (low water use, high turf stress, probable browning) to 1.0 (maximum water use).
supplemental water calculated quantity that factors in ET, precipitation, crop factor, stress factor, and irrigation-system efficiency to determine the scheduled water needs.
timed-delay relay relay that locks a switch position (on or off) for a set period of time initiating from the time that it receives the activation signal.
transpiration water that is cycled from the soil through the plant to the atmosphere.

turf coefficient crop parameter for converting ETo to ET. There are two generally accepted coefficients for turf grasses — warm-season grass: 0.6 and cool-season grass: 0.8.
warm-season grass grass varieties suitable for regions with relatively mild winters. They include Bermuda, Zoysia, and St. Augustine, and typically require 25% less water than cool-season grasses.
water budget method scheme for regulating the moisture content in the soil by factoring applied water (precipitation and irrigation) against the accumulated ET losses for a moderately lengthy time period.
water deficit generally the difference between the effective precipitation and the crop needs as defined by ET.
yield threshold depletion level of soil moisture at which further loss will threaten the turf health. This condition is often used to trigger full moisture recovery when using the budget method.

APPENDIX II. Relative Humidity as it Relates to Evapotranspiration

Relative Humidity (RH) in atmosphere is a measure of continually changing moisture content only when it is used together with other weather-related parameters such as temperature. Water vapor content in the atmosphere is not uniform; it varies with land mass categories (e.g., arid versus tropical) and latitude, and for a given location, shows considerable variation over time especially with the passage of weather fronts. Warmer climates are capable of holding more moisture. Equatorial regions hold ~ten times the moisture of polar regions. Similarly, in atmosphere, water vapor-content decreases rapidly with altitude because of cooling temperatures. More than half the total water in the atmosphere is contained within about one mile above sea level. This fact explains why higher-altitude regions generally receive relatively less precipitation.

Definition of RH: the ratio of the actual vapor pressure to the saturation vapor pressure at a given temperature expressed as a percentage. Temperature is related to RH by the Ideal Gas Law: $\mathbf{P\nu=RT}$; where $\mathbf{P}$ = vapor pressure, ν = specific volume, $\mathbf{R}$ = a gas constant, and $\mathbf{T}$ = temperature. Distilling this relationship to the content essential for our consideration, we note that vapor pressure is directly proportional to temperature. This fact implies that at higher temperature water vapor has more energy, i.e., more of it can remain in the vapor phase. When the temperature of an air volume is lowered, the accompanying reduction of the vapor pressure means that the air can hold less water vapor. If this air mass had been initially saturated (RH = 100%), the cooling causes the excess water vapor to be condensed, for example, as rain, dew, or clouds and fog. Understanding the concepts of vapor pressure and energy exchanges helps one to grasp the fact that atmospheric RH, rather than total water vapor content, is the parameter that controls rates of evaporation and transpiration. In this respect RH can be considered as the inverse potential that controls the rates at which these two natural phenomena can occur.

The forgoing has considered the maximum amount of moisture that a volume of air can contain. RH is always measured against this standard. Simply put, assuming quasi-static meteorological conditions of the atmosphere, the actual content of moisture in an air volume is little changed over a typical 24-hour period. RH however is constantly changing because of the diurnal temperature variation. With the moisture content relatively stable, the quantity of moisture that the air is capable of holding is what changes. Thus in the cool early morning hours that have the lowest possible saturation vapor content, ambient RH typically is at its highest level of the day, and conversely for hot afternoon periods. In the same vein, higher-elevation locations have relatively more diurnal RH variation because of greater variation in temperature. The latter effect arises because the thinner layer of atmosphere is less capable of holding the preceding day's solar energy close to the earth's surface.

The above considerations form the basis of why RH is a useful parameter for controlling irrigation scheduling. Considerable variation of this parameter is necessary if it is to be used as a control signal. What remains is to associate this RH variability with changing supplemental-water needs of turf, i.e., with evapotranspiration (ET). We next examine how RH is involved in ET calculations.

The ETo calculation usually involves some modification of what is known as a Penman Equation. Most agricultural data-provider networks have similar approaches that differ only in minor details. Four parameters are combined: RH, temperature, wind, and solar radiation. Earlier we showed how some of these parameters are strongly inter-related. Typically for data presentation, hourly averages are summed to calculate daily ET values. The Arizona (AZMET) hourly equation is: **ETo = W** x **Rn + (1-W) x VPD x FU2**; where **W** is a dimensionless partitioning factor, **Rn** is solar radiation (strongly related to temperature), **VPD** is the vapor pressure deficit (directly related to RH), and **FU2** is an empirical wind function. Temperature and RH are included in the makeup of both **W** and **VPD**. Because both collected terms at the right side of the equation factor RH into their makeup, it is rational to expect a strong correlation of RH behavior with the ET behavior. Indeed, the major conclusion of this study is the existence of a strong correlation of these two traces (RH and ET) that results in effective RH-controlled irrigation for the studied sites. For sites from several different meteorological-zone types, the ET needs of the turf are well matched by RH-controlled irrigation

APPENDIX III. Web-based ET/Weather Resources (western United States)

Arizona: University of Arizona, Arizona Meteorological Network (AZMET), 28 stations mostly in the southern part of the state, full data, **http://ag.arizona.edu/azmet/**

California: California Information Management Information Systems (CIMIS), ~100 stations, adequate data, **http://www.wateright.org/**

Colorado: Colorado Agricultural Meteorological Network (CoAgMet), about 30 stations, full data, **http://ccc.atmos.colostate.edu/~coag/**

Montana (east of Continental Divide), U.S. Bureau of Reclamation, Great Plains Region, AgriMet Data System, 21 stations**,** full data, **http://www.usbr.gov.pn/agrimet**

North Dakota: North Dakota Agricultural Weather Network (NDAWN), ~50 stations, **http:/www.ext.nodak.edu/weather/ndawn/**

New Mexico: New Mexico State University, 280 stations, full data, **http://weather.nmsu.edu/convert.html**

Nevada: Limited web-based information: two northern sites included in the Agrimet system (See Pacific Northwest region below.)

Oklahoma: Oklahoma now has the (fee required) MesoNet Service (also available for several other states), rainfall and accompanying high RH**,** **http://www.mesonet.org**

Pacific Northwest (Washington, Oregon, Idaho, Montana (west of the Continental Divide): Pacific Northwest Cooperative Agricultural Weather Network, Bureau of Reclamation, Agrimet Systems, ~50 stations, full data, **http:usbr.gov.pn/agrimet**

Utah: access to detailed worldwide ET and precipitation data (but not RH), **This latter set-point value introduces the use of "minimum RH" as the control parameter.** **http://climate.usu.edu**

Wyoming, eastern Colorado, Nebraska, Kansas, parts of North and South Dakota and Colorado: High Plains Regional Climate Center, good regional coverage, (fee required for detailed information), **http://www.hprcc/unl.edu/**

Texas (south central): Texas Evapotranspiration Web Site, Texas A & M University, 18 stations, full data, **http://agen.tamu.edu/wqit/petnet**

Texas (Panhandle): TX North Plains PET Network, Texas A & M University Agricultural Research and Extension Center, Amarillo TX, 9 stations, full data, **http:/amarillo2.tamu.edu.nppet/petnet1.html**

Entire country: A valuable source for the most comprehensive historical weather data (although not including ET information): National Climatic Data Center. Provides digitized and graphical data summaries called CLIMVIS reports. **http://www.ncdc.noaa.gov**