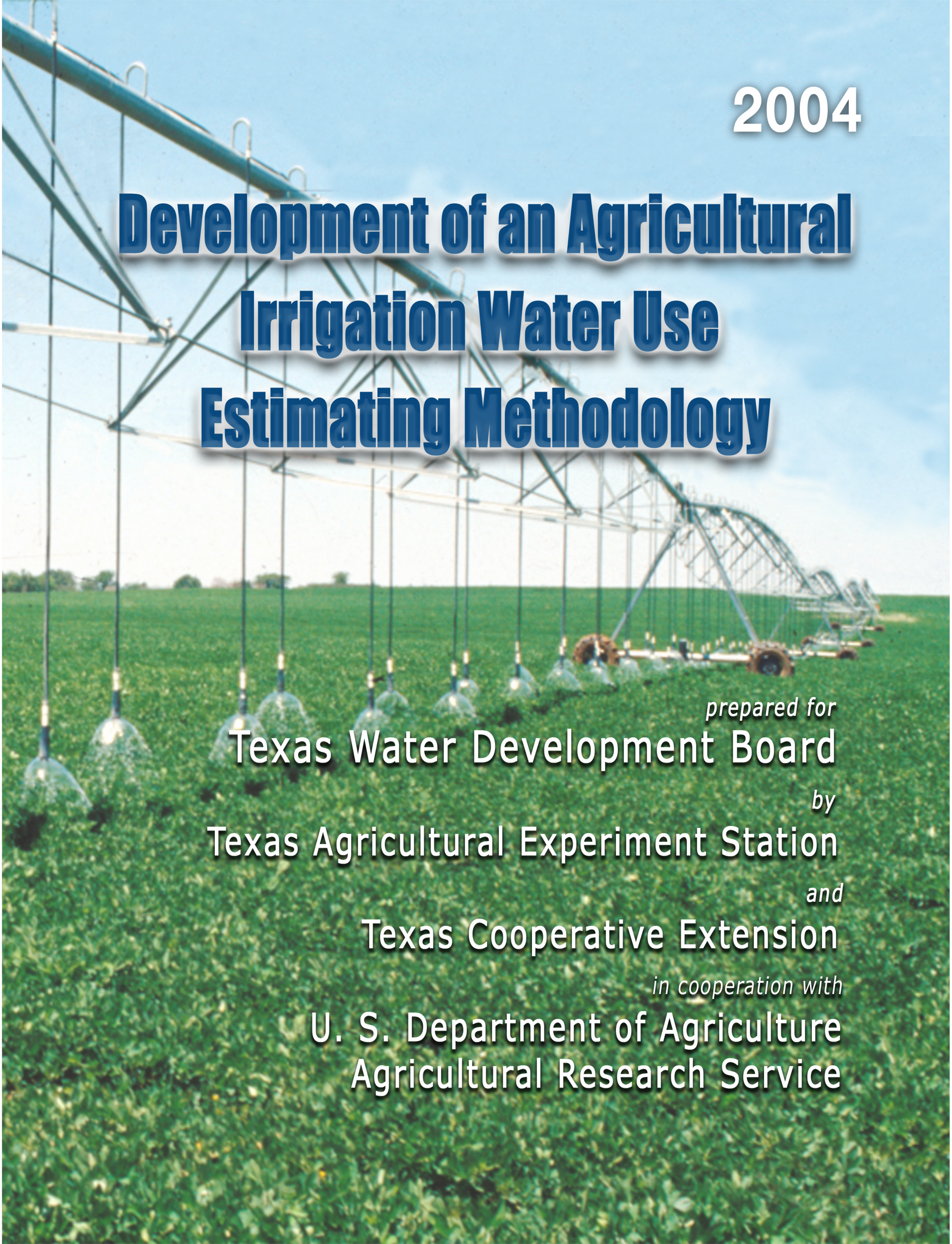

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Development of an Agricultural Irrigation Water Use Estimating Methodology

prepared for

Texas Water Development Board

by

Texas Agricultural Experiment Station

and

Texas Cooperative Extension

in cooperation with

U. S. Department of Agriculture
Agricultural Research Service

Development of an Agricultural Irrigation Water Use Estimating Methodology

by

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PREFACE

The primary focus of the investigators in this project was the identification and evaluation of scientifically based methodologies that could potentially be used in Texas to improve estimates of agricultural irrigation water use. A second project objective was to identify and evaluate the availability and quality of the data necessary for the various irrigation water use estimating methodologies. A considerable amount of time was spent consulting knowledgeable individuals outside the investigation team to insure project results and recommendations were accurate and achievable regarding the selected methodology.

The project group met quarterly to: 1) review project goals; 2) review and critique findings; and 3) maintain performance to meet the project timeline. Monthly and quarterly progress reports were completed and submitted to the Texas Water Development Board. Members of the project group met with the Texas Water Development Board in Austin on two occasions. Additional meetings were held in Uvalde, San Angelo, Lamesa, Lubbock, Weslaco, and Stanton to assess the availability and quality of necessary data in other regions of the state from Water District personnel and other individuals involved in water planning.

The project team wishes to acknowledge and express their appreciation to all the external reviewers that volunteered to review the results of this project. Their insightful comments and suggestions were vital in the construction of this report. The external reviewers were; Troy Allen, General Manager, Delta Lake Irrigation District, Edcouch, TX; Dr. Bill Dugas, Resident Director and Professor, Blackland Research and Extension Center, Temple, TX; Lawrence Friesenhahn, Owner/Operator of Friesenhahn Farms and member of the Board of Directors of the Uvalde County Underground Water District, Knippa, TX; Dr. Bill Hargrove, Director, KCARE/KWRI, Kansas State University, Manhattan, KS; Vic Hilderbran, General Manager, Uvalde County Underground Water Conservation District, Uvalde, TX; Dr. Ron Lacewell, Assistant Vice Chancellor, Texas A&M University, College Station, TX; Dr. John Sweeten, Resident Director and Professor, Texas A&M Agricultural Research and Extension Center, Amarillo, TX; Jerry Walker, Water Management Engineer, USDA-NRCS, Temple, TX; Kenneth White, Uvalde County Extension Agent, Ag and Natural Resources; and C. E. Williams, General Manager, Panhandle Groundwater Conservation District, White Deer, TX.

Review comments concerning the project report made by the Texas Water Development Board are included at the end of the final report in the section entitled “Texas Water Development Board Review Comments.” Comments and actions taken regarding the agency review are specified within this section.

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EXECUTIVE SUMMARY

The future of Texas may very well depend on its water supplies. Projected population in Texas is expected to more than double by 2060, making effective water planning critical. The centerpiece of any planning effort must be irrigated crop production, which accounted for 61 percent of total water use in the state during 2002. Eighty-six percent of the water used for irrigation comes from underground water sources, mainly aquifers. The slow recharge rate of many of these aquifers makes them basically a non-renewable resource, thus the accurate estimation of irrigation use is imperative.

The overall objective of this study was to develop and recommend a strategy for estimating irrigation use in Texas. Specific objectives of this project were to identify and analyze data requirements necessary for estimating irrigation use; and identify and assess the feasibility of the most promising methodologies for projecting irrigation use.

Evapotranspiration (ET) based modeling was selected as the recommended strategy for estimating irrigation use in the state. It is the most commonly used methodology, the simplest from a modeling standpoint, requires the least amount of data, and is the most accurate in estimating irrigation use among the current methodologies available. It is expected to take 12 to 18 months to develop ET based models for all major irrigation regions of Texas at an estimated cost of $300,000 assuming involvement of expertise already developed in the state. The cost of maintaining the required databases and analytical capabilities is estimated at $100,000 annually. Initially, the ET based models could be developed using improved specific crop acreage estimates with approximations of the remaining required data coming from existing sources in the state water planning regions.

Long-term investments in demonstrations and an agricultural weather network are essential to developing more reliable, improved estimates of irrigation use in the future. Demonstration work must be expanded and standardized with respect to data collected and location. A total of 250 to 350 demonstration sites strategically placed in the irrigated areas of the state is projected to provide sufficient coverage to insure dependable estimates of water use by crop. This would result in a total estimated annual expense of $375,000 to $700,000 annually.

Most meteorological stations in Texas do not meet the necessary agricultural related standards with respect to site location, data generated and quality assurance/quality control (QA/QC) requirements to provide a reliable source of data. The development cost for establishing an adequate statewide evapotranspiration (ET) station network (minimum of 53 stations) is estimated at $950,000. However, this cost could be reduced by contracting with the appropriate existing weather networks given that these stations and networks are brought up to the required standards, where necessary. The annual cost to operate and maintain a statewide ET network is estimated at $600,000.

Running GAM and ET based models independently will result in overestimating future water use. An interface model needs to be developed that considers changes in groundwater availability emanating from the GAM models and other relevant factors to project modifications in the amount and/or crop composition for use in the decadal projection by the ET Irrigation Water Use model. The cost for developing the interface model was not estimated.

1.0 SCOPE OF WORK

Population growth in Texas is projected to more than double by 2060 creating an even greater strain on the state's available water resources. To effectively address the issue of adequate supply versus use, solution-oriented water planning is critical to the future of Texas. The centerpiece of any planning in a region that significantly involves agriculture must address irrigation and the associated crop production. Irrigation accounted for 61 percent of the total 2002 water use in Texas. Inaccurate projections of future irrigation water use could lead to inappropriate decisions and subsequent water resource polices that could permanently and adversely affect the future of the citizens of Texas. What makes accurate irrigation use estimation essential is that 86 percent of the water used for irrigation comes from groundwater sources, mainly aquifers. The typical recharge rate of many of these aquifers is slow with the state's largest, the Ogallala, being essentially a non-renewable resource. Thus, most of these sources are finite in terms of available capacity for the future.

The Texas Water Development Board has taken an important step in state water planning by commissioning the development of Groundwater Availability Models (GAM) for most of the aquifers in Texas. GAM provides an avenue to assess and monitor remaining ground water supplies within the aquifers over time. The next step involves estimating both current and future irrigation use, which is necessary to evaluate future supplies and the impact of potential alternative policies that can affect these supplies. The development (including assessment and selection) of an accurate, representative, and "standardized" irrigation use methodology, and an evaluation of its feasibility including data requirements was the focus of this project.

The overall objective was to develop a recommended methodology for estimating irrigation use in the state. The specific objectives of the project were to:

1) Identify and analyze data requirements necessary for estimating accurate agricultural irrigation use; and
2) Identify and assess the feasibility of the most promising methodology for use in projecting agricultural irrigation use.

Presentation of the project results is provided as an overview of the recommended methodology followed by the results of Tasks 1 and 2. Task 1 provides a thorough appraisal of data requirements and appropriate sources of data for establishing baseline irrigation estimates (i.e. current agricultural irrigation water use estimates). Task 2 includes an overview of the irrigation use methodologies used in other major irrigation states followed by a detailed feasibility assessment of the irrigation use projection methods considered for use in Texas.

2.0 OVERVIEW OF RECOMMENDED METHODOLOGY

Selection of a recommended irrigation water use methodology for the state was conducted based on an analysis of several factors. First, an assessment of the model to identify and accurately reflect regional crops and production practices addressed the availability and status of the scientific methods involved. Second, the strengths and weaknesses associated with the respective methodology, including the feasibility of adopting it for statewide use was evaluated. Third, the data requirements and assessment of their availability within the state was identified. Finally, the cost associated with developing and maintaining the irrigation use methodology throughout the irrigated regions of the state was estimated.

Research of most of the greatest irrigated states in the U.S. as well as states surrounding Texas revealed two-thirds of the states used some form of evapotranspiration (ET) based modeling to estimate irrigation use. The remaining states used a variety of techniques including satellite imagery (SI), crop growth models (CGM) and survey analysis to determine use. ET, SI and CGM were selected for further evaluation and analysis.

Satellite imagery was eliminated as a possibility given its stage of development and limited availability. Further refinements into SI techniques need to occur before it can be considered beyond a research tool. Research studies indicate SI has a 25 to 30 percent best error rate in estimating irrigation use and has a difficulty in determining irrigated acreage by crop type especially in high rainfall or intensively irrigated areas. Furthermore, SI can be used (if the imagery contains the precise bands needed) to estimate landscape evapotranspiration (ET). The most precise SI methods for estimating landscape (field by field) ET still require dependable ground level weather stations. The variability in rainfall and vast crop diversity in Texas would make it exceptionally difficult to utilize SI at this time in developing accurate irrigation estimates with a 25 percent to 30 percent error range. In addition, the availability of SI data is very limited at the present time. In fact, the primary satellite has recently expected operational difficulties in some thermal bands and is being corrected by software methods. Current NASA plans do not include a Landsat replacement.

Aerial photography and videography offers another potential option for lower level remote sensing data for estimating irrigated areas and/or ET, yet it is costly and likely prohibited unless interrelated with the USDA-Farm Service Agency's (FSA) digital orthographic data. FSA data are currently only color photography that does not contain the remote sensing bands needed (visible and infrared bands) for crop identification, crop cover, or thermal bands (infrared) for estimating crop ET.

The evapotranspiration based methodology was selected as the recommended methodology in preference to crop growth models for several reasons, but two in particular are data requirements and simplicity. The data necessary to develop ET based estimates of irrigation use include:

1) Irrigated acreage by crop,
2) Percentage of ET applied by producers by crop,

3) Differential soil moisture estimates, and
4) Weather related data such as rainfall, temperature, wind speed and solar radiation.

CGM also require all the aforementioned data. In addition, distribution among the various types of irrigation delivery systems, soil types and crop yields has to be identified on a county level. Currently, CGM are only developed for the major row crops in Texas. Additional CGMs would need to be developed for crops or groups of similar crops such as vegetables.

The additional data and model specification required of crop growth models allows for a more detailed analyses/results beyond the estimation of irrigation use, which could be beneficial but adds to the complexity of the process. It is estimated that approximately 14,400 computer runs would be required to do one statewide estimate of irrigation use. While these computer runs could be “batched” to help relieve the input/output problem, programmers running the CGM would be required to have extensive training in CGM to run the models and diagnose problems. If the CGM can be properly specified, the error in irrigation use is estimated to range between 10 to 15 percent by experienced scientific personnel.

Both ET based and Crop Growth Models can be designed to interface with GAM where appropriate with additional programming. The ability to interactively run these models on a decadal basis is viewed as an important requirement to accurately simulate the impact of changing water availability conditions in the future. The major obstacle to overcome will be the determination of a set of “rules” that dictate the change in irrigated crop acreage or crop composition for input into the irrigation use model given a projected decrease in water availability by GAM.

The recommended ET based methodology utilizes calibrated crop evapotranspiration (ET) values from a representative evapotranspiration (ET) network in estimating reference irrigation water use for the various irrigated crops in a particular region. These crops can include but are not limited to corn, cotton, grain sorghum, hay, pasture, peanuts, soybeans, wheat, sunflowers, grasses and vegetables. Water use calculations are based on the respective crop ET, the effective monthly rainfall, the percent of potential ET applied in the field to a particular crop (and includes all pumping, conveyance and application losses; -note that the percentage can be more or less than the reference ET value), the soil profile moisture utilized by each of the crop(s) during the growing season and county level acreage estimates for the respective crop(s).

The ET based methodology is essentially one that utilizes a water balance approach to estimating irrigation use. The heart of the ET based model is centered around the crop water use equation and is specified as follows:

$$ET_C * P_T = IRR_C + ER + SSM_D \quad \textbf{(1)}$$

where:

ET_C = Crop evapotranspiration (or crop water use) for maximum production potential (in.),

P_T = Grower factor which represents a fraction of the crop evapotranspiration pumped on a crops' seasonal basis and includes all irrigation systems and associated efficiencies (can be more or less than 1.0 reference crop ET, ETc),
IRR_C = Irrigation applied on a seasonal basis to a crop (in.),
ER = Effective rainfall computed from seasonal rainfall occurring during the crop season (in.), and
SSM_D = Seasonal soil moisture depletion used in crop production which is extracted from the soil profile during the respective growing season (in.).

Rearranging the equation and solving for IRR_C yields:

$$IRR_C = ET_C * P_T - ER - SSM_D \quad \textbf{(2)}$$

The summary equation for all categorized crops grown per county is:

$$IRR_{CTY} = \sum_{1}^{n} (IRR_C / 12 * A_C) \quad \textbf{(3)}$$

where:

n = Number of categorized crops of interest per county, and
IRR_{CTY} = Total quantity of irrigation volume applied (or pumped) to the crops grown within a county in a given year or season, (ac-ft), and
A_C = Acreage of crop c in a given county.

Similarly, the summary equation for the counties within a region is:

$$IRR_{REG} = \sum_{1}^{n} IRR_{CTY} \quad \textbf{(4)}$$

where:

IRR_{REG} = Total quantity of irrigation volume applied (or pumped) to crops grown within a region in a given year or crop season, (ac-ft).

ET based irrigation use modeling has a history in Texas. It has been utilized in Region A during the Senate Bill 1 and 2 planning efforts. Subsequently, ET based methodology was employed to estimate irrigation use in the Southern Ogallala GAM project (water planning Regions O and F). In a limited validation test with one of the major irrigation districts in Region A during the Senate Bill 1 planning process, it was found to estimate irrigation water use to within three percent when measured against well depletion records.

It is expected to take 12 to 18 months to develop the ET based models for all the major irrigation regions of Texas at an estimated cost of $300,000 assuming involvement of the expertise already developed in the state. The cost of maintaining the required databases and analytical capabilities is estimated at $100,000 annually.

Initially, the ET based models could be developed using the improved acreage estimates with approximations of the remaining required data coming from existing sources within the regions. This approach should improve current irrigation use estimates. Subsequently, long-term investments in improving the accuracy of data will lead to more reliable/improved estimates of the state's total irrigation use.

Three essential types of data are required for the ET methodology: 1) irrigated acreage by crop, 2) actual producer diverted or pumped water use by crop, and 3) weather related data. The accuracy of these data is paramount to the development of any realistic estimates of irrigation use.

Irrigated Acreage By Crop - Farm Service Agency (FSA) is the only logical source for primary irrigated crop acreages. Data on irrigated acres are readily available and inexpensive, if not free to obtain. This does not imply that there is no cost associated with the compilation and manipulation of the data. Virtually every irrigated crop acre in Texas is accounted for in the FSA database for producers that receive farm payments. Where there are voids in the FSA data, the Census of Agriculture estimates need to supplement the FSA data to improve estimates, particularly with irrigated pasture, which is not fully certified by farmers with the FSA. County tax rolls should also be used to validate total irrigated estimates for the counties.

Water Use by Crop - The number of demonstration projects on private farms being conducted by the Texas Cooperative Extension (TCE) and Water Districts in the primary irrigated regions of the state is close to the sufficient number needed for developing water use estimates by crop and region. This is particularly true in the High Plains region that encompasses more than 70 percent of the state's irrigated acreage. However, due to personnel and financial constraints, minimum information on soil moisture is not being collected with the current exception of the water programs in Region A. The current Texas Water Development Board well metering program is a step in the right direction, however, significant additional data needs to be collected for it to be useful in water planning. TCE and Water District personnel conducting demonstrations have expressed a willingness to collect the additional information if the cost of this activity is supported. The estimated cost is in the range of $1,500 to $2,000 per demonstration, which includes travel, personnel, and equipment costs (with the exception of water meters). A total of 250 to 350 demonstration sites strategically placed throughout the irrigated areas of the state is projected as adequate to provide sufficient coverage to result in accurate estimates of water use by each crop and cultural practice. This would result in a total estimated annual support expense of $375,000 to $700,000 annually statewide.

Weather Data - There are numerous meteorological stations and weather networks located throughout Texas. However, most do not meet the necessary agricultural related standards with respect to site location, data generated, and quality assurance/quality control (QA/QC) to provide a reliable source of data for use in the agricultural irrigation use estimates model. Also, potential integration of National Weather Service rainfall data resources may be desired to better represent a spatially averaged effective rainfall within the counties. The development cost for establishing an adequate statewide evapotranspiration (ET) station network across the state (minimum of 53 stations) is estimated at $950,000. However, this cost could be reduced by cost-sharing and contracting with the appropriate existing ET networks given that these stations and networks could be brought up to the required standards, where necessary. It is also estimated that the annual cost to operate and maintain a statewide ET network meeting the needed QA/QC requirements would be $600,000.

A long-term average of all data inputs should also be maintained and utilized to reduce year-to-year variability within the assessments for evaluating long-term scenarios. Recent farm programs that have increased planting flexibility combined with volatile input and output prices have resulted in large annual planted acreage swings between crops. A five-year moving average was shown to have the least variance between years among the models considered when analyzing irrigated acreage, but still it is able to identify changes that are inherent to agriculture's cyclical nature. It is expected that a comparative analysis of other input data would reveal similar results.

Interfacing GAM and ET Water Use Models

Running the GAM and the ET based Irrigation Water Use models independently will result in overestimating future water use, which could lead to the development of erroneous water policies. An interface model needs to be developed that accommodates the changes in groundwater availability emanating from the GAM models and projects the resultant modifications in the amount and/or the crop composition for use in the decadal projection by the Irrigation Water Use model.

Initially, this interface model could be as simple as a set of arbitrary rules that changes crop acreage and/or crop composition as water availability decreases. This simple interface model should be replaced as time permits with a more sophisticated model similar to the one developed by Lacewell and McCarl, 1995. This type of model approach not only considers changes in water availability but factors in farm program provisions, input prices, output prices, technological changes, yield improvements among other factors in projecting changes in crop composition and irrigated acreage. The more complex approach should improve the accuracy of projected water use estimates and provide a good avenue for water planning groups to evaluate the impact of potential policies. No cost estimate was made for the development of the simple or the more complex interface models since it was considered beyond the scope of this project.

The project timeline is delineated into two separate tabled timelines. First is the outline to make the ET based irrigation models functional to the point where they can be used in the water planning process with existing data (Table 2.1). The second timeline outlines the process required to initiate the collection and integration of improved data (Table 2.2). Improvement in weather and water use data will be critical to the accurate assessment of irrigation water use in future water planning efforts.

Table 2.1 ET Based Irrigation Model Development Timeline

Months 0-2
- Recruit a project manager.

Months 3-6
- Recruit two technical programmers.
- Review methodology and associated data requirements.
- Procure computer equipment and software.
- Conduct planning meeting with programmers to determine irrigation regions to be modeled.

Months 7-9
- Conduct assessment of available weather data by region.
- Conduct assessment of available demonstration data by region.
- Obtain Farm Service Agency county crop acreage pertaining to irrigated regions.
- Obtain long-term monthly quad rainfall data from the Texas Water Development Board (TNRIS).
- Obtain digital soils data from the USDA-NRCS.
- Develop respective crop seasons and associated effective rainfall seasons for each region.

Months 10-12
- Analyze and develop a program to consolidate Farm Service Agency data into similar water use crop categories for input into the ET based estimation model.
- Analyze long-term monthly quad rainfall data from the Texas Water Development Board (TNRIS) for input into the ET based estimation model.
- Compute effective rainfall using a modified procedure of the USDA-NRCS method for input into the ET based estimation model.
- Analyze digital soils data from the USDA-NRCS for input into the ET based estimation model.
- Obtain applicable long-term weather data for the regions.
- Obtain applicable demonstration data for the regions.
- Initiate development of computerized regional ET based estimation models.

Months 13-15
- Analyze long-term weather data for input into the ET based estimation model.
- Analyze data from demonstrations in order to calculate "grower factors" for each crop by region for input into the ET based estimation model.
- Input of all required, applicable model data.
- Initiate preliminary ET based irrigation water use model runs.
- Develop depletion "rules" including crop mix change for interface models between GAM and ET based estimation models.

Months 16-18
- Validate regional ET irrigation water use models.
- Develop GAM-ET regional interface models.

Table 2.2 Enhanced Data Improvement Timeline

Months 7-9
- Identify demonstration and weather data coordinator.

Months 10-12
- Develop quality assurance/quality control (QA/QC) standards for weather stations and demonstrations.
- Identify the total number and locations of demonstrations/weather stations needed to meet QA/QC standards to provide statistically reliable data.

Months 13-15
- Identify existing demonstrations and weather networks meeting QA/QC standards.
- Identify number and location of any additional demonstrations and weather stations needed.

Months 16-18
- Obtain MOAs from existing weather station networks that meet or can be modified to meet QA/QC standards to provide data and for possibly expanding regional coverage (additional weather stations).
- Obtain MOAs with Texas Cooperative Extension and/or Water Districts to conduct demonstrations meeting QA/QC standards.

TASK 1

DEVELOP METHODOLOGY FOR BASELINE WATER USE ESTIMATES

Irrigated acreage and water use by crop are the key elements to estimating accurate irrigation water use. A precise estimate of current water use is needed to accurately project future water use. Three pieces of data are essential to any of the irrigation use projection methodologies considered. These are: 1) irrigated acreage by crop, 2) actual water use by crop, and 3) weather data. In Task 1, the accuracy and availability of these data in Texas are evaluated. In addition, the validity of using single-year data versus a multi-year average was examined.

3.0 IRRIGATED ACRES

Differences in the amount of irrigated acreage can significantly influence projected water use estimates. These differences are magnified when projected over a 60-year planning horizon. The focus of this objective is to compare and discuss alternative sources of irrigated acreage with continued groundwater availability in the future. Four sources of irrigated acreage analyzed include the Natural Resource and Conservation Service (NRCS), a combination of Texas Agricultural Statistics Service (TASS) and Census of Agriculture data, Farm Service Agency (FSA) data, and satellite imagery interpolations.

3.1 Description of Surveys

NRCS Survey: The NRCS conducts a survey of irrigated acres every five years based upon the experience and judgment of their county field personnel, and in cooperation with the Texas Water Development Board (TWDB) and the Texas State Soil and Water Conservation Board (TSSWCB) and Texas County Extension Agents. In the past, this survey has been the source of irrigated acres used by the TWDB (TWDB, 2003-personal communication) for water use forecasts. Some of the regional water planning groups have questioned the accuracy and representation of these data. However, this may be a mute point of concern. The NRCS has indicated that the survey may not be continued in the future (NRCS, 2003-personal communication).

TASS/Census: The combination of TASS and Census data provides another alternative for estimating county level irrigated acreage. TASS provides annual estimates by county for most major irrigated crops in the state. However, TASS provides no estimates of the minor irrigated crops and forages and does not provide county level breakdowns of all the major irrigated crops. The Census of Agriculture provides a detailed breakdown of all irrigated crops by county every five years. However, there is up to a two-year delay before Census data are released, and there have been questions regarding the completeness and accuracy of these surveys. Both TASS and Census rely on producer surveys utilizing a sampling technique in estimating crop acreage and over time sample sizes have been decreased due to cost containment reasons.

FSA: FSA data are available for 243 different crops (corn, wheat, guar, etc…) making it extremely versatile for crop acreages throughout the state. The primary function of the FSA is to administer farm programs enacted by Congress. Producers are responsible for registering irrigated acres of program crops each year with the FSA program payments. Recent disaster programs have not only compensated program crops, but also non-program crops. This has led to virtually every acre being certified by crop with FSA annually including most irrigated grasses. Prior to 2002, FSA irrigated acreage delineated by crop was only maintained at the county level. While the data were available, a county-by-county requisition of FSA offices was required to obtain regional data. Starting in 2002, FSA compiles and maintains a centralized database of this information at the state headquarters in College Station, which should make the data more readily available for any future water planning efforts.

Satellite Imagery: Another potential source for estimating irrigated acreage is satellite imaging. Some states in the West and the Great Plains are using Landsat remote sensing imagery information (Mercier and Egbert, 1999) to estimate irrigated acreage including the U.S. Geological Survey (USGS). A study performed in 1992 by the USGS used Landsat Thermatic Mapper (Qi et al. 2002) to classify and map the location of irrigated land across the High Plains aquifer. This study showed that Landsat had a difference of 300,000 irrigated acres in the High Plains aquifer area when compared with the Census of Agriculture data. This same study documented that only 77.5 percent of the pixels for each sub-region were correctly classified (Qi et al. 2002a and 2002b).

Another study was performed using the same Landsat technology in the Lake Altus Drainage Basin of Oklahoma and Texas (Masoner et al. 2003). In this study, when data from Landsat were compared with data from the TWDB and Oklahoma Water Resources Board, there was a 23 percent difference in the acre-feet of irrigation water use. This suggests that there was also a difference in irrigated acreage between the two.

Few images are available that could be used to determine individual crops due to the need to acquire imagery as close as possible to maximum greenness for individual crops on a cloud free day. Even with correct date selection, there are other limitations to using Landsat multi-spectral satellite imagery, such as spectral range and spatial resolution. Some agricultural crops or vegetation species are too spectrally similar to be differentiated by Landsat at the current time (Masoner et al. 2003). In arid West Texas, irrigated crops are generally easier to distinguish than in the more humid East. In the East, a combination of irrigated and rain-fed agriculture is used and without detailed ground truth observations are difficult to estimate. Satellite imagery is also being used to estimate latent heat fluxes from agricultural areas. There are continuing improvements being made in the acreage and flux estimation of this technology through advances in spectral ranges and resolution.

Remote sensing may become a viable means to estimate irrigated acres and water use in the future. Landsat has experienced operational difficulties in the past that are currently being corrected by software methods. NASA is not currently pursuing plans for implementation of Landsat 7 (Williams, 2004). Since no satellite estimated irrigated acres for Texas are currently available, no comparison was made for the satellite survey method. However, technology in this area is advancing rapidly with increased spectral ranges and resolution, and should not be overlooked in the future. Morse et al. (1990) used Landsat imagery in assessing an irrigated area in Idaho for water rights adjudication. They reported an average coefficient of determination of 0.90 for Landsat identification compared with county USDA Farm Services Administration summer aerial photography.

3.2 Methodology

The year 2000 was selected to compare the three sources of irrigated acreage due to availability of data from all sources. This corresponded to the last year the NRCS survey was conducted and the year utilized as the baseline for current Senate Bill 2 estimates. Similar 2000 data originating from FSA were collected through a survey of all county FSA offices in the

TWDB Regions A, O, L, and M shown in Table 3.1. These regions accounted for 85 percent of Texas' total irrigated acreage in the year 2000 according to the NRCS data (Figure 3.1). TASS estimates of irrigated crop acreage for 2000 were supplemented with 1997 Census of Agriculture data where TASS data was not available in 2000. All sources were evaluated in terms of planted irrigated acreage. The crops of cotton, corn, wheat, sorghum and peanuts composed the majority of irrigated acreage and are the crops that were analyzed in this analysis.

The data were analyzed by comparing the cumulative totals by crop(s) from all three surveys. In addition, statistical hypothesis testing for means and variances of surveys, and χ^2 contingency table tests were performed on selected counties. Hypotheses were tested at a significance level of α=0.01 (or 1 percent uncertainty of assuming the wrong result). A test for the equality of means was performed using t-tests, and variances were tested using F-tests in EXCEL™. The means and variance test(s) indicate similarity of the surveys at the state level. Contingency table analyses provide an indication of dependency between the surveys and crop types at the county level. The selected counties for analyses were Castro County in Region O, Frio County in Region L, and Carson County in Region A for the contingency table analysis.

Table 3.1 Counties in TWDB Regions A, O, L & M.

Region	County	Region	County	Region	County	Region	County	Region	County
A	Armstrong	**A**	Ochiltree	**O**	Hale	**L**	Atascosa	**L**	LaSalle
A	Carson	**A**	Oldham	**O**	Floyd	**L**	Bexar	**L**	Medina
A	Childress	**A**	Potter	**O**	Motley	**L**	Caldwell	**L**	Refugio
A	Collingsworth	**A**	Randall	**O**	Cochran	**L**	Calhoun	**L**	Uvalde
A	Dallam	**A**	Roberts	**O**	Hockley	**L**	Comal	**L**	Victoria
A	Donley	**A**	Sherman	**O**	Crosby	**L**	Dewitt	**L**	Wilson
A	Gray	**A**	Wheeler	**O**	Dickens	**L**	Dimmitt	**L**	Zavala
A	Hall	**O**	Deaf Smith	**O**	Yoakum	**L**	Frio	**M**	Maverick
A	Hansford	**O**	Parmer	**O**	Terry	**L**	Goliad	**M**	Webb
A	Hartley	**O**	Castro	**O**	Lynn	**L**	Gonzales	**M**	Zapata
A	Hemphill	**O**	Swisher	**O**	Garza	**L**	Guadalupe	**M**	Jim Hogg
A	Huthchinson	**O**	Briscoe	**O**	Gaines	**L**	Hays	**M**	Starr
A	Lipscomb	**O**	Bailey	**O**	Dawson	**L**	Karnes	**M**	Hidalgo
A	Moore	**O**	Lamb	**O**	Lubbock	**L**	Kendall	**M**	Willacy
								M	Cameron

Figure 3.1 Texas Water Development Board Regional Planning Groups Irrigated Acreage, 2000 Survey.

3.3 Results

Two questions need to be answered: Is there a significant difference between the sources of irrigated acreage relative to the projected water use, and which source of irrigated acreage is most appropriate to be used in calculations for the best accuracy? Regions A, O, L, and M cumulative total irrigated acres for the five major crops obtained from TASS/Census, NRCS, and FSA are presented in Table 3.2. All sources are reasonably similar. The largest difference in total acreage is a six percent (274,279 acres) difference between the FSA and the TASS/Census. There are, however, appreciable differences in acreage between the crops. The largest difference in acreage between sources would be the FSA reporting 20 percent (158,546 acres) less corn than the NRCS while at the same time reporting 23 percent (265,173 acres) more acres of wheat. This discrepancy in acreage by crop type can have a substantially distorted effect on water use. For example, if a producer pumps on average, 20 inches of irrigation water on corn and 10 inches on average on wheat, a difference of roughly 500,000 acre-feet would be computed. The breakdowns of the different sources of irrigated acreage are reported in Table 3.2 and in Figure 3.2.

Table 3.2 Irrigated acreage in Regions A, O, L and M as reported from the different data sources for the year 2000.

Crop	TASS/Census	NRCS	FSA	Average
Cotton	2,222,900	2,171,951	2,200,112	2,198,321
Corn	952,053	966,798	808,252	909,034
Wheat	787,600	903,847	1,169,020	953,489
Sorghum	369,300	313,419	403,205	361,975
Peanuts	182,700	244,314	208,243	211,752
Total Acreage	4,514,553	4,600,329	4,788,832	4,634,571

Source: TASS/Census website, FSA – Potter County, Texas Water Development Board Report 347 (2001).

The differences in irrigated acreage have a cumulative effect over the 60-year planning horizon. First, numbers differ within crops, which cause a distortion in acreage numbers at the county level, which in turn causes differences at the regional level. The greatest difference in regional data is with the TASS/Census data reporting 265,000 fewer acres in Region A than the FSA data. Most of Region A's irrigated acres consist of wheat and corn, which are low and high water use crops, respectively. As shown earlier, the magnification of these inaccuracies could cause a large distortion in the future irrigation water use needs. The differences in total irrigated acreage of the major crops by region are illustrated in Figure 3.3 while the major irrigated crop acreage by region is shown in Figure 3.4. Irrigated acreage in two counties from each region have been selected at random and are presented in Figure 3.5 to illustrate the differences at the county level. Differences in the data sources were as large as 29 percent (27,055 acres) between the TASS and the NRCS data in Yoakum county and as small as < 0.5 percent (288 acres) between TASS and NRCS.

An additional problem is accounting for failed crops. The census data provides planted and harvested acres but gives no indication if any planted acres were failed crops. The assumption of failed acres must be derived from the data. This also holds true for the NRCS data. The FSA data designates failed crops for each crop in the county that occurs.

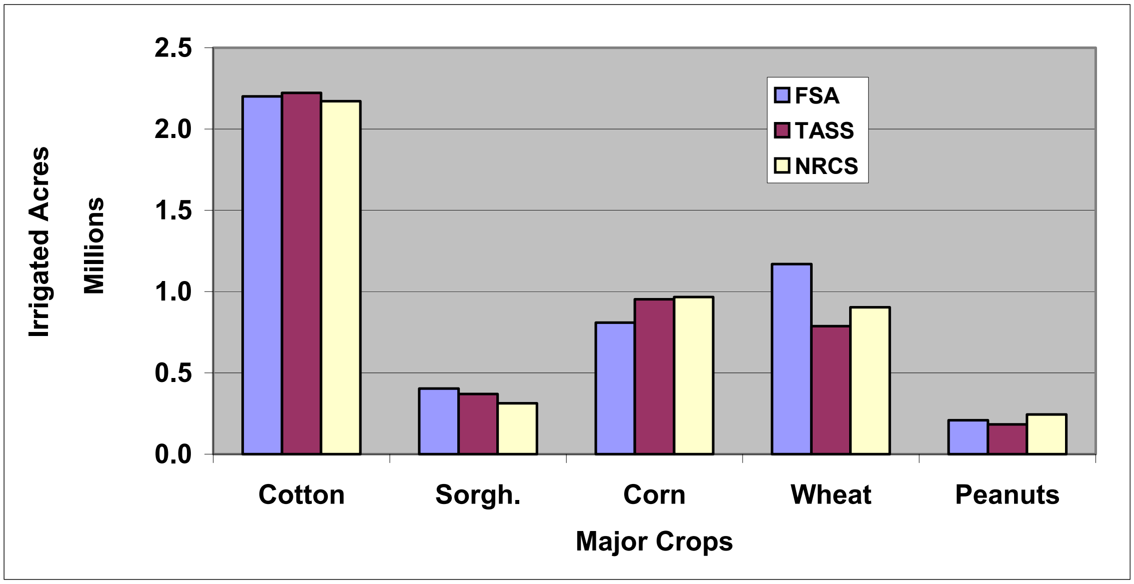

Figure 3.2 Irrigated acreage for Regions A, O, L, & M by crop and source (2000).
Source: TASS/Census website, FSA - Potter County, Texas Water Development Board Report 347 (2001).

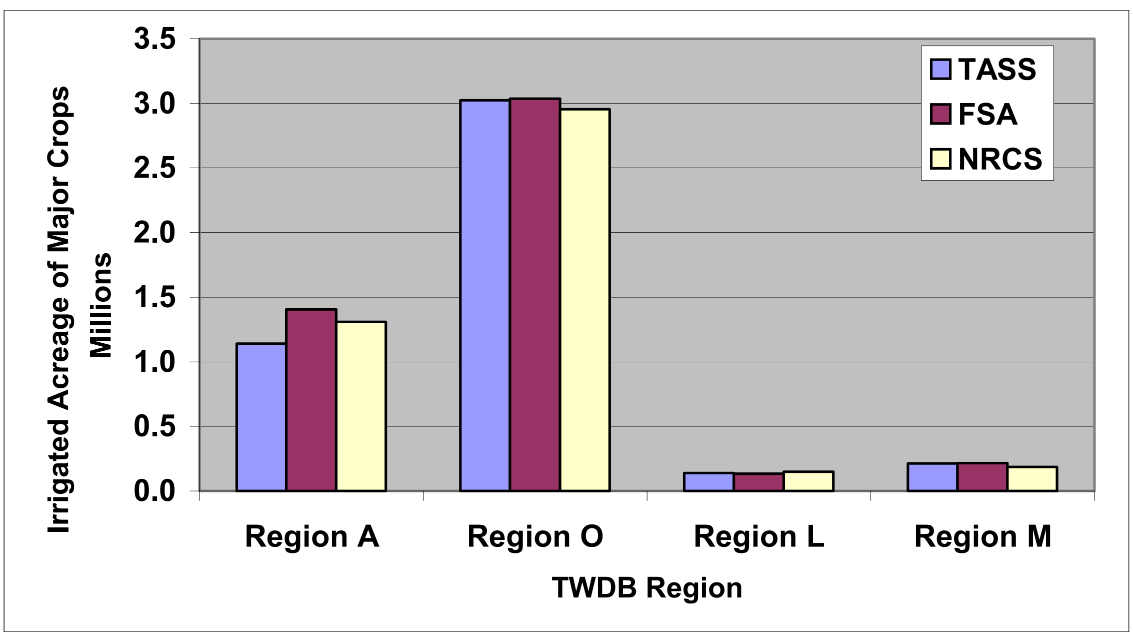

Figure 3.3 Total irrigated acreage of the 5 major crops in Regions A, O, L, and M by source (2000).
Source: TASS/Census website, FSA-Potter County, Texas Water Development Board Report 347 (2001).

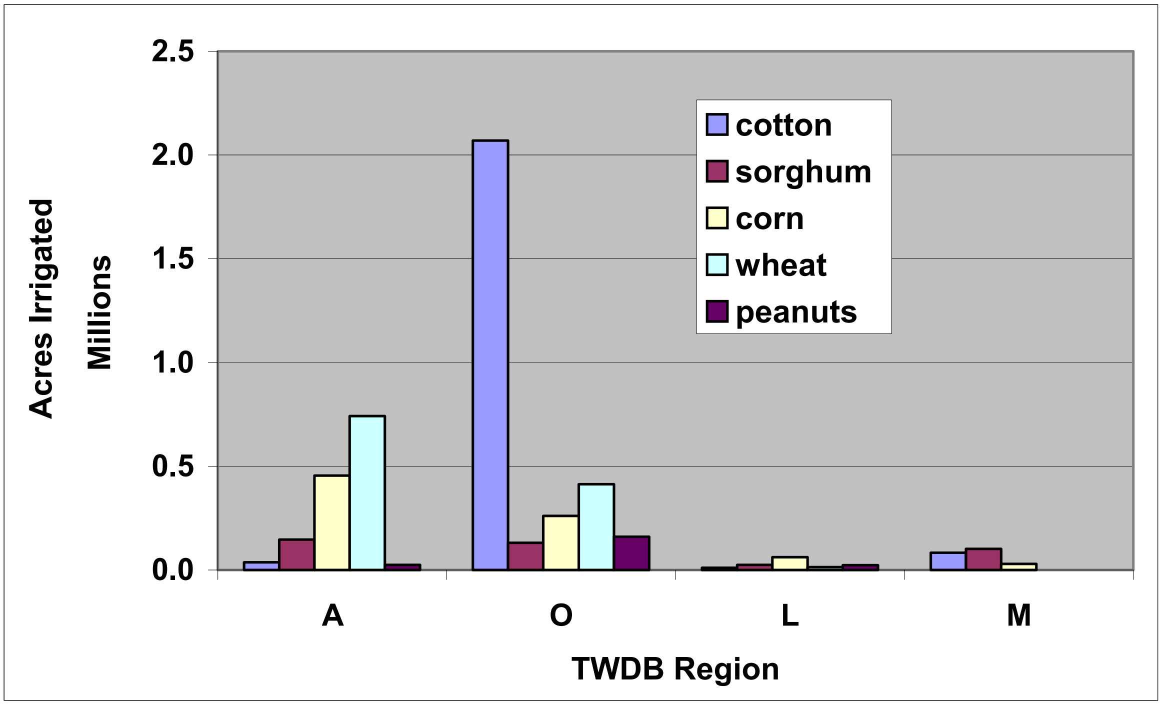

Figure 3.4 Comparison of FSA irrigated acreage by crop and region (2000).
Source: FSA – Potter County.

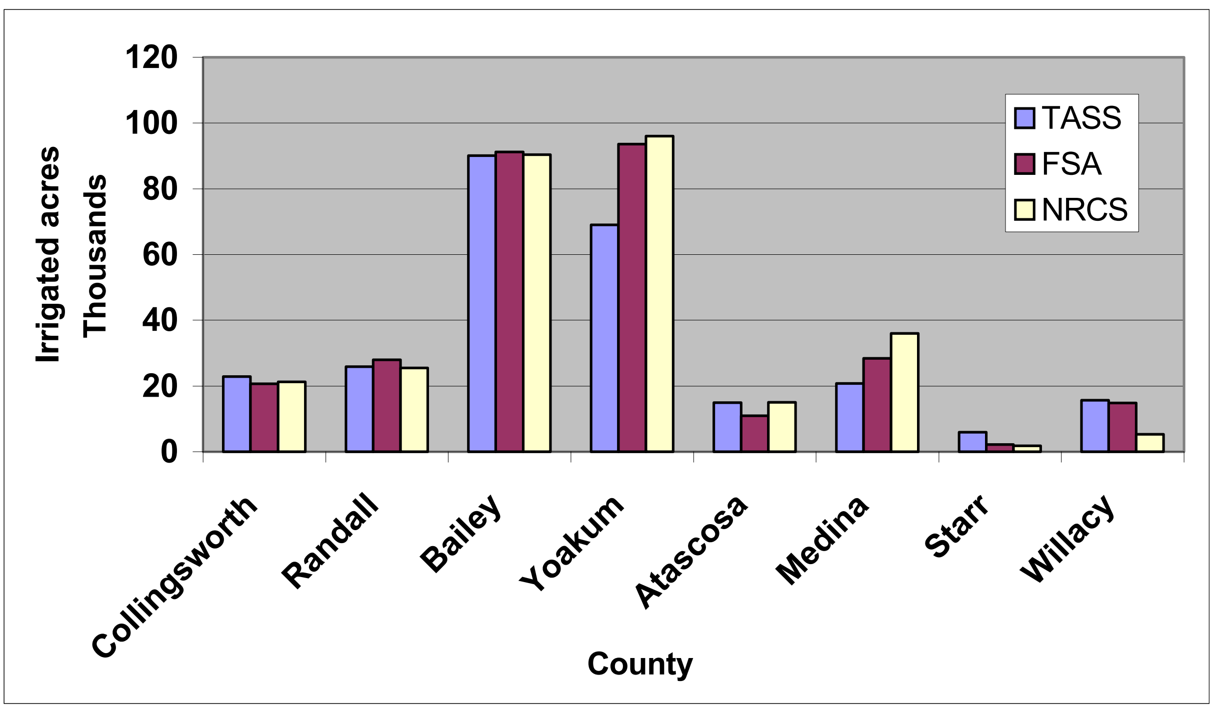

Figure 3.5 Three sources of irrigated acreage compared for randomly selected counties.
Source: TASS/Census website, FSA – Potter County, Texas Water Development Board Report 347 (2001).

The hypotheses test for means and variances between the survey methods are shown for corn, wheat, cotton, and sorghum shown in Tables 3.3, 3.4, 3.5, and 3.6, respectively. An example interpretation of these tables is as follows: in Table 3.3, when the FSA mean corn acres in the counties was compared with the TASS/Census mean corn acres, the t-test was applied to test for equality of means, and the f-test was applied for equality of variances. The patterned areas in the tables show results that test equality for means and variances between the survey methods. When the mean corn acres for the counties from the FSA survey was compared with the mean corn acres from the NRCS via the t-test, the hypothesis that the means were equal passed, and similarly for the variances. Assuming that the crop acres are normally distributed, if the means and variances are equal, the survey methods would yield the same result. Thus, the FSA and NRCS surveys for corn were comparable; the FSA and TASS/Census surveys were comparable to the NRCS surveys for wheat; the FSA and TASS surveys, and the NRCS and TASS surveys were comparable for sorghum. No agreement between the surveys was found for cotton. While these tests *do not* indicate or assure any degree of representation accuracy of the sample values, the results suggest that the FSA survey estimates agree within reasonable limits with other (TASS & NRCS) survey methods.

Table 3.3 Mean and variance tests (α=0.01) for corn in Regions A, O, L, M counties.

	TASS	NRCS
FSA	Means and variance **not** equal	Means equal, variances equal
TASS		Means equal, variance **not** equal

Table 3.4 Mean and variance tests (α=0.01) for wheat in Regions A, O, L, M counties.

	TASS	NRCS
FSA	Means equal, variances not equal	Means equal, variances equal
TASS		Means equal, variances equal

Table 3.5 Mean and variance tests (α=0.01) for cotton in Regions A, O, L, M counties.

	TASS	NRCS
FSA	Means equal,Variances not equal	Means equal,Variances not equal
TASS		Means equal,Variances not equal

Table 3.6 Mean and variance tests (α=0.01) for sorghum in Regions A, O, L, M counties.

	TASS	NRCS
FSA	Means equal, Variances equal	Means equal, Variances not equal
TASS		Means equal, variances equal

Contingency tables for Frio, Castro, and Carson counties are shown in Tables 3.7, 3.8, and 3.9, respectively.

Table 3.7 Contingency table of acres for Frio County in Region L.

Frio County				
	FSA	TASS	TWDB	Total
Corn	4,380	842	8,000	13,222
Sorghum	4,026	4,300	4,000	12,326
Cotton	676	0	1,500	2,176
Wheat	3,897	3,500	2,000	9,397
Total	12,979	8,642	15,500	37,121

χ^2-Stat		
12.8	1624.5	1113.2
18.7	713.0	255.5
9.5	506.6	384.9
113.8	787.2	943.2
		4638.7

For Castro County, since the calculated final χ^2-statistic of 4,638 (in bold) is much greater than the theoretical $\chi^2_{\alpha=0.01}$ of 16.8 (from statistical tables), the null hypothesis that there is no relationship between survey method and crop acreage is rejected. Thus, we conclude that depending on which survey source is selected, the crop acreage for Castro County will be different. Similar conclusions were drawn for Carson County. While, an exhaustive contingency table analysis by county for all 254 counties in Texas would be required to state the differences for survey methods by county, we can conclude that in general, differences by the survey method at the county level will be encountered. The overall statistical conclusion is no major difference in survey methods exists for state aggregates, but differences in acreages are very likely if examined at the individual county level.

Table 3.8 Contingency table of acres for Castro County in Region O.

Castro County				
	FSA	TASS	TWDB	Total
Corn	75,584	87,990	83,345	246,919
Sorghum	7,598	13,000	12,138	32,736
Cotton	75,024	85,300	84,967	245,291
Wheat	89,853	120,000	90,346	300,199
Total	248,059	306,290	270,796	825,145

χ^2-Stat		
24.7	146.6	65.9
511.3	59.3	181.1
22.3	363.2	247.9
1.7	658.7	678.1
		2960.8

Table 3.9 Contingency table of acres for Carson County in Region A.

Carson County				
	FSA	TASS	TWDB	Total
Corn	15,965	16,352	15,618	47,935
Sorghum	12,168	12,000	11,943	36,111
Cotton	682	0	682	1,364
Wheat	51,423	30,000	51,467	132,890
Total	80,238	58,352	79,710	218,300

χ^2-Stat		
155.3	977.4	203.0
92.0	570.9	117.1
65.1	364.6	67.9
136.1	858.3	178.6
		3786.3

3.4 Recommendations

It is recommended that the FSA survey be used as the primary source of irrigated acreage in Texas. The reasons are:

1) Virtually every irrigated acre of major crops is registered with the FSA to insure against failure (these crops are typically referred to as program crops).

2) Recently, non-program crops are being registered with the FSA because disaster legislation has included compensation for these crops such as hay or pasture. However, non-program crop acreage, primarily irrigated pasture, should be

validated with Census data to ensure accuracy. Irrigated acreage reported on tax rolls should be used as a second source for validation.

3) The FSA has digitized the registered crops by field, and county and state level aggregates can be generated through geo-database operations.

4) The FSA irrigated acreage values are readily available every year; whereas, the Census data are limited to every five years and data are not released until two years later; and the NRCS survey is also conducted every year but, concerns of its accuracy and its availability in the future cause significant interest.

4.0 WATER USE BY CROP

Once the irrigated acreage by crop has been established, the next step in estimating baseline water use is to determine how much irrigation water is applied to different crops within the various water planning regions. Water use and irrigation management can differ by county due to available water, irrigation systems utilized, soil types, climatic differences and economic factors. Therefore, water use needs to be addressed at the county level for planning purposes.

4.1 Description

Currently, the primary source for crop irrigation by county is from the USDA-Natural Resource and Conservation Service (NRCS) surveys. Similar to irrigated acres, crop irrigation reported in the NRCS data is obtained from a survey conducted every five years by their county personnel in cooperation with the Texas Water Development Board (TWDB), the Texas State Soil and Water Conservation Board and Texas County Extension Agents. NRCS provides the current source of irrigated acreage estimates used by the TWDB in making crop irrigation predictions. However, the NRCS has indicated that the five-year survey will not be continued in the future (NRCS, 2003-personal communication). In the past, questions have risen regarding the accuracy of the survey information.

An alternative crop water use source could be utilized by expanding the Texas Cooperative Extension (TCE) AgriPartner Demonstration Program into all irrigated counties in Texas. The TCE grower demonstration data has provided the basis for irrigation use estimates reported by Region A for both Senate Bill 1 and Senate Bill 2 water plans. The TCE irrigation and water management data represent the 21 counties in Region A with approximately 66 field demonstrations that have been conducted annually since 1998. Demonstrations obtain irrigation, rainfall, net soil water, crop yield and other data for all major crops grown within a county. In Region A, the major crops are corn, cotton, grain sorghum, peanuts, silage, soybeans, sunflowers and wheat. Twice a week, producers or extension assistants measure and record irrigation, rainfall and soil water levels at each demonstration site. The TCE demonstrations utilize volunteer, cooperating crop producers. Bi-weekly measurements are shared with producers to help them assess how much total water (irrigation, rainfall and soil water) is available to their crop. The three measurements are tabulated in comparison to the corresponding daily, weekly and seasonal water use reported by the North Plains ET (evapotranspiration) Network (a part of the TXHPET Network) for fully irrigated crops. Past irrigation measurements recorded from the TCE producer demonstrations significantly correspond to groundwater district depletion data. Only limited, partial data, in comparison to TCE and water district demonstration data, currently exists in other water planning regions in Texas. However, similar irrigation, water management and crop production demonstration data are potentially attainable to improve the accuracy of future regional and statewide water plans.

Another potential water use source is the current Texas Water Development Board water metering program. An improved, coordinated plan that will deliver annual crop irrigation, water management, production and other data needed to expand the AgriPartner demonstration procedure state wide is partially in place. The TWDB has/is providing funds to install water meters on irrigation wells or systems in conjunction with growers in ten or more groundwater districts. TWDB commitments to water meter funding include both Hudspeth and Culbertson County groundwater districts in Far West Texas, Mesa groundwater district on the Southern High Plains, North Plains and Panhandle on the High Plains, Tri County and Rolling Plains districts, Evergreen groundwater district plus others. Approximately 500 water meters coordinated by the TWDB are in place. In addition, all irrigation wells within the Edwards Aquifer Authority are now equipped with water meters. High Plains at Lubbock and Delta Lake in the Rio Grande Valley are funded by Senate Bill 1094 to provide successful groundwater and surface water management practices that reduce irrigation and depletion. All surface water delivered for irrigation in the state is metered. This extensive location of water meters that can identify annual irrigation are in place, awaiting a plan of action that will provide accurate crop irrigation data for other water planning regions, similar to that developed by the TCE AgriPartner Demonstration Program in Region A.

The current Texas Water Development Board water metering program is a step forward in the water planning process. However, meters are typically read annually which can and has caused problems with accuracy and interpretation due to malfunctioning meters. New technology becoming available that allows remote monitoring of meters at a relatively low cost could minimize this current problem. More importantly, additional information could be collected from these sites to make them valuable in water planning. These data would include soil moisture, crop(s) grown and their associated yields, acres irrigated and the delivery system used. Information of this detail does not have to be collected at every meter site, however, enough similar sites need to be monitored in this manner to assure a statistically correct water use inference within region.

Another possible source of estimating water use by crop is by using satellite imagery. This technique uses satellite images taken of a large area, which can be broken down to a sub-field basis to determine the differences in water that is utilized by the plant. Currently, limited research in Texas is being conducted on satellite analysis. It may become a feasible methodology in the future when the interpretation processes have been improved to the point where errors in estimating irrigation use are reduced to acceptable levels. A report by the California Department of Conservation in 2002 utilized a mixture of geographic information system (GIS), air photos, local input, soil quality data and current land use information to produce maps of important farming areas with 10 different types of farmland categorized mostly by soil quality (California Department of Conservation – Farmland Conversion Report, 1998-2000). A study preformed near Colombo, Sri Lanka utilized the cost effective, large aperture scintillometer (LAS), as a means of measuring plant ET. When compared with the surface energy balance algorithm for land (SEBAL), LAS had an average deviation of 17 percent for 10-day periods. However, this deviation fell to 1 percent when ET was calculated on a monthly basis (Hemakumara et al. 2002). Another study in the James River basin of South Dakota (Kolm, 1985) evaluated remote-sensing techniques to map irrigated crop types and acreage using Landsat imagery. These results offered that only 50 percent of the irrigated land could be identified, and of that 50 percent, only 79 percent could be adequately classified by crop type. This results in a 39 percent overall level of accuracy (Kolm, 1985). Some agricultural crops or vegetation species are too spectrally similar to be differentiated by Landsat. However, technology in this area is advancing rapidly with increased spectral ranges and resolution, and should not be overlooked for potential use in the future.

4.2 Methodology

The number of inches of irrigation water applied per crop by county from the TCE demonstration data and the NRCS survey water management data for the year 2000 were compared. The NRCS figures were taken from the TWDB Report 347 (Surveys of Irrigation in Texas, 2001). The TCE demonstration data were collected from the *Agri-Partner Crop Irrigation and Production Summary* (New, 2003). The TCE demonstration water use numbers were incorporated with reported NRCS irrigated acres to compare the total water applied in inches for each county. Four major crops were used in this analysis; corn, cotton, wheat and sorghum. These crops were chosen because they reflect a justifiable representation of the irrigated acreage in Region A. The five counties within Region A that had the most comparative crop data were selected for comparison: Dallam, Sherman, Hartley, Moore and Potter. Due to the limited availability of TCE demonstration data regionally, only Region A data were evaluated.

4.3 Results

TCE demonstration data, which utilizes crop ET, monthly effective rainfall, percent of potential ET pumped onto the crop(s), soil profile moisture utilized by the crop(s) during the growing season, and crop acreage of the respective crop(s) reduce inaccuracies that may arise with survey approaches. The outcome of this methodology and computation resulted in excellent agreement for the year 1997. Irrigation use results indicated agreement to within 97 percent of the measured well decline within one of the larger regional water districts.

Results from this analysis are presented in Table 4.1. Differences between the two sources of data were substantial. The total percent difference between the two data sources was 27 percent or 408,535 acre-feet. The largest difference in inches applied per acre between counties was 8.81 inches in Potter County. NRCS reported 19.23 inches while TCE demonstration data reported 10.42 inches. According to the Farm Service Agency (FSA) data, 86 percent of all irrigated acres in Potter County are composed of wheat and sorghum. The combination of good drought tolerance and typically lower crop receipts for these two crops makes the practice of growers applying 19 inches of irrigation water per acre questionable. The largest difference in total acre-feet pumped within a single county is Sherman County. The NRCS reports 123,977 more acre-feet than the TCE demonstration data estimates.

Table 4.1 Comparison of total water applied per irrigated acre by selected counties using TCE Agri-Partner demonstration data and NRCS data.

		NRCS		**Agri-Partner**		
County	acres	inches	acre-feet	inches	acre-feet	% Difference
Dallam	247,141	22.3	458,870	17.3	356,089	-22%
Sherman	228,911	20.6	393,710	14.1	269,733	-31%
Hartley	187,169	23.0	358,174	17.4	270,927	-24%
Moore	143,787	24.3	291,620	16.8	201,661	-31%
Potter	6,225	19.2	9,977	10.4	5,405	-46%
Percent difference of total acre-feet for the year 2000						-27%

4.4 Demonstration Programs and Data Availability

Until more accurate remote sensing technology is developed, field demonstration data obtained with cooperating growers is required for use with the proposed water planning methodology. Water demonstration program data should include irrigation, rainfall and net soil water available to each crop. The Texas Cooperative Extension (TCE) Agri-Partner Demonstration program has successfully obtained representative data since 1998 in elected regions. More than 500 irrigation, water management and crop production demonstrations have been conducted on about 55,000 acres with approximately 400 growers. These demonstration data were used by the Panhandle Region A Water Planning Group in response to Senate Bills 1 and 2. The TCE Agri-Partner program is only being conducted in the Panhandle District, which includes most counties in the Region A water planning area. Its future is uncertain, however, due to the lack of sufficient funds for sustained operations.

The grower demonstration program has been discussed with the TCE, Water District personnel and others in water planning for Regions O, F, L and M. There is agreement that demonstrations are currently the most appropriate for use in a statewide water planning methodology. There is additional agreement that sufficient rainfall and irrigation data can be and in some counties are being collected. However, there is limited to no soil water data being collected, except in Region A. Soil water measurements beginning at or near crop planting and extending until harvest are required in order to not over predict irrigation. Also, some ET network weather stations are inaccurate in water planning regions where there is significant irrigation. In regions where weather stations are available but not standardized, daily crop water use is being calculated or reported differently by station or interrogating network, presenting conflicting information for growers, consultants and others to choose from. TCE and Water District personnel contacted tentatively agree that together they can/will conduct crop production demonstrations that provide irrigation, rainfall and net soil water measurements for regional water planning. All unanimously agree and emphasize, that currently they do not have people, money, equipment, or travel resources to conduct the needed water related demonstrations for the entire state. Demonstrations are one of TCE's long-term educational methods with growers and the agricultural industry. Water Districts are responsible for knowing/measuring water managed and used within their boundaries.

Statewide water planning data can be significantly improved and standardized using demonstration programs. When a standardized procedure is developed, administered and conducted accurately, the data obtained can provide a sound basis for the Texas Water Plan by region. Irrigation, rainfall, net soil water and crop yield are minimum requirements for demonstration water program data. The utilization of a standardized ET network needs to be associated with the data. Irrigation should be measured using water meters, hour meters in conjunction with system design sheets or a combination of the two. Rain gauges are required at each demonstration site. Soil water sensors should be accurately installed at a minimum of one, two and three feet and at one location in the demonstration field. Where more than one soil type occurs in the field, sensors should be installed in each type. Sensor placement is needed in the crop row soon after plant emergence. All measuring devices and instruments should be read and recorded a minimum of weekly.

The demonstration program is projected to cost in the range of $1,500 to $2,000 per demonstration site annually if planned and coordinated appropriately. The estimated cost includes travel, personnel, and equipment costs (with the exception of water meters that are in place in some counties). Demonstrations should be selected to incorporate the primary irrigation delivery systems used within the region. A total of 250 to 350 demonstration sites strategically placed in the irrigated areas of the state should provide sufficient coverage to result in dependable estimates of water use by crop. This would result in a total estimated annual expense of $375,000 to $700,000 annually.

4.5 Recommendations

Our recommendation for future water use estimation involves the TCE/water district demonstration data. We make this recommendation based on the following:

1) TCE/water district demonstration data are typical average producer practices gathered at the county level and are more accurate and representative.
2) TCE/water district demonstration data has less future availability issues, given adequate support.
3) Previous data analysis suggests that TCE/water district demonstration data are more representative of actual irrigation by crop.

5.0 AVAILABILITY OF AGRICULTURAL WEATHER DATA IN THE STATE

5.1 State Availability of Weather Data

Representative weather data are required to compute accurate evapotranspiration (ET) values using the revised ASCE ET equation (Walter et al. 2002) for use with the Texas A&M-Amarillo (TAMA) Evapotranspiration Network Based methodology. (A copy of the newly proposed drafted standard is included in Appendix A due to the time dated web access and due to latest revisions not being publicly posted). While there exists a seemingly "wealth" of meteorological data within the state, an assessment of the types of data available and the quality assurance/quality control (QA/QC) associated with the datasets is warranted before proceeding with their use. Several of these available datasets may not be suitable for application with an agriculturally based water use methodology. Additionally, the type of data available varies throughout the differing regions of the state. Furthermore, there is typically no standardization among the data instrumentation or reporting format. In several areas of the state, there are voids in coverage regarding agriculturally based meteorological stations. Within recent years, several of these irrigated regions have initiated meteorological networks such as those in the Winter Garden, and the West Texas central region. These networks along with the lower Rio Grande networks and along the Gulf Coast region currently address the majority of the irrigated areas in Texas. The largest area, occupying over 70 percent of the state's irrigated lands, is in the High Plains where the Texas High Plains ET Network (a combination of the North Plains and South Plains ET networks) is located. Although the networks have been in existence for over a decade and have provided the best available data for agricultural applications, sustained operational funding issues persist, as is the case for many ET related networks throughout the state.

5.2 General Description of the Data Available

Meteorological data has been compiled over varying time intervals by various universities, governmental, public, private, state and federal agencies throughout Texas. As such, most datasets are configured to record parameters to meet certain mission-oriented objectives of the respective entity. Suitability of the data as to time polling, sampling interval, averaging and sensitivity or output increment vary and the respective parameters must be qualified before data can be assumed suitable for use in the ET based methodology model.

The following lists the nominal parameters available from all the various sources of data investigated for this study. All parameters are not available from each of the agency-associated sources, but rather vary according to source. The compiled, partial parameter list is as follows:

1) Average air temperature
2) Maximum air temperature
3) Minimum air temperature
4) Wind speed
5) Wind direction
6) Wind run

7) Visibility
8) Average dew point temperature
9) Solar radiation
10) Precipitation
11) Mean days of freezing
12) Mean days with measurable precipitation
13) Amount of snow
14) Amount of hail
15) Amount of sunshine
16) Cloudiness
17) Average morning relative humidity
18) Average evening relative humidity
19) Hourly relative humidity
20) Soil temperatures
21) Soil salinity
22) Soil moisture
23) Soil dialectric constant
24) Growing degree units
25) Maximum dew point temperature
26) Minimum dew point temperature
27) Wind speed at 0400
28) Wind speed at 1600
29) Wind speeds at higher heights
30) Leaf wetness
31) Pan evaporation
32) Offshore measurements
33) Sea surface temperature
34) Wave height
35) Ocean salinity
36) Tide measurement
37) Number of days of precipitation
38) Percent of average precipitation
39) Heating degree days
40) Lake evaporation
41) Lake precipitation
42) Barometric pressure
43) Sky conditions
44) Maximum temperature at 0600
45) Maximum temperature at 2400
46) Minimum temperature at 0600
47) Minimum temperature at 2400, and
48) Fire potential status.

Besides acquisition programs varying among sites, instrumentation brands and models differ among many of the respective sites and are also located at various heights, normally adhering to differing agency protocol. Thus, comparison of several parameters from the many sources is not readily achievable, thereby limiting its use with the proposed methodology. The most appropriate sites to use appear to be the university and federal research based sites since many of these utilize similar instrumentation that is suitable for agricultural application and generally conform to an accepted standard for agricultural based applications (ASAE, 2004). Additionally, several of the university based ET networks were part of a Texas Water Resources Institute statewide effort (Marek, 2000) to standardize instrumentation and data programming to yield the needed, standardized outputs for use in the ASCE ET equation (Walter et al. 2002).

5.3 Assessment of Accuracy of the Data

Accuracy of the sources requires that a visual time series analysis be conducted once ascertainment of instrument type and height is known regarding a particular data source. Similarly, this process should be conducted on a weekly or bi-weekly basis to assure that recently collected data is correct. A few comparisons of past data regarding meteorological networks of the Texas High Plains ET network (TXHPET) versus the Texas Tech Mesonet (TTM) illustrate the points mentioned above. (TXHPET is an operationally merged network of the North Plains ET (NPET) network and the South Plains ET network (SPET)). All comparisons typically consist of average daily values over a year to prevent overall influence by isolated influences such as by storms or weather fronts.

Figures 5.1 through 5.3 show good agreement among similarly located instrumentation at Muleshoe (TTM) versus Earth (TXHPET) for daily values of air temperature, relative humidity, dew point temperature, respectively, for 2002. However, precipitation measurements are site specific and substantially spatially different as reflected in Figure 5.4 between the sites of Abernathy (TTM) and Lubbock (TXHPET), which are located reasonably near each other. Seldom will two precipitation stations in West Texas agree over any length of time. Thus, there is an inherent pitfall in using a single value of rainfall for county representation with this or any similar methodology. A comparison of wind speed data from other sites shows both reasonably good (Figure 5.5 between Muleshoe and Farwell) and poor agreement (Figure 5.6 between two Lamesa locations). Some of these type differences can be due to site location with building or other structure influence. Similarly, some sensor differences may also occur between networks. Looking further at solar radiation, sometimes agreement is good as in Figure 5.7 between two Lamesa locations (TXHPET and TTM sites). However, there is a distinct difference detectable in Figure 5.8 regarding solar radiation measurement between Muleshoe (TTM) and Farwell (TXHPET). The difference is either due to a drift in one of the sensors or a possible difference in wavelength bandwidth being gathered between the two-pyranometer units, and thus data from one of the sensors in the network is not readily comparable or suitable for use in the ET equations without introducing substantial cumulative errors over time. It is for this reason that standardization and a good QA/QC program is needed regarding instrumentation and collected data processes.

Additionally, there exists a significant number of “school net sites” throughout the state and are typically operated for educational purposes by local TV networks. These school networks are usually placed upon rooftops or in areas of convenience to school systems and children and do not represent the condition of agricultural lands or practice. Therefore, these data sites serve only as an educational tool, and the data are not representative and warranted for use with the ET based methodology.

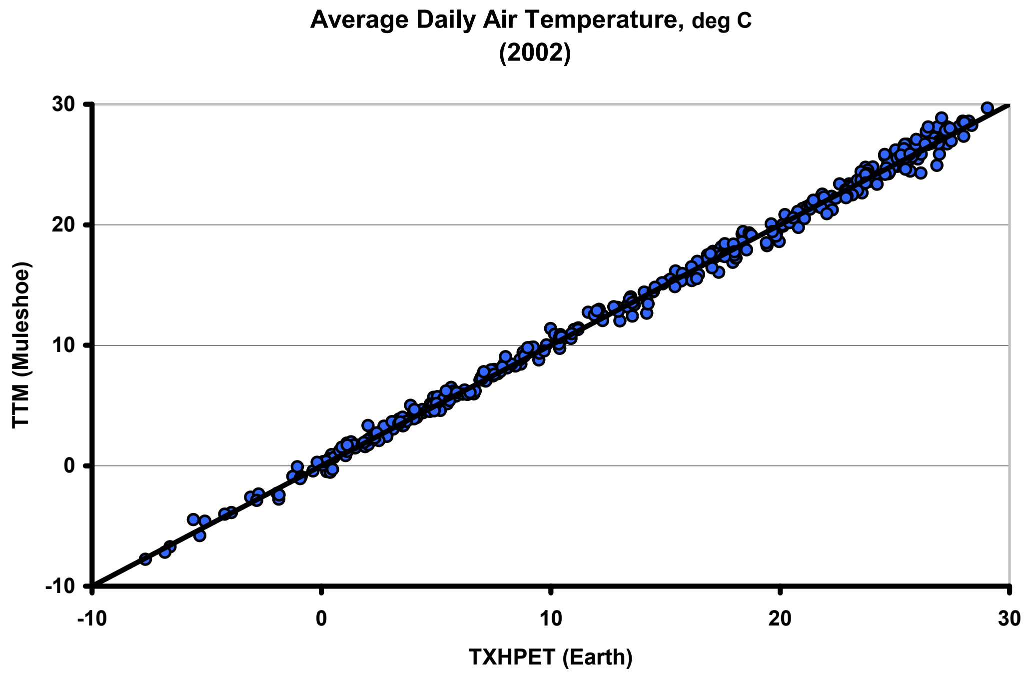

Figure 5.1 Daily air temperature comparison between Muleshoe and Earth.

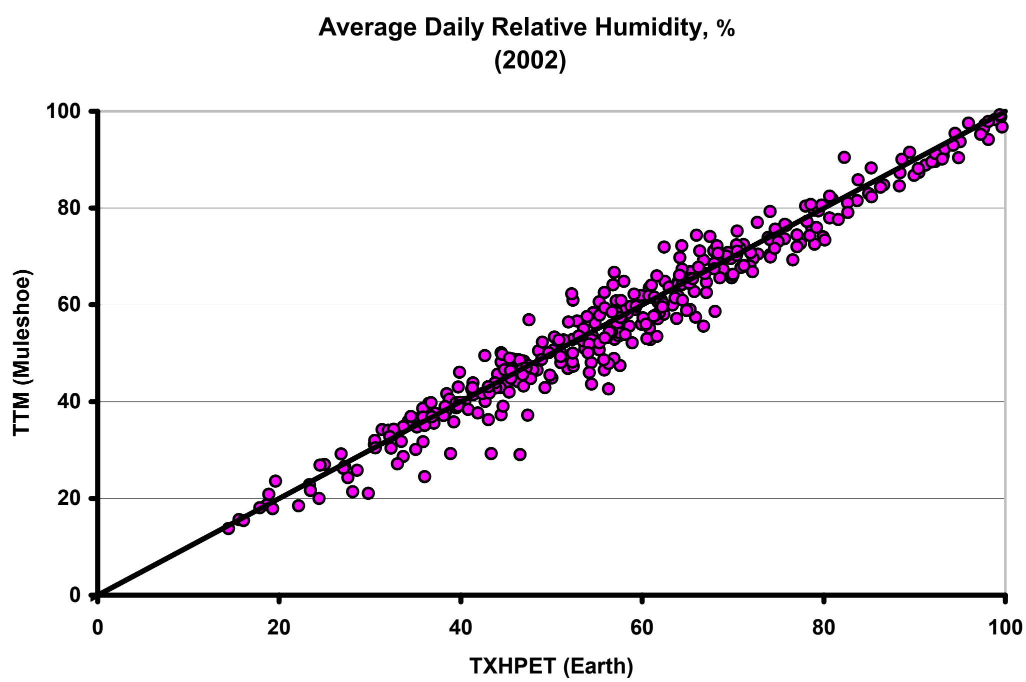

Figure 5.2 Daily relative humidity comparison between Muleshoe and Earth.

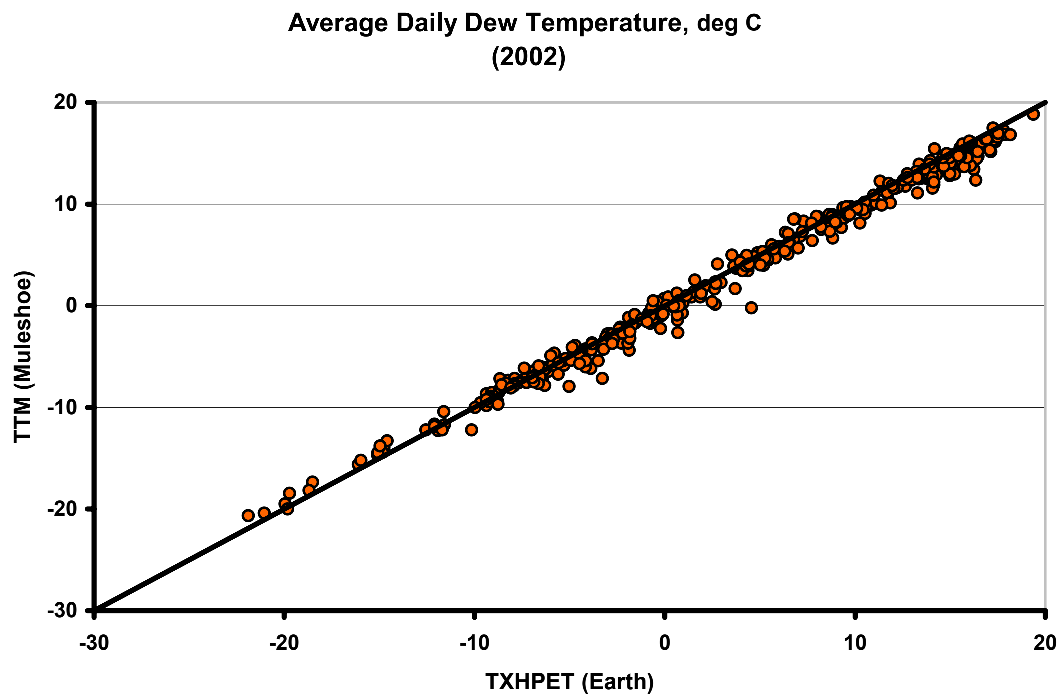

Figure 5.3 Daily dew temperature comparison between Muleshoe and Earth.

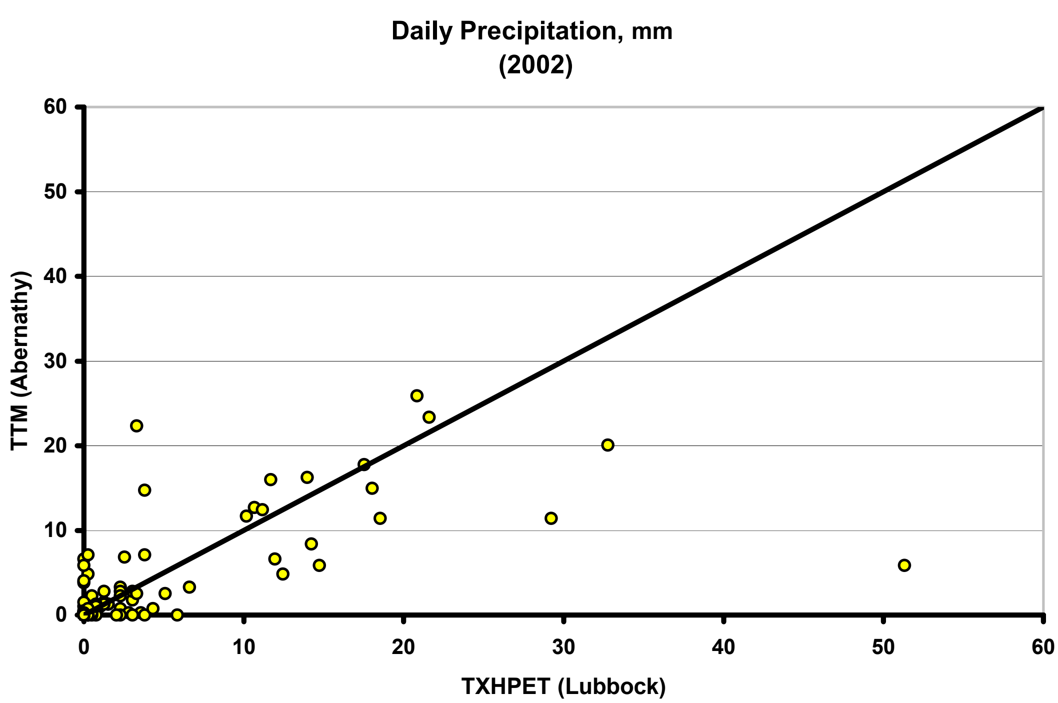

Figure 5.4 Daily precipitation comparison between Abernathy and Lubbock.

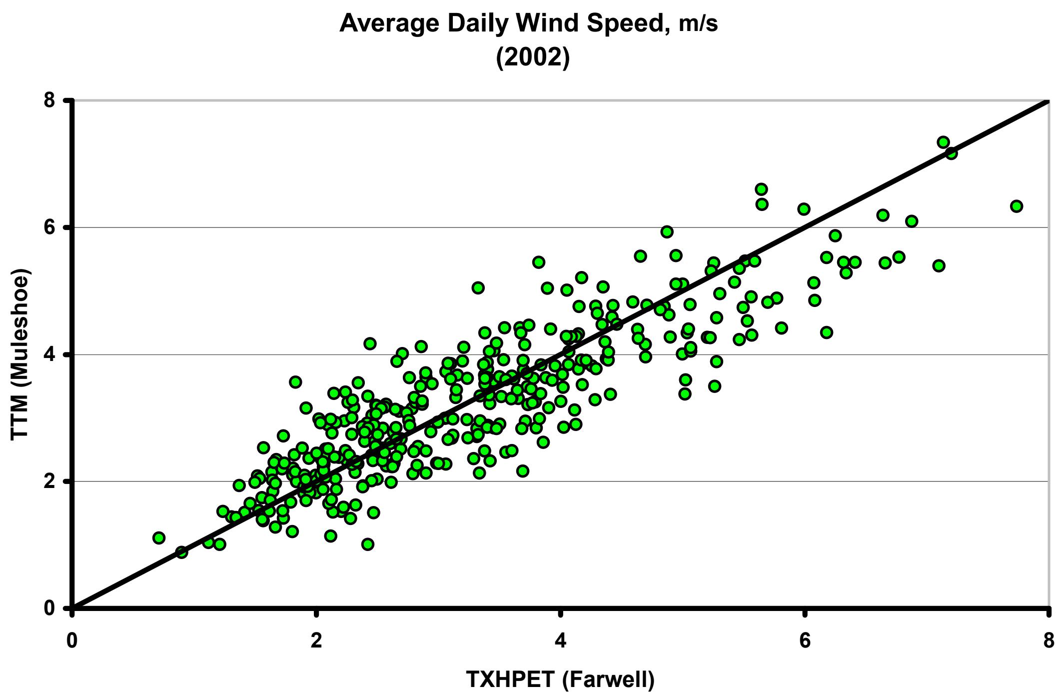

Figure 5.5 Daily wind speed comparison between the Muleshoe and Farwell.

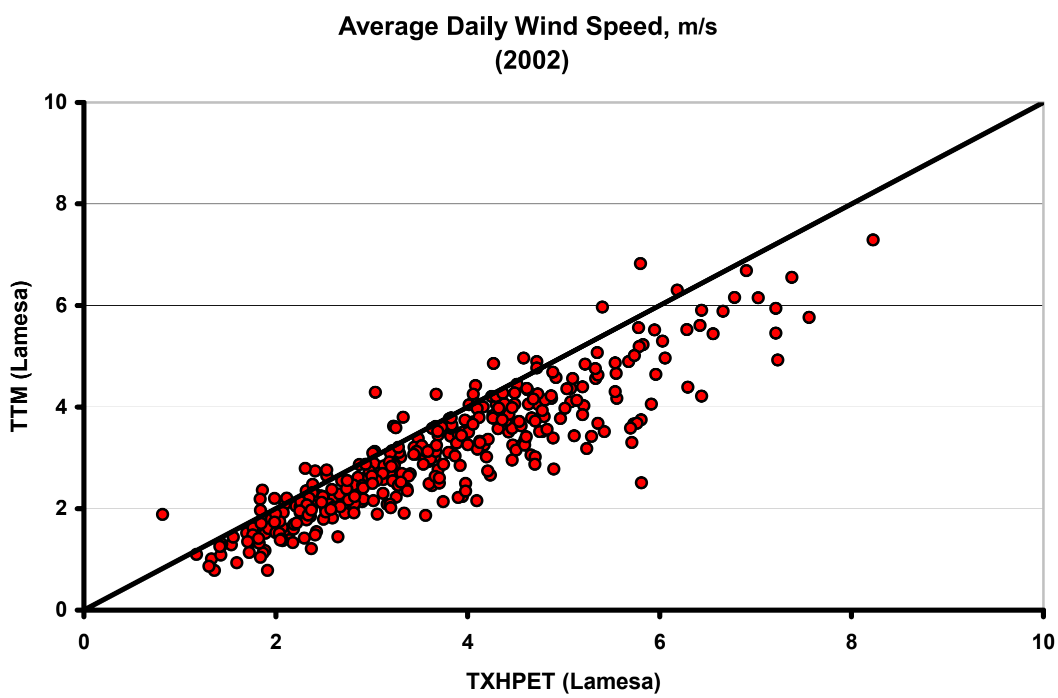

Figure 5.6 Daily wind speed comparison between two Lamesa locations.

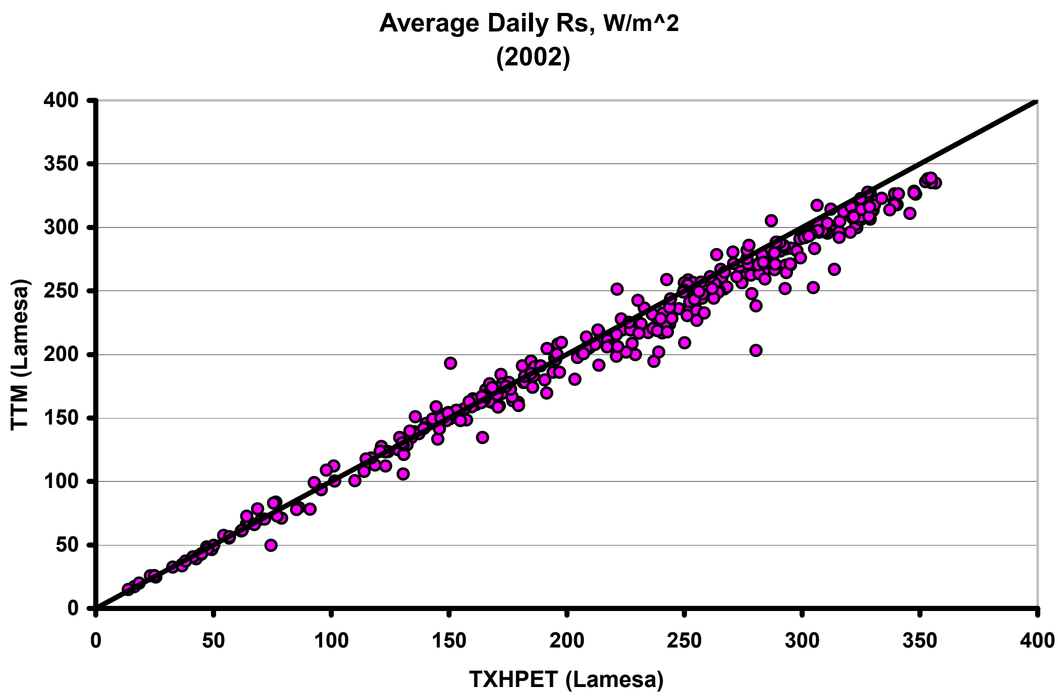

Figure 5.7 Daily solar radiation comparison between two Lamesa sites.

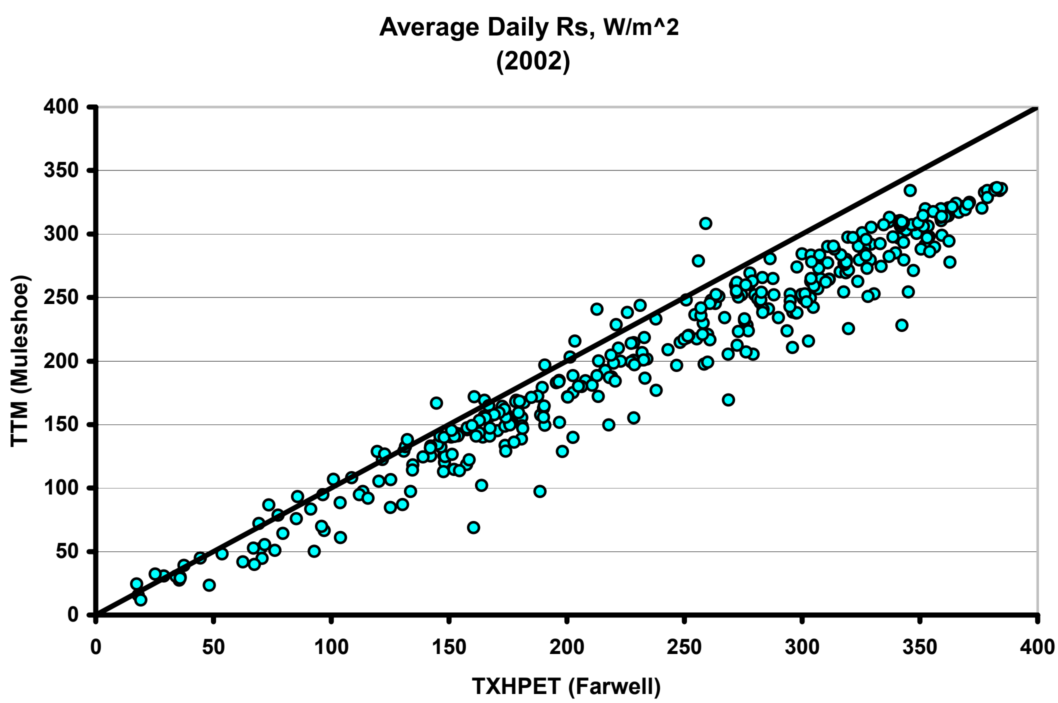

Figure 5.8 Daily solar radiation comparison between Muleshoe and Farwell.

5.4 Listing of Specific Data Sources

The following lists the principal sources of meteorological stations available in Texas:

1) Metar Units
2) National Weather Station (NWS)
3) NOAA-(IWIN stations)
4) U.S. Army Corp of Engineers
5) Forest Service
6) Bureau of Reclamation
7) USDA-NRCS – (SCAN network)
8) Universities (TAMUS, TTU, etc.)
9) Texas Water Development Board
10) Federal Research Units (ARS)
11) Texas Department of Transportation (DOT)
12) Commercial TV Stations
13) Airports (FAA)
14) Public Safety Services Network
15) Groundwater Conservation Districts, and
16) Municipalities

Data from several of these sources can specifically be found at the following web based links:

1) http://amarillo2.tamu.edu/nppet/petnet1.htm
2) http://lubbock.tamu.edu/irrigate/et/etMain.html
3) http://webgis.tamu.edu/
4) http://uvalde.tamu.edu/pet/
5) http://sanangelo.tamu.edu/agronomy/weather/etinfo.htm
6) http://texaset.tamu.edu/
7) http://www.mesonet.ttu.edu/
8) http://www.wrh.noaa.gov/wrhq/nwspage.html
9) http://www.wcc.nrcs.usda.gov/scan/Texas/texas.html
10) http://iwin.nws.noaa.gov/iwin/tx/tx.html
11) http://www.ncdc.noaa.gov/oa/ncdc.html
12) http://www.usbr.gov/main/water/
13)
14) http://www.met.tamu.edu/personnel/students/weather/weather_interface.html
15) http://nimbus.met.tamu.edu/weather.shtml
16) http://www.tamu.edu/ticc/greenness.htm
17) http://www.southernregion.fs.fed.us/sacc/weather/wxmaps/MAP SACC RAWS.htm
18) http://www.fs.fed.us/r3/fire/swapredictive/swaweather/swa-raws.htm
19) http://www.tamu.edu/ticc/
20) http://iwin.nws.noaa.gov/iwin/tx/tx.html

Additional information regarding sampling intervals, output intervals and other data parameters can be found in the weather assessment presentation notes in Appendix C.

5.5 Minimum Data Requirements for Methodology

Minimum agricultural data instrumentation required for the data inputs with the ASCE ET equation are outlined below. However, differences in how the data are computed can make a cumulative difference over seasons of crop ET computation. For instance, simple averages computed from only sampled maximum and minimum points vary from the geometrically weighted time-averaged values compiled in a running average manner within meteorological station programs. Typically, better representation is attained using the running average process. However, as a substitute due to the lack of such data, parameters can be estimated with simple averages, recognizing that representation of actual field conditions are not as good when using the simple technique. These running and average type computations and other details are outlined within the ASCE standard in Appendix A.

The suggested instrumentation (Howell and Marek, 2000) for a meteorological station should include the following (Table5.1):

Table 5.1 ET network station instrumentation and height specifications.

Parameter	Measurement Instrument	Sensor Height
Solar radiation	Li-Cor LI-200 silicon pyranometer	1.5 -2.0 m
Temperature	Thermistor type Viasala HMP-35C or HMP-45C	1.8 m
Relative Humidity	Capacitance type Viasala HMP-35C or HMP-45C	l.8 m
Wind speed	Cup type RM Young Anemometer starting threshold @ .2m/s	2.0 m
Wind Direction	RM Young Vane potentiometer starting threshold @ .8m/s	2.0 m
Precipitation	Tipping bucket .0l-inch (typically 6 inch diameter)	2.0 m
Soil Temperature	Thermistor type @ 2 and 6 inches	
Radiation shield	Gill type with l2 plates	
Barometric Pressure	Silicon capacitive type-Viasala	

The minimum data required for computation involves air temperature, relative humidity, solar radiation, wind speed, and precipitation. Station elevation is also required along with longitude and latitude. A more detailed description of the instrument and measurement procedures of agricultural weather stations is included in Appendix B. The suggested output format (Howell and Marek, 2000) from the data-logger is recommended in the following table.

Table 5.2 Suggested description of the hourly data outputs for an ET network.

Hourly Outputs (24 each day)

ID	Parameter	Designation
1	output id	129
2	month	Month
3	dom	Day of Month

4	year	Year
5	doy	Day of Year
6	time	Time
7	sig	Site program signature (CRC)
8	battery	Battery voltage
9	temp	Internal temperature (C)
10	soil2	2" Soil temperature (C)
11	soil6	6" Soil temperature (C)
12	air	Air temperature (C)
13	dew	Dew temperature (C)
14	rh	Relative humidity (%)
15	svp	Saturation vapor pressure (kPa)
16	vp	Actual vapor pressure (kPa)
17	vpd	Vapor pressure deficit (kPa)
18	Rs	Solar radiation (Watts)
19	ws	Wind speed (m/s)
20	dir	Wind direction (degrees)
21	sd	Standard deviation wind dir (degrees)
22	precip	Hourly precipitation (.01 inches)
23	0-15	Precipitation 1-15 minute into hour
24	15-30	Precipitation 16-30 minute into hour
25	30-45	Precipitation 31-45 minute into hour
26	45-60	Precipitation 46-60 minute into hour
27	bp	Barometer pressure (kPa)

Table 5.3 Suggested description of the daily data outputs for an ET network.

Daily Summary

ID	Parameter	Designation
1	output id	139
2	year	year
3	doy	day
4	time	2400
5	sig	Site signature
6	soil2	24 hour average 2" soil temperature
7	soil6	24 hour average 6" soil temperature
8	max2	24 hour maximum 2" soil temperature
9	time	Time of previous event
10	max6	24 hour maximum 6" soil temperature
11	time	Time of previous event
12	min2	24 hour minimum 2" soil temperature
13	time	Time of previous event
14	min6	24 hour minimum 6" soil temperature
15	time	Time of previous event
16	airT	24 hour average air temperature

17	maxT	24 hour maximum air temperature
18	time	Time of previous event
19	minT	24 hour minimum air temperature
20	time	Time of previous event
21	dewT	24 hour average dew temperature
22	maxdewT	24 hour maximum dew temperature
23	time	Time of previous event
24	mindewT	24 hour minimum dew temperature
25	time	Time of previous event
26	RH	24 hour average RH
27	maxRH	24 hour maximum RH
28	time	Time of previous event
29	minRH	24 hour minimum RH
30	time	Time of previous event
31	VP	24 hour average VP
32	maxVP	24 hour maximum VP
33	time	Time of previous event
34	minVP	24 hour minimum VP
35	time	Time of previous event
36	VPD	24 hour average VPD
37	maxVPD	24 hour maximum VPD
38	time	Time of previous event
39	minVPD	24 hour minimum VPD
40	time	Time of previous event
41	SR	24 hour average solar radiation
42	maxSR	24 hour maximum solar radiation
43	time	Time of previous event
44	maxWS	24 hour maximum wind speed
45	time	Time of previous event
46	WS	24 hour average wind speed
47	dir	24 hour average wind direction
48	wsSD	24 hour standard deviation of wind direction
49	precip	24 hour precipitation
50	bp	24 hour barometric pressure
51	bpmax	24 hour maximum barometric pressure
52	time	Time of previous event
53	bpmin	24 hour minimum barometric pressure
54	time	Time of previous event

5.6 Estimated Cost to Develop and Maintain an Agricultural Weather Station Network

The development cost of a statewide agricultural weather station network is estimated in regards to the purchase, establishment, and operation of strategically located meteorological stations along with personnel and support equipment requirements necessary for installation throughout the various irrigated regions of the state of Texas. These areas within the state are essentially located in the High Plains, the Rolling Plains, the West Texas area, which includes the San Angelo region and farther west and southwest irrigated areas, the Winter Garden area around Uvalde, the lower Rio Grande region and the Gulf Coast area. For purposes of this cost establishment report, it is assumed that newly located, initial sites and characterizations with the respective equipment are to be incurred. It is estimated that the meteorological stations within the respective networks will incur acquisition expenses of $7,500 per station currently for the base hardware alone. The cost of the meteorological units proposed and used in this estimation process are based on dedicated, operationally stable and proven units with associated instrumentation for the acquisition of agriculturally based meteorological data suitable for input into the respective ET reference equation. Siting requirements regarding representation of the meteorological station is referenced (ASAE, 2004) and a copy of ancillary suggested document is included in Appendix B. Communication costs and installation estimates are for hard-line telephone connectivity. Personnel requirements will entail a project field manager, two technical field people to install and program the units and a program person to handle the telecommunications and downloading efforts. Vehicle costs are also included in the support estimates. The total estimated costs incurred by a statewide, ET based system of network(s) over a startup type implementation horizon is estimated in Table 5.4.

Table 5.4 Establishment startup costs of ET networks throughout the major irrigated regions of Texas based on acquisition cost of $7,500 per station.

Irrigated Area of Texas	Proposed minimum number of base ET stations	Estimated cost of met. hardware	Estimated personnel expenses*	Estimated computing & acquisition equipment	Estimated support & installation expenses*
High Plains	24	$ 180,000	$ 92,740	$ 5,000	$ 85,358
Rolling Plains	3	$ 22,500	$ 11,592	$ 5,000	$ 10,670
West Texas Area	6	$ 45,000	$ 23,185	$ 5,000	$ 21,340
Winter Garden	6	$ 45,000	$ 23,185	$ 5,000	$ 21,340
Rio Grande Valley	10	$ 75,000	$ 38,642	$ 5,000	$ 35,566
Gulf Coast Area	4	$ 30,000	$ 15,456	$ 5,000	$ 14,226
Central Computing & Acquisition Site	-	-	$ 100,000	$ 35,000	-
Subtotals	**53**	**$ 397,500**	**$ 304,800***	**$ 65,000**	**$ 188,500**
Estimated State Totals	**53**	**$ 955,800**			

*Budget denotes a proportional cost basis over the multiple areas of the state, although some areas may share vehicle resources and require more resources than others and shifting within the area categories may occur.

Maintenance requirements, as compared with the equipment procurement, site characterization and selection costs involved in Table 5.4, include ongoing, replacement and upgrade estimates of the respective ET networks, which are essential if integrity of the data is to be assured. Each meteorological station associated with Table 5.4 is estimated to have a maximum life expectancy of 10 years with a total of $5,000 per unit being required each decade for replacement. These replacement and maintenance costs are essential for sustained operations and have been the downfall of many attempted ET acquisition systems in the past. Thus, the associated unit replacement cost is proportionally annualized for the decadal maintenance costs and are included in Table 5.5. Sensor recalibration and the estimated replacement costs are also included in the table. Costs associated with the support expense include travel requirements to service the respective locations on an annual basis and for servicing within the year. Transportation mileage, and annualized replacement costs for the required, supporting vehicles and other associated equipment are included. Note that no overhead or indirect costs are included with the cost figures, except for moderate benefit costs typically associated with state type personnel. Personnel costs include a project field manager, an instrumentation person and two technical personnel to assist with data basing and QA/QC protocols associated with the data. The budget does not address any programming associated with dissemination venues that would be possible and would be of potential benefit to other agencies and water related personnel. The costs also do not reflect demonstration expenses for monitoring, compiling data and developing grower factors and soil moisture data.

Table 5.5 Annual estimated statewide ET network maintenance and upgrade costs based on the minimum number of stations proposed throughout the major irrigated areas of Texas.

Irrigated Area of Texas	Anticipated number of base ET stations	Replacement & calibration estimate of met. sensors	Estimated personnel expenses	Estimated computing & acquisition upgrades	Estimated support expense
High Plains	24	$ 48,000	$ 78,829	$ 10,000	$ 38,038
Rolling Plains	3	$ 6,000	$ 9,854	$ 2,000	$ 4,755
West Texas Area	6	$ 12,000	$ 19,707	$ 3,000	$ 9,509
Winter Garden	6	$ 12,000	$ 19,707	$ 3,000	$ 9,509
Rio Grande Valley	10	$ 20,000	$ 32,845	$ 6,000	$ 15,849
Gulf Coast Area	4	$ 8,000	$ 13,138	$ 3,500	$ 6,340
Central Computing & Acquisition Site	-	-	$ 100,920	$ 25,000	$ 77,592
Subtotals	**53**	**$ 106,000**	**$ 275,000**	**$ 52,500**	**$ 161,592***
Annual Estimated State Totals	**53**	**$ 594,592**			

*Budget support costs are proportional based on number of stations throughout the state network and include items such as travel and vehicles.

The minimal number of stations required throughout the irrigated regions of the state was determined to total 53. However, it was discussed at length that more representation may be required. As such, an additional 23 meteorological stations may be warranted within the various irrigated areas of the state. This brings the total number of stations to 76. The following table (Table 5.6) illustrates the additional partitioning of the stations proposed, given additional available funding.

Table 5.6 Suggested number of statewide ET stations in the irrigated regions of Texas.

Irrigated Area of Texas	Anticipated number of base ET stations
High Plains	30
Rolling Plains	6
West Texas Area	10
Winter Garden	10
Rio Grande Valley	10
Gulf Coast Area	10
State Station Totals	**76**

Additional budget costs for the station expansion are not included. The additional stations, however, do not proportionately increase the budget as some vehicle and personnel costs can be accommodated from the minimal ET estimates. Travel, station and maintenance, however, must be included if the additional stations are implemented.

6.0 SINGLE VS MULTI-YEAR BASELINE

The freedom to farm bill combined with volatile weather patterns have created large year-to-year variations in the amount of irrigated acreage and in the crop composition associated with that acreage. The purpose of this sub-objective analysis is to examine the validity of using single versus multi-year acreage averages in constructing baseline water use estimates.

6.1 Description

Historically, a specific year's crop acreage and cropping patterns have been used as the baseline from which irrigation water use projections are generated. In recent water plans, the year selected corresponded to the year when the NRCS survey was conducted. Estimated water use either assumed irrigated acreage and crop composition remained unchanged or modified according to future water use expectations. Concerns have arisen in recent years over the validity of using a single-year irrigated acreage distribution of data as a baseline to make projections of future water use, essentially for a decade. Since 1974, there has been a reduction in irrigated acreage and with more efficient technology and farming practices and other factors, it will continue to decline. The increasing flexibility given to producers in the last three farm bills to change crop composition, or to not plant at all in response to changing commodity and input prices is leading to increased volatility in the irrigated acreage and crop composition. Of particular interest in the Texas High Plains is the impact of volatile rising natural gas prices and the distortion it may cause in the total irrigated acreage, crop composition and acreage distribution.

6.2 Methodology

To examine the issue of a single-year versus multi-year acreage base, the TASS/Census data for the major irrigated crops (cotton, corn, sorghum, wheat, and peanuts) grown in Regions A, O, L, and M during a 21-year period (1981-2002) were used. The TASS data were one source of information that provided readily accessible, annual data during this time period. A simple comparison of the variation in total irrigated acreage and irrigated acreage by crop was conducted to identify any significant changes.

6.3 Results

Total irrigated acreage in Regions A, O, L, and M varied greatly from 1981 to 2002 with a high of over five million acres in 1981 and a low of approximately three and a quarter million acres in 1987. Distortions were magnified when examining acreage by crop. The major irrigated crops grown in these regions are cotton, corn, peanuts, sorghum, and wheat. In most years, cotton, corn and wheat will make up eighty-five to ninety percent of the irrigated acreage, which results in acreage changes in these crops more volatile than changes in the total irrigated acreage. The irrigated acreage of the major crops for Regions A, O, L, and M from 1981 to 2002 are illustrated in Table 6.1. Corn had a 38 percent (405,121 acre) decrease in acreage from 1998 to 2002 while wheat had a 38 percent increase (426,100 acres), and as mentioned earlier, corn producers apply more water to the crop than wheat producers typically do. Cotton's irrigated acreage varied greatly from year to year. There were 2,293,100 acres of cotton in 1981, then falling to 1,683,100 acres in 1982, which could have been influenced by changes in the farm program. Roughly every four years, cotton acreage rapidly goes from a peak to a valley as presented in Figure 6.1. Using a single-year value as opposed to a multiple year moving average would distort these trends. Using a three-year average as opposed to the five-year would have more variation due to such trends. In 1992, sorghum had a 252 percent (676,600 acres) increase from the previous year due to cotton crop failure, which poses an interesting problem with the TASS data.

In 1992, Region A had 1,361,900 acres of irrigated cotton planted but only 452,400 harvested due to a weather problem. Most of the 909,500 acres were likely plowed out and planted to sorghum, which would account for most of the acreage increase for sorghum in 1992. The problem is that many of the 909,500 acres were counted twice. Once as cotton and then as sorghum behind the failed cotton crop. The question then arises, should planted acres or harvested acres be used to determine the number of acres irrigated and for what duration of the crop season? The problem with counting planted acres only is there will be acres that are counted twice as in the previous example. The problem with only counting harvested acres is that some acres won't be counted at all. For instance, economic factors could cause irrigated wheat pasture that was counted in planted acreage, to be "grazed out" and not harvested. Thus, these acres will not be counted as irrigated acres. For this analysis, planted acres were used to provide a liberal perspective. This is further supported by the fact that typically a "hail out" occurs when considerable water has been expended on a planted crop within Region A.

Table 6.1 TASS irrigated acres by major crop in Regions O, A, M and L, 1981-2002

Year/Crop	Cotton	Sorghum	Wheat	Peanuts	Corn	Total
1981	2,293,100	803,400	1,208,200	0	707,700	5,012,400
1982	1,683,100	1,086,300	1,207,700	0	682,300	4,659,400
1983	1,332,500	555,100	1,069,600	0	567,700	3,699,500
1984	1,768,100	708,900	1,032,000	0	742,300	4,251,300
1985	1,487,000	730,600	987,800	0	680,200	3,885,600
1986	1,363,000	635,100	1,100,800	0	612,500	3,711,400
1987	1,308,200	461,700	865,300	0	612,500	3,247,700
1988	1,564,900	407,700	824,400	0	610,400	3,407,400
1989	1,469,700	626,800	901,900	0	744,835	3,743,235
1990	1,689,800	461,800	940,500	0	746,620	3,838,720
1991	2,003,100	444,600	812,700	0	796,090	4,056,490
1992	1,515,200	1,121,200	893,900	0	823,713	4,354,013
1993	1,758,200	431,700	866,200	98,500	944,988	4,099,588
1994	1,813,000	438,600	803,600	106,500	1,029,958	4,191,658
1995	2,087,700	457,600	790,800	97,100	936,192	4,369,392
1996	1,947,700	648,600	806,000	134,900	1,020,238	4,557,438
1997	1,800,800	550,000	852,400	180,600	1,032,867	4,416,667
1998	1,884,700	378,100	732,800	242,800	1,078,221	4,316,621
1999	2,046,400	559,100	761,300	229,000	935,888	4,531,688
2000	2,222,900	369,300	787,600	182,700	952,054	4,514,554
2001	2,022,800	541,800	939,500	217,800	690,077	4,411,977
2002	1,953,300	447,000	1,158,900	80,900	673,100	4,313,200

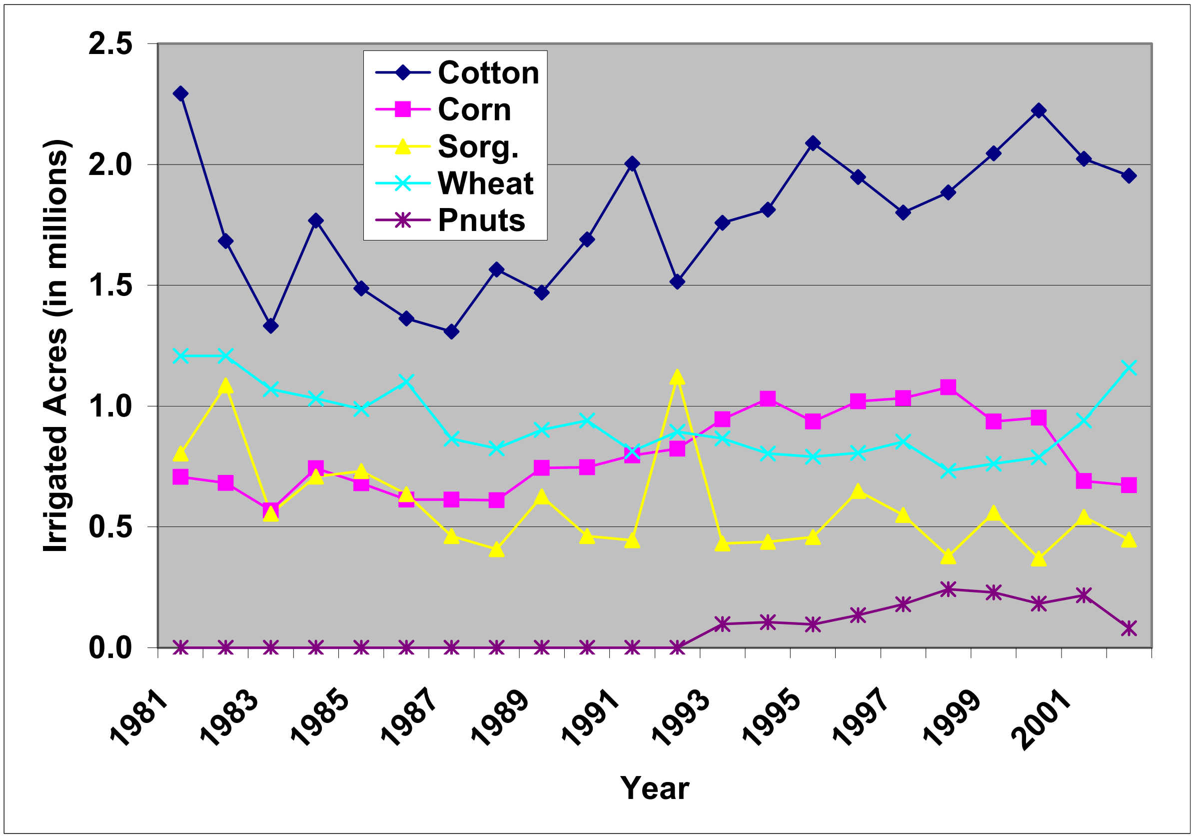

Figure 6.1 TASS irrigated acreage of the major crops in Regions A, O, L, and M from 1981-2002.
Source: Texas Agriculture Statistics Service

The variance in irrigated crop acreages suggests that the use of a single-year crop acreage base can cause dramatic distortions in projected water use estimates. These distortions, whether caused by fluctuating natural gas prices, commodity prices, weather or other factors can alter both acreage levels and crop composition. On the other hand, failing to account for the natural occurring events can cause additional distortions.

One suggested solution to the acreage base problem could be the use of an equally weighted, moving average of acreage(s) over a number of years. This would allow years where "events" that caused cropping patterns to be factored in, but the effects dampened when averaged with other years. The real question remaining may be, "How many years should acreages be averaged over?" For example, a five-year average may be long enough to smooth out some years that have significant altering "events". However, it may also be that too long a period that minimizes trends in crop acreages. A three-year averaging system is another alternative, but it may over-emphasize certain distortions. Actual reported acreage for the twenty-one year time period as well as for the three and five year equally weighted, moving average values are illustrated in Figure 6.2.

Descriptive statistics may also be used to further determine the validity of the different methods. This analysis concentrates on the standard deviation and the coefficient of variation.

The standard deviation is a statistic that measures how tightly the observations in a data set are clustered around the mean. The closer the data are to the mean, the less variability there will be in the data set. The coefficient of variation measures relative variability, which is, the variability relative to the magnitude of the data mean. The coefficient of variation is unitless; therefore, it is good for comparing the variation between groups. The standard deviation and the coefficient of variation are presented in Table 6.2.

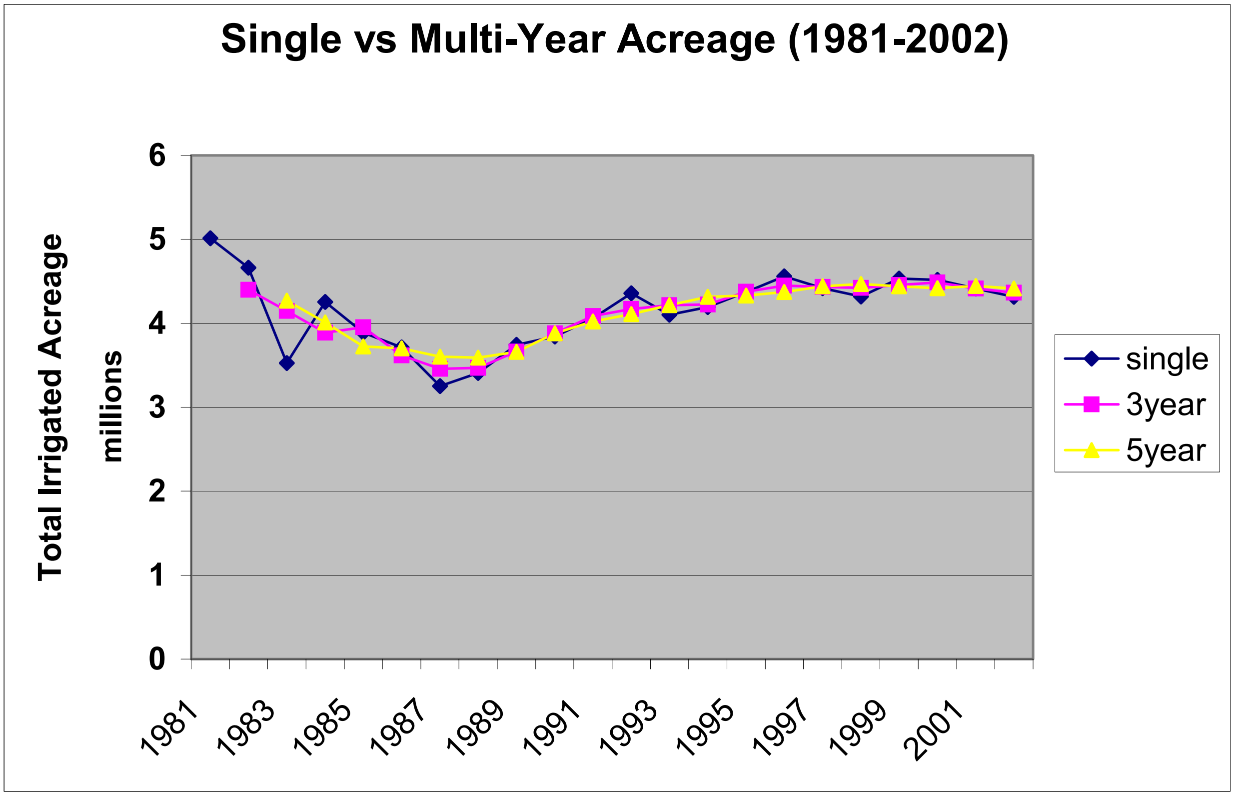

Figure 6.2 Comparison of total irrigated acreage of the major crops for a 3-year and a 5-year equally weighted moving average (1981-2002).

Table 6.2 Descriptive statistics of single, 3 and 5 year averages.

	Single Year	3-Year	5-Year
Mean of Acreage	4,157,234	4,108,724	4,085,536
Standard Deviations from the Mean (ac.)	438,363	345,141	320,211
Coefficient of Variation	10.54%	8.40%	7.84%

6.4 Recommendations

The five-year equally weighted moving average acreage computation appears to be the most appropriate of the three considered baselines. It has less variation between years and smoothes out the outliers in the acreages. The single-year acreage use catches too much "interference" from past patterns that may not be relevant in the future. The three-year moving average computation appears to be a vast improvement over the single-year model but still may react too harshly to past trends. The five-year moving average model has the least variance between years, but still is able to identify changes that are inherent to agriculture's cyclical nature.

Currently, the TASS data are the most readily available source for past cropping information. However, there is a problem with "ghost" acres that were counted twice in 1992. Other prior years may also contain similar "ghost" acres. The FSA data handle this problem by denoting failed crop acreage with an "F" designation. This data may also have a problem. Farmers have to file a notice of loss with the FSA to be eligible for disaster programs or for insurance purposes. Not all farmers file the lost crop to FSA, so the FSA query typically doesn't represent all of the failed acreage within the county.

6.5 Summary and Conclusions

The key to estimating future irrigation use is the accurate assessment of baseline water use. Three pieces of information are essential in making baseline water use estimates; irrigated acreage by crop, water use by crop, and weather data. Considerable time and, if necessary, money should be invested to insure these baseline data requirements are the "best" estimates available. Failures to accomplish this task will more than likely lead to inaccurate projections and potentially errant policies being developed. This information should be monitored and compiled annually for water planning implementation purposes.

Irrigated Acreage By Crop. Farm Service Agency (FSA) is the only logical source for primary irrigated crop acreages. It is readily available and inexpensive, if not free to obtain. Virtually every irrigated crop acre in Texas is contained in their database. The Census of Agriculture estimates need to supplement the FSA data to improve estimates of irrigated pasture, which may not be certified with the FSA. County tax rolls should be used to validate total irrigated estimates for the counties.

Water Use by Crop. The number of demonstration projects on private farms being conducted by the Texas Cooperative Extension (TCE) and Water Districts in the primary irrigated regions of the state is very close to sufficient for developing water use estimates by crop and region. However, due to personnel and financial constraints, minimum information on soil moisture is not being collected with the exception of water planning in Region A. Personnel conducting demonstrations have expressed willingness to collect soil moisture information if the cost of this activity is subsidized. The estimated cost is in the range of $1,500 to $2,000 per demonstration, which includes travel, personnel, and equipment costs (with the exception of water meters).

Weather Data. There are numerous meteorological stations and weather networks located throughout Texas. However, most do not meet the necessary agricultural related standards with respect to site location, data generated, and quality assurance/quality control (QA/QC) to provide a reliable source of data for use in the Agricultural Irrigation Use estimates model. Also, potential integration of National Weather Service rainfall data resources may be desired to better represent a spatially averaged effective rainfall within the counties. The development cost for establishing an adequate statewide evapotranspiration (ET) station network across the state (minimum of 53 stations) is estimated at $950,000. However, this cost could be significantly reduced by contracting with the appropriate existing ET networks given that these stations and networks could be brought up to and maintained at the required standards, where necessary. It is also estimated that the annual cost to operate and maintain the statewide ET network meeting the needed QA/QC requirements would be $600,000.

Single versus multi-year. Recent farm programs that have increased planting flexibility combined with volatile input and output prices have resulted in large planted acreage changes between crops. A five-year moving average had the least variance between years among the models considered but still is able to identify changes that are inherent to agriculture's cyclical nature.

TASK 1
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TASK 2

METHODOLOGY FOR ESTIMATING FUTURE IRRIGATION USE

The accurate estimation of future irrigation use is critical to evaluating and developing strategies to ensure proper water use to benefit the citizens of Texas. The objective of Task two is two-fold: First, provide a review of the different irrigation use projection methodologies utilized in the major irrigation states, with particular emphasis on the states surrounding Texas; and second, provide a detailed description and assessment of the two irrigation use methodologies selected for consideration in Texas. These are Evaportranspiration (ET) based modeling and Crop Growth modeling.

7.0 REVIEW AND DISCUSSION OF AGRICULTURAL WATER USE ESTIMATING METHODOLOGIES

Irrigation remains the largest user of freshwater in the United States and water withdrawals totaled 153 million acre-feet (maf) during 2000. Irrigation accounts for about 65 percent of total water withdrawals nationally. Withdrawals have decreased since 1980 and have stabilized between 150 and 153 maf between 1985 and 2000. More surface water is being used for irrigation. However, the withdrawals from groundwater for irrigation have been increasing continuously, from 23 percent in 1950 to 42 percent in 2000 (USGSa, 2004). Sources of data for irrigation withdrawal and irrigated acres include State and Federal crop reporting programs. Water use for irrigation is usually estimated using information on irrigated crop acreages along with specific crop water consumption coefficients or irrigation-system application.

An essential prerequisite for water management and the planning process is to correctly estimate future irrigation water use. Estimation methods vary from one geographic area to another. Estimation methods include climatic variables, crop composition, application efficiencies, conveyance losses, and other irrigation practices such as pre-irrigation. Other methods of estimating irrigation water use also include extrapolation of sample data on crop water-application rates or power-consumption coefficients. The comparison and analyses of methodologies being used for projecting agricultural water use would act as a baseline for developing water management plans and addressing water related policy issues to optimize beneficial use of water resources. In this section, a brief description of methods used to estimate irrigation water use, advantages and disadvantages of each methodology and their use in selected states are presented.

7.1 Brief Description of Estimation Methods

There are primarily three methods to estimate crop water use. These are evapotranspiration (ET) based method, crop growth simulation model, and remote sensing or geographic information system (GIS) based method. Despite different characteristics of each method, most of them require ground based meteorological data, usually with a daily time step. Especially, the application of a specific method on a large irrigation area requires access to a network of meteorological stations with a suitable spatial density and data consistency.

7.1.1 Evapotranspiration (ET) Based Method

The crop water need is the amount of water required by the various crops under an optimal crop growth condition (Snyder et al. 1989). ET based methodologies of irrigation water use focus on the crop water need. The crop water need always refers to the amount of water the crop requires when it reaches its full production potential under the given environment. Even though many methods have been developed to estimate ET, each method selected should be tested regionally before it is adopted.

The most commonly used method is the modified Penman method. Penman (1948) combined the energy balance with the mass transfer method and derived an equation to compute the evaporation from an open water surface with standard climatological conditions of sunshine, temperature, humidity and wind speed. This so-called combination method was further developed by many researchers and experimented on cropped surfaces by introducing resistance factors.

The modified Penman method was once considered to offer the best results with minimum possible error in relation to a living grass reference crop. According to FAO (1998), however, advances in research and the more accurate assessment of crop water use have revealed weaknesses in this method. The Penman method was believed to overestimate ET, even by up to 20 percent, for low evaporative conditions. To achieve satisfactory results, local calibration of the wind function is necessary. For example, the California Irrigation Management Information System (CIMIS) uses the modified Penman, also known as the CIMIS Penman, equation to estimate reference ET (ET_o). The CIMIS Penman equation employs the modified Penman equation with a wind function that was developed at the University of California, Davis (California Department of Water Resources 2004) with hourly weather data.

The Blaney-Criddle method (Blaney and Criddle, 1950) was used to determine consumptive use of crops grown in the Socorro-Sierra Water Planning Region. The method uses average monthly air temperatures, monthly percentage of annual daylight hours based on the latitude of the area under study, seasonal consumptive use coefficients, and length of growing season to estimate the total consumptive use. Once a value is obtained for the total consumptive use, it is necessary to account for effective rainfall (New Mexico Water Planning, 2002).

The Blaney-Criddle method estimates the amount of consumptive water used by plants during their normal growing season. The results are closely related with mean monthly temperatures and daylight hours. Despite several advantages of this method like available climactic data, ease of use, and its broad acceptance, however, a distinct disadvantage of this method is its inaccuracy. It provides a rough estimate especially under extreme climatic conditions. For example, in windy, dry, sunny areas, the ET is underestimated (up to some 60 percent), while in calm, humid, clouded areas, the ET is overestimated (up to some 40 percent). Another disadvantage of this method is that it requires long-term records or records of a sufficient number of years to develop coefficients with which the local consumptive use is calculated (FAO, 1998).

Other methods include the Lowry-Johnson, Jensen-Haise and Thornthwaite. Among them, Jensen-Haise is the most accurate method. However, this method needs solar radiation data and crop coefficient curves to calculate crop water use. There are few weather stations where solar radiation is measured where crop coefficient curves have been developed for all crops growing in the given area. The Jensen-Haise Method requires considerable transposition and estimation of these data for use (Trelease, 1970).

The American Society of Civil Engineers (ASCE) ET in Irrigation and Hydrology Committee in cooperation with the Water Management Committee of Irrigation Association has developed a standardized reference ET equation (Walter et al. 2003). The standardization of reference ET will provide common national basis for expression of evaporative use and consistency in calculation of ET and will facilitate transfer of crop coefficients. Presently, the standardization effort report is under review by the Environmental and Water Resources Institute (EWRI) of the ASCE.

7.1.2 Plant Growth Models in Water Use Estimation:

Crop growth simulation models are research tools usually applied in assessing the relationship between crop productivity and environmental factors. They have been known to be efficient in determining the response of crop plants to changes in weather and climate. Examples of such models include EPIC (Meinardus, 1998), CERES, GAPS, SOYGRO and IBSNAT. In most cases, these crop models have been developed for a particular local situation and they are not always applicable in other regions without modification or calibration. Therefore, when introducing such crop models into new regions, their applicability must be evaluated (Seidl et al. 1999)

Crop Environment Resource Synthesis (CERES) is a group of models that has a series of modules for growth simulation of various crops, with CERES-Maize of particular importance. CERES-Maize model is a predictive, deterministic model designed to simulate crop (maize) growth, soil, water and temperature and soil nitrogen dynamics at a field scale for one growing season (Boote et al. 2003). It is related to other CERES models, such as the CERES-Wheat model. The model is used for basic and applied research to study the effects of climate (thermal regime, water stress) and management (fertilization practices, irrigation) factors on the growth and yield of wheat. It is also used to evaluate nitrogen fertilization practices on nitrogen uptake and nitrogen leaching from soil and in global change research to evaluate the potential effects of climate warming and changes in precipitation and water use efficiency due to increased carbon dioxide (Al-Kaisi and Broner, 1998).

These crop growth models are computer programs that predict daily plant growth based on daily weather data, soil, management, and genetic information. The models compute growth based on light interception and computations of daily photosynthesis, which can be reduced by temperature, water and nitrogen stress. Carbohydrate fixed by photosynthesis is then partitioned to plant components based on crop growth stage, and stress. Thus, the model is able to integrate daily effects of temporal stress on growth and yield (Batchelor, 1999). Crop growth models require immense spatial data as inputs (Paz et al. 1998). Research versions of the models can be cumbersome, and time consuming to set up input files to analyze a field. It is also difficult to visualize the nearly 200 daily variables computed and stored as model output. A spatial interface is needed to facilitate this process, and to expedite visualization of model output (Amor et al. 2001). Also, this visual interface would facilitate management and analysis of the vast amount of data required to use crop growth models to analyze spatial yield variability (Seidl et al. 1999).

7.1.3 Using Remote Sensing and Geographic Information System (GIS) Technology:

Geographic Information System (GIS) refers to a computer technology that utilizes geographic location as the organizing theme around which data and information can be organized, linked, and integrated. The GIS provides the capacity to analyze, model, and display multiple sets of information using computerized maps as the primary form of system output (Satti and Jacobs, 2003). The satellite imagery and other geo-spatial technologies can be used to assess crop quality and distribution, current and potential land use, soil type and other factors. Images and other remotely sensed information such as aerial photographs can be coupled with GIS computer programs.

The remote sensing (USGSb, 2004) has been a popular tool readily accepted into agricultural research and management because it can provide a synoptic perspective critical for understanding biophysical relationships at a regional scale. In other words, the remote sensing can be used to estimate irrigated acreage because it contains information such as high or low altitude aerial photography and satellite imagery.

In determining actual acres irrigated, timing of the photographs or images is critical. If taken too early, areas affected by shallow ground water from spring runoff are difficult to separate from areas where irrigation water is applied. If taken too late in the season, harvesting might have been completed for some crops. In areas where successive crops are grown on the same land, more than one set of images may be needed. In some areas, cloud cover also may be a problem (Thelin and Heimes, 1987).

It is difficult to identify specific crops from imagery and field surveys will be required to verify the accuracy of crop determination. For example, uncertainty in crop determination is frequent in areas where a large variety (more than 200) of crops are grown that may appear similar in aerial photographs. Reliability in the use of aerial photography is more in areas where crop variations are minimal, or if these tools are only used to determine general cropped or irrigated acreages (USGS, 2003).

The use of computer-processed Landsat satellite data to identify irrigated crop types and estimate crop acreage is more successful in arid and semiarid lands where crop diversity is minimal, dryland crop production is minimal, soils are warm and well drained, crop calendars are more diverse temporally, and fields are planted entirely with one crop type. However, remote sensing is a timely and cost effective way to provide these maps to GIS models annually. A derivative of this method has been used to provide estimates of crop water use for farm-level irrigation water use efficiency for irrigated areas in South Australia (Van Niel and McVicar, 2001). Remote sensing is a valuable source of data in rice-based agriculture, especially when regional-scale issues are the concern. However, there are some limitations of remote sensing regarding agricultural applications such as data availability, length of recording period, limited mapping capability, requirement of personnel expertise, availability of computer facilities, and cost.

Costs of using remote sensing can be difficult to assess since numerous factors are involved for different agencies and organizations. A favorable assessment of satellite imagery and analysis costs as determined for Idaho (Allen – personal communication, 2004) indicated that approximately $30,000 was required for processing. The costs related to the eight time period scene acquisitions and terrain corrections bring the cost to nearly $54,000 for the study area. (Assuming overhead and software, this figure would representatively approach a cost of $100,000 annually.) These cost estimates are based on a well number of 5,000 within the study area. Given that the number of wells in the Texas High Plains has been estimated to exceed 125,000 (Marek et al. 2004), the cost of attribution would escalate proportionally. Additionally, the size and distribution of irrigated lands and correspondingly the number of scenes required would be increased in Texas. Subsequently, the cost would be proportionately higher, especially since irrigation occurs over longer time periods in Texas than within that of Idaho.

Satellite imagery remains a possible methodology for estimating irrigated crop water use in the future. However, the necessary improvements in accuracy may take 10 to 15 years. If the improvements occur, satellite imagery may be a lower cost alternative for estimating irrigated crop water use. It should be noted that demonstration data will still be required to calculate satellite imagery programming during the transition phase. In fact, a limited amount of demonstrations will have to be conducted during the operational phase to validate satellite imagery projections which may limit or eliminate any potential cost savings.

7.2 Advantages and Disadvantages of Methodologies

Each method has its own advantages and disadvantages. Due care is required to be taken into consideration before using any method for estimating irrigation water use for a specific area or region. The advantages and disadvantages of the three most commonly used methods are listed in Table 7.1.

Table 7.1 Advantages and disadvantages of methodologies commonly used.

Method	Advantage	Disadvantage
ET Based Model	1. Easy to apply using commonly available weather data 2. Easy to understand and visualize 3. High acceptance rate 4. Has been conventionally used and applied in agricultural water use estimation across country	1. Site-specific data requirement 2. Long-term data is required 3. Requires calibration for a specific area or region.
Crop Growth Model	1. Determine the response of crop plants to changes in weather and climate 2. Better performance with rain fed than irrigation water use 3. Integrate daily effects of temporal stress on growth and yield	1. Requires large quantity of spatial data as inputs 2. Site specific and crop specific 3. Discrepancy between predicted water use and observed later in the growing season
Remote Sensing/GIS	1. More successful in arid and semiarid land 2. Useful in identifying crop types and crop acreage in areas where crop calendars are more diverse 3. Cost effective way to provide maps to GIS models	1. Limited mapping capacity 2. Requires expertise and computer facility 3. Data limitation due to discrete time events 4. Lack of information on plant growth and environment status

7.3 Methodology of Estimating Irrigation Water Use in Selected States

It is pertinent to look into the overall situation of irrigation in selected states before discussing details of methodologies being used in these states to estimate agricultural water use. Table 7.2 gives a summary of irrigated land, water withdrawals along with sources of water for year 2000 and irrigation water use estimation methods currently in use in some of the states in the U.S. Note that California is at the top of the list in irrigated land as well as water use. Nebraska and Texas are second and third, respectively, in irrigated acres. However, in terms of total water use, Idaho and Colorado are second and third, respectively, and Nebraska and Texas are fourth and fifth. This ranking is partially a reflection of the relative per acre water use due to cost, crop, and efficiency factors associated with production. Following the summary table, estimation methodologies currently in use are discussed for each selected state in this section.

Table 7.2 Irrigated land, water withdrawals, and irrigation annual water use estimation methodologies being used in selected states, 2000.

State	Irrigated Land (1,000 ac.)	Water Used for Irrigation (1,000 acre-feet)			Estimation Methodologies
		Ground	Surface	Total	
Arkansas	4,510	7,290	1,580	8,870	GIS-Landsat Theuamatic Mapper, Digital Land Use/Land Cover (LULC)
California	10,100	13,100	21,100	34,200	ET (SIMETAW, CUP), GIS
Colorado	3,400	2,420	10,400	12,820	ET (Modified Blaney-Criddle, Penman-Montieth), State CU Model, Colorado Decision Support System
Idaho	3,750	4,170	15,000	19,170	FAO-MBC, Kimberly Penman Equation, Remote Sensing (SEBAL)
Kansas	3,310	3,840	323	4,163	Regional Standard ac-ft/ac, County Standard, Hydro Data Software
Nebraska	7,820	8,320	1,540	9,860	PET, Crop ET, Conveyance Losses
New Mexico	998	1,380	1,830	3,210	ET (Blaney-Criddle), Effective Rainfall
Oklahoma	507	635	170	804	General Irrigation Rate (Region Specific), Irrigated Base Acres
Texas	6,490	7,290	2,390	9,680	ET, TAMA Model, Crop Growth Models, GIS
Total	40,882	48,445	54,333	102,778	

Source: USGSa 2004.

7.3.1 Arkansas

Water withdrawals for irrigation in Arkansas in 2000 were estimated to be 8.87 maf (USGSa, 2004). Of this amount, 82 percent is groundwater. Irrigation water use has increased by 61 percent since 1980. Although the average annual rate of water application decreased about 40 percent between 1980 and 1995, the number of irrigated acres increased. In Arkansas, irrigated acreage surpassed 4.51 million acres, making it the fourth ranking irrigated state. Even with yearly rainfall exceeding 40 inches, extended droughts make irrigation a requisite for economically viable agriculture (Robinson et al. 2003).

Most of the irrigated acres in Arkansas are found in the Mississippi Alluvial Valley (MAV), known as "the Delta". The accurate assessment of agricultural land use for this region was prerequisite for estimating agricultural water use (Gorham, 1999). Under the financial support of the Arkansas Soil and Water Conservation Commission (ASWCC), the Center for Advanced Spatial Technologies (CAST) at the University of Arkansas began to develop digital land-use/land-cover (LULC) maps focusing on agricultural land-use for the 27 Arkansas counties within MAV. Landsat Theumatic Mapper (TM) satellite imagery (Bellow and Graham, 1992) was used to develop LULC maps for counties in MAV. Maps for each county were produced for spring, summer, and fall.

In the land image selection work, the planting patterns and phenologies of the major crops were examined (Arkansas Agricultural Statistics Service, 1993). Informal interviews with both FSA field office personnel and local University of Arkansas agronomy department faculty were also conducted for this work. Increased frequency in temporal resolution is the most reliable factor for improving agricultural studies. In the past most agricultural land use maps portrayed a somewhat static, year to year, picture of the landscape. The maps generated for the MAVA-LULC project depict season to season land-use/land-cover patterns (Gorman, 1999).

7.3.2 California

California ranks first among states in irrigation water use. In California, more than 10.1 million irrigated acres used 34.2 maf of water in 2000 (USGSa, 2004). Groundwater withdrawals for irrigation use were 13.1 maf and withdrawals for irrigation use from surface water sources were 21.1 maf. Agricultural water use is estimated by multiplying water requirement for different crops by their corresponding region-wide irrigated acreage. Irrigation acreage forecast is developed mainly through land use survey and mapping irrigated acreage. The land use survey focuses on qualifying irrigated acreage. Department of Water Resources (DWR) excludes acreage of dryland farming to calculate water use. For areas that produce multiple crops per year in the same field, annual irrigated acreage is counted as the sum of the acreage of the individual crop types.

Forecasts of agricultural acreage start with land use data that characterizes existing crop acreage. The projected irrigated acreage in 2020 was determined by three different sources including research, crop market outlook study, and results from the Central Valley Production Model. By using these different sources, it is possible to determine the best estimate of future irrigated acreage. DWR considered factors such as national and international markets and the transformation of irrigated land to urban usage to project the future irrigated acreage.

As the first procedure for projecting agricultural water use, DWR used a method based on a relationship of measured ET with observed evaporation, temperature, and other climatologic conditions. A benefit of this ET correlation method was to easily apply a measured ET estimate to other areas with similar climates. Also, growing seasons were determined by ET/evaporation ratio correlation between a measured ET and PAN evaporation. This ET/evaporation ratio method shows that crop water use was within ±10 percent of crop season measured ET. ET rates for specific crops were calculated with different crop coefficients, a basis for calculating ET of Applied Water (ETAW) and applied water.

DWR considered other factors that affected the amount of water applied to a given field such as soil characteristics, water delivery systems, irrigation management, water quality, weather conditions, and effective rainfall. For example, applied water during a dry year exceeds the base year because of low effective rainfall with a considerable increase in crop ETAW.

A Simulation Model for Evapotranspiration of Applied Water (SIMETAW) was developed by the California Department of Water Resources and University of California, Davis to simulate weather variables including reference ET (ET_o), crop ET (ET_c), effective rainfall, and ETAW. ETAW is a seasonal estimate of the water requirement for ET of a crop minus any water supplied by effective rainfall and needed to determine consumptive use requirements. Since all calculations for ETAW and effective rainfall are done on a daily basis, estimate of ETAW is greatly improved compared with previous ET methods. The actual water requirement is estimated by dividing by the application efficiency. The use of the widely adopted Penman-Monteith equation for reference evapotranspiration (ET_o, the potential amount of evaporation and transpiration that a well-watered reference plant or crop can have) and improved crop coefficients for estimating crop evapotranspiration is used to improve the ETAW accuracy (Orang et al. 2003).

The Consumptive Use Program (CUP) was developed to improve estimates of crop coefficient (K_c) and crop evapotranspiration (ET_c) values to help growers and water agencies. The daily Penman-Monteith equation was used in the CUP to estimate reference evapotranspiration (ET_o) from mean monthly values for solar radiation, maximum and minimum air temperature and dew point temperature, and wind speed. Since CUP was designed to account for factors affecting Kc that are generally ignored in other water requirement programs, it provides estimates of near bare soil evaporation during initial growth of crops based on ETo rates and irrigation or rainfall frequency. One improvement is to account for the influence of rainfall and/or irrigation frequency on K_c and ET_c during initial growth. For tree crops, it is important to account for cover crops, which has not been done in the past. Another improvement is to compute and apply all ET_o and K_c values on a daily basis to determine crop water requirements. The user-friendly Excel™ program, CUP, was developed to improve long-term estimates that account for rainfall, cover crop, and immaturity effects with new information on midseason K_c values and bare soil evaporation (Orang et al. 2003).

7.3.3 Colorado

According to USGS (2004), there were 3.4 million irrigated acres in Colorado in 2000 with an estimated use of 12.82 maf of water. The irrigated acreage, crop pattern and climate data are used to estimate the current and future water use for irrigation. Colorado Water Conservation Board characterizes (CWCB, 2003) eight major basin regions for agricultural water use. These regions are also divided into two categories, regions with existing Colorado Decision Support System (CDSS) data and ones without CDSS.

For regions with existing CDSS data, the monthly irrigation water requirement (IWR) is calculated with the help of climate data of State of Colorado's Consumptive Use (StateCU) Model. The calculation of IWR is based on the modified Blaney-Criddle and the Penman-Montieth method. StateCU Model estimates the irrigation water requirement as potential evapotranspiration minus effective precipitation (CWCB, 2003). However, the wide application of StateCU method in these regions is restricted by the lack of adequate climate data.

The main concern in regions without CDSS data is to estimate the irrigated acreage and crop distribution (CWCB, 2003). CWCB is developing statewide climate dataset as a part of CDSS data, which will be used to measure the unit-crop use efficiency. The unit-crop use efficiency is the irrigation water requirement for a unit area of a single crop. This value can be multiplied by the total acreage of a crop to determine the irrigation water requirement of the total acres of the crop (CWCB, 2003).

The procedure to estimate IWR through StateCU model is not applicable without available climate data. Therefore, the amount of water applied per unit resulting from the historic diversions and groundwater pumping will be compared with the unit-crop use efficiency for the expected IWR and consumptive crop use amount (CWCB, 2003).

For the projection of irrigation use in 2030, CWCB assumed that the irrigated acreage in 2030 would remain constant and would be the same as the current irrigated acreage and the existing CDSS data are used to calculate the total expected crop irrigation water use. If there are changes in the irrigated acreage, the modified unit-crop use efficiency is calculated by comparing total water requirement and total diversion from water source. This value will be multiplied by the new irrigated acreage to estimate the total future irrigation use (CWCB, 2003).

The State of Colorado's Consumptive Use Model is used to calculate the consumptive use of crop and non-crop regions in Colorado. The modified Blaney-Criddle and the original Blaney-Criddle consumptive use methods are used for calculating the irrigation water use. The level of analysis that the StateCU model provides is presented below.

- Crop irrigation water requirement by structure (monthly or daily)
- Water supply limited crop consumptive use by structure (monthly)
- Water supply limited crop consumptive use by structure and priority (monthly)
- Depletion by structure and priority (monthly)
- Other “non-irrigation” consumptive uses (monthly)
- Consumptive uses and losses report

The StateCU Model estimates crop consumptive water use through structures (with the factors such as location, associated climate stations, crop types, and acreage). While regions that have existing structure dataset run analysis with this model, the additional dataset works are necessary to run adequate analysis in the model.

7.3.4 Idaho

There were 3.75 million irrigated acres in Idaho in 2000. Irrigation water use was estimated at 19.17 maf out of which 15.0 maf came from surface water and 4.17 maf from groundwater sources. For estimating water consumptive use on a statewide basis for Idaho, ET estimation was based on the Blaney-Criddle equation (Blaney and Criddle, 1950) using as input, irrigated acreage, weather, and crop-specific data. Later, the estimation was improved by using the FAO-modified Blaney-Criddle method due to its accuracy and responsiveness of the equation and the primary data requirement of air temperature. The grass-based method was converted into an alfalfa-reference method by multiplying conversion ratios using Kimberly lysimeter data and the Kimberly Penman equation. These ratios were found to be transferable to other Idaho sites.

The estimation of ET with data of the weather station was severely limited by the insufficient number of stations. For further improvement in the estimation process, the University of Idaho (UI) and IDWR developed a water-resource application through their cooperative project for mapping ET called SEBAL (Allen et al. 1996). The Idaho Department of Water Resources (IDWR) adopted remote sensing and GIS tools to estimate ET. The results obtained by these tools were used as inputs to the ET equations (Allen et al. 1996).

The Surface Energy Balance Algorithm for Land (SEBAL) is an image-processing model comprised of twenty-five computational steps that calculate ET and other energy exchanges at the earth’s surface using digital image data collected by Landsat or other remote-sensing satellites measuring visible, near infrared and thermal infrared radiation (Allen et al. 1996). In SEBAL, ET is computed as a component of the energy balance on a pixel-by-pixel basis.

The accurate prediction of past, current and future ET with SEBAL enhanced the ability to maintain water resources and provided valuable information for calculating complete water balances for the Bear River Basin and for calibrating and operating ground-water flow models (IDWR, 2000). SEBAL also showed the ability to estimate daily ET application accurately. The application of SEBAL does not require intensive ground, meteorological or land use information (Bastiaanssen et al. 1998). As SEBAL has been copyrighted and commercialized, the academic development of METRIC has emerged. The METRIC (Mapping Evapotranspiration with High Resolution and Internalized Calibration) configuration does require ground based weather stations to determine the reference crop ET, primarily for alfalfa, to index the remote sensing imagery (Allen, 2003).

One of the objectives of this application of SEBAL is to predict the ET fluxes from irrigated areas of the Bear River basin of Idaho through comparison between SEBAL and lysimeter measurements of ET. The Idaho portion of the Bear River Basin had three lysimeters from which the ET values were derived. Because ET values from lysimeters were subject to some random error that varied from reading to reading, ET values were averaged to reduce the random error components and uncertainties of the ET measurements (IDWR, 2000). Through the analysis of ET value from three lysimeters using SEBAL, shortcomings in the data were identified and confirmed. SEBAL provided an independent means to identify and confirm lysimeter ET data (Allen et al. 1996).

7.3.5 Kansas

In Kansas, irrigation is the largest sector of water use and takes into account about 87 percent of the total annual non power-related water withdrawals. In 1995, the source of more than 90 percent of water used for irrigation was groundwater (Kansas Water Office and Kansas Department of Agriculture, 1998). There were approximately 30,000 points of diversion, including wells, streams, and canals. The regions for the largest scale irrigation are located on the Upper Arkansas and Cimarron Basins because the underlying Ogallala aquifer has the greatest aquifer saturated thickness (Solley et al. 1993).

As a part of the Kansas water plan, the Kansas Water Authority approved the assessment of high irrigation water use in October 1998. The objectives of this assessment are to measure potentially inefficient irrigation water usage and finally reduce the "high irrigation use", or an amount of water that exceeds the "reasonable" irrigation level of applied water for a specific area by 2010 (Kansas Water Office, 2002).

There are two ways to measure "high irrigation use". One is to measure the number of points of diversions and the amount of water applied in acre-feet per acre (AF/A). The other is to identify the number of irrigation water rights for which the reported water use exceeds the annual authorized allocation under their respective water right permits. Regional AF/A standards were used to decide appropriate water for irrigation use. Standards for eastern Kansas, central Kansas and western Kansas were 1.0, 1.5, and 2.0 AF/A, respectively (KWO-DWR, 1998-1999).

The new county-based standards adopted by Kansas Department of Agriculture in September 2000 are the maximum amounts that can be authorized for a new irrigation water right permit. These values will be used as the benchmark for amounts considered reasonable for irrigation. With the new county-based values, it is assumed that the typical annual water use would be less than these standards except during the very dry season.

In the assessment data set, all the reported water data were obtained from the KDA-DWR's Water Right Information System. In order to compare reported AF/A to new county based values, this data set counted only areas which reported both the amount of water diverted and the number of acres irrigated during the growing season. Also, monthly rainfall was obtained from Hydrodata software of Hydrosphere Data Products Inc for the comparison reason. The time period used for this assessment was 1991 – 1999 (KWO, 2002). Three data parameters were used in this assessment. First, the total number of irrigation points of diversion that reported higher acre-foot per acre than the county-based acre-foot per acre standards. Second, the total amount of irrigation water reported used over the county-based acre-foot per acre standards, and third, the number of irrigation water rights that appear to use water in excess of their respective authorized quantities (KWO, 2003).

7.3.6 Nebraska

The irrigated acres in 2000 in Nebraska were 7.82 million. Agricultural water use during the 2000 crop growth season was estimated to be 9.86 maf. Groundwater formed 84 percent of all irrigation water use. Agricultural water use is calculated with data from many sources. The sources of the irrigated acreage of crops include state and federal data from the Census of Agriculture and National Agricultural Statistics Service of United States Department of Agriculture.

According to the amount of water used, four categories of crops were developed: high water consumptive crops, low water consumptive crops, hay and small grains (State of Nebraska, 1998). In order to estimate crop water requirements for the four representative categories, potential evapotranspiration (PET) and precipitation data were used. PET was calculated with data from a network of automated weather stations established by the University of Nebraska. Each station measured and recorded weather information such as the air temperature, relative humidity, incoming radiation, and wind speed. Recorded weather data in each station were collected by a computer in the University of Nebraska. The relationship between PET and crop ET during crop growth has been examined and ET for each crop was estimated (University of Nebraska Cooperative Extension, 1996).

Crop irrigation requirement was also calculated for the four categories at all stations to calculate the irrigation use. Because of different soil infiltration conditions, the irrigation use was obtained considering actual amount of water delivered (Nebraska Agricultural Statistics Service, 1995). County irrigation use for each crop category was calculated from the crop irrigation use, the percentages, and the efficiency of each method (Steele, 1988).

Crop water use per county consisted of the use by sprinkler system and the use of other water application methods. The crop water use by sprinkler system was equal to the irrigation use calculated with crop irrigation requirement. The crop water use by other water application method was estimated with the crop irrigation requirement and the efficiency loss due to the inefficient application method. Conveyance loss from canals was also calculated by subtracting district use from the adjusted diversion that considered several factors like losses in other states, concurrent use for power and recreation, and reservoir losses. Conveyance losses were allocated to counties in proportion to the length of canal in them (State of Nebraska, 1998).

7.3.7 New Mexico

In the Socorro-Sierra County Water District, a large acreage of grapes in Socorro county are irrigated primarily with surface water while a smaller acreage in Socorro County are irrigated with groundwater (New Mexico Water Planning, 2002). A crop water use model was adopted to estimate agricultural water use because the amounts for both diversions and consumptive purposes are not directly measured (Jensen et al. 1990).

The Blaney-Criddle model (Blaney and Criddle, 1950) was used to calculate the crop consumptive water use that primarily makes the projection of agricultural water use in the planning regions. Total consumptive water use is calculated in the model with such data as degrees Fahrenheit, monthly percentage of annual daylight hours based on the latitude of the area under study, seasonal consumptive use coefficients, and length of growing season (New Mexico Water Planning, 2002).

U.S. Bureau of Reclamation (1997) defined effective rainfall as a percentage of the total monthly rainfall, and for each inch increment in rainfall there is a corresponding decrease in the percentage of effective rainfall. Then, the total water consumptive use by crop is obtained multiplying the consumptive use estimate by the irrigated acreage of crop. However, the total crop water use does not consider any incidental depletions or irrigation efficiency factors (Blaney and Hanson, 1965).

The data for irrigated acreage was obtained from the New Mexico Agricultural Statistics Service (NMASS, 1995, 1996, 1997, and 1998) and the USDA Census of Agriculture (USDA, 1999). However, the USDA and NMASS data sets indicate that irrigated acreages and cropping quantities vary from year to year. The crop consumptive use was evaluated to address this variability. For example, when there are discrepancies between USDA and NMASS estimates, the larger value was used to calculate the crop consumptive water use. Also, some components were added to explain the difference especially when the total acres for all crops did not equal the total acres of irrigated land.

Water use estimates in this region showed a large degree of year-to-year variability in water use by irrigated agriculture. Wilson et al. (2003) found that the strongest correlation to water use was with precipitation. Additional survey was made among interest groups such as the irrigation districts, acequia associations, and ditch associations in the planning region to evaluate the crop consumptive water use.

7.3.8 Oklahoma

Agricultural water use forecasts were developed in cooperation with the Bureau of Reclamations Oklahoma City Project Office under the authority of Technical Assistance to States Program. It is very difficult to project an exact water use in the future for a specific year because of the changes in affecting factors such as weather, socioeconomic and politic forces. However, it is necessary to adopt plausible guidelines to be used in planning for future projected irrigation water use.

Oklahoma used the potential irrigated acreage and the general irrigation rate to project the future irrigation water use. According to the Oklahoma Water Resource Board (OWRB), the potential irrigated acreage includes not only acres currently being irrigated, but also those lands that have been irrigated or are accessible to developed irrigation systems. The potential irrigated acre by county is based on the biennial survey of the Oklahoma State University, which includes the number of actual irrigated acres and acres potentially available for irrigation.

The general irrigation rate adopted by the Planning Committee considers climate, geology, soil and surface and groundwater availability. The rate assumed that cultivated lands in the east require one acre-foot of irrigation water per acre of farmed land, increased need of 1.5 acre-feet in the mid-region counties and 2 acre-feet in the western counties (OWRB, 1999).

The total projected water use of each region was calculated by multiplying the potential irrigated acres by the general irrigation rate of the region mentioned above. The use of the potential irrigated acres instead of actual irrigated acres makes the projected water use for irrigated acreage higher than actually reported. Results under methodologies and assumption, compared with an actual estimate in 1990 are higher than the total results in each water planning region. However, they are much less than those projected in the 1980 Oklahoma Comprehensive Water Plan.

7.3.9 Texas

In Texas, the acreage of an individual crop under irrigation historically had been estimated through comprehensive irrigation surveys. The water use for each crop had been estimated in the past by multiplying irrigated acreage and the water requirement of each crop calculated by the USDA-Natural Resource Conservation Service (NRCS). The ET based water application for individual crops has also been in use by the Texas Water Development Board (TWDB) for comparing the NRCS estimates of irrigation applications. Total water use for both county and region is calculated by adding individual crop irrigation water uses. The conveyance loss for crops using surface water determines the total water use (TWDB, 2003).

During the first round of planning, the TWDB provided the baseline agricultural water use based on the amount of irrigated acres in each region with the opportunity to revise both the TWDB baseline and projected use for regions. Four out of sixteen regions used the TWDB projections. The regions with significant portion of agricultural water use include Regions A, F, L, M, and O.

The ET methodology has been used for developing an irrigation water use model for Texas Panhandle Water Planning Area (Region A) by research and extension faculty at the Texas A&M University Agricultural Research and Extension Center at Amarillo. This group, hereafter termed the Texas A&M-Amarillo (TAMA) group, utilized calibrated crop ET values from the Texas High Plains Evapotranspiration (TXHPET) network in estimating irrigation water use (crop evapotranspiration) for the irrigated crops of corn, cotton, grain sorghum, hay, pasture and other, peanuts, soybeans and wheat. (Similar type meteorological networks exist among other irrigated crop acres throughout the state). Computations were based on crop ET, daily and monthly effective rainfall, percent of potential ET applied in field practice, soil profile moisture utilized by the crop(s) during the growing season, and crop acreage of the respective crop(s). The results of this methodology and computation resulted in excellent agreement for the baseline year of 1997 used in the Region A water-planning document. Irrigation use results indicated agreement to within 97 percent of the measured well decline within the largest regional water districts. Only limited data sets existed for other temporal periods and prevented additional assessment. The method appeared to be significantly better than the prior survey based approach. This methodology has been successfully employed in a subsequent project to estimate irrigation use for the Panhandle and the Southern High Plains and parts of New Mexico dealing with the Ogallala Aquifer. Currently, the methodology is being refined/improved in Region A under Senate Bill 2.

Region F revised TWDB projections and developed different scenarios using historical data and trends. The selected scenario was based on the maximum irrigation volume used in the region between 1990 and 1997. Projections for the future were reduced by one percent per decade taking into consideration the water conservation amounts due to technological improvements.

A crop growth model approach was used to estimate water savings by conveyance and in-field conservation measures for the Lower Rio Grande Valley (LRGV) irrigation districts on a USDA-CSREES project by the TAES-Temple group. Calibration of the model was limited to historic evapotranspiration estimates by major crop types, and reported conveyances losses. Ideally, a scientifically defendable validation data set would be required. The model-based approach has provided water planners in LRGV Region-M to explore water savings under alternative conservation practices (Santhi et al. 2004).

Llano Estacado Regional Water Planning Group in Region O did not use the TWDB irrigation projections with the assumption that the TWDB methodology used too many dry years, and thus irrigation water use was inflated. Region O projected irrigation water use using "average" precipitation conditions, rather than "below average" conditions. The projected declining trend in irrigation water use in Region O assumes the use of efficient irrigation technology and other economic factors that affect irrigated agriculture profitability.

For the next State Water Plan Projection (2000-2060), the cropping distribution for the 60-year planning period needs to be determined by the revised irrigated acreage developed by the 2000 Survey and the 2002 State Water Plan (TWDB, 2003). The irrigated acreages will be affected by known factors like water depletion and land conversion to non-farm use. The rate of changes in projected water use is largely the same because the 2002 State Water Plan takes into account the efficiency of water application and cropland water losses.

Changes in irrigated acreage and conveyance loss of surface water also need consideration for revision during the development of the next State Water Plan. Although the loss of water through conveyance is considerable, the 2002 State Water Plan and 2006 Regional Water Plan projections assume that no significant capital improvements of canals will be made and no reduction of canal losses will be built in to the projections (TWDB, 2003). The Water Planning Group for counties with surface irrigation will need to use assumed delivery loss, not on-farm use.

The accurate cropping pattern and water application amount per crop are the main factors that must be considered for reliable projection of water use. Remote sensing study of irrigated acreage and metering crop water application may generate better projections of irrigation water use for specific areas.

8.0 DEVELOPMENT OF AN AGRICULTURAL WATER USE ESTIMATING METHODOLOGY

Texas A&M-Amarillo Evapotranspiration Network Based Model

8.1 General Description

The continued use of a survey-based irrigation method from an earlier assessment study was shown to be inadequate in accurately estimating irrigation water use within the Texas High Plains region (Amosson et al. 1999). Using the past methodology, large differences existed between the Texas Water Development Board (TWDB) estimates and the measured drawdown in wells, as recorded by local underground water districts. Thus, alternatives were investigated and analyzed for potential use throughout the state. The following discusses the use of a proposed, alternate, meteorologically based, evapotranspiration (ET) network method to more accurately estimate irrigation water for use within the irrigated regions of Texas.

The proposed methodology utilizes calibrated crop ET values from a representative ET network in estimating reference irrigation water use for the various irrigated crops in a water-planning region. These crops can include but are not limited to corn, cotton, grain sorghum, hay, pasture, peanuts, soybeans, wheat, sunflowers, grasses and vegetables. A standard crop list within a region could coincide with crops designated as such by the new crop reporting list used by the USDA's - Farm Service Agency (FSA). Water use computations in the new methodology are based on the respective crop ET, effective monthly rainfall, percent of potential ET applied in field practice to a particular crop, which includes all pumping, conveyance and application losses (note that the percentage can be more or less than the reference value), soil profile moisture utilized by each of the crop(s) during the growing season and FSA county crop acreage for the respective crop(s). Prior computational results of this methodology produced excellent agreement in Region A of Texas. Calculated irrigation use indicated agreement to within 97 percent of the measured well decline within one of the largest regional water districts. Although limited data sets existed in the analysis, the method appears to be significantly better in terms of accuracy and representation than those using a survey-based approach.

8.2 Methodology

The approach used with this methodology is essentially one with a water balance type derivation. The proposed methodology utilizes a crop categorized, ET reference based, crop water use computation (Marek et al. 2003). An earlier effort to estimate historical irrigation requirements using a similar, rudimentary approach with much less accurate ET data and soil balance equation can be found in Heimes and Luckey (1982). As with most endeavors of this nature, the lack of representative and accurate data typically is a limiting concern, and it can certainly be in a state as large and diverse as Texas. Representative data per county are essential for the method to be accurate. County data are needed regarding crop acreage, water used by crop type, monthly rainfall, soil water holding capacity and reference crop evapotranspiration (ETc). Reported acreage differences and sources have been a concern regarding prior modeling efforts (Marek et al. 1999). There now appears to be a representative and uniform reporting solution available regarding the acreage data needed for each crop within a county. Access to this "standardized" reporting information of crop acreages is available through the USDA-Farm Service Agency (FSA) and is based upon the acreage producers' report to the FSA for their crop payment(s). The Texas A&M–Amarillo model (denoted as TAMA; referred to in an earlier section as an ET based model) developed previously (Amosson et al. 1999) promotes the use of the FSA acreage data, data regarding crop ET, a term called a "grower factor" (which represents the fraction of crop ET pumped and includes the percent of crop ET generally applied by producers per county using all irrigation type systems and efficiencies, including conveyance losses), the effective rainfall within a growing season, and the soil water holding capacity in inches per crop per acre per growing season. All of these data are required on a county-by-county basis for the model. The acreage used in the model is the acreage of the crop planted, not harvested. The grower factor could be synonymously labeled as a "pumpage factor" in some regions of Texas. However, the distinction is noted here due to the fact that for surface water allocations used throughout the southern regions of Texas, it would appear inappropriate to designate these allocations as "pumped" groundwater(s).

The TAMA model is based on the crop water use equation as follows (with the suggested units per parameter):

$$ET_C * P_T = IRR_C + ER + SSM_D \quad \textbf{(1)}$$

where:

ET_C = Crop evapotranspiration (or crop water use) for maximum production potential (in.),
P_T = Grower factor which represents a fraction of the crop evapotranspiration pumped on a crops' seasonal basis and includes all irrigation systems and associated efficiencies (can be more or less than 1.0 reference crop ET, ETc),
IRR_C = Irrigation applied on a seasonal basis to a crop (in.),
ER = Effective rainfall computed from seasonal rainfall occurring during the crop season (in.), and
SSM_D = Seasonal soil moisture depletion used in crop production which is extracted from the soil profile during the respective growing season (in.).

Rearranging the equation and solving for IRR_C yields:

$$IRR_C = ET_C * P_T - ER - SSM_D \quad \textbf{(2)}$$

The summary equation for all categorized crops grown per county is:

$$IRR_{CTY} = \sum_{1}^{n} (IRR_C / 12 * A_C) \quad \textbf{(3)}$$

where:

n = Number of categorized crops of interest per county, and

IRR_{CTY} = Total quantity of irrigation volume applied (or pumped) to the crops grown within a county in a given year or season, (ac-ft), and

A_C = Acreage of crop c in a given county.

Similarly, the summary equation for the counties within a region is:

$$IRR_{REG} = \sum_{1}^{n} IRR_{CTY} \quad \textbf{(4)}$$

where:

IRR_{REG} = Total quantity of irrigation volume applied (or pumped) to crops grown within a region in a given year or crop season, (ac-ft).

In the case above, the summary equation was designated for a region; however, the equation could be designated to represent any area of interest which could be a water district, watershed basin, state agency district, state designated region, river basin, state, etc).

8.3 Advantages

The advantages of using a TAMA type model are outlined as follows:

1) The foremost advantage of using an ET network based methodology is with the inherent accuracy and representation associated with the relatively simple type of model used, in this case, as depicted by the TAMA model.
2) County-by-county acreage representation and accuracy is based on the USDA-FSA certified crop acreage, which is soon to be readily available on the web.
3) A site-specific set of representative rainfall sites per county can be easily used with the model or use of quadrangle type monthly rainfall data can be utilized to represent a more overall, average condition, if desired. In the event, multiple quadrangles overlap a specific county or area of interest, a proportional weighting matrix can be easily developed of the multiple quadrangle values to determine an appropriate weighted, representative value for the county(s) of interest. Additionally, a scenario of analysis regarding drought year rainfall levels can be analyzed through the use of the method.
4) Crop reference ET values corresponding to actual conditions experienced can be determined from accurate meteorological data and scientifically based computational methods that represent the most advanced irrigation and crop science efforts to date. A specific year, average or long-term value of ET can also be easily used and evaluated for "what if" scenarios to analyze the respective, resultant, irrigation use per county or area of interest. Sequencing of specific ET values such as drought year values can also be arranged to determine the most "loading" use expected on the supply side of the water resource. The model can also be used to evaluate proportional patterning of rainfall influence within a region or district. These could include probability level analysis of various event patterns, for instance. This type of scenario analysis is "virtually limitless" in terms of ET scenarios that could be evaluated.

5) The soils data required for the TAMA type model is available currently on the updated USDA-NRCS web site. The soil water holding capacity of the respective soils at the farm level basis can be compiled on a foot-by-foot of depth basis applicable with respect to the rooting depth of the respective crop. Assessing the moisture level at the beginning and at the end of the crop season yields the amount of profiled water used during the production season attributable to use by a particular crop. This assessment is then used in the TAMA type model on a county-by-county basis per crop per year.
6) Crop production periods are keyed to individual and representative crop planting and growing seasons, which can be adjusted for the differing regions in the state.
7) Use of the methodology requires that average type data from multiple, individual farms be obtained and used with regards to actual producer water use, thereby representing actual water use on a county basis. An adequate number of producers are required to determine a representative sample indicative of the producer population within the respective county(s). It appears TCE water demonstration and similar related water district personnel are in a unique position to assist in the acquisition of this type data for less cost that would be required to derive the entire effort from a "ground up" type position.
8) Derivation of average value(s) of water use applied per acre per county, water district, region or area of interest can be easily obtained through summarization and averaging methods. Comparison of such data can be utilized for production efficiency evaluations or regional strategy evaluations regarding crop type and selection.
9) The approach does not depend on satellites or satellite based imagery technologies. These technologies have experienced problems regarding operational stability and re-establishment of non-functioning units. Imagery assessment and interpolation software technologies may also become copyrighted and their use restricted from a public use viewpoint, as recently experienced with some software developments.
10) With the TAMA type model, mean county irrigated crop yields can be used to index county water use.

8.4 Disadvantages

There is little viewed downside to using a TAMA type model in comparison to the potential benefits. The disadvantages of using such a model, as with other models, are in regards to the required data inputs and are outlined as follows:

1) Acreage data per crop is required on a per county basis to have adequate crop distribution representation within a desired unit of interest.
2) The method requires the use of a representative ET based network located throughout the irrigated regions of the state. An alternative to this network establishment is to use a less accurate, generalized, average ET values (i.e.-isolines), of which then only average, not actual, ET conditions can be computed and which may or may not correspond to local water usage records.

3) The TAMA model requires representative grower factor data acquired from individual farms and fields throughout the respective irrigated regions in Texas.

4) The TAMA model requires an assessment of soil profile water use for each crop within a region at the beginning and end of each respective crop-growing season.

8.5 Feasibility of Implementing Methodology Statewide

The feasibility of implementing a statewide TAMA type model methodology is viewed as being readily achievable and being relatively inexpensive given the overall value of the data to not only the total Texas water planning effort but also to the other state related data determinations that would be available to associated agencies and departments. An example of these could include determinations such as regional drought levels, drought triggering, numerous environmental related complaint support data, and insurance related damage claims with extensiveness detailed for individual crops.

Since the majority of the feasibility is again associated with data representation and acquisition, one solution to implementing the methodology is the establishment of individual ET networks throughout the state's irrigated regions. An alternative, possibly more feasible approach may be to utilize and support the appropriate, existing university based meteorological systems that conform to the QA/QC protocol requirements mentioned earlier. A supporting and ancillary approach to this implementation would be to utilize and integrate the existing states and federal agencies' network of meteorological stations into the data acquisition effort once they are converted or upgraded accordingly to the required protocols and specifications as previously mentioned and discussed in more detail below. Since these scenarios are likely to entail significant negotiations with the aforementioned agencies and other private groups, it is beyond the scope of this report to address the potentials associated with utilizing and coordinating such partnering and cooperative efforts.

8.6 Capabilities of Interfacing with GAM

The potential to integrate the ET based data into the GAM model is promising. The ET data would need to be pre-processed and integrated into the GAM model module regarding ET inputs. This integration is viewed as a relatively simple, low cost effort, although a substantial programming effort will be required to complete the conversion task. Ultimately, the ET based module integration is logically necessary, assuming that the ET concept is fully accepted and approved by the state for use in the future. It should be noted that as version differences in GAM models exist, modular preprocessor integrations would also be version specific.

8.7 Data Requirements Associated with the Methodology

Data that are applicable and representative of irrigation practice within the field are essential to the accuracy and validity of the TAMA type model concept. Data requirements of the proposed methodology include FSA County and crop data as discussed above. In addition, an estimate of the potential crop ET derived from a representative ET network, an applicable "grower factor" associated with each crop that is derived from field assessments, monthly rainfall levels and the soil moisture used by the crop during their respective growing season are needed.

Crop ET data can be obtained and utilized from a conforming, high quality control (QA/QC) type ET network [i.e. –The North Plains Evapotranspiration Network (NPET); Howell, 1998, Marek et al. 1998; South Plains ET Network, Porter, 2003, Porter 2004). Siting of the respective stations within a network is to be conducted according to established scientific methods to adequately represent the agricultural environment targeted. Both of these networks uses a modified Penman-Monteith type equation for calculation of reference evapotranspiration, ETo (sometimes referred to as potential evapotranspiration (PET)) computed from individual meteorological station data. ETos represents the water use of a well-watered grass. This grass is used as a reference crop to which other crops are field related through the use of a crop coefficient. The stations of both of the above mentioned networks have been upgraded recently along with all of their data sets (including past sets) to the recently drafted ASCE Standardized Reference Evapotranspiration Equation for Agriculture Crops (Walter et al. 2002-see Appendix A). This updated ETos reference equation allows for the use of a well-watered grass reference instead of only an alfalfa-based reference ETor. The applicable data computed from this new equation are more representative in most of Texas due to the nature of the majority of the irrigated agricultural production being located in a semiarid environment as opposed to that previously used and related to an alfalfa reference. The Texas High Plains region, which encompasses over 73 percent of Texas' irrigated acreage, is particularly more reflective of the grass reference in the equation since all ET stations are located on native grass.

ET data will specifically be required for each county within each region. Since not all counties will have a meteorological station within the county per se, a correlation matrix attributing each meteorological station's respective percentage of influence due to elevation, longitude and latitude considering known cropping differences of certain counties can be used to compute each county's relative, representative ET value. An example correlation matrix indicating attribution used in the computations for north Texas is presented in Table 8.1.

Table 8.1 Selected portion of TXHPET meteorological station correlation (proportioning) matrix identifying station attribution used in computing county crop ET values.

TXHPET Met. Station	Dallam	Hartley	Roberts	Sherman
Dalhart	1.00	0.40	-	0.20
Dimmitt	-	-	-	-
Etter	-	0.40	-	0.60
JBF	-	0.20	-	-
Morse	-	-	0.33	0.20
Perryton	-	-	0.33	-
Wellington	-	-	-	-
White Deer	-	-	0.34	-

Another significant data requirement is that of effective rainfall. The computational procedure suggested is based upon a modified procedure of the USDA Natural Resource

Conservation Service (NRCS) method (National Engineering Handbook, 1993) for computing effective rainfall values. One can utilize long-term monthly quad rainfall data from the TWDB to compute the respective seasonal crop rainfall for each crop season to represent a countywide average value. This procedure has yielded acceptable results given the spatial accuracy and applicable assumptions of hydrologic data (Amosson et al. 1999). One could also use a single point source value (single rain gage), but a bias for countywide representation will typically exist when doing so.

The respective crop season and associated effective rainfall seasons will also be required for water use computation within the model. An example of these seasons used in Region A per crop is in Table 8.2. For other regions of the state, the crop mix will be different, including those of vegetables, and the season(s) will be shorter or longer for some crops.

Table 8.2 Seasonal periods and crop categories used in effective rainfall computations.

Crop	Growing Season Used in Crop ET Computations	Season Used in Effective Rainfall (ER) Computations	Number of Months Used in ER Calculations
Corn	April 15 - October 15	April 15- August 15	4
Cotton	May 15-October 15	May 15-October 15	5
Grain Sorghum	May 15-October 15	May 15-October 15	5
Hay	April 1-November 1	April 1-November 1	7
Pasture	April 1-November 1	April 1-November 1	7
Peanuts	May 1-November 1	May 1-November 1	6
Soybeans	June 1-November 1	June 1-November 1	5
Wheat	October 1-July 1	October 1-July 1	9

The next variable required for the model computations is the grower factor that represents the applied amount of irrigation water by producers in field practice to the respective crops within an area of interest. These data can be obtained from TCE type demonstration efforts (or equivalent source) along with water meter data obtained through well monitoring on a seasonal crop basis. Water districts may also obtain and harbor some of this type data. Past monitoring results from a north Texas project gathered data based on specific crop irrigation and production field demonstrations with 46 cooperating growers in 13 Panhandle counties (New, 1998) is illustrated in Table 8.3. These irrigated fields were monitored in terms of water applied (pumped volumes) and the associated yields. This application information is used in equation 2. Differential soil moisture is typically computed to be available at a percentage of the water holding capacity level available for crop production per respective crop. The water holding capacity of the soil profile is available from the NRCS digital soils data through their web site. Rooting depth per crop needs to be computed to determine a capacity for use during the respective growing season. The respective quantities of differential seasonal soil moisture used in some of the past computations for Region A are illustrated in Table 8.3.

Table 8.3 Average differential seasonal soil moisture and TXHPET crop ET used in computations per crop category in Region A.

Crop	Differential Seasonal Soil Moisture (SSM), (inches)	Percent of TXHPET Crop ET Applied by Producers
Corn	2.41	0.86
Cotton	4.22	0.91
Grain Sorghum	3.62	0.84
Hay	1.50	0.95
Pasture	2.50	0.80
Peanuts	2.20	1.35
Soybeans	3.11	0.91
Wheat	3.84	0.79

8.8 Estimate Costs to Develop and Maintain ET Methodology

The cost of developing and initiating the TAMA type methodology at the state level involves two efforts of which each entails personnel, equipment and programming costs. The first part has to do with the development of the appropriate methodology code for the model. The second has to do with the procurement and implementation of the respective field instrumentation hardware needed for inputs into the model.

8.8.1 Development of methodology multi-regional code:

Estimates are derived with the assumption that multi-region code can be programmed by state agency personnel for the respective regional model(s) outlined in equations 2 through 4. Subsequently, applicable input data pertaining to each regional model will be needed for accurate water use computations and summation(s) from the respective code. The respective regional models can be programmed into spreadsheet workbooks, as was done in the original development effort by the TAMA development group. This spreadsheet format and coding is viewed as the simplest programming method to implement the respective models for each region. However, due to the potentially extensive size of the respective regions (number of counties) and potential number of crops involved within a region or area of interest, multiple workbooks may be required for the differing regions. This is not necessarily viewed as a limitation or disadvantage of the workbook approach with the models.

While other programming languages could be used for the development process, few allow the open source type flexibility associated with full-scaled spreadsheet workbook programs. Changes to the respective models can be easier to make than with compiled codes given that ultra-high computational speed is not required for water planning purposes associated with the regional models. Furthermore, multiple and differing analysis scenarios can be easily attained with the spreadsheet format by copying and altering aspects of the workbook(s): as an example, to alter rainfall trends to assess drought sequences and impacts on the supply side of a supply resource. However, these type assessments create and involve relatively large spreadsheet workbooks, and thus the costs of adequate computer equipment of sufficient statute to handle the multiple spreadsheet code(s) and the required personnel programming expertise to develop the models with supporting matrices are estimated in Table 8.4. (The estimates are based upon state-of-the-art programming skills typically associated with advanced university caliber personnel). The cost estimate table assumes that the respective programming code can be developed in-house and does not address an outside-the-agency development or contract. Full model code development time is anticipated at 12 to 18 months, depending on the caliber of programming expertise available or attracted and these individuals understanding of the associated water methodology. Additionally, if ET values are to be computed by the agency from meteorological data, computation equations regarding the newly drafted standardized ET equation are needed (Walter et al. 2002). The latest revised edition of the equations can be found in Appendix A. Since the computations are complex and require an understanding of psychometrics, verification with established ET networks is encouraged to assure correct computation accuracy regarding ET values.

Table 8.4 Startup development costs† for TAMA type water use methodology.

Minimum Methodology Requirements	**Estimated Cost**
Project manager*	$ 124,800
Programming personnel*	$ 138,200
Related computer equipment and software	$ 30,000
Travel	$ 7,000
State Total	**$ 300,000**

* includes benefits at 28% of budgeted salary level, but does not include insurances and other fringe costs.
† estimated cost based on an 18 month time-frame.

The methodology personnel and computer related maintenance requirement are viewed as essential, but not overwhelming since development and initiation efforts are viewed as significantly more involved as compared with the maintenance mode. Agency methodology maintenance costs are estimated in Table 8.5. Costs are reduced as compared with that of the development phase in that it is assumed that the project manager can assume responsibility for more than one project at the time initial development is complete and has a thorough understanding of what the models accomplished. Similarly, support personnel can be reduced to a single individual. However, this raises concern regarding continuity of ability to run the model should the individual leave unexpectedly.

Table 8.5 State agency annual maintenance costs for water use methodology model.

Minimum Methodology Requirements	**Estimated Cost**
Project manager (1/2 time)*	$ 41,600
Programming personnel (1.0 FTE) *	$ 50,688
Related computer equipment and software	$ 14,600
Travel	$ 3,000
State Total	**$ 109,888**

* includes benefits at 28% of budgeted salary level, but does not include insurances and other fringe costs.

9.0 CROP GROWTH MODELING FOR IRRIGATION WATER USE ESTIMATION IN TEXAS

9.1 Introduction

Crop growth models capture the biophysical processes that occur *before, during, and after* crop growth in agricultural fields. The process equations governing the consumptive water use of crops are determined from the combined simulation of field hydrology (water infiltration through the soil profile, runoff, percolation) with the evaporation from the soil transpiration by crops. Equations and their parameters are determined by curve fitting or observations from prior field experiments. Plant growth is dynamically estimated based on the crop development (phenology) and photosynthesis and respiration. Models vary in the detail to which they concern the various aspects of leaf or plant growth and/or development, as well as the detail involved in crop water uptake and hydrology. The EPIC model for instance is a generic model that can be used to simulate various crop species and varieties; the CERES-Maize is concerned with details of corn development and growth involving silking, kernel number, kernel weight, grains per ear, etc. Infiltration is also covered to varying details in the models, from simple tipping bucket routines to numerical solution of partial differential equations (Richard's equation). Likewise, the spatial extent of the models can vary from a single "representative" plant to a distributed or scaled-landscape version.

The models were written to address economic, agronomic and environmental issues such as optimum crop yield and soil loss as a function of management practice. The authors of the models were researchers from universities and Federal agricultural research agencies, i.e., USDA-ARS. The models generally have a broad user community in mind. The crop models are comprehensive in terms of accounting for water infiltration through the soil profile, evaporation loss from the soil, transpiration by plants, tillage practices, soil nutrient dynamics, and drainage management. The models, however, by their very nature, are an abstraction of actual plant and soil processes, and thus, a simplification of the atmosphere-plant-soil system. Since the crop growth models can be run continuously (on a daily time step), they can consistently and for whole years, budget for antecedent soil water storage in irrigated fields before, during, and after crop growth. Residual storage of water in the soil profile after harvest could impact the subsequent crop production. Since most of the crop growth models simulate the impact of management practices (tillage by implement, water application method), the output from the models can capture regional management variances. Although most plant or crop growth models include irrigation management as an option, few include detailed irrigation hydrology (e.g., subsurface drip irrigation or SDI, alternate row surface precision application like LEPA, low energy, precision application, or even known irrigation dynamics of surface irrigation like graded furrow or surge flow irrigation) or capture well the management constraints like pumping capacity (flow rate per unit land area) or inter- or intra-season well dynamics.

To illustrate the applicability of the crop growth model to water use estimation, several commonly used models were selected for evaluation (Table 9.1). The selected models were: CROPGRO (Boote et al. 1998), CERES (Jones and Kiniry, 1986), RZWQM (Farahani et al.

1999), and EPIC/CropMan (Sharpley and Williams, 1990). These models were selected since each of them was developed to either address a specific crop (such as CERES-Maize), or generic enough to address several crops (EPIC). These models use as basis for crop water use potential evapotranspiration (PET) or "reference evapotranspiration", computed from routine weather data; the RZWQM uses the sink term in Richard's equation to estimate plant water uptake. PET is estimated by several methods ranging from the Priestley-Taylor in CROPGRO to the Wallace-Shuttelworth form of a multi-layer Penman-Monteith equation in RZWQM. The realized evapotranspiration (or actual ET) is estimated from the PET and the leaf area index (LAI; unit area of one side of leaves per unit land area): the higher the LAI, the more the ET until LAI equals about 3.0 when ET approaches the PET rate. The models capture the root uptake rate by the crop by depth with weighting factors that can be specified to allow higher uptake in the shallow root zone than in the deep layers. Water infiltration through the soil profile in models such as CROPGRO and EPIC/CropMan is performed using a "tipping bucket" approach: water is kept in each soil layer between a lower limit (the wilting point) and higher limit (field capacity), and water flows from layer to layer when soil water exceeds field capacity. In a model such as the RZWQM model, detailed mathematical relationships using known soil physical properties simulate infiltration and vertical redistribution using formulas like the Green-Ampt equation.

The model predictions of crop yield are frequently compared against field measured crop yields (kg/ha). Often, when the predicted yields are reasonably matched with measured yields, the cumulative water use for the growing season also matches field measured soil water use. Table 9.1 provides examples from the literature in which soil-water uptake was compared with measured crop water uptake. These comparisons show that the simplified infiltration and uptake routines can be effectively employed as seen by the good agreement with soil water measurements. The table shows that models (other than RZWQM which may be the exception because the model's objective are focused on infiltration rather than crop uptake) can perform within 10 percent of observed water uptake rates. It is recommended that an additional 5 percent be used as a buffer to protect model performance against local variability and uncertainty in input data.

Table 9.1 Selected crop growth models, comparisons against measurements, and relevant water uptake routines.

MODELS	Field Testing	Water routines	References
CROPGRO Soybean (and legumes)	SW content under-predicted 0-60 cm depths 60-120 cm good predictions	- ET from Priestley-Taylor 1-D soil infiltration through profile (tipping bucket model) - Daily uptake but photosynthesis based on hourly time steps	Boote et al. (1998) Nielsen et al. (2002)
CERES-X x- Barley, wheat, Maize	Barley model soil-water within 4% RMSE of measured on fluvisols and chernozem soils Maize model tests in Kharagpur, India gave Coef. of determination (R^2) for measured SW 0-15,15-30,30-45,45-60,60-90cm respectively: 0.9,0.8,0.83,0.82, and 0.73 Maize model application in Rutigliano, Italy (semiarid Mediterranean climate) gave ET predictions within 8% of measured (from water balance via TDR probe)	- Tipping bucket/cascade infiltration in soil layers (infiltration using Field capacity/Wilting point) - Crop uptake a function of potential ET and LAI	Eitzinger et al.(2004) Jones and Kiniry(1986) Ben Nouna et al.(2000)
RZWQM	water use -12% I. corn, Eastern CO +60% I. Corn Central NE	- Green-Ampt infiltration - Wallace-Shuttelworth ET - Soil evaporation from Richard's equation - Root water uptake function of Nimah & Hanks	Farahani and DeCoursey (2000) Farahani et al. (1999)
EPIC/CropMan	7-9% relative error on Maize in Prosser, WA and Davis, CA	Tipping bucket infiltration potential water use function of LAI,PET Uptake reduced based on soil-water storage	Jara and Stockle (1999) Sharpley and Williams (1990)

1- ET = Soil-water evaporation + plant transpiration; 2-LAI = leaf are a cover above a 1 m^2 soil area, Leaf area index.; 3- RMSE = Root mean squared error

9.2 Crop Growth Simulation Methodology

9.2.1 Assumptions:

Crop modeling is built on a few simple set of assumptions as in any scientific methodology. An important assumption is that growing season changes occurring for an ensemble (population) of crops in mono-cultured fields can be represented by changes occurring to a single crop (or small group of plants) over a growing season. The same is also true for the variability of soil types. Soil properties in fields are selected at the soil series level and within soil series variability typically is ignored. The water uptake parameters such as water uptake volume by root length, rooting depth of plants, maximum leaf area and so on are either hardwired or changed by the model user. In general, model input data can be considered as aggregated (some representation of the average or "lumped" parameters or disaggregated and treated as independent or related small hydrologic elements as a distributed model).

9.3 Proposed Procedure:

Execution of the crop growth methodology will consist of the following steps:

Step 1: State soil survey for each county will be obtained and the soil textural classes (silt, clay, sand) percentages will be assessed to capture at least 60 percent of the county area. The state soil surveys are available from USDA-NRCS and online for the state at a nominal scale of 1:24,000.

Step 2: Intersect the county soil polygons with the Farm Services Administration (FSA) field maps. The FSA is digitizing all agricultural fields (tagged as irrigation vs. non-irrigated crops) covered by their insurance programs, and expects to complete digitization by end of 2004. Starting next crop year, the FSA will begin digitizing crop history at the field level (Personal communication, Bryan Crook, GIS Coordinator, Texas FSA, College Station). Prior years cropping history is available by tract number (compilation of several fields). The intersection GIS procedures will have to be performed in-house by FSA.

Step 3: Develop unique crop-soil associations to cover 60 percent of the county based on steps 1-2.

Step 4: Identify cropping and irrigation management practices by each county.

Step 5: Generate daily historical/real time climate from the Spatial Sciences Lab climate database (processed from satellite, NWS/NOAA, and Doppler radar corrections) for each crop-soil association/county

- 5.1: 4 km grid precipitation data
- 5.2: 24 km grid temperature data
- 5.3: 50 km (0.5 degree) grid wind, radiation, relative humidity data from NCEP/NOAA

Step 6: Run the CropMan/EPIC model by soil-crop association by county.

Step 7: Calibrate the crop yields from CropMan to county reported yield estimates by irrigated crop each year from the census surveys, or from the Texas Agricultural Statistics Service.

Step 8: Aggregate irrigated water use for the entire county based on step 6 runs.

Step 9: Multiply step 7 county water use by irrigation method (furrow, sub-surface etc.) by grower factors, which are the irrigation application efficiencies. The grower factors can be obtained from the TAES Amarillo field sites, or from standard application efficiencies by irrigation method.

Step 10 Display GIS maps, tables, and other formats on an interactive website.

Assuming 100 irrigated counties, and an upper limit of 8 soil types, 6 major irrigated crops, and 3 irrigation methods per county, 14,400 distinct computer runs will be required.

9.4 Advantages

Computer modeling of agricultural fields to estimate water uptake has the following advantages:

1) Cost to execute a modeling system to estimate crop water use is inexpensive relative to installation of soil-water, evaporation (lysimeter), and other hydrologic monitoring systems. Costs involve personnel (2-3 programmers, and crop/soil/agricultural engineers and scientists, estimated at $250,000/year), and computer hardware costs (estimated at $25,000/year).

2) Specific management practices in each county can be modeled. For example, irrigators may apply less than what crop water requirements due to water withdrawal limitations (deficit irrigation), or the residue management may lead to increased soil-moisture availability at planting.

3) Interfaces to use the crop models, and the affiliated databases on weather and crop parameters are available state-wide.

4) Modeling of crop growth is a mature decision making technology, with comparisons against measurements an on-going research activity around the world. Model estimates will get better with increased knowledge from field research.

5) The number of computer runs (14,400) may be high; however, scripting using Microsoft™, or other products will help reduce the labor involved.

9.5 Disadvantages

1) Models are poor at capturing within field variability of crops and soils. For study of very large areas, selection of the most common soils by texture may provide reasonable water use estimates.

2) Cumulative crop water use (total water use at end of growing season) may be more accurately predicted than for any other part of the growing season. Additionally, volumetric water use estimates must be done by considering the entire soil profile, since models may over/underestimate the shallow soil moisture regime (0-45 cm) depending on soil type.

3) Crop models do not account for water transfer mechanisms from the point of abstraction (streams, reservoirs, ground water pumps) to the point of application in the field. The "grower factors", i.e., the volume of water applied in the field divided by the volume of water extracted at the point of abstraction, is an external variable.

4) Crops other than major row and closely grown crops (particularly vegetables and orchard crops) may be difficult to simulate.

5) Neither catastrophic events nor infestation levels by pathogens is considered.

6) Based on the literature review in Table 9.1, the crop modeling approach may deviate by up to 10 percent relative to actual measurements.

7) Operational personnel must be trained on the use of crop growth models.

9.6 Feasibility of Implementing Methodology Statewide

The CropMan/EPIC interface (see Figure 9.1) consists of a weather processing, model input data processing, and model execution modules. The weather processing module takes as input raw data downloaded from the web and transforms it into a form recognized by model. The input data processing consists of selecting soils and agronomic practices. The module execution model consists of results generated by running the CropMan/EPIC model for a historical or future period of interest. If a future period is specified, then the model uses a weather generator software to generate climate. The feasibility of the crop modeling ten-step procedure outlined above requires weather data by soil-crop association within each county. The downloadable weather data consists of 4 km precipitation from ground observation corrected by satellite and Doppler radar imagery, 24 km air temperatures, and ½ x ½ degree grid solar radiation, wind speeds, and relative humidity from the NCEP/NOAA re-analysis project. All of this is currently available at very reasonable cost to the project. The cropping practices will vary by county and region. The Texas Cooperative Extension (TCE) County Agents and the Agri-Partners in Amarillo can be used to refine the database in CropMan, or additional resources such as FSA, USDA-NRCS can be consulted. The soils data are generally available for the state at a scale of 1:24,000 online through the USDA-NRCS gateway in Ft. Worth, at no cost to the project. For this project to succeed, the FSA must be involved to generate polygon intersections between their fields and the soils for each county. If further simplification as to area of irrigated areas can be done, then FSA county level irrigated areas by crops can be linked to the dominant soil series in each county; i.e., this operation will involve aggregated soils and irrigated crop data. It is proposed that crop modeling specialists run the model for each county off line, and then provide the output online. This way, the model will be appropriately applied, and the specific requirements of the TWDB can be met.

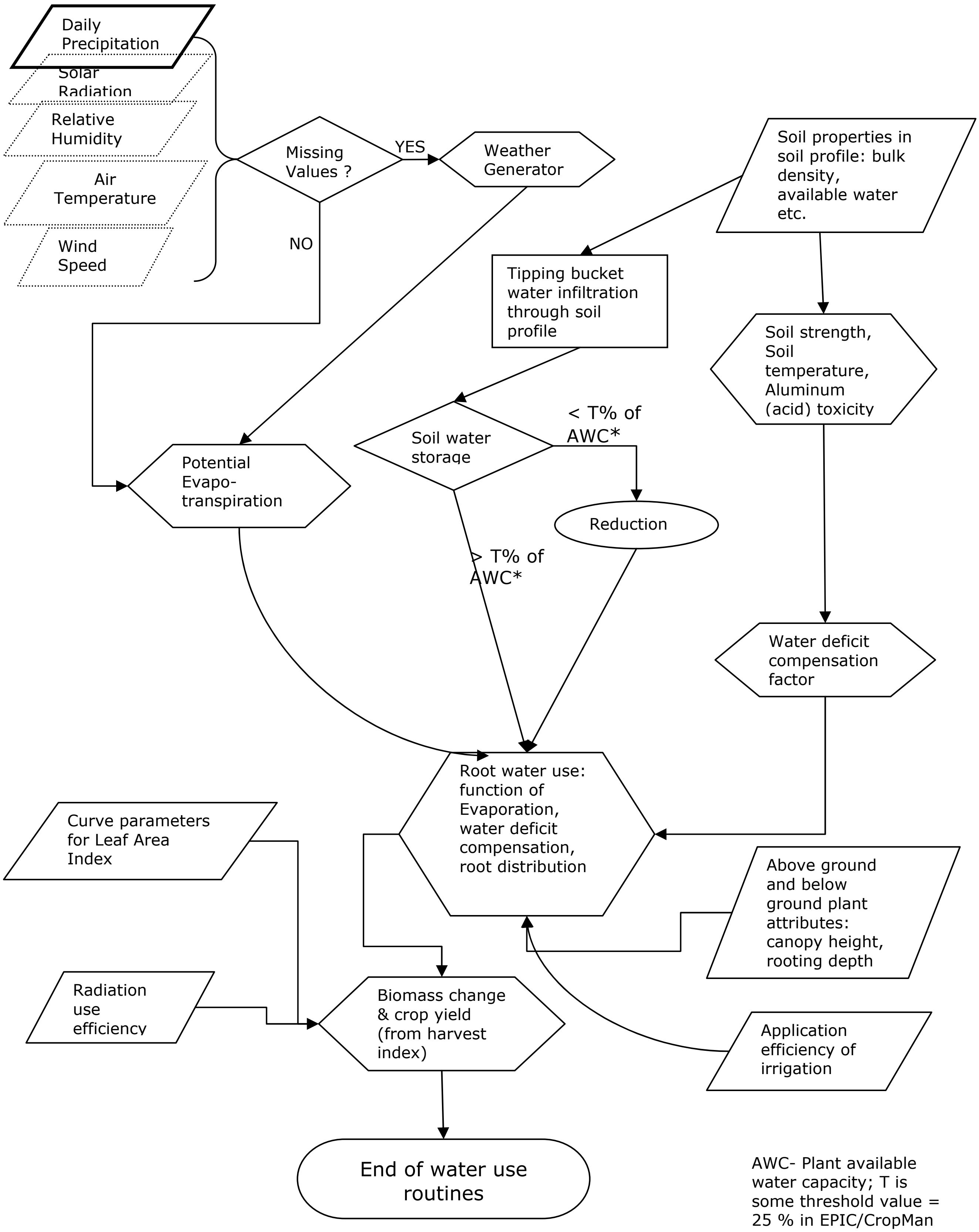

Figure 9.1 Flow chart for the water routines in EPIC and other crop growth models in common usage.

9.7 Capabilities of Interfacing with GAM

Crop models can provide the daily evapotranspiration losses of water from the soil profile, as well as recharge rates from the soil profile during the growing season. In areas with significant agricultural runoff, the crop models can provide return flows to streams and/or irrigation canals. In the arid to semiarid parts of the Texas, stream and canal reaches can be an important source of groundwater recharge. The crop models can also simulate crop production under water withdrawal limits placed by output from the GAM models; e.g., volumetric pumping limits placed on aquifers by reaching specified water levels.

9.8 Data Requirements

The primary data requirement is climate data. Daily historical or real time observations are required to run the CropMan/EPIC model. The CropMan/EPIC crop database consists of all major row and closely grown cereal crops grown in Texas. Vegetables and specialty (horticultural) crops can be modeled, but validation for these crops may be more limited than for row and closely grown cereal crops. Other forage crop species (grasses, hay, alfalfa) can be modeled similarly. Soils (at the NRCS) series level is available from the USDA-NRCS.

9.9 Estimated Costs

9.9.1 Development costs

The development cost will involve setting up the computer runs, and distribution of results through the Internet. This will require two experienced programmers and analyst estimated at $250,000 (with benefits). Hardware and software cost is estimated at $25,000 for the first year. Thus, the total development cost over two years is: $525,000.

9.9.2 Maintenance costs

Maintenance costs are somewhat cheaper since the developers will do most of the work. One full time person at $100,000/year is estimated with miscellaneous cost at $25,000.

TASK 2
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APPENDIX A

THE ASCE STANDARDIZED REFERENCE EVAPOTRANSPIRATION EQUATION

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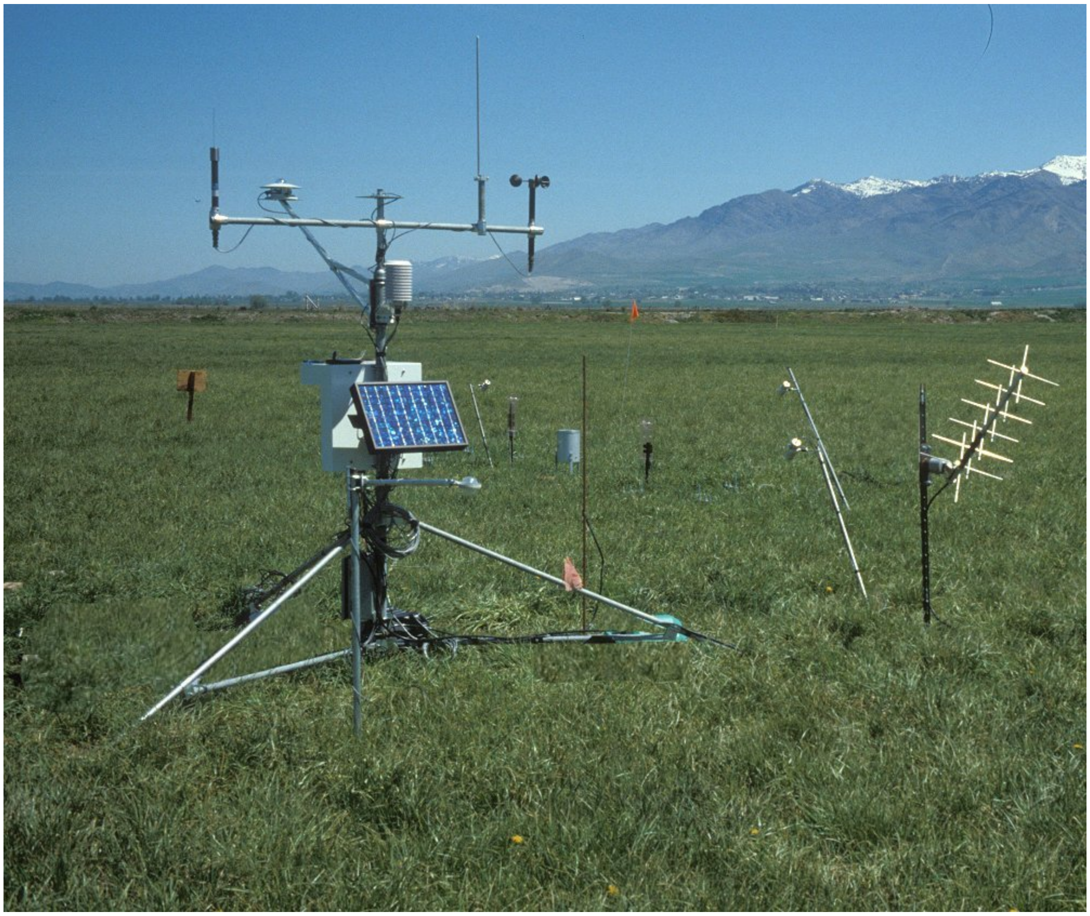

Task Committee on Standardization of Reference Evapotranspiration

Environmental and Water Resources Institute
of
the American Society of Civil Engineers

July, 2004
Final Draft

Your Passport to Professional Excellence

American Society of Civil Engineers

THE ASCE STANDARDIZED REFERENCE EVAPOTRANSPIRATION EQUATION

PREPARED BY

Task Committee on Standardization of Reference Evapotranspiration

of the

Environmental and Water Resources Institute

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THE IRRIGATION ASSOCIATION®

Irrigation Association, 2004

Abstract: This report describes the standardization of calculation of reference evapotranspiration (ET) as recommended by the Task Committee on Standardization of Reference Evapotranspiration of the Environmental and Water Resources Institute of the American Society of Civil Engineers. The purpose of the standardized reference ET equation and calculation procedures is to bring commonality to the calculation of reference ET and to provide a standardized basis for determining or transferring crop coefficients for agricultural and landscape use. The basis of the standardized reference ET equation is the ASCE Penman-Monteith (ASCE-PM) method of ASCE Manual 70. For the standardization, the ASCE-PM method is applied for two types of reference surfaces representing clipped grass (a short, smooth crop) and alfalfa (a taller, rougher agricultural crop), and the equation is simplified to a reduced form of the ASCE–PM. Standardized calculations for vapor pressure, net radiation and wind speed adjustment are recommended for application to hourly and daily calculation time steps. Guidelines on assessing weather data integrity and estimating values for missing data are provided.

THE ASCE STANDARDIZED REFERENCE EVAPOTRANSPIRATION EQUATION

Task Committee on Standardization of Reference Evapotranspiration

PREFACE

The concept of reference evapotranspiration (ET) was developed in the 1970's as a practical and definable replacement for the term potential ET. Reference ET is a function of local weather, represents the ET from a defined vegetated surface, and serves as an evaporative index by which engineers, hydrologists, water managers and other technical professionals can predict ET for a range of vegetation and surface conditions by applying "crop" coefficients for agricultural or landscaped areas. During the past decade, for convenience and reproducibility, the reference surface has been expressed as a hypothetical surface having specific characteristics. In the context of this standardization, reference evapotranspiration is defined as the ET rate from a uniform surface of dense, actively growing vegetation having specified height and surface resistance, not short of soil water, and representing an expanse of at least 100 m of the same or similar vegetation. The EWRI Task Committee concluded that two standardized surfaces were needed to serve the needs of the agricultural and landscape communities and to provide for continuity with past reference ET usage. The ASCE Penman-Monteith (ASCE-PM) equation of ASCE Manual 70 is used to represent the standardized surface and is applied for two types of surfaces (short and tall)-- clipped, cool-season grass and alfalfa.

This recommended standardization follows commonly used procedures for calculating vapor pressure terms, net radiation, and soil heat flux. The standardization represents reference ET for each of the reference surfaces using a single equation having fixed constants and standardized computational procedures. The computational procedures are relatively simple to apply, are understandable, are supported by existing and historical data, are technically defensible, and are accepted by science and engineering communities. The Task Committee recognizes that the standardized reference equation, with fixed coefficients defining vegetation and surface conditions, may not correspond precisely with local measurements of ET from surfaces similar to the clipped, cool-season grass and full-cover alfalfa definitions. However, the Task Committee encourages the use of the standardized equation and procedure when possible to represent reference ET for the establishment of reproducible and universally transferable ET estimates, climatic description, and derived crop and landscape coefficients. The standardized equation has been investigated over a wide range of locations and climates across the United States and has the Task Committee's confidence for use as a standardized index of evapotranspirative demand.

Some of the computational procedures of the standardized reference method, for example, the computation of net radiation, may be updated by EWRI from time to time in the future, as developments and improvements in generalized computational techniques are made.

The development of this standardization report by EWRI was made at the request of, and has been endorsed by, the Irrigation Association.

THE ASCE STANDARDIZED REFERENCE EVAPOTRANSPIRATION EQUATION

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THE ASCE STANDARDIZED REFERENCE EVAPOTRANSPIRATION EQUATION

Task Committee on Standardization of Reference Evapotranspiration[1] of the Environmental and Water Resources Institute of the American Society of Civil Engineers,

INTRODUCTION

In May 1999, The Irrigation Association (IA) requested the Evapotranspiration in Irrigation and Hydrology Committee – Environmental and Water Resources Institute (American Society of Civil Engineers) (ASCE-ET) to establish and define a benchmark reference evapotranspiration equation. The purpose of the benchmark equation is to standardize the calculation of reference evapotranspiration and to improve transferability of crop coefficients.

IA envisioned an equation that would be accepted by the U.S. scientific community, engineers, courts, policy makers, and end users. The equation would be applicable to agricultural and landscape irrigation and would facilitate the use and transfer of crop and landscape coefficients. In addition, IA requested guidelines for using the equation in regions where climatic data are limited and recommendations for incorporating existing crop and landscape coefficients and existing reference ET calculations.

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An ASCE-ET Task Committee (TC) comprised of the authors of this report responded to the request by IA. Their initial response is included in Appendix A. Members of the TC jointly authored several papers (Allen, et al., 2000; Itenfisu, et al., 2000; Walter, et al., 2000) at the IA 4th National Irrigation Symposium in November 2000 that described issues, challenges and analyses conducted by the TC. This report provides detail on development of the ASCE Standardized equation, recommendations on use of the equation, and example calculations. In addition, this report provides guidelines for assessing the integrity of weather data used for estimating ET and methodologies that can be used where data are limited or missing.

DEFINITION OF THE EQUATION

Evapotranspiration (ET) represents the loss of water from the earth's surface through the combined processes of evaporation (from soil and plant surfaces) and plant transpiration (i.e., internal evaporation). Reference evapotranspiration (ET_{ref}) is the rate at which readily available soil water is vaporized from specified vegetated surfaces (Jensen et al., 1990). For convenience and reproducibility, the reference surface has recently been expressed as a hypothetical crop (vegetative) surface with specific characteristics (Smith et al., 1991, Allen et al., 1994a, Allen et al., 1998). In the context of this standardization report, reference evapotranspiration is defined as the ET rate from a uniform surface of dense, actively growing vegetation having specified height and surface resistance, not short of soil water, and representing an expanse of at least 100 m of the same or similar vegetation.

ASCE-ET recommends that the equation be referred to as the "Standardized Reference Evapotranspiration Equation" (ET_{sz}). ASCE-ET is of the opinion that use of the terms *standard* or *benchmark* may lead users to assume that the equation is intended for comparative purposes (i.e., a level to be measured against). Rather, the use of the term "standardized" is intended to infer that the computation procedures have been fixed, and not that the equation is a standard or a benchmark or that the equation has undergone the degree of review in the approval process necessary for standards adopted by ASCE, ASAE, American National Standards Institute, or the International Organization for Standardization.

ASCE-ET and IA-WM members concluded that two ET_{ref} surfaces with *standardized* computational procedures were needed. The two adopted ET_{ref} surfaces are (1) a short crop (similar to clipped grass) and (2) a tall crop (similar to full-cover alfalfa). Additionally, the TC recognized that an equation capable of calculating both hourly and daily ET_{ref} was needed.

RECOMMENDATION

ET_{ref} from each of the two surfaces is modeled using a single Standardized Reference Evapotranspiration equation with appropriate constants and standardized computational procedures. The surfaces/equation are defined as:

Standardized Reference Evapotranspiration Equation, Short (ET_{os}): Reference ET for a *short* crop with an approximate height of *0.12* m (similar to clipped, cool-season grass).

Standardized Reference Evapotranspiration Equation, Tall (ET_{rs}): Reference ET for a *tall* crop with an approximate height of *0.50* m (similar to full-cover alfalfa).

The two surfaces are similar to known full-cover crops of alfalfa and clipped, cool-season grass that have received widespread use as ET_{ref} across the United States. Each reference has unique advantages for specific applications and times of the year. As a part of the standardization, the ASCE Penman-Monteith (ASCE-PM) equation (Appendix B and Jensen et al., 1990), and associated equations for calculating aerodynamic and bulk surface resistance have been combined and condensed into a single equation that is applicable to both surfaces.

The Standardized Reference Evapotranspiration Equation is intended to simplify and clarify the presentation and application of the method. As used in this report, the term ET_{sz} refers to both ET_{os} and ET_{rs}. Eq. 1 presents the form of the Standardized Reference Evapotranspiration Equation:

$$ET_{sz} = \frac{0.408\,\Delta(R_n - G) + \gamma \dfrac{C_n}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + C_d u_2)} \qquad (1)$$

where:

- ET_{sz} = standardized reference crop evapotranspiration for short (ET_{os}) or tall (ET_{rs}) surfaces (mm d^{-1} for daily time steps or mm h^{-1} for hourly time steps),
- R_n = calculated net radiation at the crop surface (MJ m^{-2} $d^{-1}$for daily time steps or MJ m^{-2} h^{-1} for hourly time steps),
- G = soil heat flux density at the soil surface (MJ m^{-2} d^{-1} for daily time steps or MJ m^{-2} h^{-1} for hourly time steps),
- T = mean daily or hourly air temperature at 1.5 to 2.5-m height (°C),
- u_2 = mean daily or hourly wind speed at 2-m height (m s^{-1}),
- e_s = saturation vapor pressure at 1.5 to 2.5-m height (kPa), calculated for daily time steps as the average of saturation vapor pressure at maximum and minimum air temperature,
- e_a = mean actual vapor pressure at 1.5 to 2.5-m height (kPa),
- Δ = slope of the saturation vapor pressure-temperature curve (kPa °C^{-1}),
- γ = psychrometric constant (kPa °C^{-1}),
- C_n = numerator constant that changes with reference type and calculation time step, and
- C_d = denominator constant that changes with reference type and calculation time step.

Table 1 provides values for C_n and C_d. The values for C_n consider the time step and aerodynamic roughness of the surface (i.e., reference type). The constant in the denominator, C_d, considers the time step, bulk surface resistance, and aerodynamic roughness of the surface (the latter two terms vary with reference type, time step and daytime/nighttime). C_n and C_d were derived by simplifying several terms within the ASCE-PM equation and rounding the result. Equations associated with calculation of required parameters in Eq. 1, the detailed derivation of the parameters in Table 1 and simplification of the terms listed in Table 2 are explained in more detail in Appendix B. Daytime is defined as occurring when the average net radiation, R_n, during an hourly period is positive.

Table 1. Values for C_n and C_d in Eq. 1

Calculation Time Step	Short Reference, ET_{os}		Tall Reference, ET_{rs}		Units for ET_{os}, ET_{rs}	Units for R_n, G
	C_n	C_d	C_n	C_d		
Daily	900	0.34	1600	0.38	mm d^{-1}	MJ m^{-2} d^{-1}
Hourly during daytime	37	0.24	66	0.25	mm h^{-1}	MJ m^{-2} h^{-1}
Hourly during nighttime	37	0.96	66	1.7	mm h^{-1}	MJ m^{-2} h^{-1}

Table 2. ASCE Penman-Monteith Terms Standardized for Application of the Standardized Reference Evapotranspiration Equation

Term	ET_{os}	ET_{rs}
Reference vegetation height, h	0.12 m	0.50 m
Height of air temperature and humidity measurements, z_h	1.5 – 2.5 m	1.5 – 2.5 m
Height corresponding to wind speed, z_w	2.0 m	2.0 m
Zero plane displacement height	0.08 m	0.08 m [a]
Latent heat of vaporization	2.45 MJ kg^{-1}	2.45 MJ kg^{-1}
Surface resistance, r_s, daily	70 s m^{-1}	45 s m^{-1}
Surface resistance, r_s, daytime	50 s m^{-1}	30 s m^{-1}
Surface resistance, r_s, nighttime	200 s m^{-1}	200 s m^{-1}
Value of R_n for predicting daytime	> 0	> 0
Value of R_n for predicting nighttime	≤ 0	≤ 0

[a] The zero plane displacement height for ET_{rs} assumes that the wind speed measurement is over clipped grass, even though the reference type is tall. This is done to accommodate a majority of weather stations that are located over grass. See comments in Appendix B following Eq. B.14b. When wind speed is measured over a surface having vegetation taller than about 0.3 m, it is recommended that the "full" ASCE Penman-Monteith method (Eq. B.1) be employed, where the zero plane displacement can be varied. However, the standardized ET_{sz} equation can be used if wind speed are adjusted following guidelines in Appendix B.

USE OF THE STANDARDIZED REFERENCE EVAPOTRANSPIRATION EQUATION

Based on an intensive review of reference evapotranspiration calculated for 49 sites throughout the United States (as described in the following section), ASCE-ET found the standardized reference evapotranspiration equation to be reliable and recommends its use for:

- Calculating reference evapotranspiration and, in turn, crop evapotranspiration (ET_c)
- Developing new crop coefficients
- Facilitating transfer of existing crop coefficients

CALCULATING STANDARDIZED REFERENCE CROP EVAPOTRANSPIRATION

This section describes data requirements, equations, and procedures necessary for calculating ET_{sz} on a daily and hourly time step. A daily time step has historically been commonly used in the calculation of ET_{ref}. Selection of the appropriate time step is a function of data availability, climate, the intended application, and user preference.

REQUIRED DATA FOR THE STANDARDIZED REFERENCE EQUATION

The calculation of ET_{sz} requires measurements or estimates for air temperature, humidity, solar radiation, and wind speed. These parameters are considered to be the minimum requirements to estimate ET_{os} and ET_{rs}. Examples of the calculation of ET_{sz} are provided in Appendix C. When humidity, solar radiation or wind speed measurements are not available, substitute values for daily and longer time periods may be estimated using procedures described in Appendix E.

The accuracy of any evapotranspiration calculation depends on the quality of the weather data, which requires good quality control and quality assurance procedures. When possible, weather data should be measured at stations that are located in open, well-watered, vegetated settings (preferably grass). Preferred locations have low growing, well-watered vegetation in the immediate and near vicinity of the weather station (~50 m) and mostly the same or other well-watered vegetation for a few hundred meters beyond that[3]. Suggestions for assessing and improving the integrity of collected weather data are described in Appendix D. Appendix D also provides guidelines for evaluating the weather station site and the possible impact upon the measured meteorological parameters. Suggestions for replacing missing data or data that are of poor quality are presented in Appendix E.

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[3] This recommendation is similar to those found in ASAE Engineering Practice EP505 (ASAE 2004).

Appendix B provides background on the development of the standardized form of the ASCE equation. The full form of the ASCE-PM equation, which includes explicit terms for aerodynamic and surface resistance, is not required, nor is it recommended, for calculation of ET_{sz}. The full form of the ASCE-PM equation is recommended when ET is measured over grass or alfalfa vegetation having substantially different height than the 0.12 m height defined for the short reference (grass) or 0.50 m height defined for the tall reference (alfalfa). Values for vegetation height are fixed in the standardized equation.

CALCULATIONS REQUIRED FOR DAILY TIME-STEPS

The calculation process for ET_{sz} for daily time steps is presented in this section. Several of the calculations are identical to those required for hourly time steps. Some equations are repeated in the hourly calculation section so as to detail that calculation process completely.

Psychrometric and Atmospheric Variables[4]

Latent Heat of Vaporization (λ)

The value of the latent heat of vaporization, λ, varies only slightly over the ranges of air temperature that occur in agricultural or hydrologic systems. For ET_{sz}, a constant value of λ = 2.45 MJ kg^{-1} is recommended. The inverse of λ is approximately 0.408 kg MJ^{-1}. The density of water (ρ_w) is taken as 1.0 Mg m^{-3} so that the inverse ratio of $\lambda\ \rho_w$ times energy flux in MJ m^{-2} d^{-1} equals 1.0 mm d^{-1}.

Mean Air Temperature (T)

For the standardized method, the mean air temperature, T, for a daily time step is preferred as the mean of the daily maximum and daily minimum air temperatures rather than as the average of hourly temperature measurements to provide for consistency across all data sets.

$$T = \frac{T_{max} + T_{min}}{2} \tag{2}$$

where:

T = daily mean air temperature [°C]
T_{max} = daily maximum air temperature [°C]
T_{min} = daily minimum air temperature [°C]

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[4] Many of the equations presented here are the same as those reported in ASCE Manual 70 (Jensen et al., 1990) and in FAO-56 (Allen et al., 1998).

Atmospheric Pressure (P)

The mean atmospheric pressure at the weather site is predicted from site elevation using a simplified formulation of the Universal Gas Law[5]:

$$P = 101.3\left(\frac{293 - 0.0065\,z}{293}\right)^{5.26} \tag{3}$$

where:

P = mean atmospheric pressure at station elevation z [kPa], and
z = weather site elevation above mean sea level [m].

Psychrometric Constant (γ)

The standardized application using λ = 2.45 MJ kg^{-1} results in a value for the psychrometric constant, γ, that is proportional to the mean atmospheric pressure:

$$\gamma = 0.000665\ P \tag{4}$$

where P has units of kPa and γ has units of kPa $°C^{-1}$.

Note: The variable γ is not the same variable as γ_{psy} used later in Eqs. 9 and 10 for converting psychrometric data (wet bulb and dry bulb temperature) to vapor pressure.

Slope of the Saturation Vapor Pressure-Temperature Curve (Δ)

The slope of the saturation vapor pressure-temperature curve[6], Δ, is computed as:

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[5] Reference: Burman et al. (1987)

[6] References: Tetens (1930), Murray (1967)

$$\Delta = \frac{2503 \exp\left(\frac{17.27\,T}{T + 237.3}\right)}{(T + 237.3)^2} \quad (5)$$

where:

Δ = slope of the saturation vapor pressure-temperature curve [kPa °C^{-1}], and

T = daily mean air temperature [°C].

Saturation Vapor Pressure (e_s)

The saturation vapor pressure[7] (e_s) represents the capacity of the air to hold water vapor.

For calculation of daily ET_{sz} , e_s is given by:

$$e_s = \frac{e^o(T_{max}) + e^o(T_{min})}{2} \quad (6)$$

where:

$e^o(T)$ = saturation vapor pressure function (Eq. 7) [kPa]

The function to calculate saturation vapor pressure is:

$$e^o(T) = 0.6108 \exp\left(\frac{17.27\,T}{T + 237.3}\right) \quad (7)$$

where vapor pressure is in units of kPa and temperature is in °C.

[7] Reference: Jensen et al. (1990) and Tetens (1930)

Actual Vapor Pressure (e_a)

Actual vapor pressure (e_a) is used to represent the water content (humidity) of the air at the weather site. The actual vapor pressure can be measured or it can be calculated from various humidity data, such as measured dew point temperature, wet-bulb and dry-bulb temperature, or relative humidity and air temperature data.

Preferred procedures for calculating e_a

When multiple types of humidity or psychrometric data are available for estimating e_a, the preferences listed in Table 3 are recommended for the calculation method. These recommendations are based on the likelihood that the data will have integrity and that estimates for e_a will be representative. The availability and quality of local data, as well as site conditions, may justify a different order of preference.

Table 3. Preferred method for calculating e_a for daily ET_{sz}

Method No.	Method	Preference Ranking	Equation(s)
1	e_a averaged over the daily period (based on hourly or more frequent measurements of humidity)[a,b]	1	7, 41
2	Measured or computed dew point temperature averaged over the daily period	1	8
3	Wet-bulb and dry-bulb temperature averaged over the daily period	2	7, 9, 10
4	Measured or computed dew point or measured wet-bulb and dry-bulb temperature at 7 or 8 am	2	8 or 7, 9, 10
5	Daily maximum and minimum relative humidity	2	7, 11
6	Daily maximum relative humidity	3	7, 12
7	Daily minimum relative humidity	3	7, 13
8	Daily minimum air temperature (see Appendix E)	4	--
9	Daily mean relative humidity	4	7, 14

[a] In many data sets, e_a may be expressed in terms of an equivalent dew point temperature.

[b] Some data logging systems may measure relative humidity (RH) and T, but calculate e_a or T_{dew} internally for output as averaged values over some time interval. See ASAE (2004) for further detail.

When humidity and psychrometric data are missing or are of questionable integrity, dew point temperature can be estimated from daily minimum air temperature as described in Appendix E. This estimation process should be verified locally. The assessment of weather data integrity is discussed in Appendix D.

e_a from measured dew point temperature

The dew point temperature (T_{dew}) is the temperature to which the air must cool to reach a state of saturation. For daily calculation time steps, average dew point temperature can be computed by averaging over hourly periods or, for purposes of estimating ET_{sz}, it can be determined by an early morning measurement (generally at 0700 or 0800 hours). The value for e_a is calculated by substituting T_{dew} into Eq. 7 resulting in:

$$e_a = e^o\left(T_{dew}\right) = 0.6108 \exp\left[\frac{17.27\ T_{dew}}{T_{dew} + 237.3}\right] \tag{8}$$

e_a from psychrometric data

The actual vapor pressure can also be determined from the difference between the dry and wet bulb temperatures (i.e., the wet bulb depression) of the air:

$$e_a = e^o\left(T_{wet}\right) - \gamma_{psy}\left(T_{dry} - T_{wet}\right) \tag{9}$$

where:

e_a = actual vapor pressure of the air [kPa],

$e^\circ(T_{wet})$ = saturation vapor pressure at the wet bulb temperature [kPa] (Eq. 7),

γ_{psy} = psychrometric constant for the psychrometer [kPa °C^{-1}], and
$T_{dry} - T_{wet}$ = wet bulb depression,
where
T_{dry} = dry bulb temperature and
T_{wet} = the wet bulb temperature [°C] (measured simultaneously).

The psychrometric constant for the psychrometer at the weather measurement site is given by:

$$\gamma_{psy} = a_{psy} P \quad (10)$$

where

a_{psy} = coefficient depending on the type of ventilation of the wet bulb [°C^{-1}], and
P = mean atmospheric pressure [kPa].

The coefficient a_{psy} depends primarily on the design of the psychrometer and on the rate of ventilation around the wet bulb. The following values are often used[8]:

a_{psy} = 0.000662 for ventilated (Asmann type) psychrometers having air movement of about 5 m s^{-1},
= 0.000800 for naturally ventilated psychrometers having air movement of about 1 m s^{-1}, and
= 0.001200 for non-ventilated psychrometers installed in glass or plastic greenhouses.

Generally, the wet-bulb and dry-bulb temperature data are measured once during the day.

<u>e_a from relative humidity data</u>

The actual vapor pressure of air can be calculated from relative humidity (RH) and the corresponding air temperature. When using RH data, it is essential that the RH and air temperature data are “paired,” i.e., that they represent the same time of day or time period and

[8] Allen et al., (1998).

that they are taken at the weather measurement site. For daily data, daily maximum relative humidity (RH_{max}) can be paired with T_{min}, which will both occur, generally, during early morning. Daily minimum relative humidity (RH_{min}) is paired with T_{max}.

Depending on the availability of the RH data, the following equations apply, with preference of method listed in Table 3:

- Daily e_a from RH_{max} and RH_{min}.

$$e_a = \frac{e^o(T_{min})\frac{RH_{max}}{100} + e^o(T_{max})\frac{RH_{min}}{100}}{2} \tag{11}$$

where:

e_a = actual vapor pressure [kPa],
$e°(T_{min})$ = saturation vapor pressure at daily minimum temperature [kPa],
$e°(T_{max})$ = saturation vapor pressure at daily maximum temperature [kPa],
RH_{max} = daily maximum relative humidity [%], and
RH_{min} = daily minimum relative humidity [%].

When computing the average daily ET_{sz} during a week, a ten-day period or a month, RH_{max} and RH_{min} are obtained by averaging daily RH_{max} or RH_{min} values.

- Daily e_a from RH_{max}

Older styles of electronic relative humidity sensors, for example those manufactured before about 1990, often experienced difficulty in accurately measuring RH when at low levels. When using equipment where errors in estimating RH_{min} may be large, or when integrity of the RH data is doubtful, the actual vapor pressure can be computed from RH_{max}:

$$e_a = e^o(T_{min})\frac{RH_{max}}{100} \tag{12}$$

When accuracy of RH data is in doubt, error in RH_{max} causes smaller error in e_a than error in RH_{min}, due to the smaller value for the multiplier $e^o(T_{min})$ as compared to $e^o(T_{max})$. In addition, RH_{max} data are generally easier to assess for accuracy than is RH_{min}. The value of RH_{max} generally exceeds 90% and approaches 100% in well-watered settings such as within irrigation projects and in sub-humid and humid climates. This proximity to 100% serves as a first check on reasonableness, representativeness, and integrity of the data. Exceptions to this trend are where substantial advection of dry or warm air from dry regions outside the area occurs during nighttime, including, but not limited to,some desert areas of New Mexico, Arizona and California.

- Daily e_a from RH_{min}

Sometimes, only high quality estimates of daily RH_{min} are available and must be used to predict e_a:

$$e_a = e^o(T_{max})\frac{RH_{min}}{100} \tag{13}$$

However, estimates using Eq. 13 may be less desirable than estimates using Eq. 11 or 12, due to greater impact of error in RH_{min} on e_a, as discussed previously. In addition, it is more difficult to assess the integrity of RH_{min} data (see Appendix D):

- Daily e_a from RH_{mean}

In the absence of RH_{max} and RH_{min} data, but where daily RH_{mean} data are available, the actual vapor pressure may be estimated as:

$$e_a = \frac{RH_{mean}}{100} e^o(T_{mean}) \tag{14}$$

where RH_{mean} is the mean daily relative humidity, generally defined as the average between RH_{max} and RH_{min} and T_{mean} is mean daily air temperature, defined in Eq. 2 Eq. 14 is less desirable than Eqs. 12 or 13 because the $e^o(T)$ relationship is nonlinear. Eq. 14 produces estimates of e_a that are closer to those by Eq. 11 and to daily average e_a computed from hourly values than is the use of alternative forms of Eq. 14, such as $e_a = RH_{mean}/100\ [e^o(T_{max})+e^o(T_{min})]/2$ described in Allen et al., (1998) or as $e_a = RH_{mean}/100\ [1/(50/e^o(T_{max}) + 50/e^o(T_{min}))]$ described in Smith et al., (1991). These latter two methods are not recommended in the standardized procedure.

Net Radiation (R_n)

Net radiation (R_n) is the net amount of radiant energy available at a vegetation or soil surface for evaporating water, heating the air, or heating the surface. R_n includes both short and long wave radiation components [9]:

$$R_n = R_{ns} - R_{nl} \tag{15}$$

where:

R_{ns} = net short-wave radiation, [MJ m^{-2} d^{-1}] (defined as being positive downwards and negative upwards),

R_{nl} = net outgoing long-wave radiation, [MJ m^{-2} d^{-1}] (defined as being positive upwards and negative downwards),

R_{ns} and R_{nl} are generally positive or zero in value.

Net radiation is difficult to measure because net radiometers are problematic to maintain and calibrate. There is good likelihood of systematic biases in R_n measurements. Therefore, R_n is often predicted from observed short wave (solar) radiation, vapor pressure, and air temperature. This prediction is routine and generally highly accurate. If R_n is measured, then care and attention must be given to the calibration of the radiometer, the surface over which it is located, maintenance of the sensor domes, and level of the instrument. The condition of the vegetation

[9] Reference: Brutsaert (1982), Jensen et al., (1990), Wright (1982), Doorenbos and Pruitt (1975,1977), Allen et al., (1998).

surface is as important as the sensor. For purposes of calculating ET_{sz}, the measurement surface for R_n is generally assumed to be clipped grass or alfalfa at full cover.

Net Solar or Net Short-Wave Radiation (R_{ns})

Net short-wave radiation resulting from the balance between incoming and reflected solar radiation is given by:

$$R_{ns} = R_s - \alpha R_s = (1-\alpha) R_s \tag{16}$$

where:

R_{ns} = net solar or short-wave radiation [MJ m^{-2} d^{-1}],
α = albedo or canopy reflection coefficient, is fixed at 0.23 for the standardized short and tall reference surfaces [dimensionless], and
R_s = incoming solar radiation [MJ m^{-2} d^{-1}].

The calculation of ET_{sz} uses the constant value of 0.23 for albedo for daily and hourly periods. It is recognized that albedo varies somewhat with time of day and with time of season and latitude due to change in sun angle. However, because the solar intensity is less during these periods, the error introduced in fixing albedo at 0.23 is relatively small (Allen et al., 1994b). Users may elect to use a different prediction for albedo, however, it is essential to ascertain the validity and accuracy of an alternative method using good measurements of incoming and reflected solar radiation. Some types of pyranometers are invalid for measuring reflected radiation due to the difference in spectral response between the instrument and reflecting surface. Predictions of R_n made using an alternate method for albedo (i.e., other than 0.23) may not agree with those made using the ASCE standardized procedure.

Net Long-Wave Radiation (R_{nl})

There are several variations and coefficients developed for predicting the net long wave component of total net radiation. The standardized ASCE procedure is the same as that adopted by FAO-56 and is based on the Brunt (1932, 1952) approach for predicting net emissivity. If users intend to utilize a different approach for calculating R_{nl}, it is essential to ascertain the validity and accuracy of their R_n method using net radiometers in excellent condition and that are calibrated to some dependable and recognized standard. In all situations, users should compare measured R_n or R_n computed using an alternative method with R_n calculated using the standardized procedure. Substantial variation (more than 5 %) should give cause for concern and should indicate the need to reconcile or justify the differences.

R_{nl}, net long-wave radiation, is the difference between upward long-wave radiation from the standardized surface (R_{lu}) and downward long-wave radiation from the sky (R_{ld}), so that $R_{nl} = R_{lu} - R_{ld}$. The following calculation for <u>daily</u> R_{nl} follows the method of Brunt (1932, 1952) of using vapor pressure to predict net emissivity:

$$R_{nl} = \sigma \ f_{cd} \left(0.34 - 0.14\sqrt{e_a}\right)\left[\frac{T_{K\ max}^4 + T_{K\ min}^4}{2}\right] \qquad (17)$$

where:

R_{nl} = net long-wave radiation [MJ m^{-2} d^{-1}],
σ = Stefan-Boltzmann constant [4.901 x 10^{-9} MJ K^{-4} m^{-2} d^{-1}],
f_{cd} = cloudiness function [dimensionless] (limited to $0.05 \le f_{cd} \le 1.0$),
e_a = actual vapor pressure [kPa],
$T_{K\ max}$ = maximum absolute temperature during the 24-hour period [K] (K = °C + 273.16),

[10] Reference: Allen (1996)

$T_{K\,min}$ = minimum absolute temperature during the 24-hour period [K] (K = °C + 273.16).

The superscripts "4" in Eq. 17 indicate the need to raise the air temperature, expressed in Kelvin units, to the power of 4. For daily and monthly calculation timesteps, f_{cd} is calculated as[11]:

$$f_{cd} = 1.35 \frac{R_s}{R_{so}} - 0.35 \qquad (18)$$

where:

R_s/R_{so} = relative solar radiation (limited to $0.3 \le R_s/R_{so} \le 1.0$),
R_s = measured or calculated solar radiation [MJ m^{-2} d^{-1}], and
R_{so} = calculated clear-sky radiation [MJ m^{-2} d^{-1}].

The ratio R_s/R_{so} in Eq. 18 represents relative cloudiness and is limited to $0.3 < R_s/R_{so} \le 1.0$ so that f_{cd} has limits of $0.05 \le f_{cd} \le 1.0$.

Clear-Sky Solar Radiation (R_{so})

Clear-sky solar radiation (R_{so}) is used in the calculation of net radiation (R_n). Clear-sky solar radiation is defined as the amount of solar radiation (R_s) that would be received at the weather measurement site under conditions of clear-sky (i.e., cloud-free). The ratio of R_s to R_{so} in the equation for R_n is used to characterize the impact of cloud-cover on the downward emission of thermal radiation to the earth's surface. Daily R_{so} is a function of the time of year and latitude. R_{so} is also impacted by station elevation (affecting atmospheric thickness and transmissivity), the amount of precipitable water in the atmosphere (affecting the absorption of some short-wave radiation), and the amount of dust or aerosols in the air.

Extraterrestrial radiation (R_a), as defined in Eq. 21, can be used as a means for determining a theoretical R_{so}envelope as illustrated in Figure 1. The envelope can be expressed in tabular form

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[11] Jensen et al., (1990); Allen et al., (1998)

or as an equation. In this section, a simple procedure[12] is demonstrated for estimating R_{so} for purposes of predicting net radiation. A more involved procedure, useful for evaluating R_s data integrity, is described in Appendix D. The clear sky envelope can alternatively be developed using measured R_s from a period of one year or longer. The measured data should be confirmed for accuracy, including sensor calibration and maintenance (levelness and cleanliness). When measured R_s data are used to define an R_{so} envelope for a location, the resulting envelope should be compared with a theoretically derived envelope to confirm that there are no substantial differences in shape or magnitude. In general, the theoretically derived curve (Figure 1) is recommended.

[12] Reference: Allen (1996)

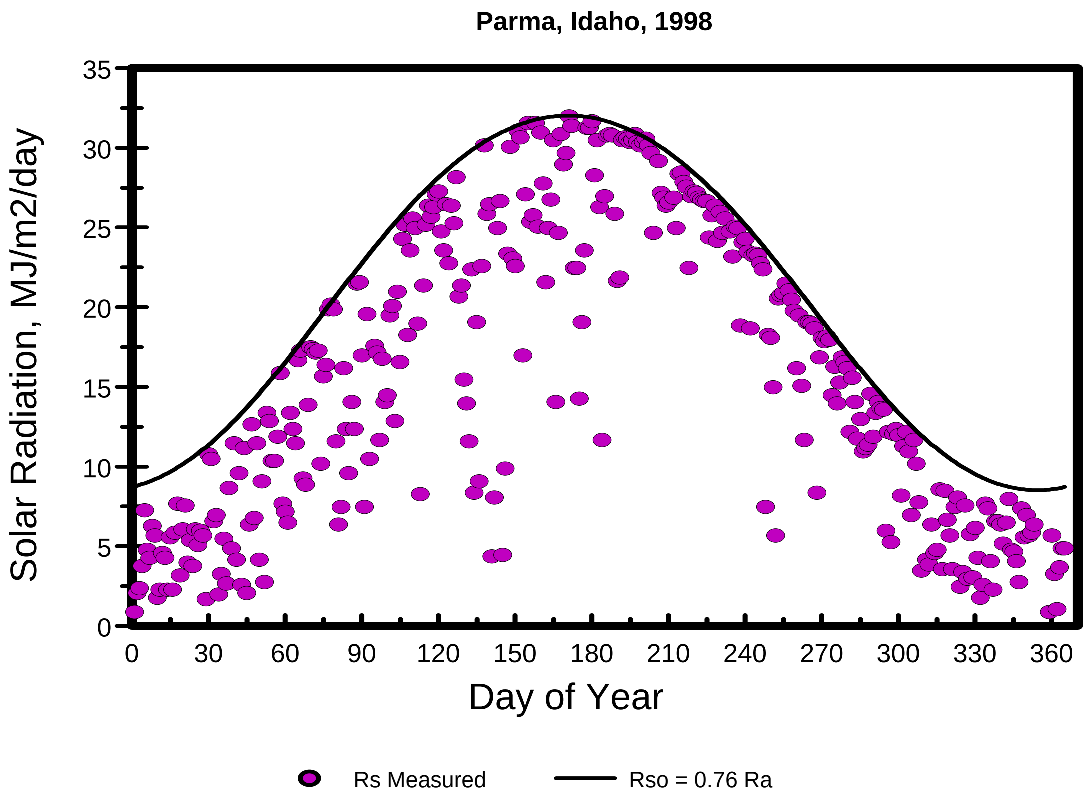

Figure 1. Daily R_s at Parma, Idaho during 1998 (elevation 703 m, Lat. 43.8°) and R_{so} envelope from Eq. 19.

When a dependable, locally calibrated procedure for determining R_{so} is not available, R_{so}, for purposes of calculating R_n, can be computed as:

$$R_{so} = \left(0.75 + 2 \times 10^{-5} z\right) R_a \qquad (19)$$

where:

z = station elevation above sea level [m].

Eq. 19 predicts progressively higher levels of clear sky radiation with increasing elevation, and is the basis for the "0.76" factor for the R_{so} curve drawn in Figure 1. Elevation serves as a surrogate for total air mass and atmospheric transmissivity above the measurement site.

When dependable, locally calibrated values are available for applying the "Angstrom" formula (see Eq. A.44), the clear sky radiation can be computed as:

$$R_{so} = K_{ab} R_a \tag{20}$$

where:

- R_{so} = clear-sky solar radiation [MJ m^{-2} d^{-1}],
- R_a = extraterrestrial radiation [MJ m^{-2} d^{-1}],
- K_{ab} = coefficient that can be derived from the a_s and b_s coefficients of the Angstrom formula, where $K_{ab} = a_s + b_s$, and where K_{ab} represents the fraction of extraterrestrial radiation reaching the earth on clear-sky days,
- a_s = constant expressing the fraction of extraterrestrial radiation reaching the earth's surface on completely overcast days (see Eq. E.2 in Appendix E), and
- b_s = constant expressing the additional fraction of extraterrestrial radiation reaching the earth's surface on a clear day (see Eq. E.2 in Appendix E).

Eqs. 19 or 20 are generally adequate for use in estimating R_{so} in Eq. 18 when predicting net radiation, R_n. More complex estimates for R_{so}, which include impacts of turbidity and water vapor on radiation absorption, can be used for assessing integrity of solar radiation data and are discussed in Appendix D. The difference in ET_{rs} or ET_{os} resulting from the use of Eq. 19 or 20, as opposed to the more complicated and accurate R_{so} equations D.1 – D.5 of Appendix D, will be generally less than a few percent over an annual period.

Extraterrestrial Radiation for 24-Hour Periods (R_a)[13]

Extraterrestrial radiation, R_a, defined as the short-wave solar radiation in the absence of an atmosphere, is a well-behaved function of the day of the year, time of day, and latitude. It is needed for calculating R_{so}, which is in turn used in calculating R_n. For daily (24-hour) periods, R_a can be estimated from the solar constant, the solar declination, and the day of the year:

[13] Reference: Duffie and Beckman (1980).

$$R_a = \frac{24}{\pi} G_{sc}\, d_r \left[\omega_s \sin(\varphi)\sin(\delta) + \cos(\varphi)\cos(\delta)\sin(\omega_s)\right] \tag{21}$$

where:

- R_a = extraterrestrial radiation [MJ m^{-2} d^{-1}],
- G_{sc} = solar constant [4.92 MJ m^{-2} h^{-1}],
- d_r = inverse relative distance factor (squared) for the earth-sun [unitless],
- ω_s = sunset hour angle [radians],
- φ = latitude [radians], and
- δ = solar declination [radians].

The latitude, φ, is positive for the Northern Hemisphere and negative for the Southern Hemisphere. The conversion from decimal degrees to radians is given by:

$$\text{Radians} = \frac{\pi}{180}(\text{decimal degrees}) \tag{22}$$

and d_r and δ are calculated as:

$$d_r = 1 + 0.033 \cos\left(\frac{2\pi}{365} J\right) \tag{23}$$

$$\delta = 0.409 \sin\left(\frac{2\pi}{365} J - 1.39\right) \tag{24}$$

where:

J is the number of the day in the year between 1 (1 January) and 365 or 366 (31 December). J can be calculated as[14]:

$$J = D_M - 32 + \text{Int}\left(275\frac{M}{9}\right) + 2\ \text{Int}\left(\frac{3}{M+1}\right) + \text{Int}\left(\frac{M}{100} - \frac{\text{Mod}(Y,4)}{4} + 0.975\right) \tag{25}$$

where:

- D_M = the day of the month (1-31),

[14] Reference: Allen (2000).

M = the number of the month (1-12), and
Y = the number of the year (for example 1996 or 96).

The "Int" function in Eq. 25 finds the integer number of the argument in parentheses by rounding downward. The "Mod(Y,4)" function finds the modulus (remainder) of the quotient Y/4.

For monthly periods, the day of the year at the middle of the month (J_{month}) is approximately:

$$J_{month} = \text{Int}(30.4\ M - 15) \tag{26}$$

The sunset hour angle, ω_s, is given by:

$$\omega_s = \arccos\left[-\tan(\varphi)\tan(\delta)\right] \tag{27}$$

The "arccos" function is the arc-cosine function and represents the inverse of the cosine. This function is not available in all computer languages, so that ω_s can alternatively be computed using the arc-tangent (inverse tangent) function:

$$\omega_s = \frac{\pi}{2} - \arctan\left[\frac{-\tan(\varphi)\tan(\delta)}{X^{0.5}}\right] \tag{28}$$

where:

$$X = 1 - \left[\tan(\varphi)\right]^2 \left[\tan(\delta)\right]^2 \tag{29}$$

$$\text{and } X = 0.00001 \text{ if } X \le 0$$

Soil Heat Flux Density (G)

Soil heat flux density is the thermal energy utilized to heat the soil. G is positive when the soil is warming and negative when the soil is cooling.

For Daily Periods

The magnitude of the daily, weekly or ten-day soil heat flux density, G, beneath a fully vegetated grass or alfalfa reference surface is relatively small in comparison with R_n. Therefore, it is ignored so that:

$$G_{day} = 0 \tag{30}$$

where:

G_{day} = daily soil heat flux density [MJ m^{-2} d^{-1}].

For Monthly Periods

Over a monthly period, G for the soil profile can be significant. Assuming a constant soil heat capacity of 2.0 MJ m^{-3} °C^{-1} and an effectively warmed soil depth of 2 m, G for monthly periods in MJ m^{-2} d^{-1} is estimated from the change in mean monthly air temperature as:

$$G_{month,i} = 0.07\,(T_{month,i+1} - T_{month,i-1}) \tag{31}$$

or, if $T_{month,i+1}$ is unknown:

$$G_{month,i} = 0.14\,(T_{month,i} - T_{month,i-1}) \tag{32}$$

where:

$T_{month,I}$ = mean air temperature of month i [°C],
$T_{month,i-1}$ = mean air temperature of previous month [°C], and

$T_{month,i+1}$ = mean air temperature of next month [°C].

Wind Profile Relationship

Wind speed varies with height above the ground surface. For the calculation of ET_{sz}, wind speed at 2 meters above the surface is required, therefore, wind measured at other heights must be adjusted. To adjust wind speed data to the 2-m height, Eq. 33 should be used for measurements taken above a short grass (or similar) surface, based on the full logarithmic wind speed profile equation B.14 given in Appendix B:

$$u_2 = u_z \frac{4.87}{\ln(67.8\, z_w - 5.42)} \tag{33}$$

where:

u_2 = wind speed at 2 m above ground surface [m s^{-1}],
u_z = measured wind speed at z_w m above ground surface [m s^{-1}], and
z_w = height of wind measurement above ground surface [m].

For wind measurements above surfaces other than clipped grass, the user should apply the full logarithmic equation B.14. A special application of Eq. B.14 is given in Appendix B for wind measured above alfalfa or similar vegetation having about 0.5 m height. It is noted that wind speed data collected at heights above 2 m are acceptable for use in the standardized equations following adjustment to 2 m, and may be preferred if vegetation adjacent to the station commonly exceeds 0.5 m. Measurement at a greater height, for example 3m, reduces the influence of the taller vegetation.

CALCULATIONS REQUIRED FOR HOURLY TIME-STEPS

Many weather data networks collect and summarize hourly data that allow the user to calculate ET_{sz} for hourly periods. This capability is important where significant shifts in wind and humidity occur hourly. The calculation process for hourly time steps is analogous to that for daily calculations. The hourly equations can be used for shorter time periods, using fractional hours as the time parameter, but care must be taken to multiply the resultant ET rate in mm/h by the fractional hour. For example, if 30-minute data are used, one would input radiation in units of MJ m^{-2} h^{-1}. Then the output, in mm h^{-1}, would need to be multiplied by 0.5 h to arrive at the ET for the 30-minute period.

Psychrometric and Atmospheric Variables[15]

Latent Heat of Vaporization (λ)

The value of the latent heat of vaporization (λ), varies only slightly over the ranges of air temperature that occur in agricultural or hydrologic systems. For ET_{sz}, a constant value of λ = 2.45 MJ kg^{-1} is recommended. The inverse of λ is approximately 0.408 kg MJ^{-1}. The density of water (ρ_w) is taken as 1.0 Mg m^{-3} so that the inverse ratio of $\lambda\ \rho_w$ times energy flux in MJ m^{-2} h^{-1} equals 1.0 mm h^{-1}.**Mean Air Temperature (T)**

For hourly periods, the mean air temperature, T, represents an average over the period.

Atmospheric Pressure (P)

The mean atmospheric pressure at the weather site is predicted from site elevation using a simplified formulation of the Universal Gas Law[16]:

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[15] Many of the equations presented here are the same as those reported in ASCE Manual 70 (Jensen et al., 1990) and used in FAO-56 (Allen et al., 1998).

$$P = 101.3\left(\frac{293 - 0.0065\,z}{293}\right)^{5.26} \tag{34}$$

where:

P = mean atmospheric pressure at station elevation z [kPa], and
z = weather site elevation above mean sea level [m].

Psychrometric Constant (γ)

The standardized application using λ = 2.45 MJ kg^{-1} results in a value for the psychrometric constant, γ, that is proportional to the mean atmospheric pressure:

$$\gamma = 0.000665\ P \tag{35}$$

where P has units of kPa and γ has units of kPa °C^{-1}.

The variable γ is not the same variable as γ_{psy} used later in Eqs. 39 and 40 for converting psychrometric data (wet bulb and dry bulb temperature) to vapor pressure.

Slope of the Saturation Vapor Pressure-Temperature Curve (Δ)

The slope of the saturation vapor pressure-temperature curve[17], Δ, is computed as:

$$\Delta = \frac{2503\ \exp\left(\frac{17.27\ T}{T + 237.3}\right)}{\left(T + 237.3\right)^2} \tag{36}$$

where:

Δ = slope of the saturation vapor pressure-temperature curve [kPa °C^{-1}], and
T = mean air temperature [°C].

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[16] Reference: Burman et al. (1987)

[17] References: Tetens (1930), Murray (1967)

Saturation Vapor Pressure (e_s)

The saturation vapor pressure[18], e_s, represents the capacity of the air to hold water vapor.

For calculation of hourly ET_{sz}, e_s is given by:

$$e_s = e^o(T) = 0.6108 \exp\left(\frac{17.27\,T}{T + 237.3}\right) \qquad (37)$$

where vapor pressure is in units of kPa and T is mean air temperature during the hourly period in °C. $e^o(T)$ is the saturation vapor pressure function.

Actual Vapor Pressure (e_a)

Actual vapor pressure (e_a) is used to represent the water content (humidity) of the air at the weather site. The actual vapor pressure can be measured or it can be calculated from various humidity data, such as measured dew point temperature, wet-bulb and dry-bulb temperature, or relative humidity and air temperature data.

Preferred procedures for calculating e_a

When multiple types of humidity or psychrometric data are available for estimating e_a, the preferences listed in Table 4 are recommended for calculation method. These recommendations are based on the likelihood that the data will have integrity and that estimates for e_a will be representative of the reference ET environment. The availability and quality of local data may justify a different order of preference.

[18] Reference: Jensen et al. (1990) and Tetens (1930)

Table 4. Preferred method for calculating e_a for ET_{sz} for hourly periods

Method No.	Method	Preference Ranking	Equation(s)
1	e_a averaged over period[a,b]	1	--
2	Measured or calculated dew point temperature averaged over period	1	38
3	Average RH and T for the hour	1	37, 41
4	Wet-bulb and dry-bulb temperature	2	38, 39, 40
5	Daily minimum air temperature (see Appendix E)	3	--

[a] In many data sets, e_a may be expressed in terms of an equivalent dew point temperature.
[b] Some data logging systems may measure RH and T, but calculate e_a or T_{dew} internally for output as averaged values over some time interval.

When humidity and psychrometric data are missing or are of questionable integrity, dew point temperature can be estimated from daily minimum air temperature as described in Appendix E. This estimation procedure should be verified locally. The assessment of weather data integrity is discussed in Appendix D.

e_a from measured dew point temperature

The dew point temperature, T_{dew}, is the temperature to which the air must be cooled to reach a state of saturation. The value for e_a is calculated by substituting T_{dew} into Eq. 37 resulting in:

$$e_a = e^o(T_{dew}) = 0.6108 \exp\left[\frac{17.27\ T_{dew}}{T_{dew} + 237.3}\right] \qquad (38)$$

e_a from psychrometric data

The actual vapor pressure can also be determined from the difference between the dry and wet bulb temperatures (i.e., the wet bulb depression) of the air:

$$e_a = e^o(T_{wet}) - \gamma_{psy}\left(T_{dry} - T_{wet}\right) \qquad (39)$$

where:

e_a = actual vapor pressure of the air [kPa],
$e°(T_{wet})$ = saturation vapor pressure at the wet bulb temperature [kPa] (Eq. 37),
γ_{psy} = psychrometric constant for the psychrometer [kPa °C^{-1}], and
T_{dry}-T_{wet} = wet bulb depression, where T_{dry} is the dry bulb temperature and T_{wet} is the wet bulb temperature [°C] (measured simultaneously).

The psychrometric constant for the psychrometer at the weather measurement site is given by:

$$\gamma_{psy} = a_{psy} P \qquad (40)$$

where:

a_{psy} = coefficient depending on the type of ventilation of the wet bulb [°C^{-1}], and
P = mean atmospheric pressure [kPa].

The coefficient a_{psy} depends primarily on the design of the psychrometer and on the rate of ventilation around the wet bulb. The following values are often used[19]:

a_{psy} = 0.000662 for ventilated (Asmann type) psychrometers, with air movement of approximately 5 m s^{-1},
= 0.000800 for naturally ventilated psychrometers with air movement of about 1 m s^{-1}), and
= 0.001200 for non-ventilated psychrometers installed in glass or plastic greenhouses (List, 1984).

<u>e_a from relative humidity data</u>

[19] Allen et al., (1998).

The actual vapor pressure of air for hourly periods can be calculated from relative humidity (RH) and saturation vapor pressure at the corresponding air temperature (from Eq. 37):

$$e_a = \frac{RH}{100} e^o(T) \tag{41}$$

where:

RH = mean relative humidity for the hourly period, %, and
T = mean air temperature for the hourly period, °C.

Net Radiation (R_n)

Net radiation (R_n) is the net amount of radiant energy available at the vegetation or soil surface for evaporating water, heating the air, or heating the surface. R_n includes both short and long wave radiation components [20]:

$$R_n = R_{ns} - R_{nl} \tag{42}$$

where:

R_{ns} = net shortwave radiation, [MJ m^{-2} h^{-1}] (defined as being positive downwards and negative upwards),
R_{nl} = net outgoing long-wave radiation, [MJ m^{-2} h^{-1}] (defined as being positive, upwards and negative downwards),

R_{ns} and R_{nl} are generally positive or zero in value.

Net radiation is difficult to measure because net radiometers are problematic to maintain and calibrate. There is good likelihood of systematic biases in R_n measurements. Therefore, R_n is

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[20] Reference: Brutsaeart (1982), Jensen et al., (1990), Wright (1982), Doorenbos and Pruitt, (1975, 1977), Allen et al., (1998).

often predicted from observed short wave (solar) radiation, vapor pressure, and air temperature. This prediction is routine and generally highly accurate. If R_n is measured, care and attention must be given to the calibration of the radiometer, the surface over which it is located, maintenance of the sensor domes, and level of the instrument. The condition of the vegetation surface is as important as the sensor. For purposes of calculating ET_{sz} , the measurement surface for R_n is generally assumed to be clipped grass or alfalfa at full cover.

Net Solar or Net Short-Wave Radiation (R_{ns})

Net short-wave radiation resulting from the balance between incoming and reflected solar radiation is given by:

$$R_{ns} = R_s - \alpha R_s = (1 - \alpha) R_s \qquad (43)$$

where:

R_{ns} = net solar or short-wave radiation [MJ m^{-2} h^{-1}],

α = albedo or canopy reflection coefficient, is fixed at 0.23 for the standardized short and tall reference surfaces [dimensionless], and

R_s = the incoming solar radiation [MJ m^{-2} h^{-1}].

The calculation of ET_{sz} uses the constant value of 0.23 for albedo for daily and hourly periods. It is recognized that albedo varies somewhat with time of day and with time of season and latitude due to change in sun angle. However, because the solar intensity is less during these periods, the error introduced in fixing albedo at 0.23 is relatively small (Allen et al., 1994b). Users may elect to use a different prediction for albedo, however, they are strongly encouraged to ascertain the validity and accuracy of an alternative method using good measurements of incoming and reflected solar radiation. Some types of pyranometers are invalid for measuring reflected radiation due to the difference in spectral response between the instrument and reflecting surface. Predictions of R_n made using an alternate method for albedo (i.e., other than 0.23) may not agree with those made using the ASCE standardized procedure.

Net Long-Wave Radiation (R_{nl})

There are several variations and coefficients developed for predicting the net long wave component of total net radiation. The standardized ASCE procedure is the same as that adopted by FAO-56 and is based on the Brunt (1932, 1952) approach for predicting net surface emissivity. If users intend to utilize a different approach for calculating R_n, it is essential to ascertain the validity and accuracy of their method using net radiometers in excellent condition and that are calibrated to some dependable and recognized standard. In all situations, users should compare measured R_n or R_n computed using an alternative method with R_n calculated using the standardized procedure. Substantial variation (more than 5 %) should give cause for concern and should indicate the need to reconcile or justify the differences.

R_{nl} is the difference between long-wave radiation radiated upward from the standardized surface (R_{lu}) and long-wave radiation radiated downward from the atmosphere (R_{ld}), so that $R_{nl} = R_{lu} - R_{ld}$. The following calculation for R_{nl} is the method introduced by Brunt (1932, 1952) that uses near surface vapor pressure to predict net surface emissivity:

$$R_{nl} = \sigma f_{cd} \left(0.34 - 0.14 \sqrt{e_a}\right) T_{K\,hr}^4 \qquad (44)$$

where

R_{nl} = net outgoing long-wave radiation [MJ m^{-2} h^{-1}],
σ = Stefan-Boltzmann constant [2.042 x 10^{-10} MJ K^{-4} m^{-2} h^{-1}],
f_{cd} = cloudiness function [dimensionless] (limited to $0.05 \le f_{cd} \le 1.0$),
e_a = actual vapor pressure [kPa],
$T_{K\,hr}$ = mean absolute temperature during the hourly period [K] (K = °C + 273.16).

The superscript "4" in Eq. 44 indicates the need to raise the air temperature, expressed in Kelvin units, to the power of 4. For periods during daytime when the sun is more than about 15° above the horizon (see procedures below), f_{cd} is calculated as:

$$f_{cd} = 1.35 \frac{R_s}{R_{so}} - 0.35 \qquad (45)$$

where:

R_s/R_{so} = relative solar radiation (limited to $0.3 \le R_s/R_{so} \le 1.0$),
R_s = measured or calculated solar radiation [MJ m^{-2} h^{-1}], and
R_{so} = calculated clear-sky radiation [MJ m^{-2} h^{-1}].

The ratio R_s/R_{so} in Eq. 45 represents relative cloudiness and is limited to $0.3 < R_s/R_{so} \le 1.0$ so that f_{cd} has limits of $0.05 \le f_{cd} \le 1.0$.

During nighttime, R_{so}, by definition, equals 0, and Eq. 45 is undefined. Furthermore, even small out of level of a pyranometer or imperfect correction for cosine error of the instrument (required for accurate measurement at low sun angle) can cause substantial deviation in the value for R_s/R_{so} when the sun is near the horizon (i.e., when R_{so} is small). Therefore, f_{cd} during periods of low sun angle and nighttime is defined using f_{cd} from a prior period having sufficient sun angle.

When sun angle above the horizon (β)[21] at the midpoint of the hourly or shorter time period is less than 0.3 radians (~15°), then:

$$f_{cd} = f_{cd\ \beta>0.3} \tag{46}$$

where:

$f_{cd\ \beta>0.3}$ = cloudiness function for the time period prior to when sun angle β (in the afternoon or evening) falls below 0.3 radians [dimensionless].

Note that if the time period is shorter than one hour, f_{cd} from several periods can be averaged into $f_{cd\ \beta>0.3}$ to obtain a representative average value. In mountain valleys where the sun may set near or above 0.3 radians (~15°), the user should increase the sun angle at which $f_{cd\ \beta>0.3}$ is computed and imposed. For example, for a location where mountain peaks are 20° above the horizon, a period should be selected for computing $f_{cd\ \beta>0.3}$ where the sun angle at the end of the time period is 25 to 30º above the horizon. The same adjustment is necessary when deciding when to resume computation of f_{cd} during morning hours when mountains lie to the east.

Only one value for $f_{cd\ \beta>0.3}$ is calculated per day for use during dusk, nighttime and dawn periods. That value for $f_{cd\ \beta>0.3}$ is hen applied to the time period when β at the midpoint of the period first falls below 0.3 radians (~15º) and to all subsequent periods until after sunrise when β again exceeds 0.3 radians. Computation of β is given in Eq. 62 in the following section.

Equations 45 – 46 will not apply at latitudes and times of the year when there are no hourly (or shorter) periods having sun angle of 0.3 radians or greater. These situations occur for latitudes at 50º for about one month per year (in winter), for latitudes at 60º for about 5 months per year, and for latitudes at 70º for about 7 months per year. At extreme latitudes, some fall and winter months have little or no daylight. Under these conditions, the application can average $f_{cd\ \beta>0.3}$ from fewer time periods or, in the absence of any daylight, can assume a ratio of R_s/R_{so} ranging from 0.3 for complete cloud cover to 1.0 for no cloud cover. Under these extreme conditions, the prediction of R_n during nighttime and low sun angle is only approximate.

The application of Eq. 46 presumes that cloudiness during periods of low sun angle and nighttime is similar to that during late afternoon or early evening. This is generally a reasonable assumption and is commensurate with the relative simplicity and moderate accuracy of Eq. 45. Some applications may wish to split the nighttime period into two halves, with the first half using $f_{cd\ \beta>0.3}$ computed from late afternoon or early evening and the second half using $f_{cd\ \beta>0.3}$ computed from R_s measured during the following morning (for the period when β is first > 0.3 radians). However, this additional computation requires looking ahead within a data set and will generally not add accuracy to the computations, since the timing of any shift in cloudiness during nighttime is unknown and due to the general, approximate accuracy of the f_{cd} function (Eq. 45).

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[21] The sun angle β is defined as the angle of a line from the measurement site to the center of the sun's disk relative to a line from the measurement site to directly below the sun and tangent to the earth's surface. This definition assumes a flat surface.

Clear-sky solar radiation

Clear-sky solar radiation, R_{so}, is used in the calculation of net radiation, R_n. Clear-sky solar radiation is defined as the amount of solar radiation, R_s, that would be received at the weather measurement site under conditions of clear-sky (i.e., cloud-free). The ratio of R_s to R_{so} in the equation for R_n is used to characterize the impact of cloud-cover on the downward emission of thermal radiation to the earth's surface. The value for R_{so} is a function of the time of year and latitude, and, in addition, the time of day for hourly calculation periods. These parameters affect the potential incoming solar radiation from the sun. Clear-sky solar radiation is also impacted by the station elevation (affecting atmospheric thickness and transmissivity), the amount of precipitable water in the atmosphere (affecting the absorption of some short wave radiation), and the amount of dust or aerosols in the air.

A daily R_{so} "envelope" was developed earlier in Figure 1 and compared to measured R_s. For purposes of calculating R_n, hourly R_{so} can be calculated using the following simple approach:

$$R_{so} = \left(0.75 + 2 \times 10^{-5}\, z\right) R_a \tag{47}$$

where:

R_{so} = clear-sky solar radiation [MJ m^{-2} h^{-1}],
z = station elevation above sea level [m], and
R_a = extraterrestrial radiation [MJ m^{-2} h^{-1}].

Equation 47 predicts progressively higher levels of clear sky radiation with increasing elevation. Elevation serves as a surrogate for total air mass and atmospheric transmissivity above the measurement site. Equation 47 is generally adequate for use in predicting the ratio R_s/R_{so} when calculating net radiation, R_n. Other more complex estimates for R_{so}, which include turbidity and water vapor effects as well as impact of sun angle are discussed in Appendix D. Those equations are recommended for assessing integrity of solar radiation data and may provide improved estimates for R_{so} for calculating R_n. The impact on ET_{SZ} of using the equations in Appendix D for R_{so} rather than Eq. 47 will generally be less than a few percent across a day and over an annual period.

Figure 2 illustrates a comparison of measured hourly solar radiation with R_{so} computed using Eq. 47 and using the more complicated, but generally more accurate, method presented as Eq. D.1-D.5 of Appendix D. Data from two days in late June are plotted. June 19 had some morning and mid-day cloudiness. June 20 was a cloud-free day. The R_s data from June 20 compare relatively well with both R_{so} methods throughout the day. The measured data plot slightly higher than either R_{so} estimate at mid-day, with the more complicated R_{so} method from Appendix D having better agreement than Eq. 48. Measured R_s exceeded the R_{so} curves for the 1100 reading on June 19 because of reflection from clouds near the weather site. In general, the solar radiation data appear to be of excellent quality and calibration.

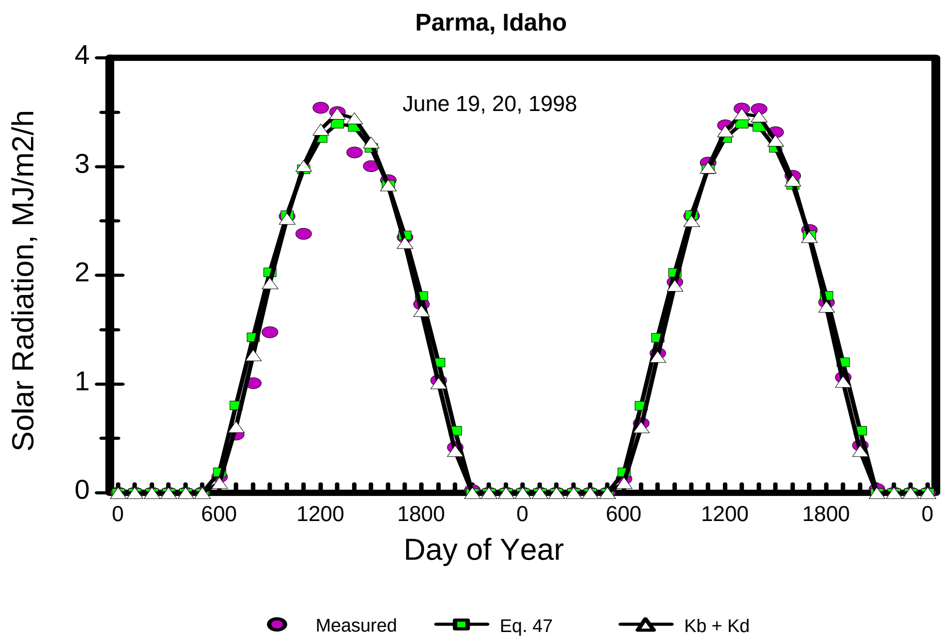

Figure 2. Measured and calculated hourly R_{so} for two days at Parma, Idaho during 1998 using Eq. 47 and using the more accurate $K_B + K_D$ method of Appendix D.

Extraterrestrial radiation for hourly periods (R_a)[22]

Extraterrestrial radiation, R_a, defined as the short-wave solar radiation in the absence of an atmosphere, is a well-behaved function of the day of the year, time of day, latitude, and longitude. For hourly time periods, the solar time angle at the beginning and end of the period serve as integration endpoints for calculating R_a:

$$R_a = \frac{12}{\pi} G_{sc}\, d_r \left[(\omega_2 - \omega_1)\sin(\varphi)\sin(\delta) + \cos(\varphi)\cos(\delta)\left(\sin(\omega_2) - \sin(\omega_1)\right)\right] \quad (48)$$

where

R_a	= extraterrestrial radiation during the hour (or shorter) period [MJ m^{-2} $hour^{-1}$],
G_{sc}	= solar constant = 4.92 MJ m^{-2} h^{-1},
d_r	= inverse relative distance factor (squared) for the earth-sun [unitless],
δ	= solar declination [radians],
φ	= latitude [radians],
ω_1	= solar time angle at beginning of period [radians], and
ω_2	= solar time angle at end of period [radians].

The latitude, φ, expressed in radians is positive for the Northern Hemisphere and negative for the Southern Hemisphere. The conversion from decimal degrees to radians is given by:

$$\text{Radians} = \frac{\pi}{180}\left(\text{decimal degrees}\right) \quad (49)$$

and d_r and δ are calculated as:

$$d_r = 1 + 0.033 \cos\left(\frac{2\pi}{365} J\right) \quad (50)$$

$$\delta = 0.409 \sin\left(\frac{2\pi}{365} J - 1.39\right) \quad (51)$$

[22] Reference: Duffie and Beckman (1980).

where J is the number of the day in the year between 1 (1 January) and 365 or 366 (31 December). J can be calculated as[23]:

$$J = D_M - 32 + \text{Int}\left(275\frac{M}{9}\right) + 2\ \text{Int}\left(\frac{3}{M+1}\right) + \text{Int}\left(\frac{M}{100} - \frac{\text{Mod}(Y,4)}{4} + 0.975\right) \tag{52}$$

where:

D_M	= the day of the month (1-31),
M	= the number of the month (1-12), and
Y	= the number of the year (for example 1996 or 96).

The "Int" function in Eq. 52 finds the integer number of the argument in parentheses by rounding downward. The "Mod(Y,4)" function finds the modulus (remainder) of the quotient Y/4.

The solar time angles at the beginning and end of each period are given by:

$$\omega_1 = \omega - \frac{\pi\ t_1}{24} \tag{53}$$

$$\omega_2 = \omega + \frac{\pi\ t_1}{24} \tag{54}$$

where:

ω	= solar time angle at the midpoint of the period [radians], and
t_1	= length of the calculation period [hour]: i.e., 1 for hourly periods or 0.5 for 30-minute periods.

The solar time angle at the midpoint of the period is:

$$\omega = \frac{\pi}{12}\left[\left(t + 0.06667(L_z - L_m) + S_c\right) - 12\right] \tag{55}$$

where:

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[23] Reference: Allen (2000)

t = standard clock time at the midpoint of the period [hour] (after correcting time for any daylight savings shift). For example for a period between 1400 and 1500 hours, t = 14.5 hours,

L_z = longitude of the center of the local time zone [expressed as positive degrees west of Greenwich, England]. In the United States, L_z = 75, 90, 105 and 120° for the Eastern, Central, Rocky Mountain and Pacific time zones, respectively, and L_z = 0° for Greenwich, 345° for Paris (France), and 255° for Bangkok (Thailand),

L_m = longitude of the solar radiation measurement site [expressed as positive degrees west of Greenwich, England], and

S_c = seasonal correction for solar time [hour].

Because ω_s is the sunset hour angle and $-\omega_s$ is the sunrise hour angle (noon has $\omega = 0$), values of $\omega < -\omega_s$ or $\omega > \omega_s$ from Eq. 55 indicate that the sun is below the horizon, so that, by definition, R_a and R_{so} are zero and their calculation has no meaning. When the values for ω_1 and ω_2 span the value for $-\omega_s$ or for ω_s, this indicates that sunrise or sunset occurs within the hourly (or shorter) period. In this case, the integration limits for applying Eq. 48 should be correctly set using the following conditionals:

$$\begin{gathered}\text{If } \omega_1 < -\omega_s \text{ then } \omega_1 = -\omega_s \\ \text{If } \omega_2 < -\omega_s \text{ then } \omega_2 = -\omega_s \\ \text{If } \omega_1 > \omega_s \text{ then } \omega_1 = \omega_s \\ \text{If } \omega_2 > \omega_s \text{ then } \omega_2 = \omega_s \\ \text{If } \omega_1 > \omega_2 \text{ then } \omega_1 = \omega_2\end{gathered} \qquad (56)$$

The above conditionals can be applied for all timesteps to insure numerical stability of the application of Eq. 48 as well as correctly computing the theoretical quantity of solar radiation early and late in the day. The user should recognize that Eqs. 48-56 and 62 presume an extensive, flat ground surface and are based on a vector to the center of the sun's disk. The calculations do not account for diffuse radiation occurring shortly before sunrise and shortly after sunset. Where there are hills or mountains, the hour angle when the sun first appears or disappears may increase for sunrise or decrease for sunset.

The seasonal correction for solar time is:

$$S_c = 0.1645 \sin(2\,b) - 0.1255 \cos(b) - 0.025 \sin(b) \tag{57}$$

$$b = \frac{2\pi (J - 81)}{364} \tag{58}$$

where J is the number of the day in the year and b has units of radians.

The sunset hour angle, ω_s, is given by:

$$\omega_s = \arccos\left[-\tan(\varphi)\tan(\delta)\right] \tag{59}$$

The "arccos" function is the arc-cosine function and represents the inverse of the cosine. This function is not available in all computer languages, so that ω_s can alternatively be computed using the arc tangent (inverse tangent) function:

$$\omega_s = \frac{\pi}{2} - \arctan\left[\frac{-\tan(\varphi)\tan(\delta)}{X^{0.5}}\right] \tag{60}$$

where:

$$X = 1 - [\tan(\varphi)]^2 [\tan(\delta)]^2 \tag{61}$$

$$\text{and } X = 0.00001 \text{ if } X \le 0$$

The user should confirm accurate setting of the datalogger clock. If clock times are in error by more than 5-10 minutes, estimates of extraterrestrial and clear sky radiation may be significantly impacted. This can lead to errors in estimating R_n on an hourly or shorter basis, especially early and late in the day. A shift in "phase" between measured R_s and R_{so} predicted from R_a according to the data logger clock can indicate error in the reported time. More discussion is given in Appendix D.

The angle of the sun above the horizon, β, at the midpoint of the hourly or shorter time period is computed as:

$$\beta = \arcsin\left[\sin(\varphi)\sin(\delta) + \cos(\varphi)\cos(\delta)\cos(\omega)\right] \quad (62)$$

where

β = angle of the sun above the horizon at midpoint of the period [radians],
φ = latitude [radians],
δ = solar declination [radians],
ω = solar time angle at the midpoint of the period [radians] (from Eq. 55).

The "arcsin" function is the arc-sine function and represents the inverse of the sine. This function is not available in all computer languages, so that β can alternatively be computed using the arc tangent (inverse tangent) function:

$$\beta = \arctan\left[\frac{Y}{\left(1 - Y^2\right)^{0.5}}\right] \quad (63)$$

where:

$$Y = \sin(\varphi)\sin(\delta) + \cos(\varphi)\cos(\delta)\cos(\omega) \quad (64)$$

and all other parameters are defined following Eq. 62.

Soil Heat Flux Density (G)

Soil heat flux density is the thermal energy that is utilized to heat the soil. G is positive when the soil is warming and negative when the soil is cooling. For hourly calculation periods, G beneath a dense cover of grass or alfalfa does not correlate well with air temperature, but can be significant. Hourly G generally correlates well with net radiation and amount of vegetative cover and can be approximated as a fraction of R_n. The following equations are based on Eq. B.13 of Appendix B for fixed vegetation height and leaf area index[24].

For the standardized short reference ET_{os} :

$$G_{hr\,daytime} = 0.1\ R_n \tag{65a}$$

$$G_{hr\,nighttime} = 0.5\ R_n \tag{65b}$$

where G and R_n have the same measurement units (MJ m^{-2} h^{-1} for hourly or shorter time periods). For the standardized tall reference ET_{rs} :

$$G_{hr\,daytime} = 0.04\ R_n \tag{66a}$$

$$G_{hr\,nighttime} = 0.2\ R_n \tag{66b}$$

For standardization, nighttime is defined as when measured or calculated hourly net radiation R_n is < 0 (i.e., negative). When the soil is warming, the soil heat flux density, G, has a positive value. The amount of energy consumed by G is subtracted from R_n when estimating ET_{os} or ET_{rs}.

Wind Profile Relationship

Wind speed varies with height above the ground surface. For the calculation of ET_{sz}, wind speed at 2 meters above the surface is required, therefore, wind measured at other heights must be adjusted. To adjust wind speed data to the 2-m height, Eq. 68 should be used for measurements above a short grass (or similar) surface, based on the full logarithmic wind speed profile equation B.14 given in Appendix B.

$$u_2 = u_z \frac{4.87}{\ln(67.8\ z_w - 5.42)} \tag{67}$$

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[24] Leaf area index (LAI) is defined as the area (one-sided) of leaves per unit area of ground surface. Units are dimensionless (i.e., m^2 m^{-2})

where

u_2 = wind speed at 2 m above ground surface [m s^{-1}],
u_z = measured wind speed at z_w m above ground surface [m s^{-1}], and
z_w = height of wind measurement above ground surface [m].

For wind measurements above surfaces other than clipped grass, the user should apply the full logarithmic equation B.14. A special application of Eq. B.14 is given in Appendix B for wind measured above alfalfa or similar vegetation having about 0.5 m height. It is noted that wind speed data collected at heights above 2 m are acceptable for use in the standardized equations following adjustment to 2 m, and may be preferred if vegetation adjacent to the station commonly exceeds 0.5 m. Measurement at a greater height, for example 3 m, reduces the influence of the taller vegetation.

Negative Values Computed for ET_{sz}

Values calculated for reference ET for nighttime hours occasionally take on negative values. In practice, the user may wish to set negative values to zero before summing over the 24-hour period. However, in some situations, negative hourly computed ET_{os} or ET_{rs} may indicate some condensation of vapor during periods of early morning dew and should therefore be registered as negative during the summing of 24-hour ET. In other situations, negative hourly ET_{os} or ET_{rs} during nighttime reflect the uncertainties in some parameter estimates including R_n and assumptions implicit to the combination equation. The impact of negative hourly values on ET summed over daily periods is usually less than a few percent. In general, it may be appropriate to retain the negative values.

DEFINITION AND APPLICATION OF CROP COEFFICIENTS

Calculation of crop evapotranspiration ($ET_{c)}$ requires the selection of the appropriate crop coefficient (K_c) for use with the standardized reference evapotranspiration (ET_{os} or ET_{rs}). It is recommended that the abbreviation for crop coefficients developed for use with ET_{os} be denoted as K_{co} and the abbreviation for crop coefficients developed for use with ET_{rs} be denoted as K_{cr}. ET_c is calculated as:

$$ET_c = K_{co} * ET_{os} \quad \underline{\text{or}} \quad ET_c = K_{cr} * ET_{rs} \qquad (68)$$

TRANSFER AND CONVERSION OF CROP COEFFICIENTS

Crop coefficients (K_C) and landscape coefficients available in the literature are referenced to either clipped, cool season grass or full-cover alfalfa. Without appropriate adjustment, crop coefficients for the two references are not interchangeable. For this standardization effort, a grass reference crop is defined as an extensive, uniform surface of dense, actively growing, cool-season grass with a height of 0.12 m, and not short of soil water. A full-cover alfalfa reference crop is defined here as an extensive, uniform surface of dense, actively growing alfalfa with a height of 0.50 m, and not short of soil water.

Grass-based crop coefficients should be used with ET_{os}, and alfalfa-based coefficients should be used with ET_{rs}. If a calculated or measured reference other than ET_{os} or ET_{rs} was used to develop the crop coefficients, it must be established that the reference equation or reference measurements provide values that are equivalent to ET_{os} or ET_{rs} (see Appendix A for comparisons between selected methods). It is important to establish the differences between ET equations since some equations developed to estimate grass or alfalfa reference ET may not agree exactly with ET_{os} or ET_{rs} during all time periods or under all climatic conditions.

K_c values that can be used with ET_{os} without adjustment include those reported in FAO-56 (Allen et al., 1998) and ASCE Manual 70 (Jensen et al., 1990, Table 6.8). Coefficients that can be used as is with ET_{os} for most practical applications are those reported by FAO-24 (Doorenbos and Pruitt, 1977) and SCS NEH Part 623 Chapter 2 (Martin and Gilley, 1993). Coefficients based on the CIMIS Penman equation (Snyder and Pruitt, 1992) should not require adjustment for use with ET_{os}. K_c values that can be used as is with ET_{rs} for most practical applications are those reported by Wright (1982) and ASCE Manual 70 (Jensen et al., 1990, Tables 6.6 and 6.9). There is a tendency for overestimation of ET using Wright (1982) in spring and fall. Thus, the K_c values by Wright (1981, 1982) have been converted for direct use with the ET_{rs} (reference…..).

Some grass and alfalfa based crop coefficients are "mean" crop coefficients (e.g., Wright, 1979; 1981; Doorenbos and Pruitt, 1977). Mean crop coefficients incorporate the effects of irrigation, rainfall, and soil type at the development site. Users of these mean crop coefficients are cautioned that differences in irrigation frequency, rainfall patterns, and/or soil drying characteristics between the development site and the study site could cause error in the ET_c estimate.

The publications referenced in the above paragraphs contain descriptions on determination and application of crop coefficients during growing periods. This information will not be presented here. The following section discusses the application of ET_{sz} and K_c during non-growing periods.

CALCULATION OF REFERENCE EVAPOTRANSPIRATION DURING NON-GROWING PERIODS

During cold periods in many regions, freezing temperatures preclude vegetation from remaining green and actively growing. These periods are referred to as non-growing periods. Evapotranspiration from non-active vegetation during non-growing periods is generally less than reference ET because plants may be dormant and therefore may have substantially increased surface resistance. Besides surface resistance, albedo or reflectance of dormant or dead vegetation is generally greater than that of green vegetation. Both of these characteristics reduce the potential rate of ET from plant residue. This may make it difficult to assess the validity of reference ET equations under these conditions.

While it is recognized that the reference ET equations do not represent measurable quantities during non-growing periods, the ET_{sz} equation can still be useful as an evaporative index. However, the user must be aware that conditions for the reference surfaces for ET_{os} and ET_{rs} may not exist during non-growing periods. Under many non-growing conditions, it is possible to incorporate the differences between dormant or dead vegetation ET and ET_{sz} into the K_c value. However there are other factors to be considered. For example, the soil heat flux estimates may be uncertain, low sun angles and snow cover will influence albedo, and short day lengths will affect the calculation of net radiation and ET_{sz} for daily time steps.

In this document the Task Committee will not recommend a methodology for the application of reference evapotranspiration during non-growing seasons. Two other ASCE Task Committees are investigating evaporative losses during non-growing seasons and are developing estimation methodologies.

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GLOSSARY OF TERMS

FOR THE

ASCE STANDARDIZED REFERENCE EVAPOTRANSPIRATION EQUATION

C_d	denominator constant that changes with reference type and calculation time step (s m^{-1})
C_n	numerator constant that changes with reference type and calculation time step (mm m^{-1} s d^{-1} ^oC kPa^{-1} or mm m^{-1} s h^{-1} ^oC kPa^{-1})
D_M	day of the month (1-31)
ET	Evapotranspiration (mm d^{-1} or mm h^{-1})
ET_c	Crop evapotranspiration
ET_{os}	Reference ET for a *short* crop with an approximate height of *0.12* m (similar to clipped grass) (mm d^{-1} or mm h^{-1})
ET_{ref}	Reference Evapotranspiration (mm d^{-1} or mm h^{-1})
ET_{rs}	Reference ET for a *tall* crop with an approximate height of *0.50* m (similar to full-cover alfalfa) (mm d^{-1} or mm h^{-1})
ET_{sz}	Standardized Reference Evapotranspiration Equation
G	soil heat flux density at the soil surface (MJ m^{-2} d^{-1} for daily time steps or MJ m^{-2} h^{-1} for hourly time steps)
G_{day}	daily soil heat flux density (MJ m^{-2} d^{-1})
$G_{hr\ daytime}$	hourly soil heat flux density during daytime (MJ m^{-2} h^{-1})
$G_{hr\ nighttime}$	hourly soil heat flux density during nighttime (MJ m^{-2} h^{-1})
G_{month}	monthly soil heat flux density (MJ m^{-2} d^{-1})
G_{sc}	solar constant (4.92 MJ m^{-2} h^{-1})
J	day of the year (1 – 365)
J_{month}	month of the year (1 –12)
K_{ab}	coefficient derived from the a_s and b_s coefficients of the Angstrom formula (unitless)
K_B	the clearness index for direct beam radiation (unitless)
K_c	crop coefficient
K_{co}	crop coefficient for use with ET_{os}
K_{cr}	crop coefficient for use with ET_{rs}
K_D	the transmissivity index for diffuse radiation (unitless)
K_G	coefficient used to calculate hourly soil heat flux (unitless)
K_t	atmospheric turbidity coefficient (unitless)
K_{time}	units conversion, equal to 86,400 s d^{-1} for ET in mm d^{-1} and equal to 3600 s h^{-1} for ET in mm h^{-1}
K_o	average difference between T_{min} and mean daily T_{dew} (^oC)
LAI	leaf area index = area (one-sided) of leaves per unit area of ground surface (m^2 m^{-2})
LAI_{active}	active (sunlit) leaf area index, m^2 (leaf area) m^{-2} (soil surface)

L_m longitude of the measurement site (expressed as positive degrees west of Greenwich, England)
L_z longitude of the center of the local time zone (expressed as positive degrees west of Greenwich, England)
M number of the month (1-12)
N maximum duration of sunshine or daylight hours (h)
P atmospheric pressure at station elevation z (kPa)
P_o atmospheric pressure at sea level = 101.3 (kPa)
R specific gas constant = 287 (J kg^{-1} K^{-1})
R_a extraterrestrial radiation (MJ m^{-2} d^{-1}) or (MJ m^{-2} h^{-1})
RH relative humidity (%)
RH_{max} daily maximum relative humidity (%)
RH_{mean} mean daily relative humidity
RH_{min} daily minimum relative humidity (%)
R_{lu} long-wave radiation emitted from the surface
R_{ld} long-wave radiation emitted from the atmosphere
R_n net radiation at the crop surface (MJ m^{-2} d^{-1} or MJ m^{-2} h^{-1})
R_{nl} net long-wave radiation (MJ m^{-2} d^{-1} or MJ m^{-2} h^{-1}), defined as being positive upwards and negative downwards
R_{ns} net short-wave radiation (MJ m^{-2} d^{-1} or MJ m^{-2} h^{-1}), defined as being positive downwards and negative upwards
R_s measured or calculated solar radiation (MJ m^{-2} d^{-1}) or (MJ m^{-2} h^{-1})
R_{so} clear-sky radiation (MJ m^{-2} d^{-1}) or (MJ m^{-2} h^{-1})
S_c seasonal correction for solar time (h)
T mean daily or hourly air temperature at 1.5 to 2.5-m height (°C)
T_{dew} dew point temperature (°C)
T_{dry} dry bulb temperature (°C)
T_{hr} mean hourly air temperature (°C)
T_K mean absolute temperature (K)
$T_{K\,hr}$ mean absolute temperature during the hour (K)
T_{Ko} reference temperature at elevation z_o (K)
$T_{K\,max}$ maximum absolute temperature during the 24-hour period (K)
$T_{K\,min}$ minimum absolute temperature during the 24-hour period (K)
T_{Kv} mean virtual temperature for period (K)
T_{hr} mean hourly air temperature (°C)
T_{max} daily maximum air temperature (°C)
T_{mean} mean air temperature for the time period of calculation (°C)
T_{min} daily minimum air temperature (°C)
T_{month} monthly mean air temperature (°C)
T_{wet} wet bulb temperature (°C)
W precipitable water in the atmosphere (mm)
Y number of the year (for example 1996 or 96)

a_{psy} coefficient depending on the type of ventilation of the wet bulb of a psychrometer (°C^{-1})
a_s coefficient of the Angstrom formula (unitless)

b_s	coefficient of the Angstrom formula (unitless)
c_p	specific heat of the air, (MJ kg^{-1} $^oC^{-1}$)
d	zero plane displacement height, (m)
daytime	hourly or shorter period when $R_n \geq 0$
d_r	inverse relative distance earth-sun (unitless)
e_a	mean actual vapor pressure at 1.5 to 2.5-m height (kPa)
$e^o(T)$	saturation vapor pressure function (kPa)
e_s	saturation vapor pressure at 1.5 to 2.5-m height (kPa)
f_{cd}	cloudiness function (unitless)
$f_{cd\ \beta>0.3}$	cloudiness function for the time period prior to when sun angle β (in the afternoon or evening) falls below 0.3 radians (unitless)
g	gravitational acceleration = 9.807 (m s^{-2})
h	reference vegetation height (m)
k	von Karman's constant, 0.41, (dimensionless)
k_{Rs}	adjustment coefficient for predicting R_s from air temperature (°C$^{-0.5}$)
n	recorded duration of sunshine during a day (h)
nighttime	hourly or shorter period when $R_n < 0$
r_a	aerodynamic resistance (s m^{-1})
r_l	bulk stomatal resistance of a well-illuminated leaf (s m^{-1})
r_s	surface resistance (s m^{-1})
t	standard clock time at the midpoint of the period
t_l	length of the calculation period (h)
u_2	mean daily or hourly wind speed at 2-m height (m s^{-1})
u_z	wind speed at height z (m s^{-1})
z	weather site elevation above mean sea level (m)
z_h	height of air temperature and humidity measurements (m)
z_o	elevation at reference level (i.e., sea level) (m)
z_{om}	roughness length governing momentum transfer (m)
z_{oh}	roughness length for transfer of heat and vapor (m)
z_w	height corresponding to wind speed (m)
α	"alpha" = albedo or canopy reflection coefficient (unitless)
α_l	constant lapse rate moist air = 0.0065 (K m^{-1})
β	"beta" = angle of the sun above the horizon (radians)
γ	"gamma" = psychrometric constant (kPa °C^{-1})
γ_{psy}	psychrometric constant for the psychrometer (kPa °C^{-1})
Δ	"delta" = slope of the saturation vapor pressure-temperature curve (kPa °C^{-1})
δ	"delta" = solar declination (radians)
ε	"epsilon" = ratio of the molecular weight of water vapor to dry air (unitless) (ε = 0.622)
λ	"lambda" = latent heat of vaporization (MJ/kg)
φ	"phi" = latitude (radians)
ρ_a	"rho" = air density (Kg m^{-3})
ρ_w	water density (Mg m^{-3}) (taken as 1.0 Mg m^{-3})

σ	"sigma" = Stefan-Boltzmann constant (4.901 10^{-9} MJ K^{-4} m^{-2} d^{-1})
ω	"omega" solar time angle (radians), solar noon = 0.
ω_s	sunset hour angle (radians)
ω_1	solar time angle at beginning of hourly or shorter period (radians)
ω_2	solar time angle at end of hourly or shorter period (radians)

APPENDIX A

DESCRIPTION OF TASK COMMITTEE'S METHDOLOGY AND PROCEDURES USED TO DERIVE THE STANDARDIZED REFERENCE EVAPOTRANSPIRATION EQUATION

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ASCE-ET RESPONSE TOTHE IRRIGATION ASSOCIATION

Cover Letter

January 26, 2000

Mr. Thomas H. Kimmell
Irrigation Association
8260 Willow Oaks Corporate Drive, Suite 120
Fairfax, VA 22031-4513

Re: Irrigation Association Request for a Benchmark Evapotranspiration Equation

Dear Mr. Kimmell:

In May 1999, the Irrigation Association (IA) requested that the American Society of Civil Engineers Evapotranspiration in Irrigation and Hydrology Committee (ASCE-ET) help establish and define a benchmark reference evapotranspiration (ET) equation.

ASCE-ET is pleased to inform you that a task committee (ASCE Task Committee on Standardization of Reference Evapotranspiration) of ASCE-ET members has developed standardized reference evapotranspiration equations for calculating hourly and daily evapotranspiration (ET) for both a short reference crop and a tall reference crop. Members of the Task Committee (TC) include renowned scientists and engineers, and both researchers and practitioners. A list of the TC members is attached. Using IA's original request as a catalyst, these experts recognized several needs for a standardized method of calculating reference ET. These needs included a standardized calculated evaporative demand that can be used for transferring crop coefficients, reducing confusion among users as to which equation(s) to use, increasing use of the crop coefficient x reference ET procedure to calculate crop ET, and developing more accurate estimates of ET.

One of the first steps in the definition of the equations was the establishment of criteria to be used for the determination of the equation(s). The criteria included:

The equation(s) should be *understandable*, i.e., represent a defined crop or hypothetical surface.

The equation(s) should be *defensible* and should be *traceable* to quality field measurements.

The approach should use *accepted methods*.

The approach should maximize *simplification* without significant loss of accuracy.

The approach should use *existing, readily available data*.

In reviewing IA's request and in their initial evaluation, the TC was concerned that the terms *standard* and *benchmark* carry connotations that may be misconstrued. These terms could lead users to assume that the calculated values determined using "the equation" were for comparison purposes or were a level to be measured against. That is not the purpose of the TC recommendation. **The objective of the TC's recommendations is to establish a methodology for calculating uniform ET estimates and thereby enhance the transferability of crop coefficients and the comparison of ET demands in various climates.**

The TC recommends that two Standardized Reference Evapotranspiration Equations along with *standardized* computational procedures be adopted. The equations are defined as:

Standardized Reference Evapotranspiration Equation, Short (ET_o): Reference ET for a *short* crop with an approximate height of *0.12* m (similar to grass).

Standardized Reference Evapotranspiration Equation, Tall (ET_r): Reference ET for a *tall* crop with an approximate height of *0.50* m (similar to alfalfa).

Two reference surfaces that are similar to known crops were recommended by the TC due to the widespread use of grass and alfalfa across the United States and due to their individual advantages for specific applications and times of the year. Furthermore, the TC concluded that hourly and daily forms of the equations were needed.

The basis of the equations is the ASCE Penman-Monteith as described in ASCE Manual 70 (Jensen et al. 1990) and the net radiation procedure described in FAO Irrigation and Drainage

Paper No. 56 (Allen et al. 1998). Future publications and summaries from the task committee will contain calculation procedures for all parameters required for applying the standardized reference ET equations. These parameters are currently defined and calculation procedures are described in the following publications: Allen et al. 1994, ASCE Hydrology Handbook (Allen et al. 1996), and FAO Irrigation and Drainage Paper No. 56 (Allen et al. 1998).

In the attached document, which describes the form of the equations, the TC has reduced the equations down to a single equation with an accompanying table of constants. The constants are a function of time step (hourly or daily) and reference surface (ET_o or ET_r).

Sincerely,

American Society of Civil Engineers
Evapotranspiration in Irrigation and Hydrology Committee
Standardization of Reference Evapotranspiration Equations Task Committee

Dr. Ronald Elliott, Chairman ASCE-ET

Ivan A. Walter, Chairman TC

Encl.
Cc: Bert Clemmens, ASCE Executive Committee

Equation As Sent to the Irrigation Association

Standardized Reference Crop Evapotranspiration Equations

ASCE Committee on Evapotranspiration
in Irrigation and Hydrology
January 2000

The Evapotranspiration in Irrigation and Hydrology Committee recommends that two Standardized Reference Evapotranspiration Equations be adopted for general practice along with *standardized* computational procedures. The standardized equations are derived from the ASCE Penman-Monteith (ASCE-PM) equation as described in ASCE Manual 70 (Jensen et al. 1990), in the ICID Bulletin (Allen et al. 1994), and in the ASCE Hydrology Handbook (Allen et al. 1996). The computation of parameters for the reference equations incorporates procedures for calculating net radiation, soil heat flux, vapor pressure deficit, and air density as described in FAO Irrigation and Drainage Paper No. 56 (Allen et al. 1998). A constant latent heat of vaporization, λ, equal to 2.45 MJ kg^{-1} is used for simplicity. Albedo for the reference surfaces is fixed at a constant 0.23. The equations assume that measurement heights for air temperature and water vapor content are made at a height in the range of 1.5 to 2.5 m above the ground. The standardized equations require that wind speed, u_2, is measured at or is adjusted to a 2 m measurement height. The coefficients in the ASCE standardized reference evapotranspiration equations presume that the weather data are measured over a grassed surface having a vegetation height of about 0.1 to 0.2 m.

The two standardized reference evapotranspiration (ET) equations are defined as:

<u>Standardized Reference Evapotranspiration Equation, Short (ET_o):</u> Reference ET for a *short* crop having an approximate height of *0.12* m (similar to grass).

<u>Standardized Reference Evapotranspiration Equation, Tall (ET_r):</u> Reference ET for a *tall* crop having an approximate height of *0.50* m (similar to alfalfa).

ASCE Standardized Reference Evapotranspiration Equation(s)

Both standardized reference equations were derived from the ASCE-PM by fixing h = 0.12 m for short crop (ET_o) and h = 0.50 m for tall crop (ET_r). The short crop and tall crop reference equations are traceable to the commonly used terms grass reference and alfalfa reference.

As a part of the standardization, the “full” form of the Penman-Monteith equation and associated equations for calculating aerodynamic and bulk surface resistance have been combined and reduced to a single equation having two constants. The constants vary as a function of the reference surface (ET_o or ET_r) and time step (hourly or daily). This was done to simplify the presentation and application of the methods. The constant in the right-hand side of the numerator (C_n) is a function of the time step and aerodynamic resistance (i.e., reference type). The constant in the denominator (C_d) is a function of the time step, bulk surface resistance, and aerodynamic resistance (the latter two terms vary with reference type, time step and daytime/nighttime).

Equation 1 presents the form of the Standardized Reference Evapotranspiration Equation for all hourly and daily calculation time steps. Table 1 provides values for the constants C_n and C_d.

$$ET_{ref} = \frac{0.408\Delta(R_n - G) + \gamma \dfrac{C_n}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + C_d u_2)} \qquad (1)$$

where ET_{ref} Short (ET_o) or tall (ET_r) reference crop evapotranspiration [mm day^{-1} for daily time steps or mm hour^{-1} for hourly time steps],

R_n net radiation at the crop surface [MJ m^{-2} day^{-1}for daily time steps or MJ m^{-2} hour^{-1} for hourly time steps],

G soil heat flux density at the soil surface [MJ m^{-2} day^{-1} for daily time steps or MJ m^{-2} hour^{-1} for hourly time steps],

T mean daily or hourly air temperature at 1.5 to 2.5-m height [°C],

u_2 mean daily or hourly wind speed at 2-m height [m s^{-1}],

e_s mean saturation vapor pressure at 1.5 to 2.5-m height [kPa]; for daily computation, value is the average of e_s at maximum and minimum air temperature,

e_a mean actual vapor pressure at 1.5 to 2.5-m height [kPa],

Δ slope of the vapor pressure-temperature curve [kPa °C^{-1}],

γ psychrometric constant [kPa °C^{-1}],

C_n numerator constant for reference type and calculation time step, and

C_d denominator constant for reference type and calculation time step.

Table 1. Values for C_n and C_d in Equation 1

Calculation Time Step	**Short Reference, ET_o**		**Tall Reference, Et_r**		**Units for ET_o, ET_r**	**Units for R_n, G**
	C_n	C_d	C_n	C_d		
Daily or monthly	900	0.34	1600	0.38	mm d^{-1}	MJ m^{-2} d^{-1}
Hourly during daytime	37	0.24	66	0.25	mm h^{-1}	MJ m^{-2} h^{-1}
Hourly during nighttime	37	0.96	66	1.7	mm h^{-1}	MJ m^{-2} h^{-1}

Equations associated with calculation of required parameters in Equation 1 and Table 1 have been standardized and will be described in a detailed report by this committee.

Definition of Crop Coefficients

Calculation of crop evapotranspiration (ET_c) requires the selection of the correct crop coefficient (K_c) for use with the standardized reference evapotranspiration (ET_o or ET_r). It is recommended that the abbreviation for crop coefficients developed for use with ET_o be denoted as K_{co} and the abbreviation for crop coefficients developed for use with ET_r be denoted as K_{cr}. ET_c is to be calculated as shown in equation 2.

$$ET_c = K_{co} * ET_o \text{ or } ET_c = K_{cr} * ET_r \tag{2}$$

References

Allen, R.G., M.E. Jensen, J.L. Wright, and R.D. Burman, 1989. Operational Estimates of Reference Evapotranspiration. *Agronomy Journal*, 81:650-662.

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Allen, R.G., W.O. Pruitt, J.A. Businger, L.J. Fritschen, M.E. Jensen, and F.H. Quinn, 1996. Chapter 4 "Evaporation and Transpiration" in ***ASCE Handbook of Hydrology,*** New York, NY, p. 125-252.

Allen, R.G., L.S. Pereira, D. Raes, and M. Smith, 1998. ***Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements***. United Nations Food and Agriculture Organization, Irrigation and Drainage Paper 56, Rome, Italy, 300 pages.

Jensen, M.E., R.D. Burman, and R.G. Allen, 1990. ***Evapotranspiration and Irrigation Water Requirements***, ASCE Manuals and Reports on Engineering Practice No. 70:ISBN 0-872627632, 332 p.

The ASCE-ET Task Committee on Standardization of Reference Evapotranspiration developed the recommendations. This Task Committee is sanctioned by the Irrigation and Drainage Council of the Environmental and Water Resources Institute, ASCE. Members of this task committee included I. A. Walter, R. G. Allen, M. E. Jensen, R. L. Elliott, R. H. Cuenca, S. Eching, M. J. Hattendorf, T. A. Howell, D. Itenfisu, D. L. Martin, B. Mecham, R. L. Snyder, T. L. Spofford, P.W. Brown, and J. L. Wright.

TASK COMMITTEE METHODOLOGY AND PROCEDURES

ASCE-ET Meetings

In response to IA, ASCE-ET committee members met on five occasions[1] to discuss the issues and needs for standardizing the definition and calculation of reference evapotranspiration, to review results of analyses, and to organize the TC report. They first met with members of IA's Water Management Committee (IA-WM) in Denver, Colorado on May 25 and 26, 1999 to review the IA request in detail and to select the basis for a Standardized Reference Evapotranspiration Equation. In August 1999, ASCE-ET held its annual meeting in Seattle, Washington and established the ASCE Task Committee on Standardization of Reference Evapotranspiration (TC). Additionally, ASCE-ET selected equations to be evaluated as candidate standardized reference ET equations.

The third meeting, held November 18 and 19, 1999 in Phoenix, Arizona involved TC members (some TC members are joint members of the ASCE-ET committee and the IA-WM committee). The purpose of that meeting was two-fold: (1) to evaluate the results of evapotranspiration estimates calculated using thirteen previously selected equations or variants on equations, data from 12 states, 36 sites, and 61 site-years; and (2) to develop a recommended Standardized Reference Evapotranspiration Equation. Prior to the Denver meeting and continuing after the Phoenix meeting, an extensive amount of e-mail exchanges between ASCE-ET and TC members shared opinions and data on several of the technical issues that needed to be associated with the standardized reference equation. These included the calculation of net radiation, latent heat of vaporization, and measurement units for meteorological data.

Additional meetings by the TC were Ft. Collins, CO, June 20-21, 2000; Phoenix, AZ, Nov. 13, 2000; Loveland, CO, April 4-5, 2001; Sacramento, CA, July 28-29, 2001; San Luis Obispo, CA, July 9-10, 2002.

Motivations For Implementation

The motivations for establishing and implementing a standardized equation were many. They included:

1. Standardized equation(s) provide a uniform calculation of evaporative demand, which improves transferability of crop coefficients from one region or state to another.

2. Practitioners have been confused by the numerous reference evapotranspiration equations that have been developed and published. The TC evaluated seven of these reference evapotranspiration equations for calculating reference evapotranspiration for grass, alfalfa, or both. A grass reference surface equation has been accepted internationally, but in the U.S.A., both grass and alfalfa reference equations are used.

3. Crop evapotranspiration (ET_c) rates are calculated as the product of reference evapotranspiration (ET_{ref}) and a crop coefficient (K_c). With standardization of a reference ET equation, the procedure will be more readily adopted by the private sector and government agencies.

4. Both the public and private sectors now operate automated weather stations that calculate ET_{ref} directly, and guidance, as to which equation to use, is needed.

5. A better hourly ET_{ref} equation is needed to improve ET_c estimation in coastal areas.

6. When summed over a 24-hour period, calculated hourly ET_{ref} should approximate calculated daily ET_{ref}.

Criteria

The TC established several criteria for the selection of the equation. The criteria used in the selection of the standardized reference evapotranspiration equation were:

1. The equation must be understandable.

2. Whether monthly, daily, or hourly data are used, the equation must be defensible, in that it will provide a precise, reliable measure of evaporative demand.

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[1] The fourth and fifth meetings were held in Phoenix, November 13, 2000 and Loveland, Colorado, April 5, 6, 2001 for review and editing of the TC report and standardization statement.

3. The equation should be a derivation of methods that have been accepted by the science and engineering communities such as those methods described in Jensen et al. (1990), Allen et al. (1989), Allen et al. (1994a, 1994b), and Allen et al. (1998).

4. Simplification of an accepted method to enhance its implementation and ease of calculations by users without significant loss of accuracy is desirable.

5. The equation should have the capability to use data from the numerous weather networks, which currently measure daily and hourly radiation, humidity, temperature, and wind speed.

6. The equation must be based on (or traceable to) measured or experimental data. Specifically, the user of the equation should be able to relate the equation to a known reference crop, evaporative index, or hypothetical surface.

7. Sums of hourly calculated ET should closely approximate daily computed ET values.

BACKGROUND FOR THE EQUATIONS EVALUATED BY THE TASK COMMITTEE

ASCE-ET members have a combined experience with numerous reference evapotranspiration equations totaling hundreds of years. The number of equations presently preferred by the members was relatively limited. They included:

1. ASCE Penman-Monteith (grass w/ h=0.12 m and alfalfa w/ h=0.50 m), Jensen et al. (1990)[2]

2. FAO-56 Penman-Monteith (grass), Allen et al.(1998)

3. Kimberly Penman (alfalfa), Wright (1982)

4. Penman (grass), Penman (1948, 1956, 1963)

5. CIMIS Penman (grass), Snyder and Pruitt (1985), Snyder and Pruitt (1992)

6. Hargreaves (grass), Hargreaves et al. (1985), Hargreaves and Samani (1985)

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[2]The ASCE Penman-Monteith method for grass reference was adopted by the USDA-SCS (now NRCS) into Chapter 2 of the NRCS Irrigation Guide, Martin and Gilley (1993)

In their many years of research and practical experience, TC members have found that no method is perfect. The following is a list of observations and concerns expressed by TC members.

1. In northern Colorado, locating a climate station over alfalfa or grass did not result in significant difference in ET_{ref} values calculated using the 1982 Kimberly Penman (alfalfa reference) or the ASCE-PM (applied to grass reference only). This is a consideration in selecting an agricultural weather station site.

2. The 1982 Kimberly Penman net radiation procedure was developed for the growing season (April-October). Its use outside that period is questionable.

3. Comparison of the ASCE Penman-Monteith for alfalfa to a simplified FAO-24 (Doorenbos and Pruitt, 1977) grass reference on a monthly time step found that the monthly ratios of ET_r/ET_o did not vary significantly during summer months.

4. Hourly computation of reference ET_o in coastal regions or windy areas where cold air advection occurs can result in significant differences among equations. Under these conditions, hourly estimates by the CIMIS Penman exceeded those by the FAO-56-PM.

5. Because of stomatal closure at night, the surface resistance (r_s) changes between day and night.

6. At Bushland, Texas and Kimberly, Idaho, comparison of daily-calculated ASCE-PM (0.50-m vegetation height) versus 1982 Kimberly Penman showed total ET estimated for the April-September period to be similar. The 1982 Kimberly Penman values were about 10% lower in the early spring and late fall months.

7. In Idaho, the 1982 Kimberly Penman more closely duplicated lysimeter ET than the ASCE-PM (height = 0.5 m), but differences were not significant. The 1982 Kimberly Penman equation had less scatter in the data, possibly because it reacts better to high wind. Additionally, the Kimberly equation places more weight on the Rn-G term than does the ASCE-PM equation.

8. At Bushland, Texas, comparisons of lysimeter-measured alfalfa and grass ET to the ASCE-PM equations, showed that on days of high wind and VPD the equations slightly under predicted ET. On other days, the ASCE-PM equations tracked the daily lysimeter well. Comparisons with hourly measured ET showed that the ASCE–PM with Manual 70 surface resistance values was slightly low during peak hourly periods.

Measure For Evaluating Equations

TC members have considerable experience comparing the ASCE Penman-Monteith (ASCE-PM) equation to ET measured using lysimeters for grass and alfalfa reference crops. TC members agreed that the ASCE-PM equation, when applied using aerodynamic and surface resistance algorithms presented in Jensen et al. (1990), provides accurate estimates of measured ET_{ref}. Wright et al. (2000) reported that the ratio of ET_r to lysimeter ET was 1.00 and the standard error of estimate was 0.65 mm d^{-1} at Kimberly, Idaho. Evett et al. (2000) reported ASCE-PM ET_r calculated using half-hour data compared well with measured reference lysimeter ET (regression r^2 of 0.91, SEE of 0.6 mm h^{-1}, slope of 0.94 and intercept of 0.2 mm). Use of daily data increased the SEE to 0.8 mm d^{-1} (r^2 = 0.91, slope = 0.98) and introduced a positive offset of 0.7 mm. Howell (1998) reported that the ASCE-PM ET_r performed well when compared to measured lysimeter evapotranspiration at Bushland, Texas. Howell et al. (2000) compared FAO-56 PM to measured grass reference lysimeter ET and reported the equation tended to overestimate grass ET for low rates and underestimate ET for high ET rates. The results were a regression r^2 of 0.701, SEE of 1.16 mm d^{-1}, slope of 0.79 and intercept of 1.39 mm. Ventura et al. (1999) compared Penman-Monteith hourly ET_o with a surface resistance of 42 and 70 s m^{-1} to lysimeter-measured ET for 0.12-m tall grass. It was reported that the root mean square errors were 0.26 and 0.44 W m^{-2}.

Since lysimeter-measured 0.12 m grass and 0.5 m alfalfa data are limited within the United States and worldwide, the TC selected the ASCE-PM reference ET values as the measure to evaluate proposed equations and variations on equations against. A detailed description of the ASCE-PM is presented in Appendix B.

Initially, TC members evaluated the performance of 12 ET_o equations and 8 ET_r equations. A listing of the equations and a brief description is provided in Table A-1. More detail is provided in Appendix B. See, for example, Table B-1 for definition of calculation of specific parameters in the equations and page B-4 for a more complete labeling and context for each equation.

Table A-1. Reference Evapotranspiration Equations and Procedures Evaluated[1]

Abbreviation	Method or Procedure	Description
ASCE-PM	ET_o & ET_r	ASCE Penman-Monteith, Jensen et al. (1990) w/Rn 56[2], G56[3], r_a & $r_s = f(h)$
FAO-56-PM	ET_o	ASCE-PM w/ h = 0.12 m, r_s = 70 s/m and albedo = 0.23, R_n 56, G = 0, λ = 2.45 MJ kg^{-1} , Allen et al. (1998)
ASCE-PMD	ET_o & ET_r	ASCE-PM, $r_a = f(h)$, albedo=0.23, daily ET_o, r_s = 70 s/m, hourly ET_o r_s = 50 & 200 s m^{-1}; daily ET_r, r_s = 45 s m^{-1}, hourly ET_r, r_s = 30 s/m & 200 s m^{-1}
ASCE-PMDL	ET_o & ET_r	ASCE-PMD, lambda = 2.45 MJ kg^{-1}
ASCE-PMv	ET_o & ET_r	ASCE-PMD & r_s specified by user
ASCE-PMDR	ET_o & ET_r	ASCE-PM with $R_n = R_{n\ Wright\ (1982)}$[4]
1982-Kpen	ET_r	1982 Kimberly Penman, Wright (1982 & 1987)
FAO24-Pen	ET_o	FAO-24 Penman, Doorenbos and Pruitt (1977)
1963-Pen	ET_o	1963 Penman, Penman (1963) (same wind function as Penman (1948))
1985-Harg	ET_o	1985 Hargreaves, Hargreaves et al. (1985)
ASCE-PMrf	ET_o & ET_r	ASCE-PM, reduced form: R_n 56, G 56, ET_o, r_s = 70 s m^{-1}; ET_r, r_s = 45 s m^{-1}; ET_o z_w & z_h = 2 m; ET_r z_w & z_h = 1.5 m, d = 0.8 m. The reduced form represented a test of the standardized equation
ASCE-PMrfh	ET_o & ET_r	ASCE-PM reduced form hourly only: ET_o, r_s = 50 s m^{-1}; ET_r, r_s = 30 s m^{-1}.
CIMIS-Pen	ET_o	CIMIS Penman (hourly) with Rn56 and G = 0, Snyder and Pruitt (1985)

[1] See table B-1 of Appendix B for definition of calculation of specific parameters in the equations and page B-4 for a more complete labeling and context for each of the Penman-Monteith equation forms.
[2] R_n 56 = net radiation calculated using FAO-56 procedures, Allen et al. (1998)
[3] G 56 = Soil heat flux calculated using FAO-56 procedures, Allen et al. (1998)
[4] $R_{n\ Wright}$= Wright = net radiation calculated using Wright (1982) procedure

Issues Addressed

Examination of Table A-1 and equations presented in the Appendices reveals that the TC evaluated several components of reference evapotranspiration. The methods for calculating net radiation and soil heat flux described in Jensen et al. (1990), Wright (1982), Doorenbos and Pruitt (1977), and Allen et al. (1998), were examined in detail. The latent heat of vaporization (λ) was evaluated over a wide range in air temperature and the impact on ET_{ref} of using a constant value (λ = 2.45 MJ kg^{-1}) was evaluated. The adoption of standardized values for surface and aerodynamic resistance occurred after intense review and discussion by e-mail between TC members and following evaluation across the U.S.A. (described later). Other components discussed in detail included the calculation of vapor pressure deficit and measurement units for meteorological data. The TC worked diligently to ensure that its recommendation for each component was within the established criteria.

Description of Evaluation

The evaluation of various ET equations and variations on equation application was accomplished in part by using REF-ET, a software program capable of calculating reference ET using up to 15 of the more common methods (Allen, 1999, 2000). For the TC comparisons, Allen modified the software to incorporate the equations and application variations listed in Table 1 that were established by the TC selected for the initial evaluation. REF-ET was distributed to TC members who had volunteered to calculate ET_o and ET_r using meteorological data within their region. A significant benefit resulting from using REF-ET was that outputs were standardized, which improved the efficiency of the TC analyses. At the 1999 meeting in Phoenix, the TC was able to evaluate results of reference evapotranspiration estimates at 36 sites within Arizona, California, Colorado, Idaho, Montana, Nebraska, Oklahoma, Oregon, South Carolina, Texas, Utah, and Washington. The elevations of sites varied from 2 to 2,895 meters. Mean annual precipitation amounts ranged from 152 to 2,032 mm. Following the 1999 meeting in Phoenix, data from Florida, Georgia, Illinois, and New York were added to the analysis.

The results obtained using REF-ET at all sites were submitted to Drs. Itenfisu and Elliott of Oklahoma State University (Itenfisu et al. 2000), where the information was compiled and several equation-to-equation comparisons were conducted. The key comparisons were:

- ET_{ref} versus ASCE-PM using daily data.
- The sum of 24 hourly ET_{ref} values versus ASCE-PM using daily data
- The sum of 24 hourly ET_{ref} values versus ET_{ref} using the same equation but with daily data.

The comparisons were made for both ET_o and ET_r. Itenfisu et al. (2000) determined the mean ratios of each equation estimate to that from the ASCE-PM, the Root Mean Square Difference (RMSD), and the RMSD as a percentage of ASCE-PM. The RMSD is calculated as the square root of the sum of the squared differences between the two estimates divided by the number of estimates

$$RMSD = \left(\frac{\sum_{i=1}^{n} (x_i - y_i)^2}{n} \right)^{0.5} \tag{A.1}$$

where

x_i = the i^{th} observation on estimate x

y_i = the i^{th} observation on estimate y

n = the number of observations.

For each of the site–year combinations, statistics were summarized for the growing season and, if available, for the full calendar year.

At the 1999 meeting in Phoenix, the TC spent two days reviewing and discussing the results for the 61 site-years. A detailed listing of the sites is presented in Appendix B. Conclusions from the analyses follow:

Review of the results of daily ET_o versus ASCE-PM ET_o for the growing season found:

1. The use of net radiation R_n computed using procedures from FAO-56 predicted ET_o and ET_r that was about 2 to 3 percent higher than that predicted using R_n computed using procedures by Wright (1982). These differences were judged to be relatively minor. It was noted that the time-based equations for predicting albedo and emissivity coefficients in the Wright (1982) procedure were developed for use only during the growing season (April-October) and for latitude of approximately 40 degrees north. Some caution should be exercised in applying the Wright (1982) procedures for R_n during the non-growing season and at sites outside an approximately 35 to 45 degree latitude band. For consistency, it is recommended that FAO-56 procedures be used to calculate R_n.

2. The 1985 Hargreaves equation revealed considerable site-to-site scatter in ratios of the Hargreaves ET_{ref} estimates to ASCE-PM estimates than for the other methods evaluated. (See Fig. A-1 and A-3) The 1985 Hargreaves equation did not perform well, and therefore should be calibrated, in high wind and coastal areas. For example, at Bushland Texas (mean monthly wind = 4.25 m/s, range: 3.23 to 5.39 m/s (Howell, et.al. 2000)) the ratio of 1985-Harg ET_o to ASCE-PM ET_o was 0.80. This equation may therefore need to be calibrated at other sites.

3. The 1963 Penman equation ET_o estimates ranged from 0.5 % less to 13% higher than ASCE-PM estimate and averaged about 7% high.

4. FAO-24 Penman, which is an ET_o equation, overestimated ET_o by about 17 % on an annual basis and by about 20 % during the growing season. Ironically, the FAO-24 Penman equation appears to provide a reasonably good estimate of ET_r unless the FAO-24 correction factors for wind and relative humidity are applied.

5. The use of a reduced form of ASCE-PM using constants for lambda (heat of vaporization) and r_s (surface resistance) resulted in a limited loss of accuracy (ranging from –0.06% to 0.04% error).

6. The reduced form of ASCE-PM was always within 1% of estimates by the original ("full-form") ASCE-PM.

The consensus of the TC was that the simplification of surface resistance, aerodynamic resistance, latent heat of vaporization and air density did not result in significant or unacceptable differences in ET_{ref} estimates. All differences were much less than the probable errors in actual ET_o measurements.

Review of the results of Daily ET_r versus ASCE-PM ET_r for the growing season found:

1. ASCE-PMDL (the ASCE-PM equation with heat of vaporization fixed at 2.45 MJ kg^{-1}) provides an excellent match to the ASCE–PM.

2. The use of the Wright (1982) Kimberly R_n procedure instead of the FAO-56 R_n procedure causes a reduction in the growing season ET_r estimate of approximately 2 to 3 percent. Largest decreases in ET_r occurred at Montana (4 to 5%), New York (4 to 5%), Georgia (3 to 4%) and Oregon (5 to 6%) stations.

3. Comparison of the 1982 Kimberly Penman to ASCE-PM for yearly data revealed that there was considerable variation, with ratios ranging from 0.86 to 1.04. (See Fig. A-2). The average ratio was about 0.94. Results indicated some correlation between the ratio and the latitude of the location. Additionally, the ratio of ET_r from the 1982 Kimberly Penman to the ASCE-PM ET_r tended to decrease with increase in ET during the peak month.

4. Comparison of the 1982 Kimberly Penman to ASCE-PM for growing seasons only, showed the ratio to range from 0.89 to 1.12 (see Fig. A-2). The average ratio was about 0.99. Ratios were within the range of 0.975 to 1.075 for more than 75% of the locations (Fig. A-2).

5. Comparison of ASCE-PMDR (i.e., the ASCE-PM using R_n from Wright (1982)) to ASCE-PM (using R_n from FAO-56) revealed that the ratio of the two methods was always 0 % to 3 % less than 1.0.

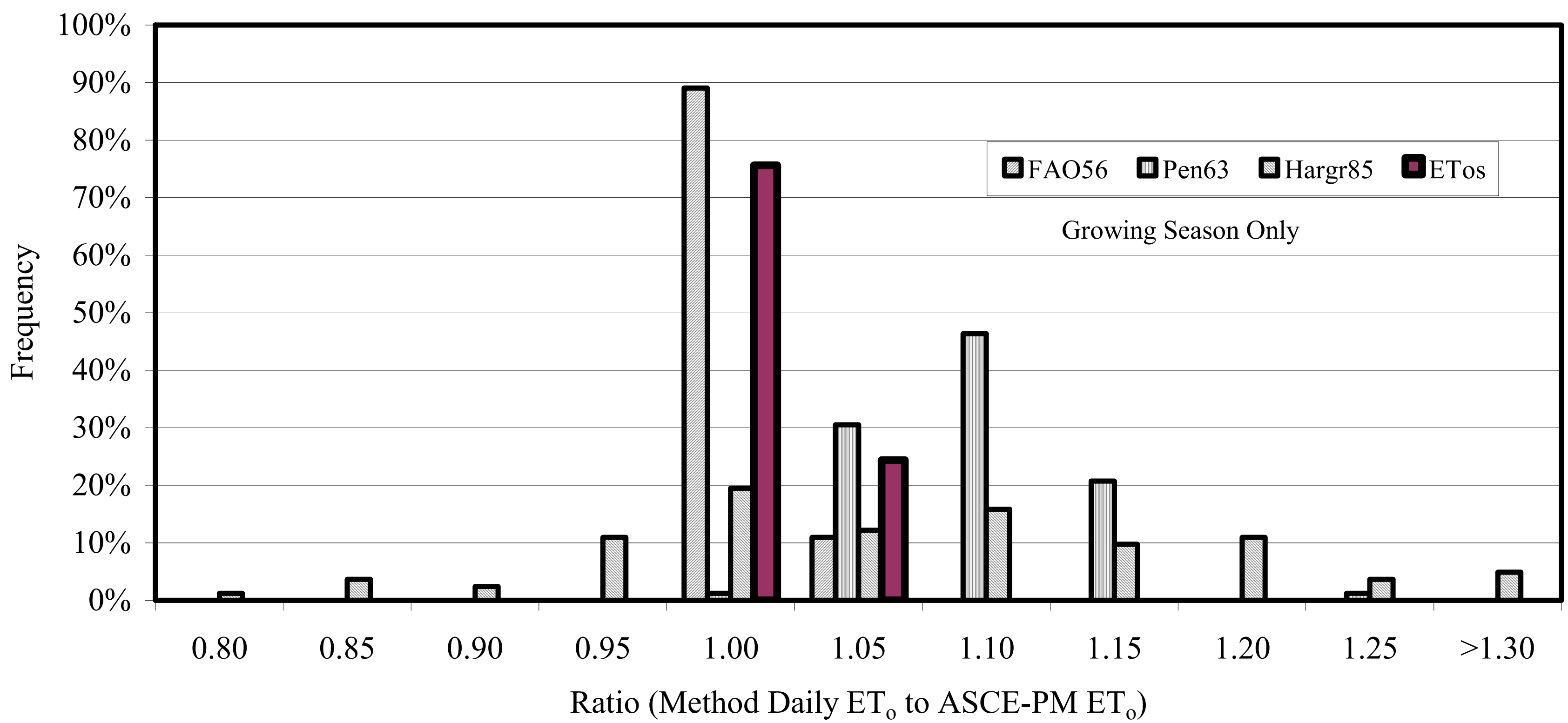

Figure A-1. Frequency of ratio of daily ET_o or ET_{os} to daily ET_o by ASCE-PM equation for 56 site-years covering 33 locations.

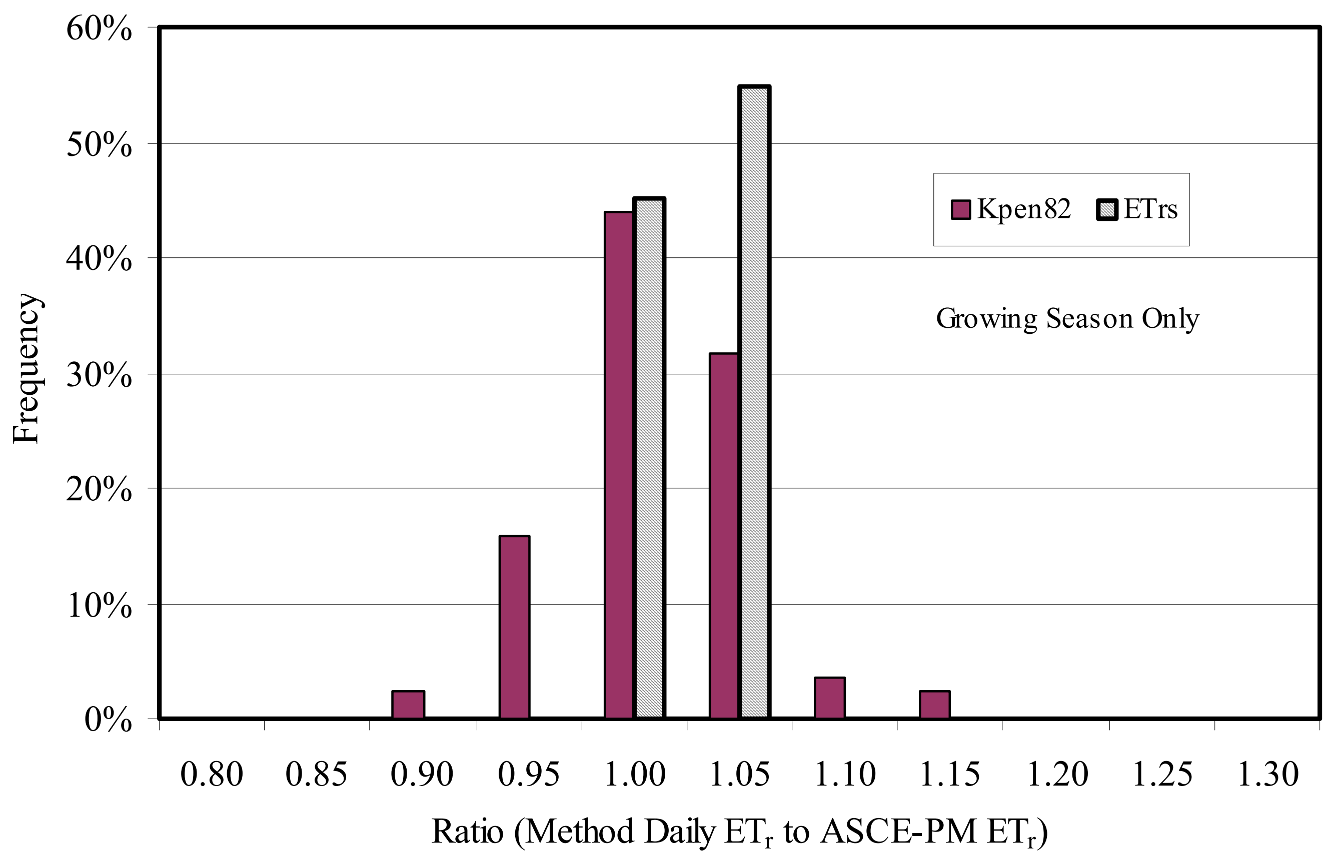

Figure A-2. Frequency of ratio of daily ET_r or ET_{rs} to daily ET_r by ASCE-PM equation for 56 site-years covering 33 locations.

When analyzing the results of summed hourly ET_o to daily ASCE-PM ET_o, the TC significant findings or discussions were as follows:

1. Soil Heat Flux (G). Concern was expressed that calculation of G in FAO-56 and ASCE Hydrology Handbook ($G=0.1\ R_n$ [for daytime] and $G = 0.5\ R_n$ [for nighttime]) might overpredict G. After viewing data provided by Cuenca from Oregon and Brown from Arizona, the TC concluded that the FAO-56 procedure provided good estimates.

2. Surface Resistance (r_s). The hourly r_s values of 50 and 200 s m^{-1} (day and night) were concluded to be reasonably accurate in matching ET_o calculated by the ASCE-PM using a daily time step. The yearly ratio averaged 0.996 and ranged from 0.938 to 1.052 and the growing season ratio averaged 1.003 and ranged from 0.940 to 1.078.

3. The ASCE-PMDL equation (same as the ASCE-PMD, but with fixed latent heat of vaporization) agreed well with and generally had a good fit relative to the ASCE-PM computed daily. The yearly ratio averaged 0.993 and ranged from 0.937 to 1.047 and the growing season ratio averaged 1.001 and ranged from 0.937 to 1.074. This indicates that the use of constant lambda does not introduce significant error.

4. The CIMIS equation (computed hourly and using R_n from FAO-56[3] and G=0) showed the most variability from site to site relative to the ASCE-PM equation computed daily, with ratios for the growing seasons ranging from 0.969 to 1.220 and averaging about 1.08. Much of the higher estimation by the CIMIS equation stemmed from using G = 0 for the hourly computations. The hourly applications of the ASCE-PM equation used $G = 0.1\ R_n$ during daytime and $G = 0.5\ R_n$ during nighttime.

When analyzing the results of summed hourly ET_r to daily ASCE-PM ET_r, the TC found the results were similar to and follow the discussion for ET_o above.

1. The results showed that the ASCE-PM applied hourly and summed daily matched the daily ASCE-PM fairly well when applied with r_s values of 30 and 200 s m^{-1} for day and night respectively (i.e., the ASCE-PMD method). The yearly ratio averaged 0.976 and ranged from 0.902 to 1.069 and the growing season ratio averaged 0.995 and ranged from 0.899 to 1.079.
2. The ASCE-PMDL (same as the ASCE-PMD, but with $\lambda = 2.45$ MJ kg^{-1}) was within acceptable accuracy. The yearly ratio averaged 0.974 and ranged from 0.902 to 1.064 and the growing season ratio averaged 0.992 and ranged from 0.897 to 1.075.

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[3] The standard CIMIS Penman application by CIMIS utilizes a R_n calculation procedure that is different from that by FAO-56.

PERFORMANCE OF THE STANDARDIZED REFERENCE EVAPOTRANSPIRATION EQUATION

Following the 1999 meeting in Phoenix, sixteen additional sites were added to improve the overall coverage for the U.S.A. The final number of site-years was 82 at 49 locations in 16 states, ranging from 73º to 125º longitude, 27º to 48º latitude, 2 to 2900 m elevation, and with 150 to 1500 mm annual precipitation. Drs. Intenfisu and Elliott recompiled the results for preparation of the final report (Itenfisu et al. 2000). To avoid confusion, the standardized ET_{ref} symbols are referred to as ET_{os} for the 0.12 m tall vegetative surface and as ET_{rs} for the 0.5 m tall vegetative surface. A comprehensive summary of the final comparison of ET_{os} and ET_{rs} to the ASCE-PM at the 49 sites was presented in Itenfisu et al. (2000) and Itenfisu et al. (2003). A partial listing of the Itenfisu et al. (2000, 2003) results and statistical summary is provided in Table A-2 and Appendix F.

Table -3 shows that the summed hourly ET_{os} and ET_{rs} compared as well or better versus daily ET_{os} and ET_{rs} as compared to the same analyses for the ASCE-PM equation. The comparisons of daily ET_{os} to daily ASCE-PM ET_o and daily ET_{rs} to daily ASCE-PM ET_r reveal only small differences; therefore, the simplifications are judged to have minimal impact on reference ET estimates. The third comparison of hourly sums of ET_{os} and ET_{rs} to daily ASCE-PM shows that ET_{os} and ET_{rs} agree closely with the ASCE-PM daily values.

Table A-2. Statistical summary of the comparisons between the Standardized Reference Evapotranspiration Equations and ASCE Penman-Monteith for the growing season for 82 site-years at 49 locations.

METHOD	RATIO				RMSD (mm d^{-1})				RMSD as % of Mean Daily ET
	Max	Min	Mean	Std Dev	Max	Min	Mean	Std Dev	Mean
Hourly Sum ET_o vs. Daily ET_o (within method)									
ASCE-PM	1.047	0.903	0.960	0.033	0.829	0.197	0.362	0.133	8.4
ASCE Stand'zed	1.081	0.941	1.012	0.028	0.663	0.228	0.334	0.084	7.7
Hourly Sum ET_r vs. Daily ET_r (within method)									
ASCE-PM	1.042	0.875	0.944	0.039	1.367	0.232	0.568	0.237	10.3
ASCE Stand'zed	1.108	0.931	1.022	0.037	1.048	0.315	0.540	0.152	9.6
Daily ET_o vs. Daily ASCE-PM ET_o									
ASCE Stand'zed	1.007	0.982	0.995	0.006	0.146	0.008	0.041	0.032	0.9
Daily ET_r vs. Daily ASCE-PM ET_r									
ASCE Stand'zed	1.025	0.974	0.998	0.010	0.300	0.014	0.069	0.058	1.28
Hourly Sum ET_o vs. Daily ASCE-PM ET_o									
ASCE-PM	1.047	0.903	0.960	0.033	0.829	0.197	0.362	0.133	8.4
ASCE Stand'zed	1.080	0.937	1.007	0.029	0.678	0.235	0.335	0.086	8.0
Hourly Sum ET_r vs. Daily ASCE-PM ET_r									
ASCE-PM	1.042	0.875	0.944	0.039	1.367	0.232	0.568	0.237	10.3
ASCE Stand'zed	1.108	0.933	1.020	0.037	1.067	0.331	0.532	0.144	9.41

The **daily-to-daily comparisons** are illustrated graphically in Figs. A-3 and A-4 for growing season periods. In these figures, the 82 site-year combinations are plotted along the horizontal axis in order of longitude (refer to Table A-3 to match a site to the corresponding site-year index). Figure A-3 shows mean ratios of daily calculations by the various ET_o equations to daily calculations by the ASCE-PM ET_o method. These ratios are the basis for the mean ratios presented in Table A-2. The similarity of the ASCE Standardized ET_{os}, FAO56-PM ET_{os}, and ASCE-PM ET_{os} results is obvious and is due to the commonality in the equations.

Mean daily ET_o and ET_r calculations for growing season periods for all locations are plotted against the full ASCE-PM equation estimates in Fig. A-5 and A-6. The data in Fig. A-5 show ET_o estimates by the original Penman method (1963 Penman) to have an approximately 0.3 mm d^{-1} bias relative to the daily ASCE-PM ET_o estimates across all locations and magnitudes of mean ET_o. Fig. A-6 shows mean growing season daily estimates of ET_r by the 1982 Kimberly Penman method to have predicted progressively lower than the daily ASCE-PM ET_r as mean ET_r for the growing season increased. Calculations by the standardized PM equation (ET_{os} and ET_{rs}) predicted closely to daily ET_o and ET_r by the full ASCE-PM equation over all sites and ranges of climate.

Comparisons of the method hourly sums to ASCE-PM daily are shown in Figs. A-7 and A-8 for growing season periods. The hourly ET_o by the 1963 Penman and CIMIS Penman equations have similar trends and both have ratios to ASCE-PM ET_o that average about 1.1 at many sites. The higher ratio by the 1963 Penman can be attributed to its linear wind function which becomes relatively strong during day time hours when wind speed and vapor pressure deficit have larger values. The higher ratios for the CIMIS equation, which has a wind function that is calibrated for hourly time steps, is partially due to the absence of the soil heat flux term in the equation as applied by CIMIS (see Appendix B). The wind functions of the CIMIS equation were developed without the inclusion of a soil heat flux term. The ET_o estimates by the FAO-PM and ASCE-PM methods applied hourly averaged about 5% below the ASCE-PM method applied daily due to the use of a constant 70 s m^{-1} surface resistance in those hourly applications

(Fig. A-7). Hourly ET_r by the ASCE-PM method averaged about 5% below daily ET_r by the ASCE-PM due to the use of a constant r_s = 45 s m^{-1} for hourly periods.

Table A-3. Summary of weather station sites in the study (listed from east to west longitude).

Site-Year Index	State	SITE	Longitude (degrees)	Latitude (degrees)	Elevation (m)	Mean Annual Precip. (mm)	Years (19--)	Peak-Month Mean ASCE-PM ET_o ($mm\ d^{-1}$)	
								Year 1	Year 2
1	NY	Willsboro	73.38	44.38	43	760	98	3.79	
2, 3	NY	Valatie	73.68	42.43	76	910	97 98	3.90	3.89
4, 5	NY	Ithaca	76.45	42.45	123	910	97 98	3.82	3.88
6	SC	Florence	79.81	34.24	40	1120	86	5.91	
7	FL	Fort Pierce	80.44	27.57	7	1422	99	4.68	
8, 9	FL	Lake Alfred	81.89	28.03	46	1270	98 99	5.66	4.88
10, 11	GA	Blairsville	83.93	34.84	584	1307	97 98	4.48	4.63
12, 13	GA	Griffin	84.28	33.26	282	1447	97 98	5.05	5.99
14, 15	GA	Attapulgus	84.49	30.76	37	1460	97 98	4.54	6.29
16	IL	Bondville	88.37	40.00	213	1008	99	5.18	
17	IL	Belleville	89.88	38.52	133	974	99	5.53	
18	IL	Monmouth	90.73	40.92	229	942	99	5.23	
19, 20	OK	Wister	94.68	34.98	143	1188	97 98	5.13	6.03
21, 22	NE	Mead	96.30	41.08	366	743	97 98	5.15	4.57
23, 24	OK	Marena	97.21	36.06	331	889	97 98	5.63	6.84
25, 26	NE	Clay Center	98.08	40.31	552	685	97 98	5.46	5.15
27, 28	OK	Apache	98.29	34.91	440	757	97 98	6.59	8.60
29, 30	NE	Champion	101.43	40.22	1029	482	97 98	6.64	6.18
31, 32	OK	Goodwell	101.60	36.60	996	447	97 98	8.56	9.68
33, 34	TX	Bushland	102.05	35.11	1170	505	97 98	7.36	9.34
35, 36	TX	Dalhart	102.32	36.20	1228	467	97 98	6.44	7.30
37, 38	CO	Ovid	102.45	40.97	1089	448	98 99	5.50	6.08
39, 40	CO	Rocky Ford	104.00	38.00	1274	279	97 99	7.08	8.02
41, 42	CO	Wiggins	104.06	40.31	1367	353	97 98	5.88	5.93
43	CO	Fort Collins	105.00	40.60	1527	383	95	5.58	
44, 45	CO	Loveland	105.11	40.40	1540	406	97 98	5.59	5.30
46, 47	CO	Center	106.14	37.71	2348	178	97 99	5.62	5.96
48, 49	CO	Colton	106	39	2743	279	82 83	4.65	4.69
50, 51	CO	Portis	106	39	2895	279	82 83	4.38	4.30
52, 53	CO	Fruita	108.70	39.18	1377	228	97 99	7.87	6.75
54, 55	CO	Yellow Jacket	108.74	37.39	2085	406	97 99	5.92	5.96
56, 57	AZ	Tucson	110.94	32.28	713	300	97 98	8.54	8.21
58, 59	ID	Ashton	111.47	44.03	1615	430	97 98	4.96	5.70
60, 61	UT	Logan	111.80	41.60	1350	433	89 90	6.21	5.77
62, 63	AZ	Phoenix Encanto	112.10	33.48	335	175	97 98	7.49	7.60
64, 65	MT	St. Ignatius	114.10	47.31	896	360	97 98	4.52	5.27
66, 67	MT	Creston	114.13	48.19	899	390	97 98	4.16	4.73
68, 69	MT	Ronan	114.28	47.54	927	380	97 98	4.31	4.70
70, 71	ID	Twin Falls	114.35	42.61	1195	222	97 98	5.69	6.44
72, 73	ID	Parma	116.93	43.80	703	237	97 98	5.66	6.10
74	WA	Paterson	119.49	45.94	109	152	98	6.65	
75	CA	Fresno	119.70	36.80	103	269	98	7.11	
76	WA	Gramling	119.73	46.29	386	178	98	7.42	
77	WA	Roza	119.73	46.29	343	178	98	5.96	
78	CA	Santa Maria	120.40	35.00	82	314	98	4.42	
79	CA	Davis	121.80	38.50	18	461	98	6.71	
80	WA	Puyallup	122.30	47.10	61	1016	98	3.48	
81	WA	Grayland	124.00	46.78	2	2032	98	2.78	
	82	Haga	124.50	42.50	9	1778	99	3.32	

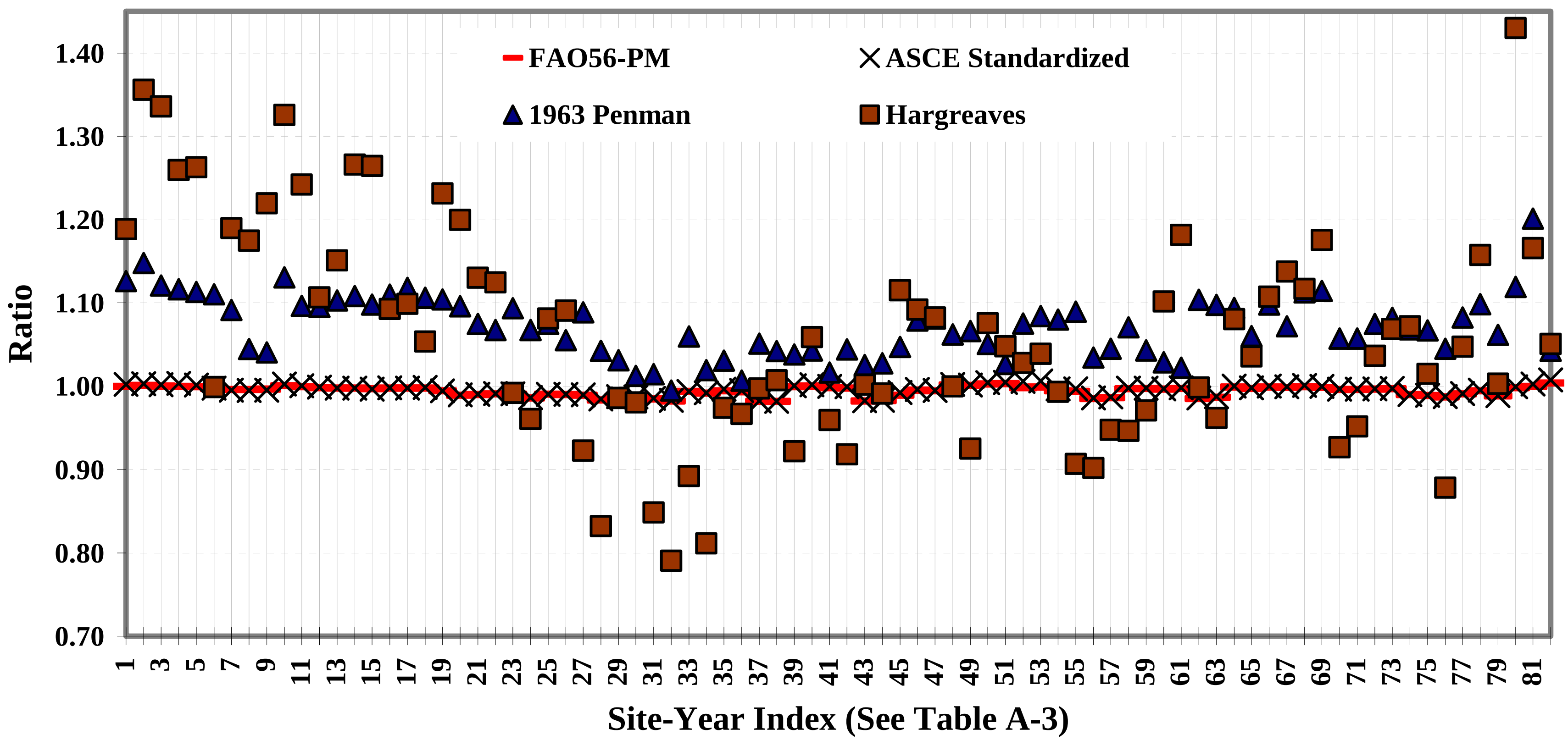

Figure A-3. Average ratio of daily ET_o or ET_{os} to daily ET_o by ASCE-PM ET_o equation.

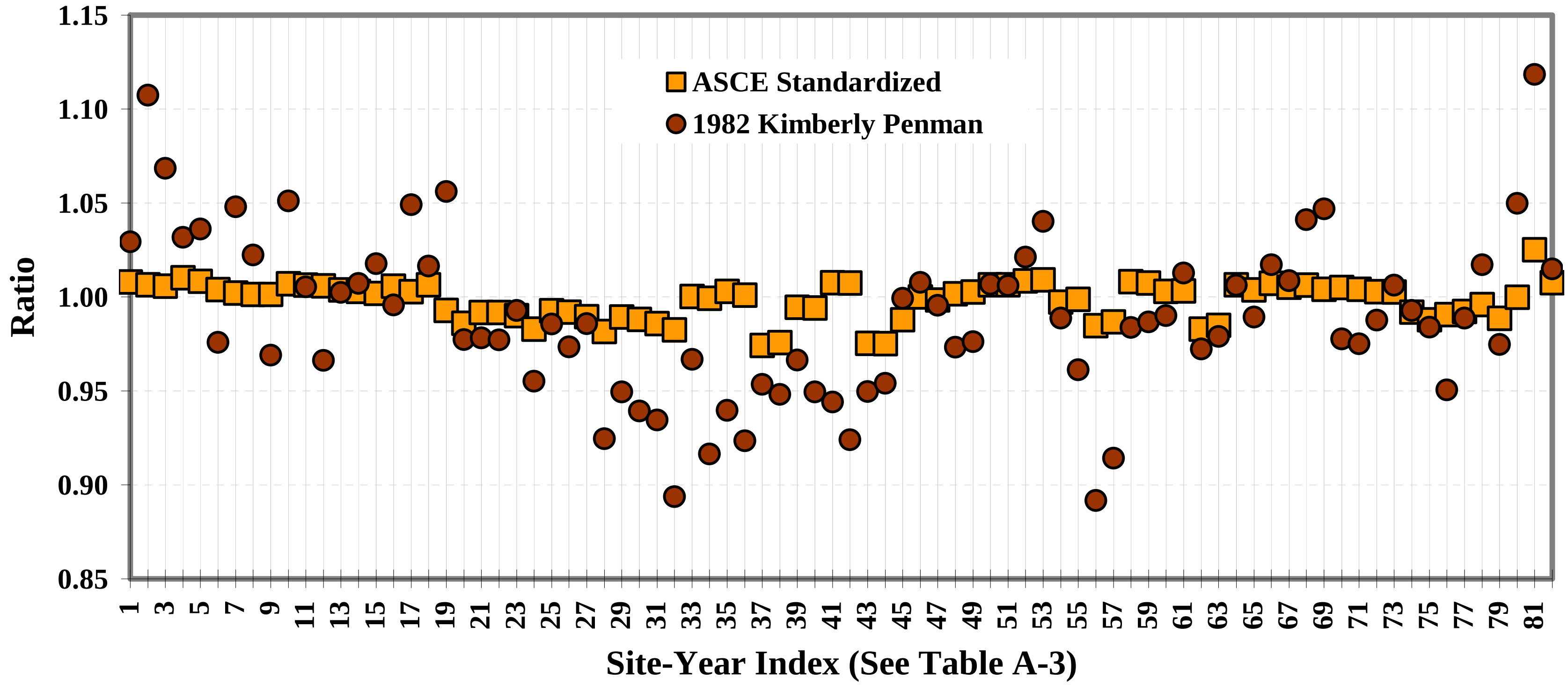

Figure A-4. Average ratio of daily ET_r or ET_{rs} to daily ET_r by ASCE-PM equation.

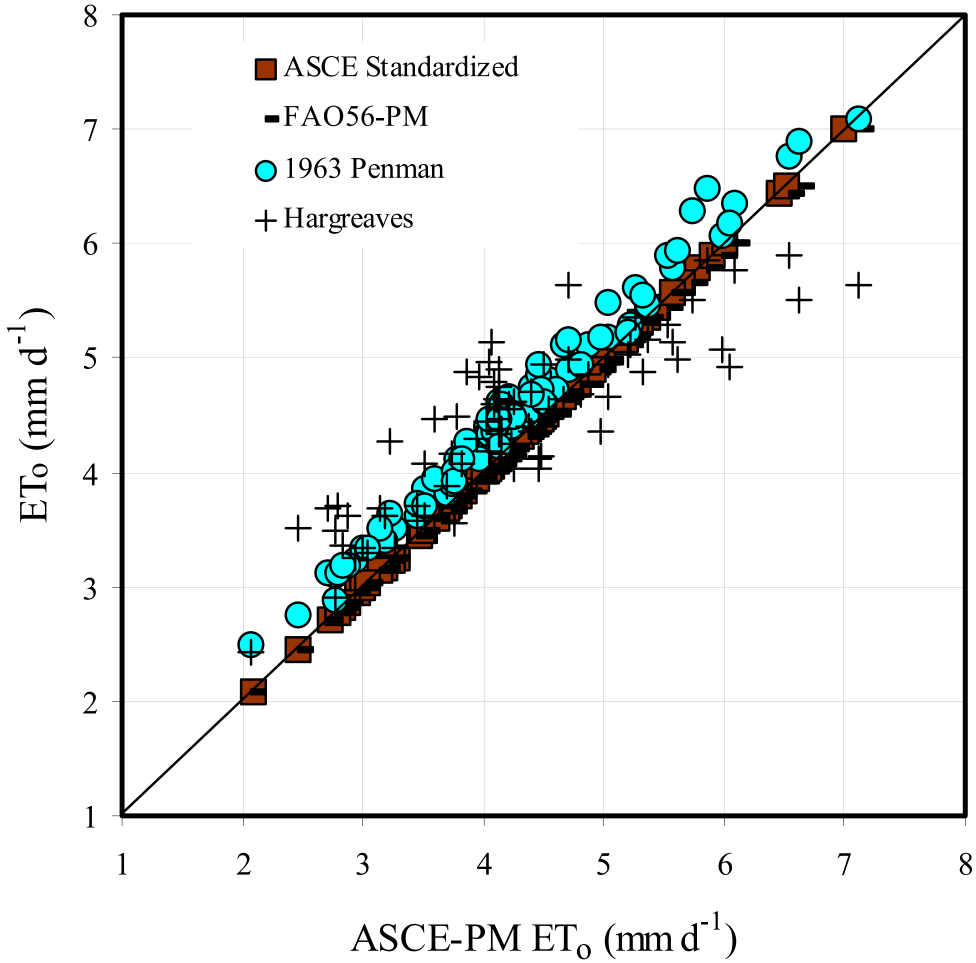

Figure A-5. Mean daily ET_o for the growing season computed using various ET_o methods and ET_{os} vs. mean daily ET_o for the growing season using the full ASCE-PM equation, for daily time steps. Each data point represents one-site year of data (82 total site-years (see Table A-3 and App. F)).

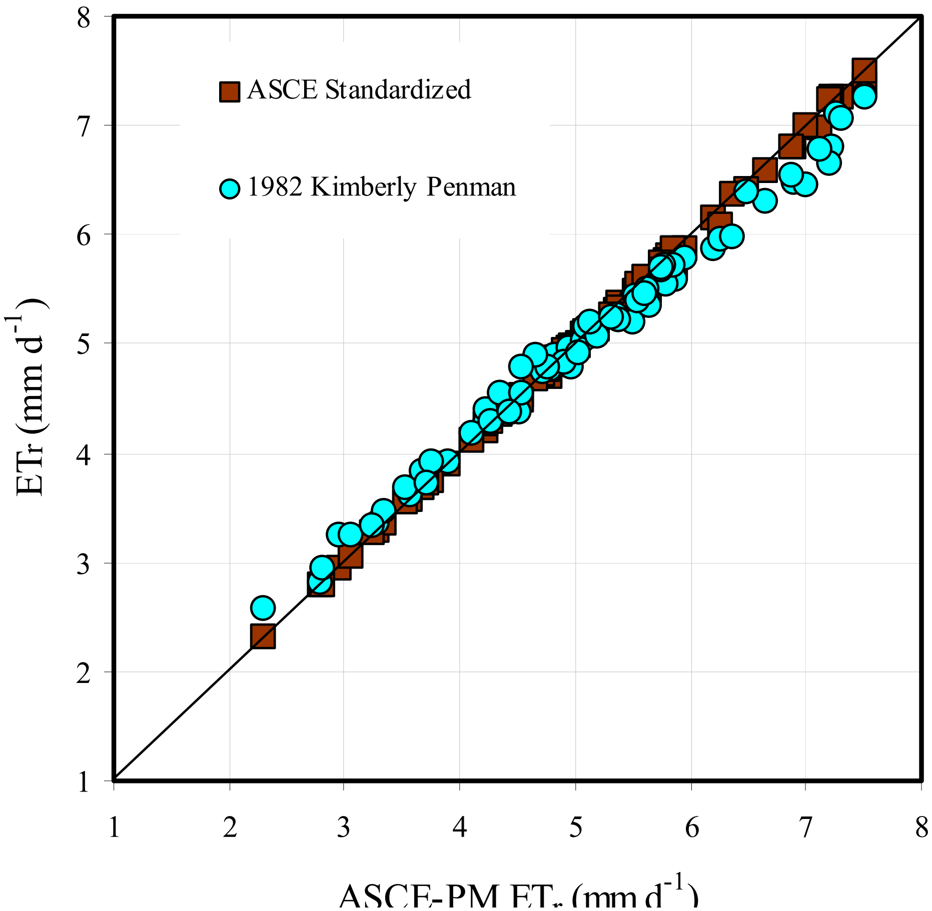

Figure A-6. Mean daily ET_r for the growing season computed using the 1982 Kimberly Penman method and ET_{rs} vs. mean daily ET_r for the growing season using the full ASCE-PM equation, for daily time steps. Each data point represents one-site year of data (82 total site-years (see Table A-3 and App. F)).

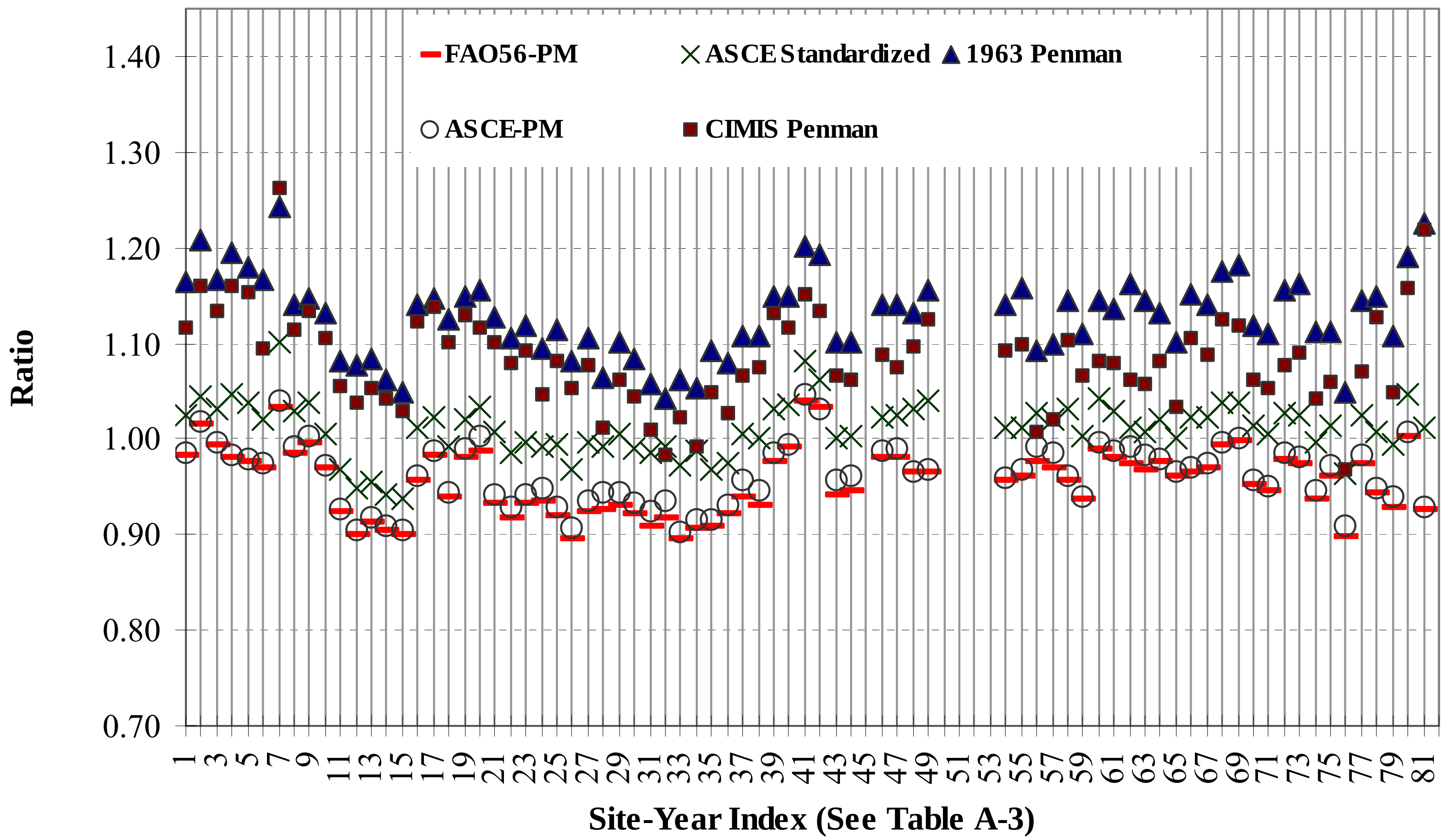

Figure A-7. Average ratio of summed hourly ET_o or ET_{os} to daily ET_o by ASCE-PM ET_o equation.

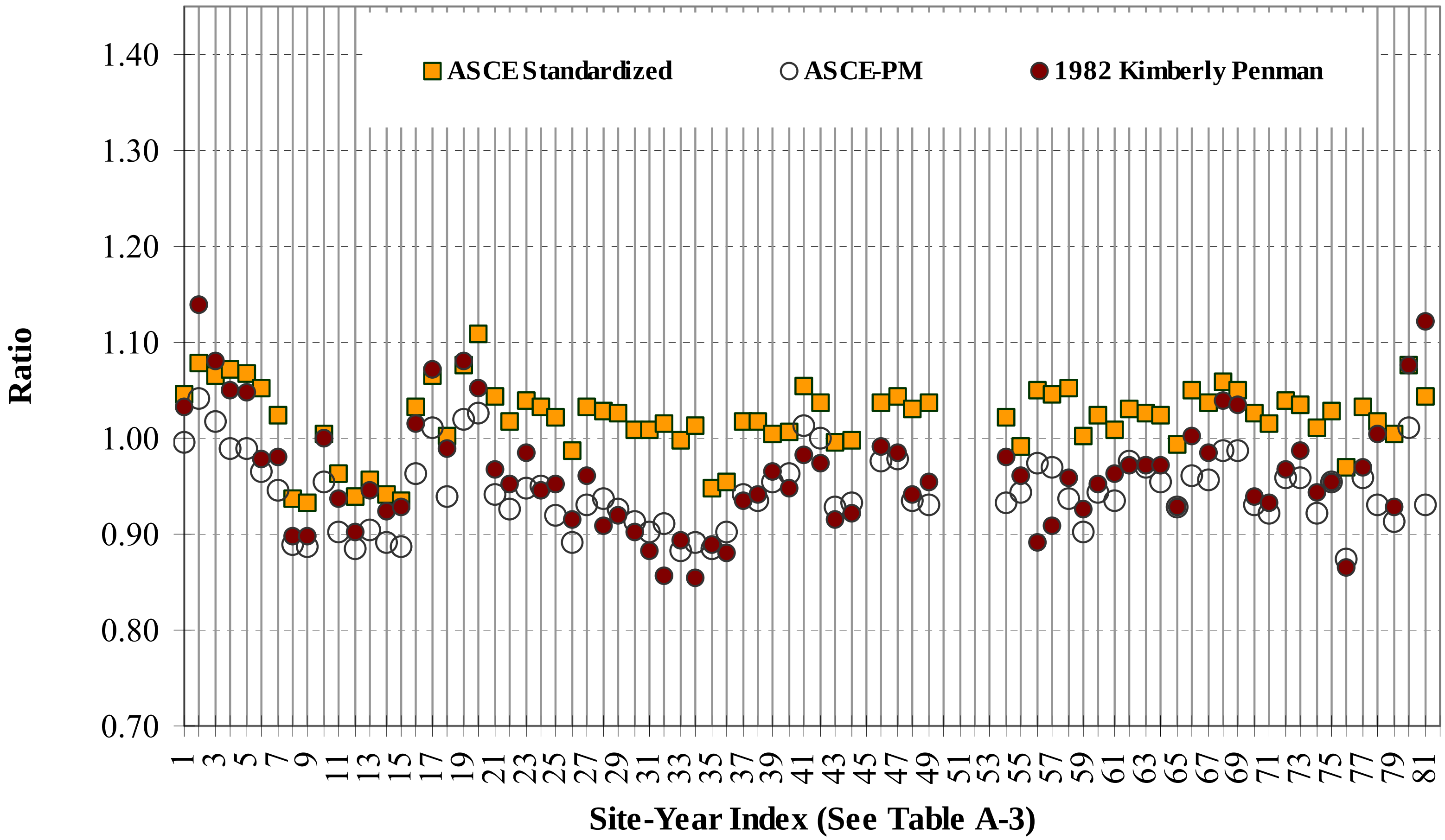

Figure A-8. Average ratio of summed hourly ET_r or ET_{rs} to daily ET_r by ASCE-PM ET_r equation.

TASK COMMITTEE CREDENTIALS

Credentials of members of the Task Committee are as follows:

Chairman Ivan A. Walter is a consulting engineer with Ivan's Engineering. He has 25 years of experience in water resources and agricultural and irrigation engineering. His engineering has involved projects related to surface and groundwater hydrology, water supply planning and development, irrigation engineering and water rights analysis. This involvement has included the investigation and analysis of evapotranspiration by agricultural crops and native vegetation, hydrologic studies and modeling of river basins, and computer modeling of surface water and groundwater hydrologic systems.

Vice-chairman Richard Allen is a professor of water resources engineering at the University of Idaho. He has 25 years of national and international experience in measuring weather and evapotranspiration and in development of methodology for computing evapotranspiration parameters. Allen was a joint author of FAO-56 and coeditor of ASCE Manuals and Reports on Engineering Practice No. 70.

Ronald Elliot is head of the Department of Biological and Agricultural Engineering, Oklahoma State University and is a co-principal investigator for the Oklahoma Mesonet.

Marvin E. Jensen is retired from the Agricultural Research Service, USDA, in 1987 and from Colorado State University in1993. Since 1993, he has been consulting on water consumption issues. He has 25 years experience in measuring evapotranspiration in field experiments and over 40 years experience in estimating evapotranspiration. Jensen was the editor of the 1974 ASCE Report Consumptive Use of Water and Irrigation Water Requirments and was senior editor of the 1990 ASCE Manuals and Reports on Engineering Practices No. 70.

Daniel Itenfisu is an irrigation engineer and was a postdoctoral fellow at Oklahoma State University during his task committee tenure. He has ten years of experience in irrigation water management, evapotranspiration and soil moisture modeling and measurements.

Brent Mecham is a Water Conservation Officer with the Northern Colorado Water Conservency District. He has more than 20 years experience in developing landscape management techniques and practices and crop coefficients.

Terry Howell is an Agricultural Engineer and Research Leader with the USDA-ARS Water Management Laboratory in Bushland, Texas. He has over 30 years experience in crop water requirements and ET measurement including lysimeter systems.

Richard Snyder is a biometeorology specialist for the University of California-Cooperative Extension. He was the principle investigator on the California Irrigation Management Information System (CIMIS), which provides reference evapotranspiration to California growers, water purveyors and public agencies. He is also involved in research to measure evapotranspiration and to refine crop coefficients.

Paul Brown is a biometeorology specialist for Arizona Cooperative Extension. He developed and presently oversees the operation of the Arizona Meteorological Network (AZMET) which provides weather-based information, including reference ET information, to Arizona growers and municipalities. His research interests include improving crop coefficients for use in arid irrigation management, and investigating the impact of weather station siting on computed values of ET_{ref}.

Simon Eching is a water use and evapotranspiration specialist with the California Department of Water Resources with applications in the CIMIS network. He has over 15 years experience in irrigation water management, crop water use, and soil moisture measurement. He has been involved in several international projects to develop weather station networks that provide reference evapotranspiration to irrigators.

Tom Spofford was Irrigation Engineer with the USDA-Natural Conservation Resources Service Technical Center in Portland, Oregon and is now National Water Management Engineer in Washington D.C.

Mary Hattendorf is an engineer with the Northern Colorado Water Conservancy District and was formerly manager of the Washington PAWS weather network for Washington State University.

James Wright is a Soil Scientist with the USDA-ARS Irrigation and Soils Research Laboratory at Kimberly, Idaho. He has 35 years experience in development of evapotranspiration equations and crop coefficients and measurement of evapotranspiration.

Derrel Martin is professor of Bioresources Engineering at the University of Nebraska and has over 25 years experience in irrigation water management, irrigated systems, and irrigation water requirements.

DATA CONTRIBUTORS

The following individuals provided weather data sets and/or REF-ET results: Paul Brown* (Arizona); Richard Snyder* and Simon Eching* (California); Ivan Walter*, Marvin Jensen*, and Brent Mecham* (Colorado); Brian Boman (Florida); Wanda Cavender and Gerrit Hoogenboom (Georgia); Richard Allen* and Peter Palmer (Idaho and Montana); Bob Scott and Steve Hollinger (Illinois); Lineu Rodriquez and Derrel Martin* (Nebraska); Art DeGaetano (New York); Daniel Itenfisu* and Ronald Elliott* (Oklahoma); Indi Sriprisan and Richard Cuenca* (Oregon); Dean Evans and Carl Camp (South Carolina); Don Dusek and Terry Howell* (Texas); Richard Allen* and Robert Hill (Utah); and Mary Hattendorf* (Washington). (*member of the ASCE TC or standardization study team).

APPENDIX B

SUMMARY OF REFERENCE EVAPOTRANSPIRATION EQUATIONS USED IN EVALUATION

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Latent Heat of Vaporization (λ) *7*
Atmospheric Pressure (P) *7*
Atmospheric Density (ρ_a) *8*
Psychrometric Constant (γ) *9*
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Wind Speed Adjustment for Measurement Height *9*

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INTRODUCTION

This appendix contains descriptions of the reference ET methods that were evaluated by the Task Committee at the 81 site-locations. The ET methods included well-known methods, (e.g. ASCE Penman-Monteith, 1982 Kimberly Penman) and hybrids of the ASCE-PM containing modifications to constants or parameterization of components. Definition of calculation procedures are summarized in Table B-1. Additional information for the hybrids of the ASCE-PM is provided in the discussion following Table B-1. Listed in Table B-1 for each parameter of each equation is the equation number, constant value, or procedure used to calculate that parameter. The labels for variations on the ASCE-PM equation are the same as those referred to in Table A-1, Appendix A.

Table B-1. Parameter equation numbers, etc. used in the Reference Equations Evaluated

Parameter	ASCE Penman-Monteith											
	"ASCE-PM"	"ASCE-PMD"	"ASCE-PMDL"	"ASCE-PMv"	"ASCE-PMDR"	ASCE Standardized Penman-Monteith	FAO-56 Penman-Monteith	1982 Kimberly Penman	1963 Penman	FAO-24 Penman	CIMIS Penman	1985 Hargreaves
Reference Types	ET_o, ET_r	ET_o, ET_r	ET_o, ET_r	ET_o, Et_r	ET_o, ET_r	ET_{os}, ET_{rs}	ET_o	ET_r	ET_o	ET_o	ET_o	ET_o
timestep	m, d, h	m, d, h	m, d, h	m, d, h	m, d, h	m, d, h	m, d, h	m, d, (h)[a]	m, d, h	m, d	h	m, d
Δ	5, 36	5, 36	5, 36	5, 36	5, 36	5, 36	5, 36	5	5	5	5	--
γ	B.12	B.12	B.12	B.12	B.12	4	4	B.12	B.12	B.12	B.12	--
λ	B.7	B.7	λ = 2.45 MJ/kg	B.7	B.7	λ = 2.45 MJ/kg	λ = 2.45 MJ/kg	B.7	B.7	B.7	B.7	--
P	B.8	B.8	B.8	B.8	B.8	3	3	B.8	B.8	B.8	B.8	--
α	α=0.23	α=0.23	α=0.23	α=0.23	α=B.25	α=0.23	α=0.23	α=B.25	α=0.23	α=0.23	α=0.23	--
R_n	15-18, 42-46	15-18, 42-46	15-18, 42-46	15-18, 42-46	B.22-B.25	15-18, 42-46	15-18, 42-46	B.22-B.25	15-18, 42-46	15-18	42-46	--
G	30,32, 65-66	30,32, 65-66	30,32, 65-66	30,32, 65-66	30,32, 65-66	30,32, 65-66	30,32, 65-66	B.26 (24-hr), 65-66 (hrly)	30,32, 65-66	30,32	G = 0.	--
R_{so}	19(24-hr), 47 (hrly)	19 (24-hr), 47 (hrly)	19 (24-hr), 47 (hrly)	19 (24-hr), 47(hrly)	19 (24-hr), 47-(hrly)	19 (24-hr), 47 (hrly)	19 (24-hr), 47 (hrly)	19 (24-hr), 47 (hrly)	19 (24-hr), 47 (hrly)	19 (24-hr)	47 (hrly)	--
u_2	Uses u_z	Uses u_z	Uses u_z	Uses u_z	Uses u_z	33, 67	33, 67	33, 67	33, 67	33	67	--
r_s	B.3-B.6	70 and 45 s m^{-1} (24-hr), 50 and 30 s m^{-1} day, 200 s m^{-1}, night	70 and 45 s m^{-1} (24-hr), 50 and 30 s m^{-1} day, 200 s m^{-1}, night	User defined	70 and 45 s m^{-1} (24-hr), 50 and 30 s m^{-1} day, 200 s m^{-1}, night	70 and 45 s m^{-1} (24-hr), 50 and 30 s m^{-1} day, 200 s m^{-1}, night (hrly)	70 s m^{-1} (all time steps)	--	--	--	--	--

Table B-1. Parameter equation numbers, etc. used in the Reference Equations Evaluated

Parameter	ASCE Penman-Monteith					ASCE Standardized Penman-Monteith	FAO-56 Penman-Monteith	1982 Kimberly Penman	1963 Penman	FAO-24 Penman	CIMIS Penman	1985 Hargreaves
	"ASCE-PM"	"ASCE-PMD"	"ASCE-PMDL"	"ASCE-PMv"	"ASCE-PMDR"							
		(hrly)	(hrly)		(hrly)							
r_a	B.2	B.2 for h=0.12m, H=0.5 m	B.2 for h=0.12m, h=0.5 m	B.2	B.2 for h=0.12m, H=0.5 m	B.2 is embedded in Eq. 1 for h=0.12m, h=0.5 m	B.2 is embedded in Eq. B.15 for h=0.12m	B.18	1.0	1.0	0.29 day 1.14 night	--
ρ	B.10	B.10	B.10	B.10	B.10	--	--	B.19	0.537	0.862	0.53 day 0.40 night	--
e_s	6, 37	6, 37	6, 37	6, 37	6, 37	6, 37	6, 37	6, 37	6, 37	6	37	--
e_a	order of preference is given in Tables 3 and 4 of the main text											

Numbers in cells refer to equations listed in the main text and appendices.

[a] The Kimberly Penman equations are not intended to be applied hourly, but they were evaluated for hourly timesteps in this study.

The variations on the ASCE Penman-Monteith equation that were evaluated by the task committee are described as follows:

1. ***"ASCE-PM" is the "full-form" ASCE Penman-Monteith*** using resistance equations by Allen et al. (1989) and in ASCE Manual 70 (Jensen et al. 1990). In ASCE-PM, r_s is computed from the leaf area index (LAI), which is a function of the height specified for the reference type (grass or alfalfa). Algorithms for LAI depend on reference type. The value of r_s (and r_a) change with height specified for the reference. The values for r_s for 24-hour timesteps, based on the ASCE LAI algorithms, are $r_s = 70$ s m^{-1} for 0.12 m tall grass and $r_s = 45$ s m^{-1} for 0.5 m tall alfalfa. This equation, when computed using a daily calculation timestep, was the measure against which the other equations were compared. The ASCE-PM method, using resistance parameters as defined in Manual 70 to be functions of vegetation height and computed with a daily timestep, was the method found to perform best against lysimeter measurements in Manual 70.

2. ***"ASCE-PMD" is the "full-form" ASCE Penman-Monteith*** and is the same as (1) except that the values for r_s for hourly or shorter timesteps were fixed at $r_s = 50$ s m^{-1} for 0.12 m tall grass and $r_s = 30$ s m^{-1} for 0.5 m tall alfalfa during daytime hours and $r_s = 200$ s m^{-1} for both 0.12 m tall grass and 0.5 m tall alfalfa during nighttime hours. The purpose of the variation was to evaluate whether use of a lower value for r_s for daytime and higher value for nighttime could improve the prediction for hourly timestep calculations relative to the ASCE-PM computed daily.

3. ***"ASCE-PMDL" is the "full-form" ASCE Penman-Monteith*** and is identical to (2) except that the value for the heat of vaporization was fixed at $\lambda = 2.45$ MJ kg^{-1}.The purpose of the variation was to evaluate whether use of a constant value for λ versus a calculated value impacted calculations significantly.

4. ***"ASCE-PMv" is the "full-form" ASCE Penman-Monteith with a user supplied resistance***. This method is the same as number 1, except that members of the TC had the option of specifying unique values for 24-hour, daytime and nighttime surface resistance, r_s, for each site. The purpose of the variation was to allow the TC members to test data from their region to determine what value for r_s resulted in accurate estimates of ET_{ref} in their region.

5. ***"ASCE-PMDR" is the "full-form" ASCE Penman-Monteith*** and is identical to (2) except that net radiation was calculated following Wright (1982) rather than Eq. 15 – 18 and 42 – 47. The purpose of this variation was to evaluate the degree to which using the Wright (1982) net radiation procedure in place of the standardized procedure impacted the ET_{ref} calculation.

6. ***ASCE Standardized Penman-Monteith equation*** is the standardized form of the ASCE-PM equation (ET_{sz}) specified by equations provided in the main text body.

7. ***FAO 56 Penman-Monteith equation.*** The FAO-56 PM method uses essentially identical calculation procedures as the standardized ET_{sz} equation, except for a constant surface resistance (70 s m^{-1}) that is applied to all timesteps and its application is to ET_o, only.

Basic equations and supporting parameter equations for equations other than the standardized equation are listed in the following sections.

ASCE PENMAN-MONTEITH METHOD

The Penman-Monteith form of the combination equation (Monteith 1965, 1981) is:

$$ET_{ref} = \left(\frac{\Delta(R_n - G) + K_{time}\, \rho_a\, c_p \dfrac{(e_s - e_a)}{r_a}}{\Delta + \gamma\left(1 + \dfrac{r_s}{r_a}\right)} \right) / (\lambda \rho_w) \qquad \text{(B.1)}$$

where

ET_{ref} = reference evapotranspiration [mm d^{-1} or mm h^{-1}],
R_n = net radiation [MJ m^{-2} d^{-1} or MJ m^{-2} h^{-1}],
G = soil heat flux [MJ m^{-2} d^{-1} or MJ m^{-2} h^{-1}],
$(e_s - e_a)$ = vapor pressure deficit of the air [kPa],
e_s = saturation vapor pressure of the air [kPa],
e_a = actual vapor pressure of the air [kPa],
ρ_a = mean air density at constant pressure [kg m^{-3}],
c_p = specific heat of the air [MJ kg^{-1} $^oC^{-1}$],
Δ = slope of the saturation vapor pressure temperature relationship [kPa $^oC^{-1}$],
γ = psychrometric constant [kPa $^oC^{-1}$],
r_s = (bulk) surface resistance [s m^{-1}],
r_a = aerodynamic resistance [s m^{-1}],
λ = latent heat of vaporization, [MJ kg^{-1}],
ρ_w = density of water, [Mg m^{-3}] (taken as 1.0 Mg m^{-3}),
K_{time} = units conversion, equal to 86,400 s d^{-1} for ET in mm d^{-1} and equal to 3600 s h^{-1} for ET in mm h^{-1}.

The aerodynamic resistance, applied for neutral stability conditions, is:

$$r_a = \frac{\ln\left[\dfrac{z_w - d}{z_{om}}\right] \ln\left[\dfrac{z_h - d}{z_{oh}}\right]}{k^2\, u_z} \qquad \text{(B.2)}$$

where

r_a = aerodynamic resistance [s m^{-1}],
z_w = height of wind measurements [m],
z_h = height of humidity and or air temperature measurements [m],
d = zero plane displacement height [m], = 0.67 h
z_{om} = roughness length governing momentum transfer [m], = 0.123 h
z_{oh} = roughness length for transfer of heat and vapor [m], = 0.0123 h
k = von Karman's constant, 0.41 [-],
u_z = wind speed at height z [m s^{-1}]
h = mean height of the vegetation [m].

Bulk surface resistance is:

$$r_s = \frac{r_l}{LAI_{active}} \qquad \text{(B.3)}$$

where
r_s = (bulk) surface resistance [s m^{-1}],
r_l = effective stomatal resistance of a well-illuminated leaf [s m^{-1}],
LAI_{active} = active (sunlit) leaf area index [m^2 (leaf area) m^{-2} (soil surface)]

For ASCE calculations for dense vegetation, LAI_{active} is calculated as:

$$LAI_{active} = 0.5\, LAI \qquad \text{(B.4)}$$

where
LAI = leaf area index [m^2 of leaf per m^2 of soil surface = dimensionless]

For clipped grass:

$$LAI = 24\ h \qquad \text{(B.5)}$$

For alfalfa:

$$LAI = 5.5 + 1.5 \ln(h) \qquad \text{(B.6)}$$

where
h = vegetation height [m]

In the "full-form" ASCE Penman-Monteith method, the following "full-form" ancillary equations are used. Many of these have been simplified for use with the ET_{sz} form of the Penman-Monteith equation and are listed in the main text.

Latent Heat of Vaporization (λ)[1]

$$\lambda = 2.501 - (2.361 \times 10^{-3})\, T_{mean} \tag{B.7}$$

where:

λ = latent heat of vaporization [MJ kg^{-1}]
T_{mean} = mean air temperature for the time interval [°C]

The value of the latent heat varies only slightly over normal temperature ranges. For ET_{sz}, a single value is taken: λ = 2.45 MJ kg^{-1}. The inverse of λ is presented as 0.408.

Atmospheric Pressure (P)[2]

Mean atmospheric pressure for a location is predicted from site elevation using a lapse-based integration of the universal gas law:

$$P = P_o \left(\frac{T_{Ko} - \alpha_1 (z - z_o)}{T_{Ko}} \right)^{\frac{g}{\alpha_1 R}} \tag{B.8}$$

where:

P = atmospheric pressure at elevation z [kPa]
P_o = atmospheric pressure at reference level (i.e., sea level = 101.3) [kPa]
z = weather site elevation [m]
z_o = elevation at reference level (i.e., sea level = 0) [m]
g = gravitational acceleration = 9.807 [m s^{-2}]
R = specific gas constant = 287 [J kg^{-1} K^{-1}]
α_1 = constant lapse rate of moist air = 0.0065 [K m^{-1}]
T_{Ko} = reference temperature [K] at pressure P_o and elevation z_o.

1 Reference: Harrison (1963)

2 Reference: List (1984), Burman *et al.* (1987)

List (1984) defined P_o = 101.3 kPa, z_o = 0 m and T_{Ko} = 288 K for the U.S. and International Standard Atmospheres,. However, Smith et al., (1990) recommended using a reference temperature of T_{mean} = 20 °C to represent mean daytime conditions during growing seasons, so that:

$$T_{Ko} = 293\,K \qquad \text{(B.9)}$$

Using T_{Ko} = 293 K from equation (B.9), equation (B.8) becomes equation 3 of the main text. The difference in prediction of P using T_{Ko} = 288 and T_{Ko} = 293 K is less than 0.7% for elevations less than 3000 m.

Atmospheric Density (ρ_a)[3]

$$\rho_a = \frac{1000\,P}{T_{Kv}\,R} = 3.486\,\frac{P}{T_{Kv}} \qquad \text{(B.10)}$$

where:

ρ = atmospheric density [kg m^{-3}]
R = specific gas constant = 287 [J kg^{-1} K^{-1}]
T_{Kv} = mean virtual temperature for period [K]

$$T_{Kv} = T_K \left(1 - 0.378\,\frac{e_a}{P}\right)^{-1} \qquad \text{(B.11)}$$

where:

T_K = mean absolute temperature [K] : T_K = 273.16 + T_{mean} [°C]
e_a = actual vapor pressure [kPa]

In derivation of the ET_{sz} equation, equation (B.11) was reduced to $T_{Kv} \approx 1.01\,(T_{mean} + 273)$ that holds for most conditions. T_{mean} is set equal to mean daily temperature for 24-hour calculation time steps.

[3] Reference: Smith *et al.* (1991)

Psychrometric Constant (γ)[4]

The pyschrometric constant, γ, is used in the numerator and denominator of the standardized Penman-Monteith equation:

$$\gamma = \frac{c_p P}{\varepsilon\ \lambda} \qquad \text{(B.12)}$$

where:

γ	=	psychrometric constant [kPa °C^{-1}]
c_p	=	specific heat of moist air = 1.013 x 10^{-3} [MJ kg^{-1} °C^{-1}]
P	=	atmospheric pressure [kPa]
ε	=	ratio of the molecular weight of water vapor/dry air ("epsilon") (ε = 0.622 for standard, dry air)
λ	=	latent heat of vaporization [MJ kg^{-1}] (λ = 2.45 MJ kg^{-1} for standardized calculations)

The simplification of λ = 2.45 MJ kg^{-1} in equation B.12 and reduction results in Eq. 4 for the ET_{sz} equation. This simplification causes less than 2% error in γ over the range of $0 < T_{mean} < 40$ °C and less than 1% error over the range of $11 < T_{mean} < 31$ °C. This translates into errors in ET_{os} and ET_{rs} that are generally less than 0.2%.

Soil Heat Flux Density (G) for hourly periods[5]

The full equation for hourly G, on which equations 66 and 67 for ET_{sz} are based, is:

$$G_{hr} = K_G \exp(-0.5\,\text{LAI})\ R_n \qquad \text{(B.13)}$$

where

K_G	=	0.4 during daytime (defined as when $R_n > 0$)
K_G	=	2.0 during nighttime (defined as when $R_n \leq 0$)
LAI	=	leaf area index [dimensionless]

Units for G_{hr} and R_n are the same.

Wind Speed Adjustment for Measurement Height

[4] Reference: Brunt (1952)

To adjust wind speed data obtained from instruments placed at elevations other than the standard height of 2 m for use in all combination equations, a logarithmic wind speed profile is used. The exception is Eq. B.1 for the full-form Penman-Monteith equation above, which uses the actual wind speed and actual measurement height in calculating r_a as in Eq. B.2:

$$u_2 = u_z \frac{\ln\left(\frac{2-d}{z_{om}}\right)}{\ln\left(\frac{z_w - d}{z_{om}}\right)} \qquad \text{(B.14)}$$

where

u_2 = wind speed at 2 m above ground surface [m s^{-1}],
u_z = measured wind speed at z_w m above ground surface [m s^{-1}],
z_w = height of measurement above ground surface [m],
d = zero plane displacement height for the weather site vegetation, m, (d = 0.67 h)
z_{om} = aerodynamic roughness length for the weather site vegetation, m, (z_{om} = 0.123 h)

This equation serves as the basis for Equations 33 and 63 of the text, where for 0.12 m tall grass, (B.14) reduces to:

$$u_2 = u_z \frac{4.87}{\ln(67.8\, z_w - 5.42)} \qquad \text{(B.14b)}$$

Allen and Wright (1997) described procedures for adjusting wind speed measured over and down-wind of non-grassed surfaces to account for differences between the vegetation at the measurement surface and the vegetation type for the reference. The Allen-Wright procedures are recommended where the vegetation upwind of the measurement site is aerodynamically different from clipped grass or full-cover alfalfa or where the "full" Penman-Monteith equation (B.1) is applied to vegetation other than the two reference types. The following (B.14c) is a special application of (B.14) for the case where wind speed is measured over and downwind of approximately 0.5 m tall alfalfa and is to be adjusted to an equivalent speed at 2 m height over grass for use in the standardized equation for ET_{os} or ET_{rs}. In this situation, the d and z_{om} in the numerator of (B.14) are set to 0.08 m and 0.062 m, representing d for clipped grass and z_{om} for alfalfa. However, the d and z_{om} in the denominator of (B.14) are set to 0.335 m and 0.062 m, representing values for alfalfa. This "hybrid" combination of using d for both grass and alfalfa in

[5] Reference: Choudhury et al. (1987), Choudhury (1989)

(B.14c) is required because coefficients used in the standardized ET_{rs} equation (1) presume that wind is measured over and downwind of grass (typical of weather stations), even for the tall reference (see Table 2 of the main text). Using these substitutions, (B.14) reduces to:

$$u_2 = u_z \frac{\ln\left(\frac{2-0.08}{0.062}\right)}{\ln\left(\frac{z_w - 0.335}{0.062}\right)} = u_z \frac{3.44}{\ln(16.3\, z_w - 5.42)} \qquad \text{(B.14c)}$$

Equation (B.14c) is used to adjust wind speed measured over alfalfa for use in calculating ET_{os} and ET_{rs}. This adjustment is necessary because the formulation of ET_{rs} was made expecting weather measurements collected over clipped grass. The process and application with ET_{os} and ET_{rs} assumes that temperature and humidity data are measured over clipped grass or that the impact of measurement of these parameters over some other surface, including alfalfa, does not significantly impact the measurements. This is generally a good assumption for well-watered vegetation.

FAO-56 PENMAN-MONTEITH METHOD

The FAO-56 Penman-Monteith equation is a grass reference equation that was derived from the ASCE equations (B.1 – B.6) by fixing h = 0.12 m for clipped grass and by assuming measurement heights of z_w = 2 m and z_h = 2 m and using λ = 2.45 MJ kg^{-1}. The result is an equation that defines the reference evapotranspiration from a hypothetical grass surface having a fixed height of 0.12 m, bulk surface resistance of 70 s m^{-1}, and albedo of 0.23. For 24-hour time steps:

$$ET_o = \frac{0.408\,\Delta (R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma (1 + 0.34 u_2)} \qquad \text{(B.15)}$$

where

ET_o = grass reference evapotranspiration [mm day^{-1}],
R_n = net radiation at the crop surface [MJ m^{-2} day^{-1}],
G = soil heat flux density [MJ m^{-2} day^{-1}],
T = mean daily air temperature at 2 m height [°C],
u_2 = wind speed at 2 m height [m s^{-1}],
e_s = saturation vapor pressure [kPa],
e_a = actual vapor pressure [kPa],

e_s-e_a	=	vapor pressure deficit [kPa],
Δ	=	slope of saturation vapor pressure temperature relationship [kPa °C^{-1}],
γ	=	psychrometric constant [kPa °C^{-1}].

The FAO-56 Penman-Monteith equation for hourly time steps assumes that r_s = 70 s m^{-1} so that:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \dfrac{37}{T_{hr} + 273} u_2 (e_s(T_{hr}) - e_a)}{\Delta + \gamma(1 + 0.34 u_2)} \quad \text{(B.16)}$$

where

ET_o	=	grass reference evapotranspiration [mm h^{-1}],
R_n	=	net radiation at the crop surface [MJ m^{-2} h^{-1}],
G	=	soil heat flux density [MJ m^{-2} h^{-1}],
T_{hr}	=	mean hourly air temperature at 2 m height [°C],
u_2	=	wind speed at 2 m height [m s^{-1}],
$e_s(T_{hr})$	=	saturation vapor pressure at (T_{hr}) [kPa],
e_a	=	actual vapor pressure [kPa],
$e_s(T_{hr})$-e_a	=	saturation vapor pressure deficit [kPa],
Δ	=	slope vapor pressure curve [kPa °C^{-1}],
γ	=	psychrometric constant [kPa °C^{-1}].

OTHER PENMAN EQUATIONS

The classical form of the Penman equation (Penman, 1948, 1956, 1963) is:

$$ET = \left(\frac{\Delta}{\Delta + \gamma}(R_n - G) + K_w \frac{\gamma}{\Delta + \gamma}(a_w + b_w u_2)(e_s - e_a) \right) / (\lambda \rho_w) \quad \text{(B.17)}$$

where:

K_w = is a units constant
a_w and b_w = are wind function coefficients
u_2 = wind speed at 2 m, [m s^{-1}]
λ = latent heat of vaporization, MJ kg^{-1},
ρ_w = density of water, [Mg m^{-3}] (taken as 1.0 Mg m^{-3})

All other terms and definitions are the same as those used for the Penman-Monteith equation. Parameter K_w = 6.43 for ET in mm d^{-1} and K_w = 0.268 for ET in mm hour^{-1}. The a_w and b_w

terms are empirical wind coefficients that have often received local or regional calibration and apply to a specific reference type of crop or surface.

THE 1963 PENMAN METHOD

The values for a_w and b_w for the original Penman equation, first applied by Penman (1948) to open water and implicitly to grass, and later by Penman (1963) to clipped grass were $a_w = 1.0$ and $b_w = 0.537$, respectively, for wind speed in m s^{-1}, $e_s - e_a$ in kPa and grass ET_o in mm d^{-1}. The equations were intended for use with daily computations. In task committee comparisons, R_n for the 1963 Penman equation was calculated similar to Eq. 15-18, and saturation vapor pressure was based on only mean daily air temperature rather than on T_{max} and T_{min} following Penman. For hourly applications, G was predicted using Eq. 66 and 67 and, for daily applications, G was predicted using Eq. 30.

THE KIMBERLY PENMAN METHOD.

The 1982 Kimberly Penman method (Wright, 1982,) uses B.17, with wind coefficients that vary with time of year. In addition, the coefficients used for computation of net radiation and the method to predict 24-hour soil heat flux are unique to the Kimberly method.

The 1982 Kimberly Penman equation was developed from intensive studies of evapotranspiration at Kimberly, Idaho using measurements of full-cover alfalfa ET from precision weighing lysimeters (Wright and Jensen 1972; Wright 1981; Wright 1982; Wright 1988). For grass ET_o, the 1996 Kimberly wind function was developed by Wright (1996) from five years of weighing lysimeter data from well-managed and well-fertilized clipped fescue grass having high leaf area and maintained at 0.8 to 0.15 m height.

The Kimberly Penman and associated wind functions were intended for application with 24-hour time steps ($K_w = 6.43$). The form and all units and definitions are the same as those in Eq. B.17. The Kimberly wind function coefficients a_w and b_w for alfalfa vary with time of year and are computed for ET_r as (Wright 1987, pers. comm. and Jensen et al. 1990):

$$a_w = 0.4 + 1.4 \ \exp\left(- \left[\left(\frac{J - 173}{58} \right)^2 \right] \right) \tag{B.18}$$

$$b_w = 0.605 + 0.345 \ \exp\left(- \left[\left(\frac{J - 243}{80} \right)^2 \right] \right) \tag{B.19}$$

where J is the day of the year. For latitudes south of the equator, one should use J' in place of J, where J' = (J - 182) for J ≥ 182 and J' = (J + 182) for J < 182. The (e_s - e_a) term in the 1982 and 1996 Kimberly Penmans is computed the same as for the Penman-Monteith equation (e_s is computed at both maximum and minimum temperatures).

In the original (Wright, 1982) definition for the 1982 Kimberly Penman equation, net long wave radiation was computed for Kimberly as:

$$R_{nl} = \sigma \left[\frac{T_{max,K}{}^4 + T_{min,K}{}^4}{2} \right] \left(a_1 + b_1 \sqrt{e_a} \right) \left(a_c \frac{R_s}{R_{so}} + b_c \right) \tag{B.20}$$

where

R_{nl}	=	net outgoing longwave radiation [MJ m^{-2} d^{-1}],
σ	=	Stefan-Boltzmann constant [4.901 10^{-9} MJ K^{-4} m^{-2} d^{-1}],
$T_{,K\ max}$	=	maximum absolute temperature during the 24-hour period [K = °C + 273.16],
$T_{K\ min}$	=	minimum absolute temperature during the 24-hour period [K = °C + 273.16],
e_a	=	actual vapor pressure [kPa],
R_s/R_{so}	=	relative shortwave solar radiation (limited to ≤ 1.0),
R_s	=	measured or calculated solar radiation [MJ m^{-2} d^{-1}],
R_{so}	=	calculated clear-sky radiation [MJ m^{-2} d^{-1}].

Eq. B.20 has the same form as used for Eq. 17 of the ET_{sz} procedure. However, coefficients a_1, b_1, a_c and b_c have different values.

Parameter a_1 for alfalfa at Kimberly (42 ° N) is:

$$a_1 = 0.26 \ + \ 0.1 \ \exp\left(- [0.0154\,(J \ - \ 180)\,]^2 \right) \tag{B.21}$$

where J is the day of the year, and where J for the southern hemisphere is replaced with J' as described for Eq. B.18-B.19. Parameter b_1 = -0.139 in Wright (1982).

Wright (1982) predicted a_c and b_c as:

$$\begin{aligned} a_c &= 1.126 \quad \text{and} \quad b_c = -0.07 \quad \text{for} \quad R_s / R_{so} > 0.7 \\ a_c &= 1.017 \quad \text{and} \quad b_c = -0.06 \quad \text{for} \quad R_s / R_{so} \le 0.7 \end{aligned} \qquad \text{(B.22)}$$

Wright (1982) predicted albedo as:

$$\alpha = 0.29 + 0.06 \sin\left[(J + 96) / 57.3\right] \qquad \text{(B.23)}$$

where J is the day of the year, and where J for the southern hemisphere is replaced with J' as described for Eq. B.18-B.19.

Soil heat flux for 24-hour periods is predicted for the alfalfa reference of Wright (1982) using the difference between mean air temperature of the current day and the mean air temperature of the previous three days:

$$G_{24} = 0.38 \left(T_{mean} - \sum_{i=1}^{3} T_{mean\ i} / 3 \right) \qquad \text{(B.24)}$$

where G_{24} is 24-hour soil heat flux in MJ m^{-2} d^{-1}, T_{mean} is mean air temperature on the current day and $T_{mean\ i}$ is the mean air temperatures of the previous three days. Equation B.24 may not predict well under all conditions. In a study on 24-hour heat flux at Kimberly and Logan, Utah, Allen and Wright (unpublished research, 1996) found that using G=0 for 24-hour periods under alfalfa and grass produced less error relative to measured G than using Eq. B.24. For hourly applications, G was predicted using Eq. 66 and 67.

THE CIMIS PENMAN METHOD.

Pruitt (Pruitt and Doorenbos 1977a) developed a_w and b_w for predicting grass ET_o for hourly periods for a clipped grass reference. These coefficients have been adopted for standard ET_o estimation in the California Irrigation Management Information Service (CIMIS) (Snyder and

Pruitt, 1985, Snyder and Pruitt, 1992). The result is the "CIMIS" Penman ET_o equation where $a_w = 0.29$ and $b_w = 0.53$ for $R_n > 0$ and $a_w = 1.14$ and $b_w = 0.40$ for $R_n \le 0$. These coefficients are applied hourly using Eq. B.17 where ET_o = mm hour^{-1}, R_n = MJ m^{-2} hour^{-1}, and $K_w = 0.268$.

The net radiation calculation for the CIMIS method as applied by CIMIS is similar to that by Dong et al.(1992) and is different than that applied during the Task Committee study. In the Task Committee application and evaluation, R_n for the CIMIS Penman equation was computed using Eq. 42-47 of the text. The decision to use the standardized R_n was based on concern for potential over-sensitivity in the CIMIS routines during the prediction of R_{nl} when R_s/R_{so} is close to 1.0.

Standard CIMIS calculations assume G = 0, although G in hourly applications should normally be considered. In the Task Committee analyses using the CIMIS Penman equation, G was set equal to G = 0 to be consistent with standard CIMIS usage.

FAO-24 PENMAN METHOD.

The FAO-24 Penman method (Doorenbos and Pruitt, 1977) was applied for daily timesteps only using net radiation as computed in the FAO-24 publication. In the FAO-24 Penman, $a_w = 1.0$ and $b_w = 0.862$ for u_2 in m s^{-1} and vapor pressure in kPa and radiation in MJ m^{-2} d^{-1}. R_n for the FAO-24 Penman equation is calculated similar to Eq. 15-18, except that only mean daily air temperature is used in place of T_{max} and T_{min}. Saturation vapor pressure is based only on mean daily air temperature. The FAO-24 “correction” (coefficient “c”) was applied using the regression equation reported by Allen and Pruitt (1991).

THE 1985 HARGREAVES METHOD

The 1985 Hargreaves method (Hargreaves and Samani, 1985 and Hargreaves et al. 1985) requires only maximum and minimum daily air temperature and can be applied on 24-hour, weekly, 10-day, or monthly time steps. It has the form:

$$ET_o = 0.0023(T_{max} - T_{min})^{0.5}\ (T_{mean} + 17.8)\ R_a \qquad \text{(B.25)}$$

where:

ET_o = grass reference ET, mm d^{-1}
T_{max} = maximum daily air temperature, °C
T_{min} = minimum daily air temperature, °C
T_{mean} = mean daily air temperature, $T_{mean} = (T_{max} + T_{min}) / 2$
R_a = extraterrestrial radiation, mm d^{-1} (see Eq. 21 – 29 in main text)
(R_a in mm d^{-1} = R_a in MJ m^{-2} d^{-1} / 2.45).

APPENDIX C

EXAMPLE CALCULATIONS FOR DAILY AND HOURLY STANDARDIZED REFERENCE EVAPOTRANSPIRATION

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EXAMPLE CALCULATIONS FOR DAILY AND HOURLY STANDARDIZED REFERENCE EVAPOTRANSPIRATION

INTRODUCTION

The following examples demonstrate application of the standardized ET_{SZ} equation and supporting calculations for daily and hourly time periods. These examples provide a standardized set of calculations for checking computer software. Various software programs are available for making the calculations for the equations presented in this standardization statement, as a means of comparing against other computer software. These standardized software programs include the REF-ET software available from the University of Idaho (http://www.kimberly.uidaho.edu/ref-et/) and the ETo spreadsheets by Snyder (2000). The REF-ET software is Windows-based and can read a wide range of file formats and unit types.

The location selected for this example application is an agricultural weather site near Greeley, CO[1] operated by the Northern Colorado Water Conservation District. The weather station utilizes electronic, automated equipment and is situated above irrigated grass having an expanse of approximately 50 x 50 m. Surroundings beyond the grassed weather surface are irrigated residential turf and agriculture. The technical data in Table C-1 describe the weather station.

[1] Data were provided courtesy of Mr. Mark Crookston and Mr. Brent Mecham of the Northern Colorado Conservancy District, Loveland, CO.

Additional constants for the Greeley site that are a part of the standardized calculations are listed in Table C-2 along with the equation number used for the calculation.

Example calculation results are presented in the following sections for daily (i.e., 24-hour) and hourly timesteps. Calculated values can be compared with computations by user software programs to confirm accuracy of the programs.

Table C-1. Characteristics of the Greeley, Colorado weather station

Attribute	Value
Latitude	40.41 degrees N
Longitude	104.78 degrees W
Elevation	1462.4 m
Anemometer height	3 m
Height of air temperature and RH meas.	1.68 m
Longitude of center of time zone	105 degrees W
Type of surface at weather station	irrigated grass
Height of vegetation of weather station	0.12 m

Table C-2. Calculation constants for the Greeley, Colorado weather station

Variable	Equation(s)	Value
Mean atmospheric pressure	3	85.17 kPa
Psychrometric Constant (γ)	**4**	0.0566 kPa $^oC^{-1}$
K_{ab} for predicting R_{so}	19, 20	0.779
Multiplier for adjusting wind speed to 2m height	33	0.921
Latitude in radians	22	0.7053 radians

DAILY CALCULATION TIMESTEP

Calculation results for daily time steps are presented in Table C-3 for 10 days in July, 2000 for the Greeley, CO agricultural weather site operated by the Northern Colorado Water Conservation District. Columns 3 - 7 of Table C-3 are the original weather data reported for the station. Average daily vapor pressure, e_a, was reported for the Greeley station. These values were calculated inside the electronic data logging system at the weather site throughout the course of a day using measured air temperature and relative humidity (via equations 37 and 41), and an average vapor pressure for the day was calculated. An equivalent dew-point temperature for each day was calculated from daily e_a using Eq. D.7a of Appendix D.

INTEGRITY OF DATA

Daily solar radiation data for the complete year 2000 are plotted in Figure D-2 for Greeley, along with clear sky R_{so} envelopes that were determined using Eq. 19 and by also using the more detailed procedure of Appendix D. The good agreement between measured R_s for cloud-free days and the computed R_{so} curves supports using the solar radiation data.

The daily mean dew-point temperature, computed from daily mean vapor pressure, was plotted against daily minimum air temperature as shown in Figure D-9a of Appendix D, and computed daily maximum relative humidity and daily minimum relative humidity are plotted in Figure D-9b. Based on the guidelines of Appendix D, the humidity and air temperature data for the Greeley location during 2000 were judged to be of good integrity and representative of a well-watered, agricultural (i.e., “reference ET”) condition.

Daily mean wind speed data were plotted vs. day of year as described in Appendix D. The wind speed appeared to follow a typical distribution with ranges and averages typical of agricultural areas. No comparisons using an independent anemometer or using wind speed data from a nearby weather station were made to confirm the accuracy of the wind data.

CALCULATIONS OF VARIABLES AND STANDARDIZED REFERENCE EVAPOTRANSPIRATION

Table C-3 contains calculations required for computation of ET_{sz} for daily time steps for the 10 day period at Greeley, Colorado. ET_{os} and ET_{rs} for the short and tall references are listed in the last two columns of the table.

Table C-3. Measured data, calculations, and ET_{os} and ET_{rs} for daily time steps for July 1-10, 2000 near Greeley, Colorado.

Month	Day	Data from Weather Station					Day of Year	T_{mean}	Δ	$e^o(T_{max})$	$e^o(T_{min})$	e_s	wind @2m
		T_{max}	T_{min}	vapor press. e_a	R_s	wind @3m							
		^oC	^oC	kPa	MJ m^{-2} d^{-1}	m s^{-1}		^oC	kPa $^oC^{-1}$	kPa	kPa	kPa	m s^{-1}
							Eq. 25	Eq. 3	Eq. 5	Eq. 7	Eq. 7	Eq. 6	Eq. 33
7	1	32.4	10.9	1.27	22.4	1.94	183[a]	21.7[b]	0.1585	4.88	1.31	3.09	1.79
7	2	33.6	12.2	1.19	26.8	2.14	184	22.9	0.1692	5.21	1.42	3.31	1.97
7	3	32.6	14.8	1.40	23.3	2.06	185	23.7	0.1762	4.91	1.69	3.30	1.90
7	4	33.8	11.8	1.18	29.0	1.97	186	22.8	0.1684	5.27	1.39	3.33	1.81
7	5	32.7	15.9	1.59	27.9	2.98	187	24.3	0.1820	4.94	1.81	3.37	2.74
7	6	36.3	15.8	1.58	29.2	2.37	188	26.0	0.1990	6.03	1.79	3.91	2.18
7	7	35.5	16.7	1.13	23.2	2.43	189	26.1	0.1996	5.78	1.9	3.84	2.24
7	8	34.4	18.3	1.38	22.1	1.95	190	26.4	0.2027	5.45	2.11	3.78	1.80
7	9	32.7	15.1	1.38	26.5	1.75	191	23.9	0.1781	4.94	1.72	3.33	1.61
7	10	32.7	15.7	1.59	27.7	2.31	192	24.2	0.1809	4.95	1.78	3.37	2.13

[a] Year 2000 was a leap year.

[b] T_{mean} was calculated from T_{max} and T_{min} following standardized procedure (Eq. 2). These values differ slightly from T_{mean} computed from hourly averages.

Table C-3. Continued.

Month	Day	$T_{k\ max}$	$T_{k\ min}$	d_r	declin.	sunset hr	R_a	R_{so}	R_s/R_{so}	R_{nl}	R_n	ET_{os}	ET_{rs}
		K	K		radians	radians	MJ m^{-2} d^{-1}			MJ m^{-2} d^{-1}	MJ m^{-2} d^{-1}	mm d^{-1}	mm d^{-1}
				Eq. 23	Eq. 24	Eq. 28	Eq. 21	Eq. 20		Eq. 17	Eq. 15	Eq. 1	Eq. 1
7	1	305.6	284.1	0.9670	0.4017	1.941	41.63	32.43	0.691	3.96	13.31	5.71	7.34
7	2	306.8	285.4	0.9670	0.4003	1.939	41.58	32.39	0.827	5.45	15.20	6.71	8.68
7	3	305.8	288.0	0.9670	0.3988	1.938	41.53	32.36	0.720	4.15	13.78	5.98	7.65
7	4	307.0	285.0	0.9671	0.3972	1.936	41.48	32.32	0.897	6.14	16.19	6.86	8.73
7	5	305.9	289.1	0.9671	0.3954	1.934	41.43	32.27	0.864	5.15	16.33	7.03	9.07
7	6	309.5	289.0	0.9671	0.3936	1.932	41.37	32.23	0.906	5.67	16.83	7.50	9.60
7	7	308.7	289.9	0.9672	0.3916	1.930	41.31	32.18	0.721	4.71	13.15	7.03	9.56
7	8	307.6	291.5	0.9673	0.3895	1.928	41.25	32.13	0.688	4.02	13.00	6.16	7.99
7	9	305.9	288.3	0.9674	0.3873	1.925	41.18	32.08	0.826	5.16	15.27	6.20	7.68
7	10	305.9	288.9	0.9674	0.3850	1.923	41.11	32.02	0.865	5.15	16.15	6.61	8.28

HOURLY CALCULATION TIMESTEP

Calculation results for hourly time steps are presented in Table C-4 for a 31-hour period spanning from 1600 hours on July 1 to 2200 hours on July 2, 2000 for the Greeley, CO agricultural weather site operated by the Northern Colorado Water Conservation District. The 31-hour period was selected to contain both nighttime and daytime conditions and to illustrate how the cloudiness function value (based on R_s/R_{so}) is selected for nighttime periods and periods of low sun angle.

Columns 4 - 7 of Table C-4 are the original weather data reported for the station. Average hourly vapor pressure, e_a, was reported in the data set. The e_a data were calculated inside the electronic data logging system at the weather site using measured air temperature and relative humidity (via equations 37 and 41) on an hourly or shorter basis.

INTEGRITY OF DATA

Integrity of the solar radiation, humidity, air temperature and wind data was assessed for daily timesteps as discussed in the previous section. Solar radiation data were additionally assessed for the hourly time steps by plotting measured R_s vs. computed clear sky R_{so} envelopes as illustrated in Figure D-3 of Appendix D. The good agreement between measured hourly R_s for cloud-free conditions and the computed R_{so} curves supports using the solar radiation data.

CALCULATION OF VARIABLES AND STANDARDIZED REFERENCE EVAPOTRANSPIRATION

Table C-4 contains calculations of variables that are required for computation of the standardized reference evapotranspiration for hourly time steps for the 31-hour period at Greeley, Colorado. Calculations for the standardized reference ET_{os} and ET_{rs} for the short and tall references are listed in the last two columns of the table.

Notes concerning the calculation of the variables in Table C-4 are the following:

- The beginning and ending times for each hourly period, expressed in radians (ω_1 and ω_2) were limited to the sunset hour angle as recommended in Eq. 57.

- The ratio R_s/R_{so} was limited to $0.3 < R_s/R_{so} <= 1.0$ as recommended following Eq. 45.

- The cloud function, f_{cd}, during nighttime periods and periods of low sun angle, was set equal to the value $f_{cd\ \beta>0.3}$ calculated for the period prior to when the sun angle at the center of a period decreased to below 0.3 radians, as recommended in the text (Eq. 45-46). The substituted value $f_{cd\ \beta>0.3}$ for f_{cd} during the dusk, nighttime and dawn periods is bolded in Table C-4.

The soil heat flux was calculated according to reference type and daytime or nighttime period using Eq. 65 and 66.

- The reference ET calculated for some nighttime hours is negative. In practice, the user may wish to set negative values to zero before summing over the 24-hour period. However, in some situations, negative hourly computed ET_{os} or ET_{rs} may indicate the condensation of vapor during periods of early morning dew and should therefore be registered as negative during the summing of 24-hour ET. In other situations, negative hourly ET_{os} or ET_{rs} during nighttime reflect the uncertainties in some parameter estimates, including R_n, and assumptions implicit to the combination equation. In general, the impact of negative hourly values on ET summed over daily periods is less than a few percent.

Table C-4. Measured data, calculations, and ET_{os} and ET_{rs} for hourly time steps for July 1-2, 2000 near Greeley, Colorado.

Month	Day	Hour	Data from Weather Station				Day of Year	Δ	$e_s = e^o(T_{hr})$	wind @2m	$T_{k\ max}$
			T_{hr}	vapor pressure e_a	R_s	wind speed @3m					
			^oC	kPa	MJ m^{-2} h^{-1}	m s^{-1}		kPa $^oC^{-1}$	kPa	m s^{-1}	K
							Eq. 52	Eq. 36	Eq. 37	Eq. 67	
7	1	1600	30.9	1.09	2.24	4.07	183[a]	0.2545	4.467	3.75	304.1
7	1	1700	31.2	1.15	1.65	3.58	183	0.2583	4.544	3.30	304.4
7	1	1800	29.1	1.21	0.34	1.15	183	0.2326	4.029	1.06	302.3
7	1	1900	28.3	1.21	0.32	3.04	183	0.2234	3.846	2.80	301.5
7	1	2000	26.0	1.13	0.08	2.21	183	0.1987	3.361	2.04	299.2
7	1	2100	22.9	1.20	0.00	1.04	183	0.1690	2.792	0.96	296.1
7	1	2200	20.1	1.35	0.00	0.58	183	0.1455	2.353	0.53	293.3
7	1	2300	19.9	1.35	0.00	0.95	183	0.1440	2.324	0.87	293.1
7	1	2400	18.4	1.32	0.00	0.30	183	0.1327	2.116	0.28	291.6
7	2	100	16.5	1.26	0.00	0.50	184	0.1194	1.877	0.46	289.7
7	2	200	15.4	1.34	0.00	1.00	184	0.1123	1.750	0.92	288.6
7	2	300	15.5	1.31	0.00	0.68	184	0.1129	1.761	0.63	288.7
7	2	400	13.5	1.26	0.00	0.69	184	0.1008	1.547	0.64	286.7
7	2	500	13.2	1.24	0.03	0.29	184	0.0991	1.517	0.27	286.4
7	2	600	16.2	1.31	0.46	1.24	184	0.1174	1.842	1.14	289.4
7	2	700	20.0	1.36	1.09	1.28	184	0.1447	2.338	1.18	293.2
7	2	800	22.9	1.39	1.74	0.88	184	0.1690	2.792	0.81	296.1
7	2	900	26.4	1.25	2.34	0.72	184	0.2028	3.442	0.66	299.6
7	2	1000	28.2	1.17	2.84	1.52	184	0.2223	3.824	1.40	301.4
7	2	1100	29.8	1.03	3.25	1.97	184	0.2409	4.195	1.81	303.0
7	2	1200	30.9	1.02	3.21	2.07	184	0.2545	4.467	1.91	304.1
7	2	1300	31.8	0.98	3.34	2.76	184	0.2660	4.701	2.54	305.0
7	2	1400	32.5	0.87	2.96	2.90	184	0.2753	4.891	2.67	305.7
7	2	1500	32.9	0.86	2.25	3.10	184	0.2808	5.002	2.85	306.1
7	2	1600	32.4	0.93	1.35	2.77	184	0.2740	4.863	2.55	305.6
7	2	1700	30.2	1.14	0.88	3.41	184	0.2458	4.292	3.14	303.4
7	2	1800	30.6	1.27	0.79	2.78	184	0.2507	4.391	2.56	303.8
7	2	1900	28.3	1.27	0.27	2.95	184	0.2234	3.846	2.72	301.5
7	2	2000	25.9	1.17	0.03	3.27	184	0.1977	3.342	3.01	299.1
7	2	2100	23.9	1.20	0.00	2.86	184	0.1782	2.966	2.63	297.1

[a] Year 2000 was a leap year.

Table C-4. Continued.

Month	Day	Hour	d_r	declin.	sunset hr angle (ω_s)	time at mid point	time corr. (S_c)	solar time angle (ω)	ω_1	ω_2	R_a	R_{so}
				radians	radians	hours	hours	radians	radians	radians	MJ m^{-2} h^{-1}	MJ m^{-2} h^{-1}
			Eq. 50	Eq. 51	Eq. 59	--	Eq. 57	Eq. 55	Eq. 53	Eq. 54	Eq. 48	Eq. 47
7	1	1600	0.9670	0.4017	1.941	15.5	-0.0618	0.904	0.773	1.035	3.26	2.54
7	1	1700	0.9670	0.4017	1.941	16.5	-0.0618	1.166	1.035	1.297	2.52	1.96
7	1	1800	0.9670	0.4017	1.941	17.5	-0.0618	1.428	1.297	1.558	1.68	1.31
7	1	1900	0.9670	0.4017	1.941	18.5	-0.0618	1.689	1.558	1.820	0.81	0.63
7	1	2000	0.9670	0.4017	1.941	19.5	-0.0618	1.951	1.820	1.941	0.09	0.07
7	1	2100	0.9670	0.4017	1.941	20.5	-0.0618	2.213	1.941	1.941	0.00	0.00
7	1	2200	0.9670	0.4017	1.941	21.5	-0.0618	2.475	1.941	1.941	0.00	0.00
7	1	2300	0.9670	0.4017	1.941	22.5	-0.0618	2.737	1.941	1.941	0.00	0.00
7	1	2400	0.9670	0.4017	1.941	23.5	-0.0618	2.998	1.941	1.941	0.00	0.00
7	2	100	0.9670	0.4003	1.939	0.5	-0.0649	-3.024	-1.939	-1.939	0.00	0.00
7	2	200	0.9670	0.4003	1.939	1.5	-0.0649	-2.762	-1.939	-1.939	0.00	0.00
7	2	300	0.9670	0.4003	1.939	2.5	-0.0649	-2.500	-1.939	-1.939	0.00	0.00
7	2	400	0.9670	0.4003	1.939	3.5	-0.0649	-2.238	-1.939	-1.939	0.00	0.00
7	2	500	0.9670	0.4003	1.939	4.5	-0.0649	-1.977	-1.939	-1.846	0.05	0.04
7	2	600	0.9670	0.4003	1.939	5.5	-0.0649	-1.715	-1.846	-1.584	0.72	0.56
7	2	700	0.9670	0.4003	1.939	6.5	-0.0649	-1.453	-1.584	-1.322	1.59	1.24
7	2	800	0.9670	0.4003	1.939	7.5	-0.0649	-1.191	-1.322	-1.060	2.43	1.90
7	2	900	0.9670	0.4003	1.939	8.5	-0.0649	-0.929	-1.060	-0.799	3.19	2.49
7	2	1000	0.9670	0.4003	1.939	9.5	-0.0649	-0.668	-0.799	-0.537	3.81	2.97
7	2	1100	0.9670	0.4003	1.939	10.5	-0.0649	-0.406	-0.537	-0.275	4.26	3.32
7	2	1200	0.9670	0.4003	1.939	11.5	-0.0649	-0.144	-0.275	-0.013	4.49	3.50
7	2	1300	0.9670	0.4003	1.939	12.5	-0.0649	0.118	-0.013	0.249	4.51	3.51
7	2	1400	0.9670	0.4003	1.939	13.5	-0.0649	0.380	0.249	0.510	4.29	3.34
7	2	1500	0.9670	0.4003	1.939	14.5	-0.0649	0.641	0.510	0.772	3.87	3.01
7	2	1600	0.9670	0.4003	1.939	15.5	-0.0649	0.903	0.772	1.034	3.26	2.54
7	2	1700	0.9670	0.4003	1.939	16.5	-0.0649	1.165	1.034	1.296	2.52	1.96
7	2	1800	0.9670	0.4003	1.939	17.5	-0.0649	1.427	1.296	1.558	1.68	1.31
7	2	1900	0.9670	0.4003	1.939	18.5	-0.0649	1.689	1.558	1.819	0.81	0.63
7	2	2000	0.9670	0.4003	1.939	19.5	-0.0649	1.950	1.819	1.939	0.09	0.07
7	2	2100	0.9670	0.4003	1.939	20.5	-0.0649	2.212	1.939	1.939	0.00	0.00

Table C-4. Continued.

Month	Day	Hour	sun angle β	R_s/R_{so}	cloud func. f_{cd}	$f_{cd\ \beta>0.3}$	R_{nl}	R_n	G_{os}	G_{rs}	ET_{os}	ET_{rs}
			radians				$MJ\ m^{-2}\ h^{-1}$	$MJ\ m^{-2}\ h^{-1}$	$MJ\ m^{-2}\ h^{-1}$	$MJ\ m^{-2}\ h^{-1}$	$mm\ h^{-1}$	$mm\ h^{-1}$
			Eq. 62	(w/ Eq. 47)	Eq. 45, 46	---	Eq. 44	Eq. 42	Eq. 65	Eq. 66	Eq. 1	Eq. 1
7	1	1600	0.757	0.881	*0.840*		0.284	1.441	0.144	0.058	0.61	0.82
7	1	1700	0.558	0.842	0.787		0.262	1.009	0.101	0.040	0.48	0.66
7	1	1800	0.361	0.260	*0.055*[b]	0.055[c]	0.017	0.244	0.024	0.010	0.14	0.19
7	1	1900	0.171	0.506	**0.055**		0.017	0.229	0.023	0.009	0.22	0.35
7	1	2000	-0.007	**1.173**[d]	**0.055**		0.017	0.044	0.004	0.002	0.12	0.21
7	1	2100	-0.167	--	**0.055**		0.016	-0.016	-0.008	-0.003	0.04	0.06
7	1	2200	-0.302	--	**0.055**		0.015	-0.015	-0.007	-0.003	0.01	0.02
7	1	2300	-0.401	--	**0.055**		0.015	-0.015	-0.007	-0.003	0.02	0.04
7	1	2400	-0.456	--	**0.055**		0.015	-0.015	-0.007	-0.003	0.01	0.01
7	2	100	-0.460	--	**0.055**		0.014	-0.014	-0.007	-0.003	0.01	0.01
7	2	200	-0.410	--	**0.055**		0.014	-0.014	-0.007	-0.003	0.01	0.02
7	2	300	-0.314	--	**0.055**		0.014	-0.014	-0.007	-0.003	0.01	0.01
7	2	400	-0.183	--	**0.055**		0.014	-0.014	-0.007	-0.003	0.01	0.01
7	2	500	-0.024	0.731	**0.055**		0.014	0.009	0.001	0.000	0.01	0.01
7	2	600	0.153	0.815	**0.055**		0.014	0.340	0.034	0.014	0.10	0.12
7	2	700	0.342	0.879	0.836		0.223	0.616	0.062	0.025	0.19	0.23
7	2	800	0.538	0.918	0.889		0.244	1.096	0.110	0.044	0.32	0.37
7	2	900	0.737	0.941	0.920		0.278	1.524	0.152	0.061	0.46	0.52
7	2	1000	0.933	0.956	0.940		0.299	1.888	0.189	0.076	0.60	0.70
7	2	1100	1.113	0.980	0.973		0.331	2.171	0.217	0.087	0.72	0.85
7	2	1200	1.242	0.917	0.888		0.308	2.164	0.216	0.087	0.73	0.88
7	2	1300	1.250	0.952	0.935		0.332	2.239	0.224	0.090	0.79	0.97
7	2	1400	1.129	0.885	0.845		0.315	1.964	0.196	0.079	0.74	0.93
7	2	1500	0.952	0.747	0.658		0.248	1.485	0.148	0.059	0.62	0.81
7	2	1600	0.757	0.531	0.367		0.134	0.905	0.091	0.036	0.44	0.60
7	2	1700	0.558	0.449	0.256		0.084	0.593	0.059	0.024	0.35	0.52
7	2	1800	0.361	0.604	0.465	0.465[c]	0.147	0.461	0.046	0.018	0.29	0.42
7	2	1900	0.171	0.427	**0.465**		0.143	0.065	0.006	0.003	0.17	0.29
7	2	2000	-0.007	0.444	**0.465**		0.143	-0.120	-0.060	-0.024	0.10	0.14
7	2	2100	-0.168	--	**0.465**		0.138	-0.138	-0.069	-0.028	0.07	0.10

[b] The value 0.055 for f_{cd} is due to a lower limit placed on R_s/R_{so} of 0.3 (Eq. 45).
[c] The value calculated for $f_{cd\ \beta>0.3}$ each afternoon occurred at 1800 hours because this is the last time period when $\beta > 0.3$ radians (Eq. 46).
[d] The value of R_s/R_{so} = 1.173 at 2000 hours must be limited to ≤ 1.0 in Eq. 45.

Table C-4. Continued, showing R_{so} computed using Eq. D.1 – D.4 of Appendix D.

Month	Day	Hour	Precip. water (W)	sin β	K_B ($w/K_t = 1.0$)	K_D	R_{so} (opt. meth.)
			mm	--	--	--	$MJ\ m^{-2}\ h^{-1}$
			Eq. D.3	Eq. D.6	Eq. D.2	Eq. D.4	Eq. D.1
7	1	1600	15.1	0.6869[e]	0.632	0.123	2.46
7	1	1700	15.8	0.5296	0.579	0.142	1.81
7	1	1800	16.5	0.3535	0.486	0.175	1.11
7	1	1900	16.5	0.1706	0.296	0.243	0.44
7	1	2000	15.6	-0.0067	0.000	0.180	0.02
7	1	2100	16.4	-0.1663	0.000	0.180	0.00
7	1	2200	18.2	-0.2972	0.000	0.180	0.00
7	1	2300	18.2	-0.3907	0.000	0.180	0.00
7	1	2400	17.8	-0.4402	0.000	0.180	0.00
7	2	100	17.1	-0.4437	0.000	0.180	0.00
7	2	200	18.1	-0.3987	0.000	0.180	0.00
7	2	300	17.7	-0.3093	0.000	0.180	0.00
7	2	400	17.1	-0.1815	0.000	0.180	0.00
7	2	500	16.9	-0.0242	0.000	0.180	0.01
7	2	600	17.7	0.1520	0.261	0.256	0.37
7	2	700	18.3	0.3350	0.466	0.182	1.03
7	2	800	18.7	0.5124	0.561	0.148	1.73
7	2	900	17.0	0.6722	0.620	0.127	2.38
7	2	1000	16.1	0.8033	0.655	0.114	2.93
7	2	1100	14.4	0.8969	0.679	0.105	3.34
7	2	1200	14.3	0.9466	0.688	0.102	3.55
7	2	1300	13.8	0.9490	0.691	0.101	3.57
7	2	1400	12.5	0.9039	0.689	0.102	3.40
7	2	1500	12.4	0.8145	0.673	0.108	3.02
7	2	1600	13.2	0.6868	0.640	0.119	2.48
7	2	1700	15.7	0.5295	0.579	0.141	1.81
7	2	1800	17.2	0.3533	0.483	0.176	1.11
7	2	1900	17.2	0.1702	0.293	0.244	0.44
7	2	2000	16.1	-0.0072	0.000	0.180	0.02
7	2	2100	16.4	-0.1669	0.000	0.180	0.00

[e]The sin(β) can also be computed as the sine of β computed earlier in this table.

APPENDIX D

WEATHER DATA INTEGRITY ASSESSMENT AND STATION SITING

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INTRODUCTION

Most automated weather stations (AWS) measure the primary variables affecting ET: solar radiation, air temperature, wind speed and humidity, and therefore provide relatively complete data for predicting ET as compared to manually-operated weather stations measuring only air temperature that were routinely used in the past. An AWS measures temperature, humidity and wind speed within the dynamic boundary overlying the ground surface. Properties of this boundary layer characterize the energy balance at the surface and are used to predict the ET rate. As studies in southern Idaho by Burman et al. (1975) have shown, the lower level of the atmosphere changes when going from desert to a patchwork of irrigated and non-irrigated fields. Humidity, temperature and wind speed variables change when entering an irrigated field surrounded by dry or poorly irrigated fields. It is important, when making calculations of ET_{sz}, that weather measurements are accurate and that the weather measurements reflect the environment that is defined by the reference surface.

WEATHER DATA INTEGRITY ASSESSMENT

Quality and accuracy of the The standardized ASCE reference ET equation (ET_{sz}) is dependent on the quality of the weather data. Weather data must be screened before use in any ET equation, including the standardized equation, to ensure that data are of good quality and are representative of well-watered conditions. This is especially important with electronically collected data, since human oversight and maintenance may be limited. When weather measurements are determined to be faulty, they can be adjusted or corrected using a justifiable and defensible procedure, or the user may elect to replace perceived faulty data with estimates. This Appendix reviews some general procedures that may prove useful when assessing the integrity and representativeness of weather data used for ET_{ref} calculation. Procedures for estimating data in situations where data are shown to be of poor quality or are missing are summarized in Appendix E.

WEATHER STATION SITING

When possible, meteorological data used for estimating ET_{ref} should be measured over and downwind of vegetation that approximates the reference surface. This is important because the standardized ET_{ref} equation was developed for use with meteorological data collected primarily over and downwind of dense, fully transpiring grass or similar vegetation exhibiting behavior similar to the definition of the reference surface condition. Feedback exists between the boundary layer above the surface and the surface, so that the energy balance and evaporation at the surface impacts temperature and humidity of the air layer above. Ideally, weather stations should be centered within large, nearly level expanses of uniform vegetation that are supplied with sufficient water through precipitation and/or irrigation to support ET near maximum levels. The preferred vegetation for the site is clipped grass. However, alfalfa or a grass-legume pasture maintained at a height of less than 0.5 m may also serve as an effective vegetation for the site. Meteorological measurements made over other short, green, actively transpiring crops will approach reference measurements, provided canopy cover exceeds approximately 70%. A station may be located on the periphery of a vegetated field provided the station is located downwind of the field during daytime hours and that vegetation is shorter than about 0.5 m so as to not impact the wind measurement. In an ideal setting, the well-watered vegetation extends at least 100 m in all directions from the weather station. However, it is recognized that frequently such a weather station site is not available, and that often some nonvegetated areas or roadways will be present near the station.

Meteorological data sets obtained from true reference settings are generally difficult to come by. Often, weather stations are located over or adjacent to: 1) annual row crops that proceed through a distinct annual growth (and cover) cycle, or 2) range and/or pasture land that is subject to seasonal deficits in soil moisture and within the vicinity of small buildings and roadways. Many urban weather stations fail both the underlying surface requirement and the recommended separation distance from obstacles. Failure of a weather station site to meet the definition of a reference condition described above does not preclude use of the data for estimation of ET_{ref}. However, data from such a station should be examined carefully before use, and may, in some cases, require adjustment to make the data more representative of reference conditions. New weather stations installed for the express purpose of estimating ET_{ref} should be located in sites that closely approximate the reference conditions outlined above.

It is the intent of this document to encourage the use of weather data and to site weather stations that adhere to the preferred guidelines. When weather data are not from an agricultural or reference environment and are shown to be substantially impacted by the lack of local ET, the user should be willing to adjust the data using procedures of this Appendix and other publications or to abandon the use of the data.

Weather stations should be isolated from nearby obstacles and obstructions that can impede airflow and/or shade the site. The recommended horizontal separation distance from such obstacles should exceed 10 times the height of the obstacle. Fences used to protect the station from unwanted intrusions by animals should be made of a porous fencing material (e.g., woven wire or chain link); fence height should not extend above the height of the anemometer.

DATA QUALITY CONTROL

Meteorological data sets acquired for the purposes of estimating ET_{ref} should be subjected to a number of quality control checks prior to use.

The first and most important quality control check involves contacting the source of the weather data to obtain information on:

1. Siting of the weather station.
2. Type and exposure of meteorological sensors employed at the station.
3. Procedures used to maintain and calibrate sensors.
4. Quality control procedures performed and/or data adjustments already performed on the data.
5. Availability of shorter interval data sets (e.g., hourly) to aid the overall QC process.
6. The station operator's experience and/or recommendations pertaining to use of the data for ET_{ref} assessment.

Recommendations pertaining to station siting were discussed in the opening section of this appendix. The types of sensors employed and their exposure (e.g., height of installation or type of radiation shelter) provide insight into expected error levels for specific measurements, and may identify measurements requiring some form of adjustment (e.g., height adjustment for wind speed).

Procedures used to maintain and calibrate meteorological sensors are of extreme importance. Maintenance can be divided into non-technical and technical categories. Non-technical maintenance activities include site maintenance (e.g., mowing, irrigation, and fence repair); cleaning sensors; and leveling radiation sensors and rain gauges. Technical maintenance involves repair and replacement of sensors and equipment, and represents an important component of the overall calibration process. Technical maintenance should be based on the concept of preventive maintenance; that is, replacement of sensors and equipment before their performance degrades. On-site calibration can be performed at regular intervals by comparing sensors with calibrated sensors that are taken to the site for inter-comparison purposes. The operator of the station should provide both the technical and non-technical maintenance protocols and schedule logs either on request basis or on a public web site.

ASAE has recently adopted Engineering Practice 505: "Measurement and Reporting Practices for Automatic Agricultural Weather Stations" (ASAE, 2004). This standard provides specifications for sensor accuracy, resolution, placement and monitoring, as well as intervals and procedures for sensor maintenance and calibration.

It is always advisable to investigate the various quality control (QC) routines that have been employed on the data set by the operator of the station. Data from weather stations operated as part of a weather network are generally subjected to some form of QC assessment (e.g., Snyder et al., 1985; Stanhill,1992; Meek and Hatfield, 1994; Snyder et al., 1996; Shafer et al., 2000). Common QC assessments include comparing incoming parameters against relevant physical extremes (e.g., relative humidity >100%); using statistical techniques to identify extreme or anomalous values; and comparing data with neighboring stations. Some networks flag questionable data while other networks may replace questionable data with estimated values. The user should be aware, however, that QC procedures of some networks contain rather broad or coarse data range assessments, so that application of a QC procedure does not necessarily provide valid data.

Seeking the advice of the station operator regarding the fitness of a given meteorological data set for ET_{ref} assessment is always advisable. The operator should have considerable insight into whether station sites approach reference conditions, and if not, suggestions on how to correct or adjust either the raw meteorological data or the final ET_{ref} values. Subsequent sections of this document provide procedures for assessing the integrity of meteorological data sets used in the computation of ET_{ref}. Possible procedures for adjusting data to better reflect reference conditions are suggested. While these procedures are applicable in many circumstances, they are by no means a universal solution to all potential problems with meteorological data. Users of the standardized ASCE Penman-Monteith reference ET equation are encouraged to seek local input regarding the subject of assessment and correction of meteorological data for use in computation of ET_{ref}.

SOLAR RADIATION

Solar radiation data can be screened by plotting measurements against clear sky R_{so} envelopes for hourly or daily timesteps. Generally, the best estimates of R_{so} should be used, which may require applying equations that include the influence of sun angle, turbidity, atmospheric thickness, and precipitable water, for example, Eq. D.1 – D.6 that are presented in the following section. For daily data sets, one can plot measured R_s and computed R_{so} against the day of the year (see Figure 1 in the text and Figure D-1 following). For hourly data, one can plot measured R_s and computed R_{so} against time of day, one day at a time, for perhaps five to ten selected "clear sky" days (Figure D-2).

After creating the R_s and R_{so} plots, the user can observe whether measured R_s "bumps" up against the clear sky envelope some of the time (i.e., on cloud-free days for daily data or during cloud-free hours for hourly data). R_s will fall below the clear sky curve on cloudy or hazy days and during times when the atmosphere is more turbid than under conditions of clean air. Conditions of relatively clean air occur following cleansing rain or snow showers. The transmissivity of the atmosphere and thus R_{so} can shift by several percent from day to day due to changes in water vapor, particulate matter and aerosols, which are all net absorbers of solar radiation. If the "upper" values of measured R_s lie routinely above or below the computed R_{so} curve by more than 3 to 5%, then the user should scrutinize the maintenance and calibration of the R_s sensor. Improper calibration, leveling errors, the presence of contaminants on the sensor (e.g., dust, salt, or bird droppings), or electrical problems can cause R_s to deviate from R_{so} on clear days. "Abrupt" changes in the clear-day relationship between R_s and R_{so} generally indicate: 1) accumulation or removal of contaminants from the sensor; 2) change in sensor level; 3) change in sensor calibration; 4) sensor replacement; or 5) problem with wiring or data-acquisition system. Pyranometer maintenance records, if available, may help explain changes in the relationship between R_s and R_{so} and aid decisions related to data adjustment. Occasionally, R_s during hourly periods may exceed R_{so} due to reflection of sunlight from nearby clouds.

Values of R_s that are consistently above or below R_{so} on clear days can be adjusted by dividing R_s by the average value of R_s/R_{so} on clear days. This adjustment should be used with appropriate caution as the procedure assumes: 1) computed values for R_{so} are correct; 2) clear days can be effectively identified (for example, during midseason at Greeley in Fig. D-1 following, there is a substantial period having no completely cloud-free days); and 3) the factor causing R_s to deviate from R_{so} is static over time. The R_{so} curves computed by Eq. D.1-D.6 following or by Eq. 19 and 20 in the main body of the report are not "perfect." They assume clean air and common relationships between the diffuse and beam components of short wave radiation along with typical spectral densities within the short wave band. Identification of clear days can be difficult in cloud prone areas, especially if hourly R_s data are not available to aid in the assessment process. Finally, many of the factors causing R_s to deviate from R_{so}, including leveling errors and contaminant accumulation (See Stanhill, 1992), may not be static over time.

DETAILED PROCEDURE FOR CLEAR-SKY SHORT WAVE RADIATION (R_{SO})

A simplified procedure for estimating R_{so} was given in the main text as Eq. 19 and 48. A more complex and generally more accurate procedure involves considering the effects of sun angle and water vapor on absorption of short wave radiation and by separating the components of beam and diffuse radiation, so that:

$$R_{so} = (K_B + K_D) R_a \qquad \text{(D.1)}$$

where:

- K_B = the clearness index for direct beam radiation [unitless]
- K_D = the transmissivity index for diffuse radiation [unitless]
- R_a = extraterrestrial radiation [MJ m^{-2} d^{-1}] or [MJ m^{-2} h^{-1}]

The following equation for K_B, extended from Majumdar et al., (1972) by Allen (1996) and Allen et al., (1998), is applied here with improved coefficients developed from the Task Committee evaluation of solar radiation data from many of the sites evaluated for ET_{os} and ET_{rs}:

$$K_B = 0.98 \exp\left[\frac{-0.00146\,P}{K_t \sin\beta} - 0.075\left(\frac{W}{\sin\beta}\right)^{0.4}\right] \qquad (D.2)$$

where:

- K_t = turbidity coefficient [unitless], $0 < K_t \le 1.0$ where $K_t = 1.0$ for clean air and $K_t \le 0.5$ for extremely turbid, dusty or polluted air.
- P = atmospheric pressure at the site elevation, as calculated in Eq. 3 [kPa]
- β = angle of the sun above the horizon [radians]
- W = precipitable water in the atmosphere [mm]

The value for K_t may vary with time of year and with cleansing of the atmosphere by precipitation. General values for K_t for a region can be determined using a pristine pyranometer that has a calibration traceable to the national or international solar standard. In general, for routine prediction of R_n and R_{so} envelopes, $K_t = 1.0$ is recommended. The value for β can be calculated using Eq. D.5 (daily) and Eq. D.6 (hourly). The "sin β" in Eq. D.2 should be limited to ≥ 0.01 for computational stability.

Precipitable water is predicted as:

$$W = 0.14 e_a P + 2.1 \tag{D.3}$$

where:

- W = precipitable water in the atmosphere [mm]
- e_a = actual vapor pressure of the air (at approximately 2 m) [kPa]
- P = atmospheric pressure at the site elevation, as calculated in Eq. 3 [kPa]

The diffuse radiation index is estimated from K_B (following Allen, 1996):

$$\begin{aligned} K_D &= 0.35 - 0.36 K_B \quad \text{for } K_B \geq 0.15 \\ K_D &= 0.18 + 0.82 K_B \quad \text{for } K_B < 0.15 \end{aligned} \tag{D.4}$$

For clear sky conditions, K_B is always > 0.15 for daily data and is nearly always > 0.15 for hourly periods, even those close to sunrise and sunset. Therefore, generally K_D for use in R_{so} can be computed as $K_D = 0.35 – 0.36 K_B$, ignoring the second conditional of Eq. D.4.

For daily (24-hour) time periods, the average value of β, weighted according to R_a, can be approximated from Allen (1996) as:

$$\sin \beta_{24} = \sin\left[0.85 + 0.3 \varphi \sin\left(\frac{2\pi}{365} J - 1.39\right) - 0.42 \varphi^2\right] \tag{D.5}$$

where:

- β_{24} = average β during the daylight period, weighted according to R_a [radians]
- φ = latitude [radians]
- J = day of the year [unitless]

The "sin β_{24}" variable is to be used in place of sin β in Eq. D.2 and represents the weighted average sun angle during daylight hours. The value for β_{24} should be limited to ≥ 0.

For hourly or shorter periods the sun angle β is calculated as:

$$\sin\beta = \sin\varphi \sin\delta + \cos\varphi \cos\delta \cos\omega \quad \text{(D.6)}$$

where:

φ = latitude [radians]

δ = solar declination ("delta")[radians]

ω = solar time angle at the midpoint of the hourly or shorter period [radians]

The user is cautioned that the R_{so} estimate is a theoretical approximation, and that there may be reasons why measured R_s for cloud-free periods deviates from the R_{so} curve. These reasons include air turbidity and haziness caused by dust and aerosols, nearly invisible clouds high overhead, and late afternoon clouding.

Daily measured R_s is plotted in Fig. D-1 for a full year at two CIMIS weather stations in the Imperial Valley of California. R_{so} has been calculated using two methods: Eq. 19 of the text and Eq. D.1 – D.5 of this appendix. Eq. 19 is a simplified procedure, where R_{so} is computed as a constant fraction of R_a, with the constant predicted from site elevation. In the case of Imperial Valley, which is at or below sea level, the constant is about 0.75 for both stations. Comparison of the R_{so} curves with measured R_s from Calipatria, California (Figure D-1a) indicates that the pyranometer was measuring about 12% low on clear-sky days through about day 200. At around day 200, the sensor was replaced, and readings for clear-sky days increased to about 5 to 10% higher than the R_{so} curves. R_s data from the nearby Seeley weather station (about 40 km to the SW) during the same year did not exhibit this shift in data. Therefore, for the Calipatria data for year 1999, the data user would be encouraged to contact the data collector and provider for information concerning pyranometer calibration and the user may wish to pursue options for applying some sort of correction to the data, for example, by multiplying R_s by about 1.12 for days prior to day 200 and by about 0.95 for days following day 200. The user could also consider substituting data from the nearby Seeley station. The more theoretical R_{so} curve from

Eq. D.1-D.5 exceeded the more simple R_{so} curve from Eq. 19 by a few percent during mid summer at Seeley and Calipatria, and fit the measured R_s on clear-sky days more closely at Seeley during mid-summer (Fig. D-1b). R_s measured at Seeley on some of the clear-sky days during spring and fall routinely lay a few percent above the R_{so} curves. This indicates that the pyranometer calibration may have been a few percent high or that the theoretical R_{so} curve is a few percent low for this location. The data user may wish to investigate the pyranometer calibration at this site and perhaps conduct an independent assessment of clear-sky R_s using an accurate pyranometer having calibration traceable to the National Standard housed with the Solar Radiation Research Laboratory (http://srrl.nrel.gov/bms/) located in the National Renewable Energy Laborabory (NREL) at Golden, CO (http://www.NREL.GOV/). However, agreement between measured R_s and R_{so} at Seeley appears to be good enough for application in the standardized equations without any adjustment or correction.

A few unreasonably low values of R_s are shown in Figure D-1a and b, where measured R_s was reported as less than 0.1 R_a. Generally, the lower bound for 24-hour R_s is about 0.2 R_a. The very low values probably occurred due to sensor or datalogger malfunction or during site maintenance. Missing or faulty data should be substituted by data from surrounding stations as described in Appendix E.

A third set of daily measured R_s is plotted in Fig. D-2 for a full year at Greeley, Colorado. Both R_{so} curves (Eq. 19 and Eq. D.1-D.5) follow the upper bound of measured R_s quite well for the Greeley data. Agreement is good throughout the year, except for the late spring – early summer period, when there were no days having completely clear conditions. This was confirmed by scanning records of hourly R_s, which indicated that essentially all days at Greeley during late spring – early summer were subject to afternoon clouding during 2000. This example is included to caution the data user that sometimes deviation of measured R_s from the R_{so} curve for extended periods may be real and valid. The good agreement between measured R_s for cloud-free days and the computed R_{so} curve for winter, early spring and fall periods supports using the solar radiation data from this weather station for the year shown. The R_{so} curve computed using Eq.

D.1 – D.5 dropped a small amount below the R_{so} curve from Eq. 19 during summer (day 180 on) due to increased absorption by relatively higher humidity levels of the atmosphere during this period.

Figure D-3 illustrates a comparison of hourly measured solar radiation with R_{so} computed using the simple method of Eq. 47 of the text and using the more complicated method described above, Eq. D.1-D.6. The data are from the agricultural weather station near Greeley, Colorado, and data from only two days in August are shown. August 5 had a brief period of cloudiness at around 0800 and then some cloudiness during the afternoon. August 6 was essentially a cloud-free day. The R_s data from August 6 compared well with both R_{so} methods throughout the day. The measured data plotted slightly higher than the simpler R_{so} estimate from Eq. 47 during the morning hours and slightly below the R_{so} estimate during the afternoon. This may hint of a slight error in the level of the instrument or in the time setting for the data-logger clock. In general, the solar radiation data appear to be of excellent quality and calibration.

Plotting hourly measured R_s against the theoretical R_{so} can be helpful in detecting errors or shifts in the reported times associated with the data set (i.e., errors in datalogger time clocks). Plotting of data can also provide an indication of a lack of level of the instrument. Shifts in time and lack of instrument level can both cause measured R_s to plot out of phase with the theoretical R_{so} curve.

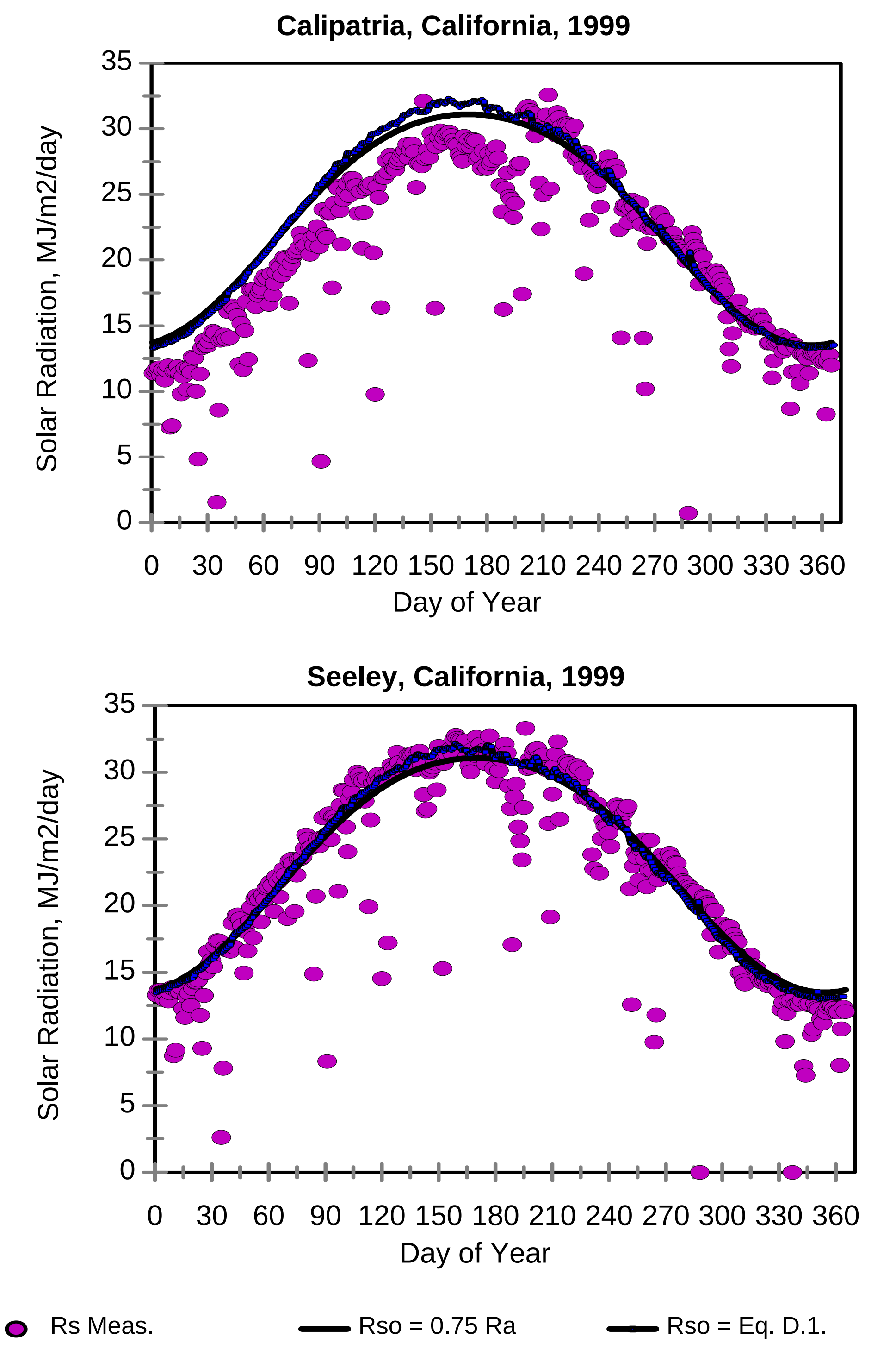


Figure D-1. Daily Measured R_s and Calculated R_{so} using Eq. 19 of the text and using Eq. D.1 – D.5 for Calipatria (top) and Seeley (bottom), California CIMIS stations in the Imperial Valley during 1999.

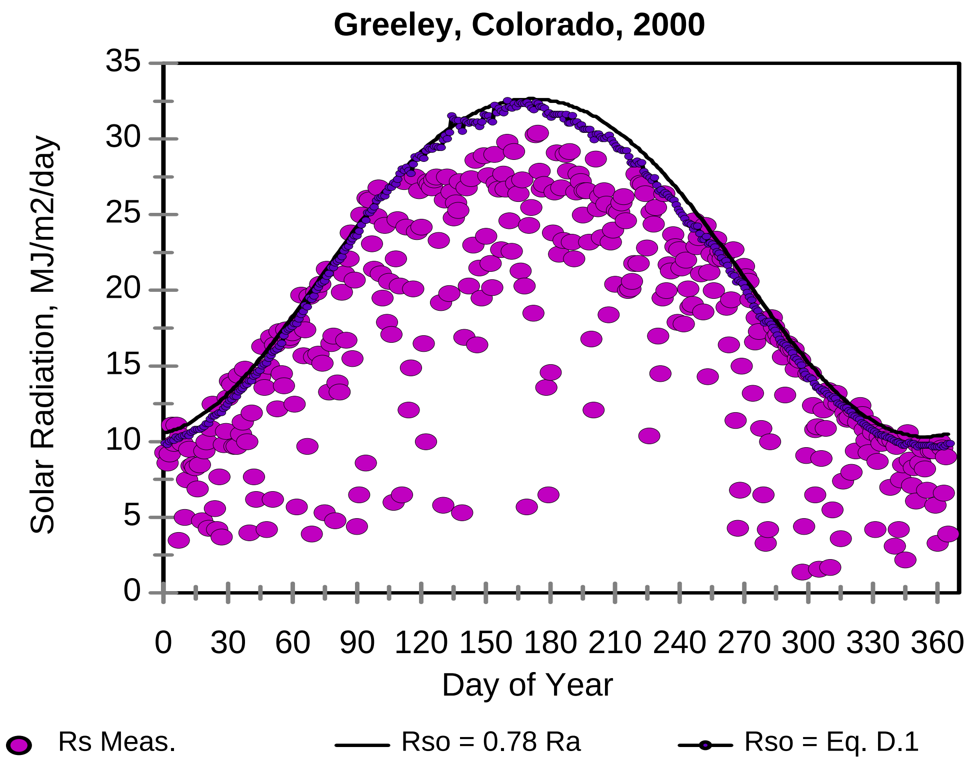


Figure D-2. Daily Measured Rs and Calculated Rso using Eq. 19 of the text and using Eq. D.1 – D.5 for Greeley, Colorado during 2000.

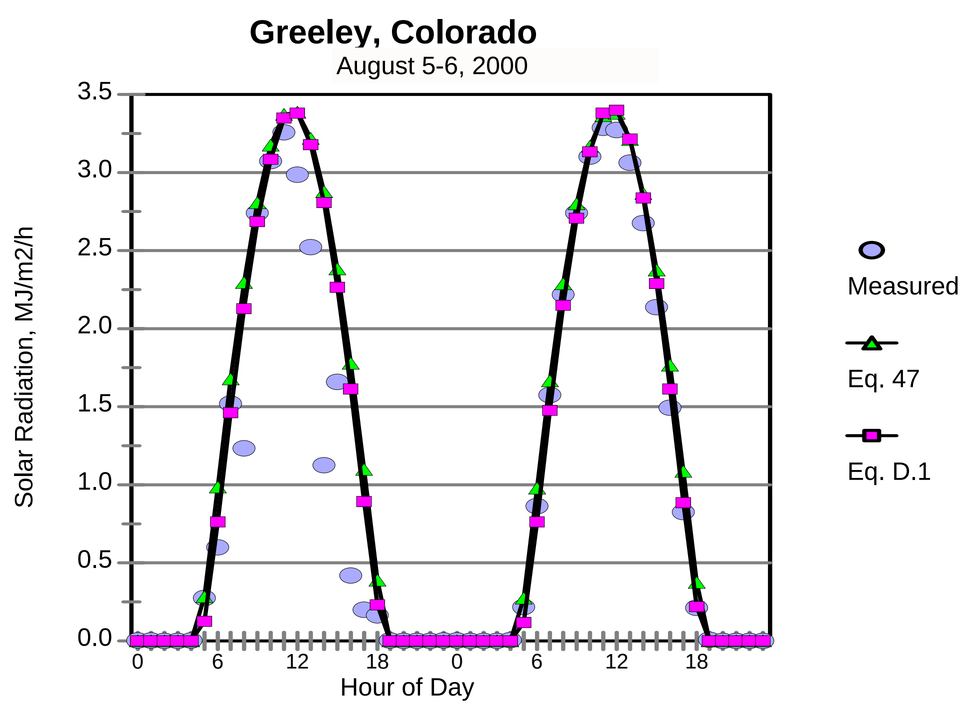


Figure D-3. Hourly measured solar radiation and clear-sky envelopes for two days in August, 2000 near Greeley, Colorado.

NET RADIATION

Where net radiation data are measured, values can be compared with R_n estimated from solar radiation as a means of integrity assessment. One should not expect measured R_n to exactly agree with estimated R_n. However, significant variation between the two should be cause for a closer investigation of the measured data. Some net radiometers do not accurately measure the long wave component of net radiation. In addition, the R_n measurement should be made over a well-watered surface of clipped grass or full-cover alfalfa so that albedo is similar to that defined for ET_{sz}. A shift in the relationship between measured and estimated R_n may reflect a change in the quality or condition of the surface at the measurement site. Other measurement related factors that can shift the relationship between measured and estimated R_n include scratched or dirty radiometer domes, an off-level sensor, or condensation of moisture inside domes of the R_n sensor.

Figure D-4 shows hourly measured net radiation and net radiation calculated using the standardized net radiation procedure for one day at Kimberly, Idaho. Agreement between measured and calculated R_n is judged to be very good, even during nighttime periods.

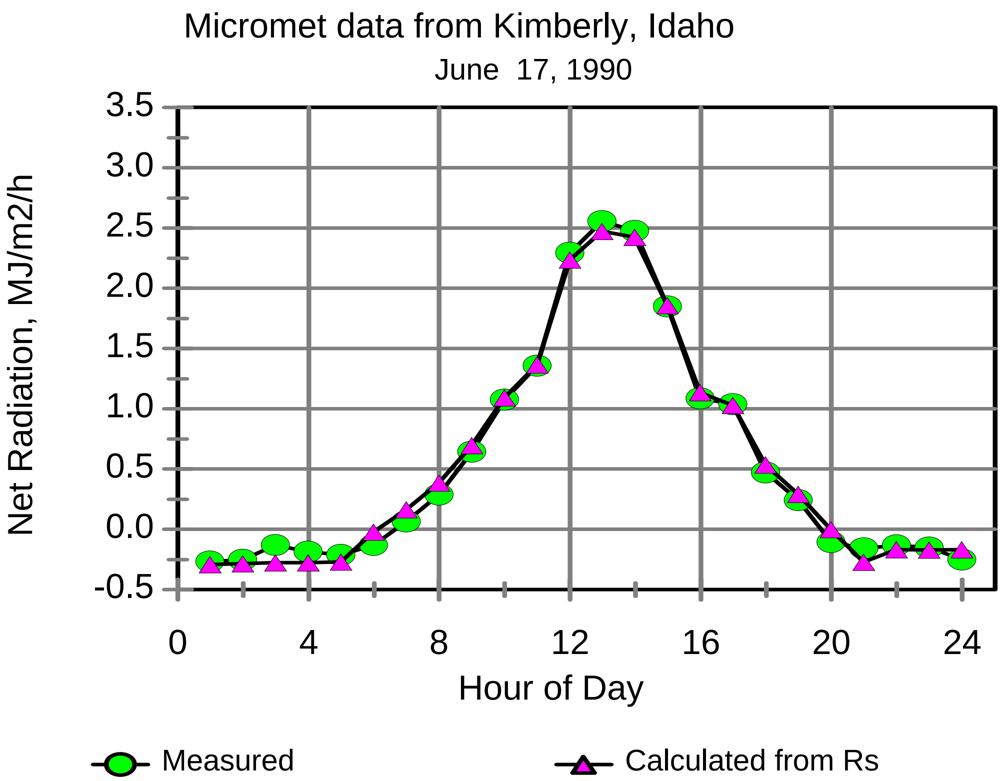


Figure D-4. Measured and calculated hourly net radiation for one day at Kimberly, Idaho over clipped grass (R_n was calculated using Eq. 42-44). Data courtesy of Dr. J.L. Wright, USDA-ARS, Kimberly.

HUMIDITY AND AIR TEMPERATURE

RELATIVE HUMIDITY

Humidity and air temperature data should be screened to identify questionable or erroneous data. A portion of the screening process involves the user having a sense of what are reasonable and unreasonable values. For example, relative humidity (RH) values chronically lower than 5 to 10% in arid regions and 30% in subhumid regions are uncommon and may indicate problems with the sensor. Similarly, RH values in excess of 100% do not occur in the natural environment and may indicate that the sensor is out of calibration. The accuracy of most modern-day electronic RH sensors is generally within +/- 5% RH (ASAE, 2004); thus, recorded RH values in excess of 105% provide good evidence that the sensor is out of calibration.

All RH values in excess of 100% should be set equal to 100% prior to use in the ET_{sz} computation process. Use of this simple adjustment procedure, however, does not alleviate sensor calibration errors in recorded RH data that lie below 100%. Some type of proportional adjustment to all data may be warranted. One should use RH data sets containing values in excess of 100% with caution. Furthermore, RH values in excess of 100%, if not accompanied by a QC flag, may indicate that the data set has not been subjected to rigorous QC.

If hourly data are available, it is advisable to examine the diurnal variation of RH on selected days to ensure that RH approaches maximum and minimum levels during the coolest and warmest portions of the day, respectively. Hourly time series of RH should also be examined for the presence of spikes and spurious values of RH that may indicate sensor malfunction. Finally, one should check RH data on several days having heavy and/or sustained precipitation events or when dew or fog events are known to have occurred. Relative humidity should approach 90-100% during a sustained precipitation, fog, or dew event, and should approach 100% in the evening hours following a heavy rain event.

DEW-POINT TEMPERATURE

Dew-point temperature (T_{dew}), as calculated from RH, may be reported in lieu of RH in some data sets. Any errors in RH will affect e_a (since $e_a = RH*e_s(T)/100$), and thus the computed T_{dew}. Values for daily average or early morning T_{dew} should be compared to minimum temperatures (T_{min}). In humid regions, the T_{dew} measurement will approach T_{min} on many days. Exceptions occur on days that feature a change in air mass (e.g., frontal passage), or that have high winds and/or cloudiness at night. T_{dew} may approach T_{min} in arid and semiarid environments if nighttime winds are light and measurements are made over a surface exhibiting behavior similar to the reference definition (i.e., sufficient evaporation to cause evaporative cooling). It is not uncommon in arid and semiarid regions to have T_{dew} 2 to 5 ^oC lower than T_{min} under reference conditions (see discussion below) but well below T_{min} if the measurement site is subjected to local aridity. If daily average T_{dew} regularly exceeds T_{min}, then the humidity sensor may be out of calibration. Such data should be examined closely and possibly adjusted prior to use (see Appendix E).

When it is not observed, T_{dew} can be computed from e_a by[1]

$$T_{dew} = \frac{116.91 + 237.3 \ln(e_a)}{16.78 - \ln(e_a)} \qquad \text{(D.7)}$$

where:

T_{dew} = dew point temperature [^oC]
e_a = actual vapor pressure [kPa]

Figure D-5 illustrates the use of comparisons between T_{min} and T_{dew} and use of plots of daily RH_{max} and RH_{min} to detect errors in hygrometer data from an AWS in SE Colorado. The large shifts in mean daily T_{dew} relative to T_{min} at days 15 and 200 are obvious. Following day 200, the data began to follow an expected pattern and relationship with T_{min}, with T_{dew} in close

[1] Reference: Bosen (1958); Jensen *et al.* (1990)

proximity to T_{min}. Similar obvious shifts in RH_{max} and RH_{min} are apparent also (bottom plot of Figure D-5). During the last half of the year, values for RH_{max} exceeded 100% by a small amount. However, these errors in RH are considered to be small relative to those occurring during the first part of the year, where the T_{dew} data required substantial correction. Daily RH_{min} after day 200 regularly fell below 10%, which is considered to be very low reading for a reference site. This reflects a relatively "harsh" evaporative environment. The proximity of T_{dew} to T_{min} during the same period indicated the general presence of an evaporative surface.

Figure D-6 shows T_{dew} and T_{min} for the same station and year as in Figure D-5, but following correction of T_{dew} using the following relationship:

$$T_{dew} = T_{min} - (T_{min} - T_{dew})_{station\ 2} \qquad (D.8)$$

where $(T_{min} - T_{dew})_{station\ 2}$ is the measured difference on the same day between T_{min} and T_{dew} at an AWS about 50 km distant. The use of $(T_{min} - T_{dew})_{station\ 2}$ preserved the difference observed between T_{min} and T_{dew} at the adjacent station, and therefore the relative dryness of the air mass, but adjusted for differences in minimum daily air temperature between the two sites. The resulting plots of T_{min} and T_{dew} in Fig. D-6 illustrate good continuity of the relationship between T_{min} and T_{dew} for the corrected period (days 15 – 200) and original observations following day 200. The occasionally low values for T_{dew} during days 15 – 200 were present in the data set for station 2.

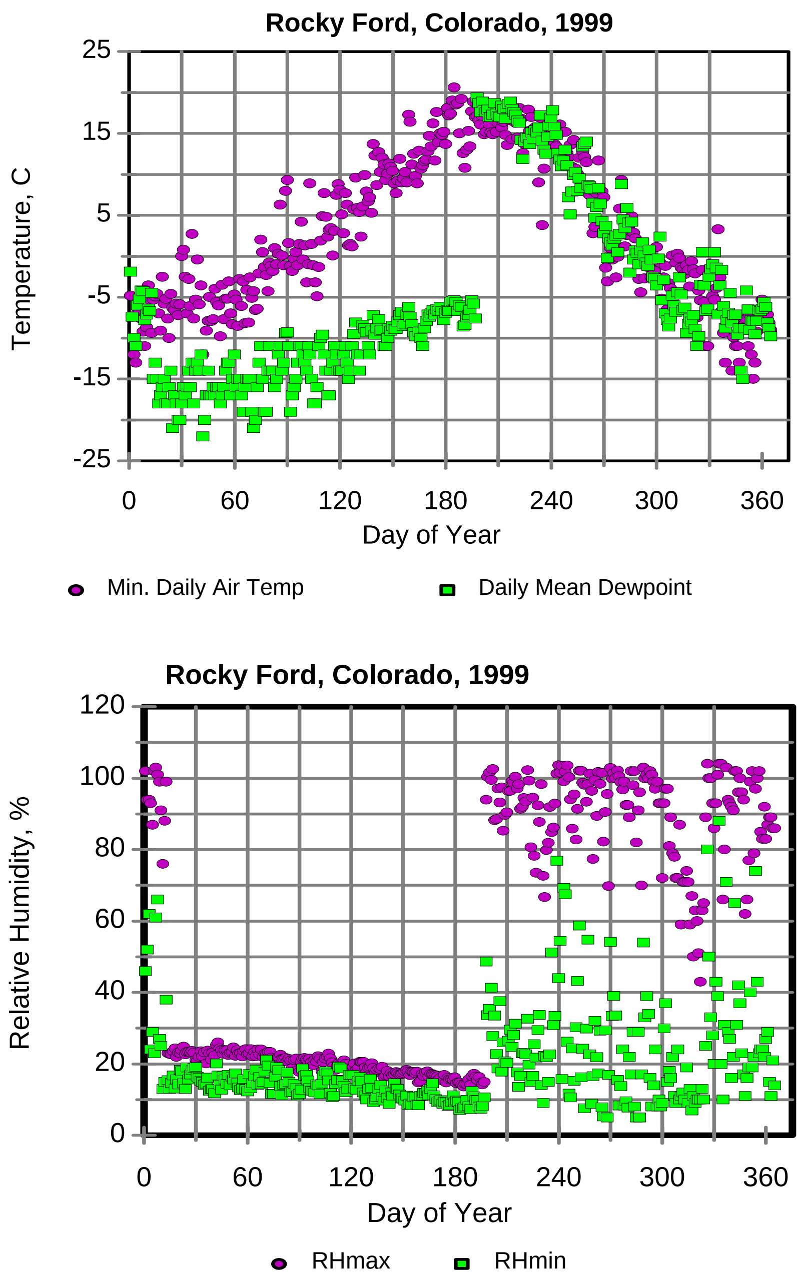


Figure D-5. Measured daily minimum air temperature and mean daily dewpoint temperature (top) and daily maximum and minimum relative humidity (bottom) recorded for Rocky Ford, Colorado during 1999.

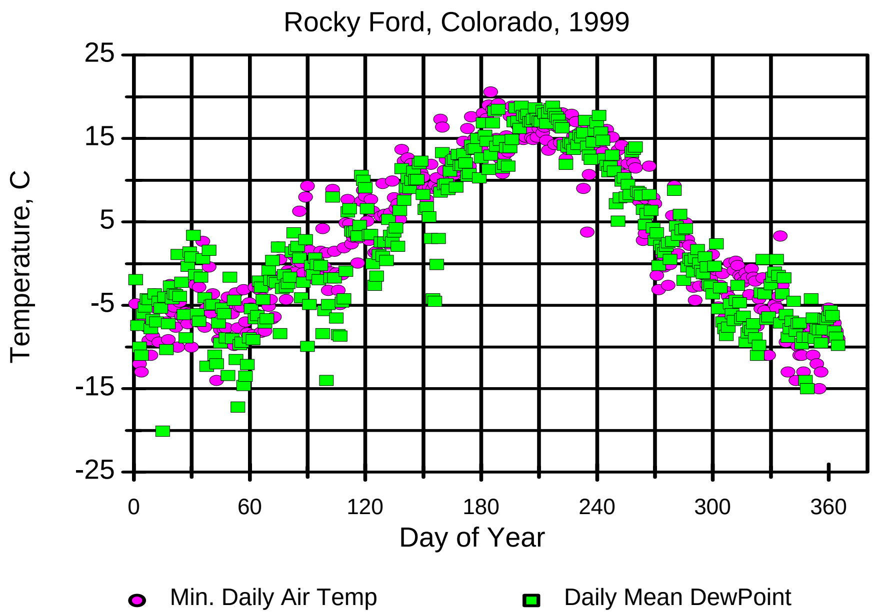


Figure D-6. Measured daily minimum air temperature and mean daily dewpoint temperature for Rocky Ford, Colorado during 1999, where T_{dew} for days 15 to 200 was replaced by estimates using Eq. D-8.

Plots of hourly or shorter period T_{dew} data may assist in identifying problems in T_{dew} data. Dew point and vapor pressure are relatively conservative parameters and often exhibit little change over a day, especially in humid regions. Often, T_{dew} will increase somewhat during midmorning due to evaporation of water and increased capacity for the air to contain vapor (see for example, Fig. D-7 and D-10). Dew point will then stabilize or decline slightly during the mid-day hours as the vapor near the surface gets mixed into a progressively deeper boundary layer. Hourly variation in T_{dew} is greater in semiarid and arid settings, especially in areas prone to strong regional advection, where T_{dew} can drop substantially during afternoon as warm, dry air from outside an irrigated area "breaks into" the boundary layer established over the irrigated area. However, large changes in T_{dew} during the day, except under circumstances such as a change in air mass (e.g., frontal activity or sea/land breeze) or large change in wind direction, could signal an error or bias in the T_{dew} measurement. It is common in the western Great Plains of the U.S.

to have distinct drylines, which extend either N-S or NE-SW. A dryline, which is an atmospheric transition zone having large gradients in vapor content, may move during the day, with larger T_{dew} values in front of the dryline (typically the eastern side) and with substantially smaller T_{dew} values behind the dryline (typically the western side). Allen (1996) provided illustrative plots of hourly T_{dew} data and expected trends over time. Comparison of hourly T_{dew} to T over a 24-hour period is illustrated in Figure D-7.

AIR TEMPERATURE

In general, air temperature is the simplest and most consistent weather parameter to measure and the parameter most likely to be of highest quality, provided it is measured in a reference-type of environment. Air temperature extremes in a data set should be compared to historical record extremes, if such data are available for locations near the site. Temperatures that routinely exceed the recorded extremes for a region indicate a problem with either the sensor or with the radiation shield used to house the sensor. Sensors mounted in non-aspirated radiation shields may produce erroneously high temperatures on days having light winds due to solar heating of the shield (Gill, 1983). Consistently hot temperatures from a sensor mounted in an aspirated radiation shield may indicate problems with the ventilation system. An effective check for spuriously high or low temperature extremes is to compare the average of the daily extremes (T_{max} and T_{min}) with the mean daily temperature as averaged by the data logger for the day. Many automated weather stations now generate a recorded average temperature for the 24-hr period that can be used in this comparison. Differences between the average computed from the temperature extremes and the recorded 24-hr average for the day will generally run within 2 ^oC. Data should be subjected to closer scrutiny on days when the two averages deviate by more than 3 ^oC. Precipitation events, air mass changes, and unusual wind conditions can cause deviations in excess of 3 ^oC.

When hourly temperature data are available, it is advisable to plot the diel (hourly) temperature trend on selected dates to ensure that temperatures attain maximum and minimum values at the appropriate time of the day. For most locations, minimum temperatures occur shortly before sunrise, and maximum temperatures occur in mid-afternoon (1400-1600). It is also important to examine diel temperature profiles for spikes or spurious temperatures that could indicate a malfunctioning sensor.

Figure D-7 illustrates hourly measurements of both air temperature and dewpoint temperature during a single day over a grassed surface near Kimberly, Idaho. Measurements were made using electronic instrumentation and dual measurements using independent systems from different manufacturers were used for purposes of data back-up and redundancy. The two air temperature sensors (TC = thermocouple and RMY = RM Young chilled mirror system) tracked

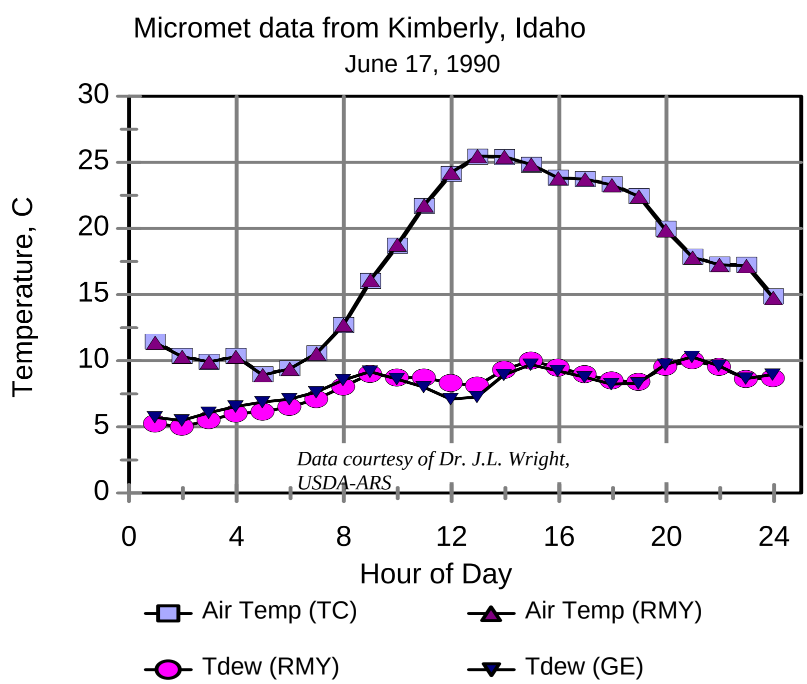


Figure D-7. Hourly air temperature and measured dewpoint temperature from dual sensor systems near Kimberly, Idaho, July 17, 1990. Data courtesy of Dr. J.L. Wright, USDA-ARS, Kimberly, Idaho.

each other consistently throughout the 24-hour period. The two dewpoint temperature measurements (RMY = RM Young chilled mirror system and GE = General Eastern chilled mirror system) tracked each other closely throughout the period. The closeness of the data measurements from two independent, colocated systems is useful in confirming the accuracy of the data and the proper functioning of both instrument systems. In addition to validation of the air temperature and measured dewpoint temperatures, the data in Fig. D-7 show that minimum daily air temperature, recorded as 9.0 ^oC at about 5 am was about 3 ^oC above the dewpoint temperature (6.2 ^oC) measured at the same time. This difference is in line with that expected from a well-watered reference environment as discussed in the following section.

IMPACT OF NON-REFERENCE WEATHER STATION SITE ON TEMPERATURE AND HUMIDITY

Temperature and humidity data that pass QC checks still may not be advisable for use in estimating ET_{ref}. The moisture status of the underlying surface impacts both temperature and humidity due to the energy balance and impacts of evaporative cooling. Therefore, data collected away from well-watered vegetation (e.g., at airports or over dry, paved, and fallow surfaces) can be negatively influenced by the local aridity, especially in arid and semiarid climates. Data from dry or urban settings may cause overestimation of ET_{os} or ET_{rs} due to air temperature measurements that are too high and humidity measurements that are too low, relative to the reference condition. Under these "arid" measurement conditions, the ET_{os} and ET_{rs} calculations may reflect ET demand of the "ambient," "non-reference" environment, for instance where average net rainfall plus irrigation is substantially less than ET_o or ET_r, so that air temperature is elevated. However, these estimates of ET_{os} and ET_{rs} may over-predict the ET_{os} and ET_{rs} that would occur for a well-watered setting. An extreme example of the impact of local aridity on ET_{os} was observed in a study near Parker, AZ, (Brown, 2001) where weather stations were installed in adjacent 15-ha fields containing irrigated alfalfa and fallow ground. Data from each station were used to estimate ET_{os} using the ET_{sz} equation. Monthly totals of ET_{os} computed using the fallow station data set exceeded similar ET_{os} totals computed using the alfalfa data set by 18-26% during months of June through September (Figure D-8).

Often, an assessment of RH, T_{dew}, and e_a can indicate whether meteorological data were collected in a reference type of environment. Under reference conditions, daily RH_{max} generally exceeds 90% and may approach 100% during early morning hours, provided skies are clear and winds are light (Allen, 1996). Minimum temperatures under these circumstances will approach T_{dew}. One can therefore plot and then visually scan plots of RH_{max} or average (or early morning) T_{dew} and T_{min} as a function of time to determine if humidity data reflect the reference condition.

For example, Figure D-9a shows daily T_{min} and T_{dew} for the year 2000 for the agricultural weather station near Greeley, Colorado. Mean daily T_{dew} (calculated from daily average measured vapor pressure) follows T_{min} relatively closely throughout the year, and is generally within a few degrees Celsius of T_{min}. Figure D-9b shows daily maximum and minimum RH for 2000 at Greeley. The RH_{max} tends toward 90 to 100% during many days. Minimum relative humidity (RH_{min}) runs a little below the expected 25 to 35% range for a reference setting in a semi-arid environment (Allen, Brockway and Wright, 1983; Allen 1996, Allen et al., 1996). Overall, the humidity and air temperature data at Greeley during 2000 are judged to be relatively accurate and reflective of a "reference" condition.

If RH_{max} is consistently below 80% for a substantial portion of the growing season record, or if T_{dew} deviates more than 3–4 ^{o}C less than T_{min} for a substantial portion of the growing season record, then the humidity data should be subjected to further scrutiny. Among the factors to investigate are: 1) type, maintenance, and calibration of the RH or T_{dew} equipment; 2) presence of cloudiness or wind flow at night, which tend to reduce RH_{max}; 3) that the site may not be representative of well-watered conditions; and 4) that the region has characteristically very dry air so that irrigated areas are subject to substantial advection of hot, dry air, for example in

Imperial Valley, CA, and portions of Arizona and New Mexico. Historically, humidity has been among the most difficult routine meteorological parameters to accurately measure. The quality of RH measurements has improved in recent years due to improvements in sensor technology. Prior to 1990, many agricultural weather networks used polystyrene humidity sensors. These sensors degraded rather quickly in agricultural environments (Howell at al., 1984; Brown et al., 1987), and RH measurement errors in excess of 5% RH were common under the best of circumstances (Brown et al., 1987). Most networks now utilize thin-film capacitance RH sensors that are stable for periods in excess of one year and accurate to within 2-3% RH if properly maintained and calibrated (Tanner, 2001).

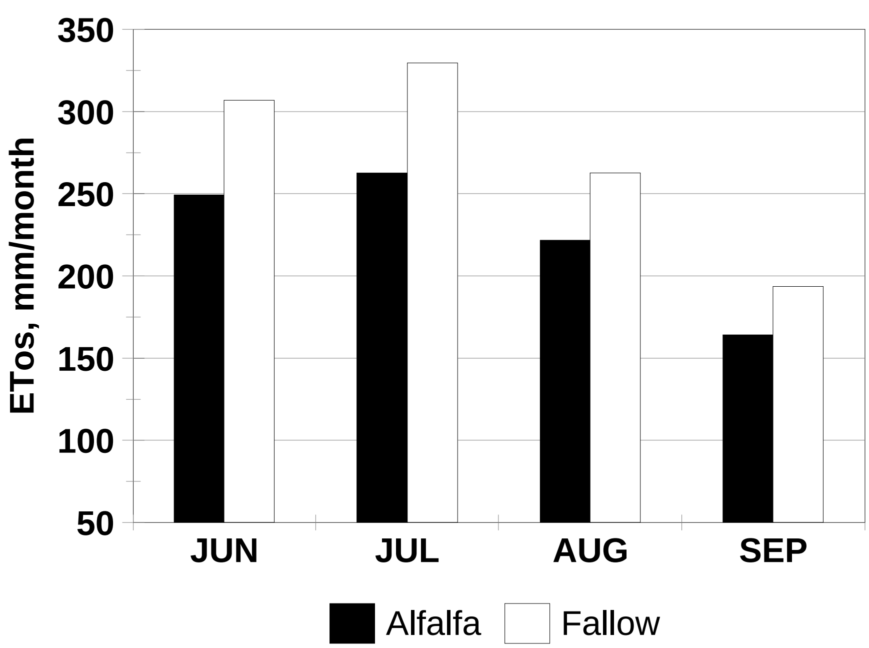
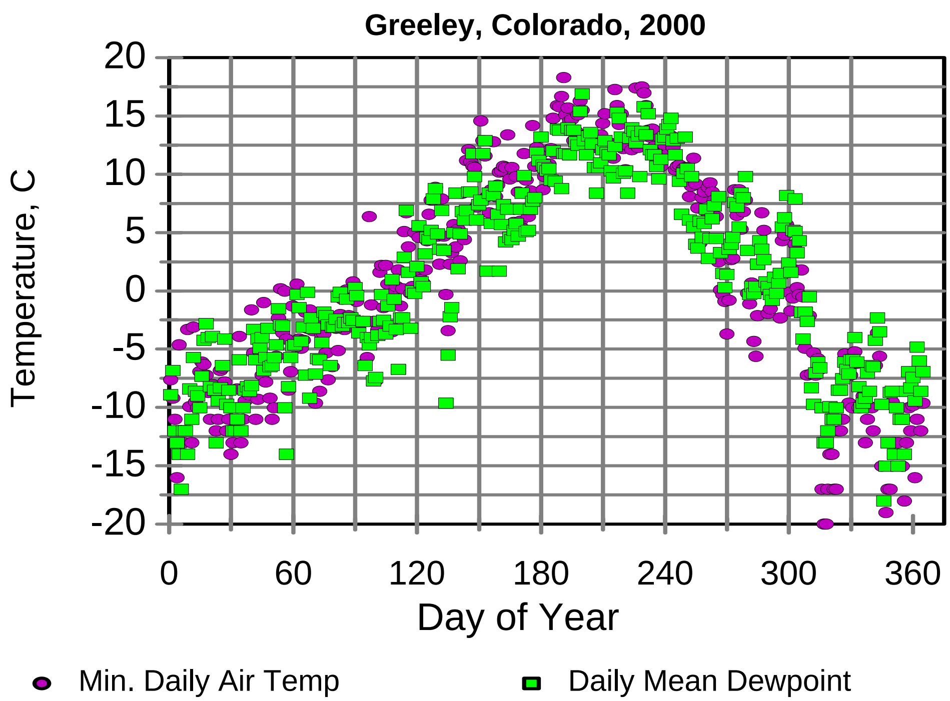


Figure D-8. ET_{os} by month for the summer of 2000 at Parker, AZ computed using meteorological data collected under reference (alfalfa) and non-reference (fallow) conditions.



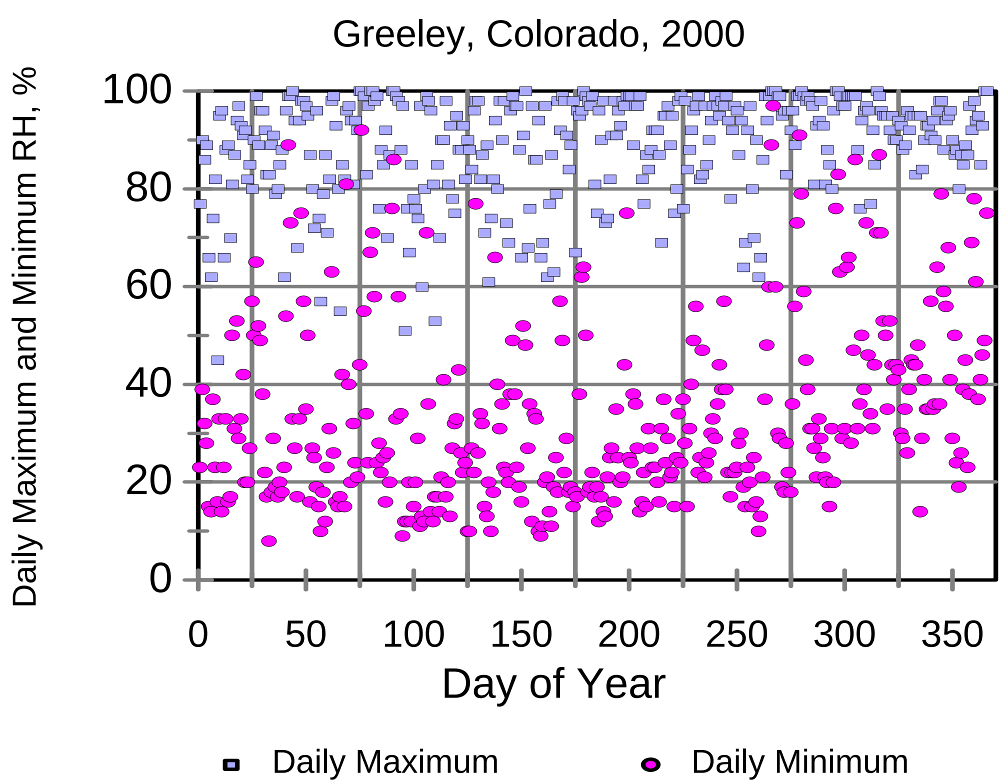


Figure D-9. a) Daily minimum air temperature and daily mean dew point temperature vs. day of the year and b) daily maximum and daily minimum relative humidity vs. day of the year for Greeley, Colorado, during 2000.

Psychrometers, dewcells, and chilled mirror hygrometers can provide high quality humidity data, as shown in Fig. D-7, provided the sensors receive proper maintenance and are operated within the design range. These sensors are not in widespread use for general climate monitoring in remote, automated weather stations due to cost and maintenance factors. The RH and T_{dew} assessments described here may not be effective at identifying data representative of a suitable reference environment in regions prone to cloudiness and large nighttime winds. Cloudiness lowers net loss of long-wave radiation at night, which inhibits cooling and may prevent T_{min} from approaching T_{dew} at night. High nighttime wind speed enhances the transfer of sensible heat and dry air to the surface, slowing the rate of cooling and preventing full humidification of the atmospheric boundary layer above well-watered surfaces.

Often, dewpoint temperature is consistent between locations having similar surface conditions. For example, Fig. D-10 shows hourly dewpoint temperatures for four Agrimet weather stations (data from U.S. Bureau of Reclamation) in southern Idaho that are up to 140 km apart. The recorded dewpoint temperatures and their trend during the day are largely consistent. The four stations (Rexburg, Monteview, Ashton, and Aberdeen) are situated in irrigated agricultural settings. Dewpoint data taken from a desert weather station (Flint Creek, Idaho, lat. 42.08°, long. 112.18°) is substantially lower, averaging 11 °C below the average for the four Agrimet stations. Air temperature at Flint Creek averaged 4 °C above the Agrimet stations over the 24-hour period. The impact of aridity on both dewpoint temperature and air temperature at Flint Creek is obvious and is manifested in erroneously high ET_{ref} estimates if applied without correction.

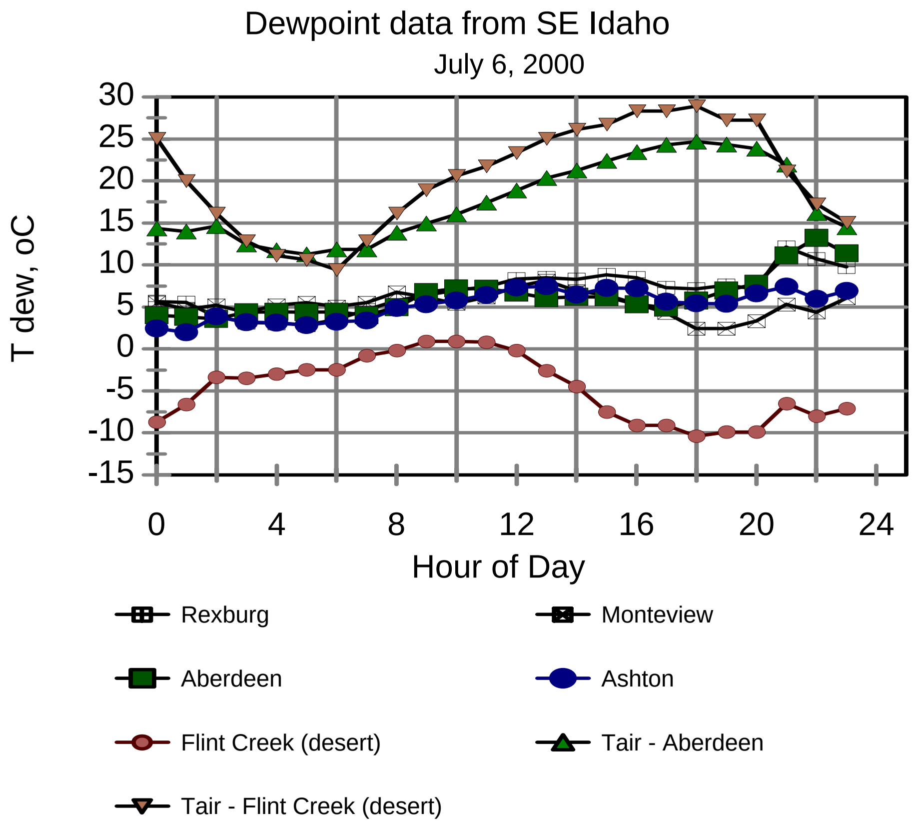


Figure D-10. Hourly dewpoint from four irrigated regions of southeast Idaho and from a desert weather station (Flint Creek) on July 6, 2000. Also shown are air temperatures at Aberdeen and Flint Creek.

Adjustment of temperature and/or humidity data may be warranted when the weather station site is known to be in a local environment that substantially departs from a reference condition and assessment of humidity data indicates that the aridity is impacting the weather data. Allen and Pruitt (1986) and Allen (1996) suggested simple, empirical adjustment procedures to make "non-reference" weather data more representative of well-watered reference conditions. Allen and Gichuki (1989) and Ley et al. (1996) suggested more sophisticated approaches. Annex 6 of FAO-56 includes procedures for evaluating and adjusting humidity and air temperature data for aridity of the weather station site.

ESTIMATING T_{DEW} USING T_{MIN}

Often, substituting $T_{dew} = T_{min} - K_o$ for measured T_{dew}, (i.e., using Eq. E.1 of Appendix E), can improve estimates of daily ET_{os} and ET_{rs} when data are from a non-reference, arid setting. In arid and semiarid regions, it is best to check with the source of weather data to determine if K_o values have been developed for the area. For example, in Arizona the value of K_o was found to vary from 2 to 5 ^oC over the course of a year. When local information on K_o is not available, a K_o in the range of 2 to 4 ^oC is recommended for semiarid and arid regions (Allen, 1996). In humid regions where T_{dew} approaches T_{min} on most nights, K_o is set equal to 0 ^oC. Some irrigated areas in very dry, advective climates can have extended periods during which T_{min} is more than 5 ^oC above T_{dew}. These areas include portions of SE California, southern Arizona and New Mexico. Caution should be exercised in the specification of K_o.

Using minimum air temperature measurements from a non-reference setting to predict dew point temperature using K_o with Eq. E.1 of Appendix E may tend to overestimate the true T_{dew} and e_a that would have occurred under reference conditions. This occurs because measured T_{min} is higher in the dry setting than in a reference setting and thus T_{dew} based on $T_{min} - K_o$ where T_{min} is elevated due to aridity may be somewhat overpredicted. However, because e_s in the Penman-Monteith equation will be predicted using the same T_{min} values used to predict T_{dew}, e_s and e_a will be essentially equally "inflated." Therefore, the e_s - e_a difference in the standardized ET_{ref} equation in general will approximate the e_s - e_a difference anticipated for the reference condition. As a consequence, a more accurate estimate for ET_{os} or ET_{rs} may result than if the actual measurement of T_{dew} from the arid setting had been used. When humidity is adjusted using $T_{dew} = T_{min} - K_o$, no further adjustment is generally needed to the air temperature data set to account for effects of aridity of the weather measurement site.

Use of the $T_{dew} = T_{min} - K_o$ adjustment may produce a slight upward bias in computed net radiation (R_n). The adjustment when T_{min} is impacted by station aridity inflates e_a above levels expected for reference conditions. This error in e_a causes atmospheric long-wave radiation to be overestimated, which in turn causes a 1 to 3% overestimation in R_n. This impact is considered to be relatively minor.

DISCUSSION

The impacts of aridity upon data collected at an automated weather station received considerable consideration and deliberation by Task Committee members. The availability of experimental data that were collected specifically for evaluating impacts of aridity on weather data was a constraint. Brown (2001) data, however, demonstrate that significant error in predicted ET_{sz} can occur under very arid conditions. The magnitude of expected error under more moderate climates and the typical patchwork of irrigated and non-irrigated fields should be less.

Important questions concern the magnitude of errors in ET_{sz} associated with non-ideal sites (i.e., those lacking substantial transpiring vegetation). How well does a station represent the average expected ET over an adjacent irrigated green crop? The TC has attempted to provide guidelines for the user of AWS data to adjust for, or evaluate, the probable error associated with data from an AWS based on the data it provides. Making a simple check by substituting dew point based on minimum air temperature minus a constant will indicate if there is a potential problem. Analysis of T_{min}-T_{dew} relationship from nearby stations can provide valuable insight as to whether data are representative of the reference condition.

WIND SPEED

Accuracy of wind speed measurements is difficult to assess unless duplicate instruments are used. Nevertheless, one should visually inspect wind records for the presence of consistently low wind speed values that may indicate a malfunctioning or failed anemometer or the presence of ice if air temperatures are near or below 0 °C. Consistent and low wind speeds can indicate dirty anemometer bearings that will increase the anemometer wind speed threshold and might eventually seize and stop the anemometer altogether. Wind speeds from failed anemometers will usually appear as small, constant values (less than 0.5 m s^{-1} or the wind speed threshold for a new anemometer) if the anemometer is monitored with a data logger. With a failed anemometer, recorded maximum and mean wind speeds will often have the same values and be equal to any numerical offset in the calibration equation.

Maximum wind speed data, if available, can assist in the assessment of low wind speed data, with a gust factor (ratio of maximum wind speed (m s^{-1}) to mean daily wind speed (m s^{-1})) serving as a useful index. If plotting the gust factor over time indicates a period of excessively large values, then the anemometer may be malfunctioning. For example, Figure D-11a shows data from an anemometer that was malfunctioning between Day 109 to 117 due to bearing contamination. Gust factors often increase as contamination increases the friction in the bearings. The increasing bearing friction has a greater impact on cup rotation at small as opposed to large wind speeds and thus causes an increase in the ratio of maximum to mean wind speed. The gust factor will exhibit a sudden drop to 1.0 when the anemometer seizes or fails electronically. The data analyst must be cautious, however, in interpretation of a gust factor, because some weather periods can have more gusty, turbulent air flow than others.

Any appreciable period having daily mean wind speeds of less than 1.0 m s^{-1} should be viewed with caution. Aside from exceptionally calm periods or anemometer problems, other possible reasons for daily wind speeds of less than 1.0 m s^{-1} would include excessive vegetation height at the station or the presence of blocking structures in the nearby landscape (e.g., solid fences or buildings).

Data from a nearby station may also assist in the assessment of wind speeds at a particular site. In some cases, winds at two nearby locations are related which indicates the ratio of the wind speeds at the two locations will remain nearly constant. By plotting this ratio over time, one can identify a problem anemometer. A sudden and consistent change in the ratio often indicates a failed anemometer; a gradual change in ratio may indicate growing contamination in the bearings (Figure D-11b).

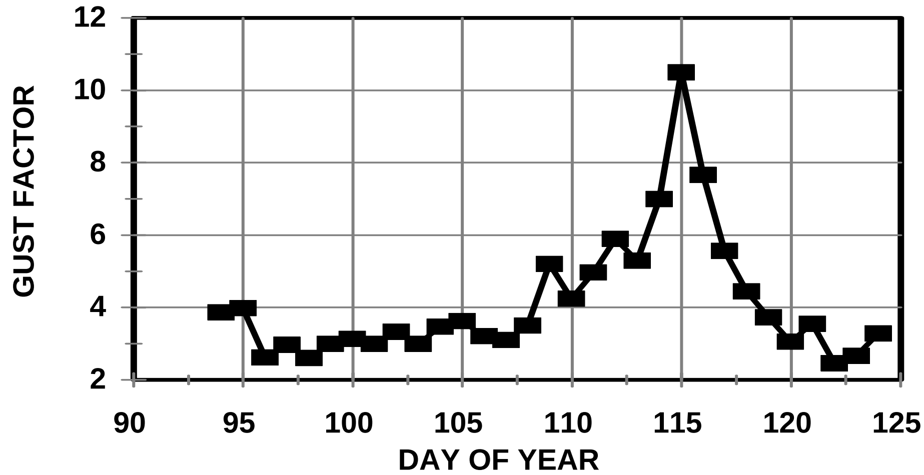


Figure D-11.a) Plot showing the increase in the gust factor at Eloy, AZ during a period when an anemometer was failing due to bearing contamination.

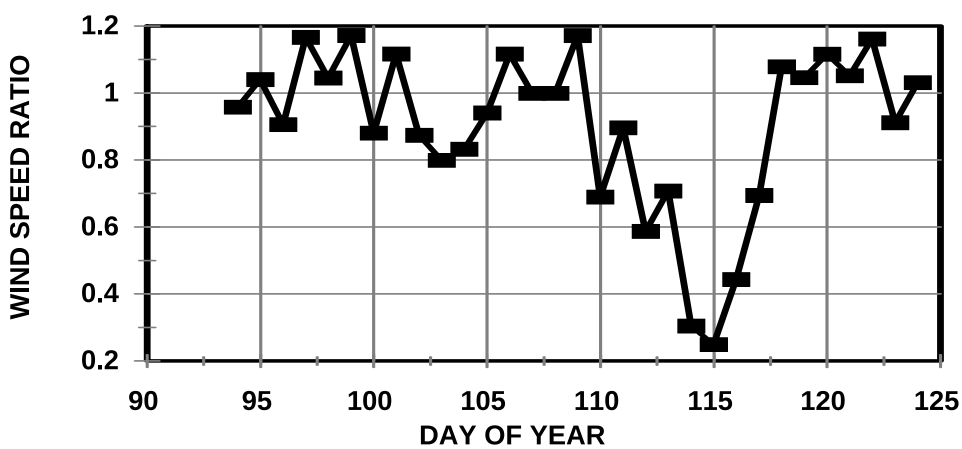


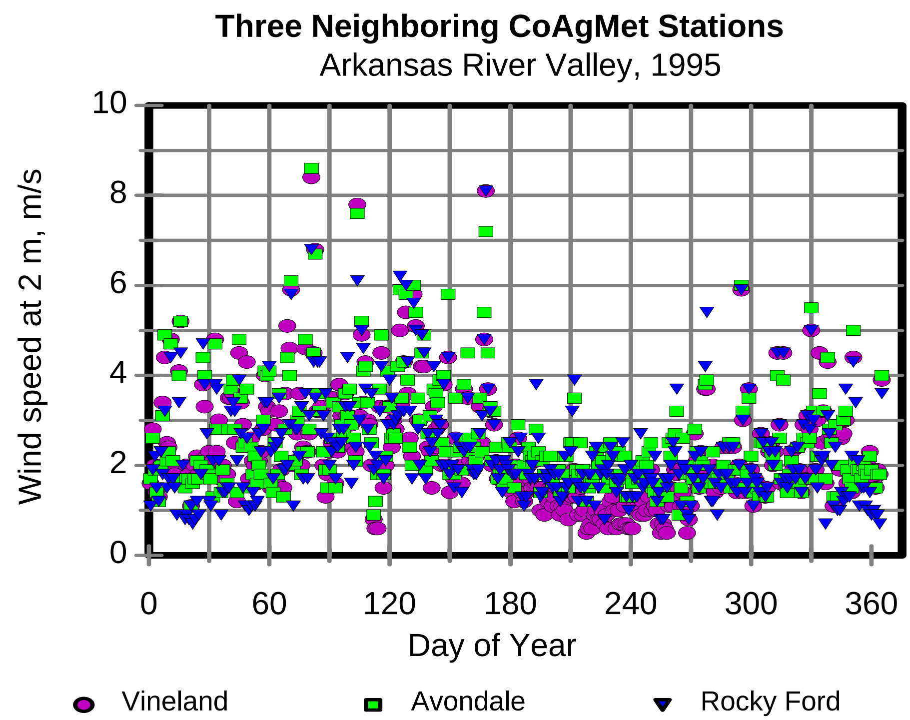
Figure D-11b) Ratio of daily mean wind speeds at Eloy, AZ to those at Maricopa, AZ during the period of anemometer failure described in a).

As an illustration of comparing wind speed data from two or more locations, daily wind speed data from three neighboring CoAgMet AWS stations located in the Arkansas River Valley of Colorado are plotted in Figure D-12a. The Vineland and Avondale stations are within 15 km (10 miles) of one another and the Rocky Ford station is about 60 km (40 miles) further east. All stations are located in agricultural environments and wind was measured at 2 m above the ground. The similarity in wind speed records is apparent. The Vineland station had some fields of corn planted near the weather station during 1995 (personal commun., R.Allen, 2001) that impeded wind speed measurements during late summer. This is evident in viewing the daily wind plot in Figure D-12a, where daily wind speeds for Vineland fell below those at Avondale and Rocky Ford from day 190 through day 270. Ratios of wind speed for Vineland to wind speed at Rocky Ford show a similar pattern (Figure D-12b), with ratios routinely falling below 0.7 during the period from day 210 through day 270 when the corn crop was tallest. Ratios of wind speed for Avondale to Rocky Ford followed a consistent average of 1.0 all year, as is expected, with some inconsistencies during winter months. This example illustrates the use of data from neighboring stations to discern shifts or anomalies in a data set.

A good preventive maintenance program is required to keep anemometers functioning at peak performance levels. Weather station anemometers should be replaced with newly reconditioned (new bearings) and calibrated anemometers at regular intervals. An annual replacement in light to normal wind regions or semi-annual replacement in windy regions should be considered for anemometers located in agricultural settings. Some providers of weather data employ a standard practice of replacing anemometers on a regularly scheduled basis. The replacement schedule is typically based on local experience or recommendations of the manufacturer and may be as short as six months. ASAE (2004) provides detailed recommendations on periodic sensor maintenance. An alternative technique for evaluating anemometers involves redundancy in instrumentation and requires placement of a second anemometer[2] of the same design, but with fresh bearings, at the weather station for a three or four day period at least once each year, and comparing recorded values. Variations between recordings can signal a need to replace bearings, switches, or other parts.

Wind speeds over non-reference surfaces may exhibit a systematic upward bias relative to wind speeds measured over reference surfaces. Vegetation in excess of the recommended reference-surface height will impose a greater frictional drag on the near surface atmosphere and reduce wind speed relative to the reference condition. Smooth, dry surfaces will generate an opposite bias; wind speeds over these surfaces will generally be higher than those measured over reference surfaces. Allen and Wright (1997) have suggested procedures for adjusting non-reference wind speed data to better represent reference conditions; however, these procedures are somewhat complicated and have not been validated for a wide range of conditions.

[2] If a second data logger is used to record the temporary anemometer, one should be careful to synchronize data logger clocks. Also, one should be careful that adjacent anemometers do not interfere with one another's wind stream.



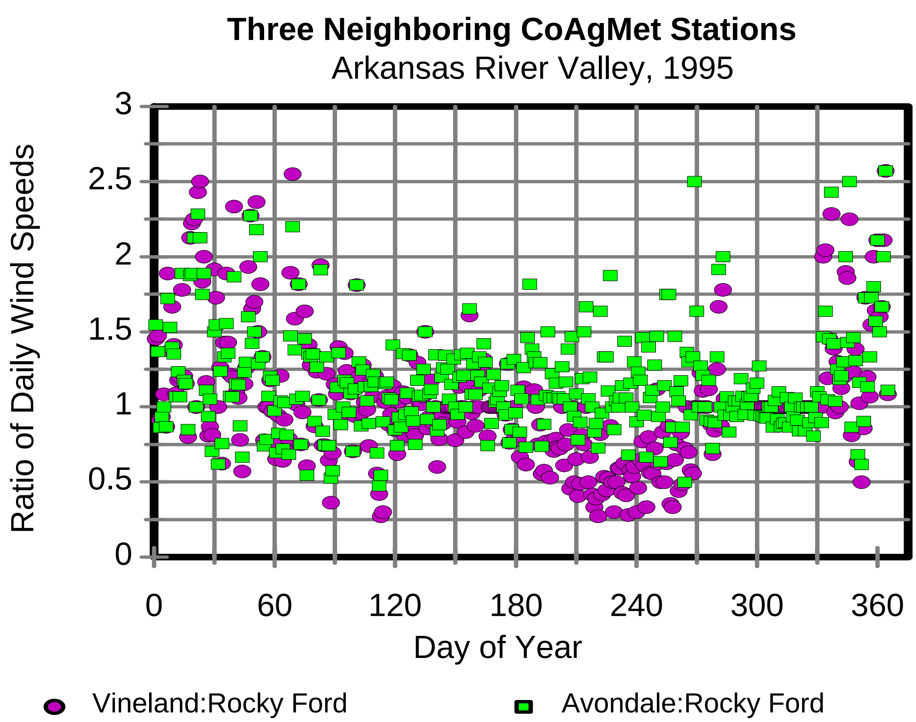


Figure D-12 Daily mean wind speeds recorded at three neighboring AWS stations in SE Colorado during 1995 (a) and ratios of wind speeds to those at Rocky Ford for the same stations (b).

APPENDIX E

ESTIMATING MISSING CLIMATIC DATA

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INTRODUCTION

The calculation of reference evapotranspiration with the standardized ASCE Penman-Monteith reference ET equation requires air temperature, vapor pressure, radiation, and wind speed data. The climate data should reflect the environment within the area for which an estimate of ET is required. If some of the required weather data are missing or do not accurately represent an irrigated site/region or are erroneous, then it may be possible that data can be estimated in order to apply the equation. The quality of calculated reference ET values depend on the quality and completeness of weather data. If the estimated data for missing periods are reasonably representative of a site within an irrigated area, then it is likely that the reference ET values from the standardized equation calculated with these data will be more reliable than reference ET estimates made using other more empirical ET methods. This appendix provides procedures for estimating solar radiation, vapor pressure, and wind speed data when they are missing or of questionable quality. Users should employ some type of "flagging" procedure to clearly identify data that have been estimated.

MINIMUM DATA REQUIREMENTS

Many of the suggested procedures for estimating missing data rely upon measured maximum and minimum air temperatures. Daily maximum and minimum air temperature, or at the very least, daily mean air temperatures are considered to be the absolute minimum data requirements necessary to apply the standardized Penman-Monteith method. In situations where solar radiation, humidity and wind speed data are available, but air temperature data are missing, temperature may be estimated from a nearby weather station site using some form of regression or interpolation/extrapolation procedure. Estimated temperature data should not be used at a site if the temperature data are subsequently used to estimate humidity and solar radiation data, as the resulting ET_{ref} would essentially have been calculated using no local data.

ESTIMATING MISSING HUMIDITY DATA

Where daily humidity data are missing or are of questionable quality, vapor pressure, e_a, can be estimated for the reference environment by assuming that dew-point temperature (T_{dew}) is near the daily minimum air temperature (T_{min}):

$$T_{dew} = T_{min} - K_o \tag{E.1}$$

where K_o is approximately 2 to 4 ^oC in dry (semiarid and arid) climates and K_o is approximately 0 ^oC in humid to subhumid climates. Background on this relationship is discussed in Appendix D and an illustration of the trend for close proximity between T_{dew} and T_{min} is provided. Further discussion and caveats of this relationship are given in Allen (1996) and Allen et al., (1998).

An alternative to applying Eq. E.1 is to assume that relative humidity, RH, approaches 90 to 100% during early morning hours (before sunrise) over well-watered (i.e. reference) settings (as illustrated in Figure D-2b), so that the assumption that RH_{max} ~ 90% or RH_{max} ~ 100% can be employed. Daily vapor pressure is then calculated using the estimated RH_{max} and measured T_{min} in Eq. 12 of the text.

When humidity data are available from a nearby station, for example within 100 km, the user may elect to predict T_{dew} for a site having no humidity data or having faulty data using Eq. D.8 of Appendix D. This relationship presumes that differences between T_{dew} and T_{min} are similar between stations. Similar results and estimates of humidity can be obtained by transferring RH measurements between locations and calculating e_a using the transferred RH data and local air temperature (using Eq. 7 and 11-13 or Eq. 37 and 41 in the text). It is recommended that similarity in relationships between T_{dew} and T_{min} or in RH be confirmed using temporary measurement of humidity or by analysis of data from adjacent stations.

By definition, reference ET_{os}, or ET_{rs}, is ET from an extensive surface of well-watered vegetation. Therefore, when humidity data are available from only a site that is known to deviate substantially from a reference environment, then use of "adjusted" dew-point temperature in the standardized PM equation may produce more reliable and representative reference ET than those obtained using the original humidity data from the non-reference site. Further information and recommendations on coping with impacts of weather station environment are given in Appendix D. The user should "flag" any estimated humidity data and describe the procedures that were used.

ESTIMATING MISSING RADIATION DATA

Solar Radiation Data Derived From Observed Sunshine Hours

If observed hours of sunshine are measured, solar radiation for 24-hour and longer time periods can be calculated using the Angstrom formula, which relates solar radiation to extraterrestrial radiation and relative sunshine duration:

$$R_s = \left(a_s + b_s \frac{n}{N}\right) R_a \qquad \text{(E.2)}$$

where

- R_s = solar or shortwave radiation [MJ m^{-2} day^{-1}],
- n = actual duration of sunshine [hour],
- N = maximum possible duration of sunshine or daylight hours [hour],
- n/N = relative sunshine duration [-],
- R_a = extraterrestrial radiation [MJ m^{-2} day^{-1}] (Eq. 21 to 29 in the text),
- a_s = constant expressing the fraction of extraterrestrial radiation reaching the earth's surface on overcast days (when n = 0),
- b_s = constant expressing the additional fraction of extraterrestrial radiation reaching the earth's surface on a clear day,
- a_s+b_s = fraction of extraterrestrial radiation reaching the earth's surface on a clear day (when n = N).

R_s is expressed in Eq. E.2 in MJ m^{-2} day^{-1} for R_a in MJ m^{-2} day^{-1}. Depending on atmospheric conditions (humidity, dust) and solar declination (latitude and month), the Angstrom values a_s and b_s will vary. Where no actual solar radiation data are available and no calibration has been carried out for improved a_s and b_s parameters, the values a_s = 0.25 and b_s = 0.50 from FAO-24 and FAO-56 are recommended.

The potential daylight hours, N, are given by:

$$N = \frac{24}{\pi} \omega_s \qquad \text{(E.3)}$$

where ω_s is the sunset hour angle in radians and is calculated using Eq. 27 or 28 in the text.

Solar Radiation Data From a Nearby Weather Station

For 24-hour and longer time periods, solar radiation can be relatively similar over large areas. Similarity in solar radiation depends on (i) the size of the region; (ii) the air masses governing rainfall and cloudiness being nearly identical within the region; and (iii) the physiography of the region being nearly homogenous. Differences in relief strongly influence the movement of air masses and development of cloud systems, so that these should be negligible if radiation data are to be transferred between locations.

Generally, daily calculations of reference ET using estimated radiation data are justified when utilized as a sum or as an average over a multiple-day period so that differences due to frontal activity tend to average out. This is the case for the computation of total evapotranspiration demand between successive irrigations or when planning irrigation schedules. Under these conditions, the relative error for one day may be compensated by an error for another day within the time period. Daily ET estimates should not be utilized as true daily estimates but used only to compute averages over the period under consideration.

Solar Radiation Data Derived From Air Temperature

Solar radiation can be estimated based on an empirical equation derived using the difference between maximum and minimum air temperature and extraterrestrial solar radiation. The difference between the maximum and minimum air temperature is related to the degree of cloud cover at a location. Clear-sky conditions result in higher air temperatures during the day (i.e., T_{max}) than under cloudy conditions because the atmosphere is transparent to incoming solar radiation. Clear-sky conditions result in relatively lower air temperatures during nighttime (i.e., T_{min}) than under cloudy conditions because less outgoing long-wave radiation is absorbed and reemitted by the atmosphere. On the other hand, under overcast conditions, T_{max} is often lower than for clear days because a significant portion of the incoming solar radiation never reaches the earth's surface and is absorbed and reflected by the clouds. Similarly, T_{min} will be relatively higher because cloud cover acts as an absorbing and reemitting blanket and therefore decreases the net outgoing long-wave radiation. Therefore, the difference between the maximum and minimum air temperature (T_{max} - T_{min}) can be used as an indicator of the fraction of extraterrestrial radiation that reaches the earth's surface. This principle has been utilized by Hargreaves and Samani (1982) to develop estimates of ET_o using only air temperature data.

The Hargreaves-Samani style of radiation prediction formula has the form:

$$R_s = k_{Rs} \sqrt{(T_{max} - T_{min})}\ R_a \qquad (E.4)$$

where

R_a = extraterrestrial radiation [MJ m^{-2} d^{-1}],
T_{max} = maximum air temperature [°C],
T_{min} = minimum air temperature [°C],
k_{Rs} = adjustment coefficient (0.16 .. 0.19) [$°C^{-0.5}$].

The adjustment coefficient k_{Rs} is empirical and differs for 'interior' or 'coastal' regions[1]:

- for 'interior' locations, defined as where the local land mass dominates and air masses are not strongly influenced by a large water body, $k_{Rs} \cong 0.16$;
- for 'coastal' locations, situated on or adjacent to the coast of a large land mass and where air masses are influenced by a nearby water body, $k_{Rs} \cong 0.19$.

R_s predicted by Eq. E.4 should be limited to $\leq R_{so}$ which is the R_s for a cloud-free day. The temperature difference method is recommended for locations where it is not appropriate to import radiation data from a regional station, either because homogeneous climate conditions do not occur, or because data for the region are lacking. For island conditions, the methodology is not appropriate due to moderating effects of the surrounding water body. Allen (1997) provides examples for applying Eq. E.4 to predict daily and monthly values for solar radiation and procedures for site specific auto-calibration of k_{Rs}.

MISSING WIND SPEED DATA

Wind Speed Data From a Nearby Weather Station

Extrapolating wind speed data from a nearby agricultural weather station, as for radiation data, relies on the assumption that the airflow is relatively similar within a relatively 'homogeneous' region. There is generally relatively large variation in wind speed through the course of a day, which can translate into substantial differences in concurrent measurements of wind speed at two locations. However, when averaged over times periods of one day or longer, differences between locations become smaller.

Data from a weather station may be extrapolated to a nearby location where ET_{ref} is to be predicted if the governing air masses are of the same origin and where the same weather frontal systems govern the regional air flow. The surrounding relief of the two locations should be similar. In areas having large differences in relief, density-induced "drainage" of air and shielding and direction of air movement by relief can cause substantial differences in observed wind speed over relatively short distances. Where short periods of wind data are available for the location, ratios of wind speed between two locations can be established and used to estimate wind data for the data-short location.

Wind speed data from airports in the U.S. typically are measured at a height of 10 m. In arid and semiarid areas, the airport anemometer is often surrounded by non-irrigated, short grass. Measured wind speed adjusted from a height of 10 m to 2 m using the logarithmic wind profile will typically exceed the wind speed over an irrigated area during the growing season because of large differences in vegetation roughness and the damping effect caused by the heat sink as water evaporates.

When extrapolating wind speed data from another station, trends in other meteorological parameters and relief should be compared. Strong winds are often associated with low relative humidity and light winds are common with high relative humidity. Thus, trends in variation of daily maximum and minimum relative humidity should be similar in both locations. In mountainous areas, data should

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[1] The values presented here for K_{Rs} are based on work by Hargreaves and Samani (1982) and Allen (1995) and were

not be extrapolated from the nearest station but from nearby stations with similar elevation, surrounding vegetation, and exposure to the dominant winds. The pairing of stations may vary from one season to another, depending on the dominant winds.

Empirical Estimates of Monthly Wind Speed

The variation in average wind speed between monthly periods is often relatively small and fluctuates around average values. Therefore, in situations of no, or faulty, wind speed data, monthly values of wind speed may be estimated based on general information available for the regional climate, taking seasonal changes into account. Or, if regional information is unavailable, general values for wind speed suggested in Table E-1 can be employed. Caution should be exercised.

TABLE E-1
General classes of wind speed data (taken from FAO-56)

Description	mean wind speed at 2 m
light wind	... ≤ 1.0 m s^{-1}
light to moderate wind	1–3 m s^{-1}
moderate to strong wind	3–5 m s^{-1}
strong wind	... ≥ 5.0 m s^{-1}

A preliminary value of 2 m s^{-1} can be used as a first estimate of 2-m wind speed for an agricultural setting. This value is based on an average computed from over 2 000 weather stations around the globe (Allen et al., 1998).

In general, estimated wind speed at 2 m should be limited to about $u_2 \geq 0.5$ m s^{-1} when used to calculate standardized reference ET. This lower limit accounts for the influence of boundary layer instability caused by buoyancy of air in promoting exchange of heat and vapor at the surface when air is calm. This effect occurs when the wind speed is small and buoyancy of warm air induces air exchange at the surface.

As with humidity and solar radiation data, estimated wind speed data should be flagged in the data set and the user should describe procedures that were used to make the estimates.

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reported in FAO-56.

MISSING MAXIMUM OR MINIMUM AIR TEMPERATURE DATA

Some weather data sets contain daily mean air temperature summaries, but do not contain values for maximum and minimum air temperature. Daily maximum and minimum air temperatures are used in the standardized reference ET procedure for calculating net radiation and the saturation vapor pressure. During the process of calculating daily ET_{ref} using data sets where T_{max} and T_{min} are not available, but where daily mean air temperature and solar radiation data are available, accuracy of calculations for net radiation and saturation vapor pressure can be improved by estimating values for T_{max} and/or T_{min} by inverting Eq. E.4 and solving for T_{max} - T_{min}:

$$(T_{max} - T_{min}) = \left(\frac{R_s}{k_{Rs} \; R_a} \right)^2 \qquad \text{(E.5a)}$$

where

R_s = measured solar radiation [MJ m^{-2} d^{-1}],
R_a = extraterrestrial radiation [MJ m^{-2} d^{-1}],
T_{max} = maximum air temperature [°C],
T_{min} = minimum air temperature [°C],
k_{Rs} = adjustment coefficient, defined previously [°$C^{-0.5}$].

Values for T_{max} and/or T_{min} can be estimated using $T_{max} - T_{min}$ from E.5a as:

$$T_{max} = T_{mean} + \frac{(T_{max} - T_{min})}{2} \qquad \text{(E.5b)}$$

$$T_{min} = T_{mean} - \frac{(T_{max} - T_{min})}{2} \qquad \text{(E.5c)}$$

The estimated values for T_{max} and T_{min} should be clearly identified in the data set as estimated values.

APPENDIX F

Summary of

Reference Evapotranspiration Comparisons by the Task Committee

The following tables summarize intercomparisons between various reference evapotranspiration equations that were used by the Task Committee in formulating recommendations for the standardization. The summaries include comparisons for hourly calculation timesteps (summed to daily totals and labeled as "sum of hourly") and for daily calculation timesteps. Table F-1 summarizes weather station location information for the sites and years investigated. Table F-2 summarizes statistics for ratios of each method against the ASCE-PM (full-form ASCE Penman-Monteith method) where the ASCE-PM method, applied daily, served as the comparison basis in all cases. The methods summarized in Table F-2 are the FAO-56 Penman-Monteith, the Standardized ASCE-PM, the 1963 Penman, the Hargreaves, and the 1982 Kimberly Penman. These methods are defined in Appendix B.

Tables F-3 to F-10 summarize ratios of computations by the various reference equations to computations by the daily ASCE-PM method (as the comparison basis) by location. Ratios are summarized for sum-of-hourly compared to daily timesteps and for daily timesteps compared to daily timesteps. The tables also compare "within method" comparisons of sum-of-hourly to daily calculations. Comparisons are given for both reference types (short and tall), where specific methods or coefficients applied vary with reference surface type. The reference methods summarized in Tables F-3 to F-10 include various forms of the ASCE Penman-Monteith method and applications of the ASCE Penman-Monteith equation using different coefficients or parameter calculations. These forms and variations are defined in Appendix B, pages 1-4. It is noted that in Tables F-6 and F-10, sum-of-hour calculations are compared against sum-of-hour calculations by the ASCE-PM, applied hourly using surface resistance values from ASCE manual 70 (70 s m^{-1} for ET_o and 45 s m^{-1} for ET_r). The Task committee, however, recommends the use of smaller resistance values for hourly or shorter time steps during daytime to provide predictions that are commensurate with daily calculation time steps, as is done for the standardized method. The smaller values for resistance increase the sum-of-hour predictions by the ASCE-PM method by about 5% as shown in Tables F-4 and F-8.

Table F-1. Summary of weather station sites used in the study (listed from east to west longitude).

Site-Year Index	State	SITE	Longitude (degrees)	Latitude (degrees)	Elevation (m)	Mean Annual Precip.	Years (19--)	Peak-Month Mean ASCE-PM ET_o (mm d^{-1})	
								Year 1	Year 2
1	NY	Willsboro	73.38	44.38	43	760	98	3.79	
2, 3	NY	Valatie	73.68	42.43	76	910	97 98	3.90	3.89
4, 5	NY	Ithaca	76.45	42.45	123	910	97 98	3.82	3.88
6	SC	Florence	79.81	34.24	40	1120	86	5.91	
7	FL	Fort Pierce	80.44	27.57	7	1422	99	4.68	
8, 9	FL	Lake Alfred	81.89	28.03	46	1270	98 99	5.66	4.88
10, 11	GA	Blairsville	83.93	34.84	584	1307	97 98	4.48	4.63
12, 13	GA	Griffin	84.28	33.26	282	1447	97 98	5.05	5.99
14, 15	GA	Attapulgus	84.49	30.76	37	1460	97 98	4.54	6.29
16	IL	Bondville	88.37	40.00	213	1008	99	5.18	
17	IL	Belleville	89.88	38.52	133	974	99	5.53	
18	IL	Monmouth	90.73	40.92	229	942	99	5.23	
19, 20	OK	Wister	94.68	34.98	143	1188	97 98	5.13	6.03
21, 22	NE	Mead	96.30	41.08	366	743	97 98	5.15	4.57
23, 24	OK	Marena	97.21	36.06	331	889	97 98	5.63	6.84
25, 26	NE	Clay Center	98.08	40.31	552	685	97 98	5.46	5.15
27, 28	OK	Apache	98.29	34.91	440	757	97 98	6.59	8.60
29, 30	NE	Champion	101.43	40.22	1029	482	97 98	6.64	6.18
31, 32	OK	Goodwell	101.60	36.60	996	447	97 98	8.56	9.68
33, 34	TX	Bushland	102.05	35.11	1170	505	97 98	7.36	9.34
35, 36	TX	Dalhart	102.32	36.20	1228	467	97 98	6.44	7.30
37, 38	CO	Ovid	102.45	40.97	1089	448	98 99	5.50	6.08
39, 40	CO	Rocky Ford	104.00	38.00	1274	279	97 99	7.08	8.02
41, 42	CO	Wiggins	104.06	40.31	1367	353	97 98	5.88	5.93
43	CO	Fort Collins	105.00	40.60	1527	383	95	5.58	
44, 45	CO	Loveland	105.11	40.40	1540	406	97 98	5.59	5.30
46, 47	CO	Center	106	38	2348	178	97 99	5.62	5.96
48, 49	CO	Colton	106	39	2743	279	82 83	4.65	4.69
50, 51	CO	Portis	106	39	2895	279	82 83	4.38	4.30
52, 53	CO	Fruita	109	39	1377	228	97 99	7.87	6.75
54, 55	CO	Yellow Jacket	109	37	2252	406	97 99	5.92	5.96
56, 57	AZ	Tucson	110.94	32.28	713	300	97 98	8.54	8.21
58, 59	ID	Ashton	111.47	44.03	1615	430	97 98	4.96	5.70
60, 61	UT	Logan	111.80	41.60	1350	433	89 90	6.21	5.77
62, 63	AZ	Phoenix Encanto	112.10	33.48	335	175	97 98	7.49	7.60
64, 65	MT	St. Ignatius	114.10	47.31	896	360	97 98	4.52	5.27
66, 67	MT	Creston	114.13	48.19	899	390	97 98	4.16	4.73
68, 69	MT	Ronan	114.28	47.54	927	380	97 98	4.31	4.70
70, 71	ID	Twin Falls	114.35	42.61	1195	222	97 98	5.69	6.44
72, 73	ID	Parma	116.93	43.80	703	237	97 98	5.66	6.10
74	WA	Paterson	119.49	45.94	109	152	98	6.65	
75	CA	Fresno	119.70	36.80	103	269	98	7.11	
76	WA	Gramling	119.73	46.29	386	178	98	7.42	
77	WA	Roza	119.73	46.29	343	178	98	5.96	
78	CA	Santa Maria	120.40	35.00	82	314	98	4.42	
79	CA	Davis	121.80	38.50	18	461	98	6.71	
80	WA	Puyallup	122.30	47.10	61	1016	98	3.48	
81	WA	Grayland	124.00	46.78	2	2032	98	2.78	
	82	Haga	124.50	42.50	9	1778	99	3.32	

Table F-2. Statistical summary of the comparisons between various reference ET methods, using growing-season results from 82 site-years of daily and 76 site-years of hourly data.

METHOD	RATIO				RMSD (mm d^{-1})				RMSD as % of Mean Daily ET
	Max	Min	Mean	Std Dev	Max	Min	Mean	Std Dev	
Daily ET_o vs. Daily ASCE-PM ET_o									
FAO56-PM	1.004	0.982	0.994	0.006	0.155	0.005	0.039	0.035	0.8
ASCE Stand'zed	1.007	0.982	0.995	0.006	0.146	0.008	0.041	0.032	0.9
1963 Penman	1.201	0.995	1.072	0.036	0.772	0.167	0.430	0.092	10.4
Hargreaves	1.430	0.791	1.057	0.127	2.235	0.439	0.927	0.308	22.2
Daily ET_r vs. Daily ASCE-PM ET_r									
ASCE Stand'zed	1.025	0.974	0.998	0.010	0.300	0.014	0.069	0.058	1.28
1982 Kim Penman	1.118	0.892	0.988	0.043	1.706	0.169	0.662	0.267	12.2
Sum-of-Hourly ET_o vs. Daily ET_o (within method)									
ASCE-PM	1.047	0.903	0.960	0.033	0.829	0.197	0.362	0.133	8.4
FAO56-PM	1.043	0.901	0.958	0.032	0.829	0.197	0.365	0.137	8.5
ASCE Stand'zed	1.081	0.941	1.012	0.028	0.663	0.228	0.334	0.084	7.7
1963 Penman	1.182	0.955	1.047	0.036	1.373	0.185	0.429	0.179	8.9
Sum-of-Hourly ET_r vs. Daily ET_r (within method)									
ASCE-PM	1.042	0.875	0.944	0.039	1.367	0.232	0.568	0.237	10.3
ASCE Stand'zed	1.108	0.931	1.022	0.037	1.048	0.315	0.540	0.152	9.6
1982 Kim Penman	1.054	0.910	0.976	0.032	1.008	0.322	0.539	0.071	10.1
Sum-of-Hourly ET_o vs. Daily ASCE-PM ET_o									
ASCE-PM	1.047	0.903	0.960	0.033	0.829	0.197	0.362	0.133	8.4
FAO56-PM	1.041	0.896	0.952	0.034	0.889	0.200	0.389	0.152	8.9
ASCE Stand'zed	1.080	0.937	1.007	0.029	0.678	0.235	0.335	0.086	8.0
1963 Penman	1.225	1.039	1.124	0.043	1.186	0.326	0.684	0.152	16.3
CIMIS Penman	1.220	0.969	1.080	0.047	0.966	0.290	0.579	0.137	13.9
Sum-of-Hourly ET_r vs. Daily ASCE-PM ET_r									
ASCE-PM	1.042	0.875	0.944	0.039	1.367	0.232	0.568	0.237	10.3
ASCE Stand'zed	1.108	0.933	1.020	0.037	1.067	0.331	0.532	0.144	9.41
1982 Kim Penman	1.138	0.855	0.963	0.059	1.923	0.416	0.759	0.304	13.8

Table F-3. Ratio of method Daily ETo to Daily ASCE-PM ETo

								YEARLY SUMMARY										GROWING SEASON									
State	Site	Year	Elevation (m)	Latitude	Longitude	Mean Annual Precip (mm)	Peak-Month Mean Daily ETo (ASCE PM) - mm	ASCE PM (YR)	ASCE PMD (YR)	ASCE PMDL (YR)	ASCE PMDR (YR)	ASCE PMrf (YR)	ETos (YR)	F56 PM (YR)	F24 Pen (YR)	1963 Pen (YR)	1985 Harg (YR)	ASCE PM (GS)	ASCE PMD (GS)	ASCE PMDL (GS)	ASCE PMDR (GS)	ASCE PMrf (GS)	ETos (GS)	F56 PM (GS)	F24 Pen (GS)	1963 Pen (GS)	1985 Harg (GS)
AZ	Phoenix	1997	335	33.48	112.10	175	7.49	1.000	0.999	0.995	0.994	0.986	0.986	0.986	1.193	1.119	1.019	1.000	0.999	0.994	0.991	0.986	0.986	0.985	1.184	1.104	0.998
AZ	Phoenix	1998	335	33.48	112.10	175	7.60	1.000	0.999	0.995	0.994	0.988	0.988	0.987	1.206	1.105	0.984	1.000	0.999	0.994	0.989	0.987	0.987	0.987	1.204	1.098	0.962
AZ	Tucson	1997	713	32.28	110.94	300	8.54	1.000	0.999	0.996	0.991	0.986	0.986	0.985	1.153	1.025	0.902	1.000	0.999	0.995	0.988	0.986	0.986	0.985	1.166	1.034	0.902
AZ	Tucson	1998	713	32.28	110.94	300	8.21	1.000	0.999	0.997	0.991	0.987	0.987	0.987	1.188	1.031	0.944	1.000	0.999	0.996	0.987	0.987	0.987	0.986	1.211	1.045	0.947
CA	Davis	1998	18	38.50	121.80	461	6.71	1.000	0.998	0.998	0.984	0.989	0.983	0.989	1.217	1.064	1.033	1.000	0.998	0.998	0.985	0.989	0.989	0.988	1.242	1.062	1.003
CA	Fresno	1998	103	36.80	119.70	269	7.11	1.000	0.999	0.998	0.982	0.990	0.990	0.989	1.217	1.064	1.066	1.000	0.999	0.997	0.980	0.989	0.989	0.989	1.262	1.067	1.015
CA	Santa Maria	1998	82	35.00	120.40	314	4.42	1.000	0.998	1.000	0.982	0.993	0.993	0.993	1.177	1.077	1.143	1.000	0.998	1.000	0.977	0.995	0.995	0.995	1.215	1.098	1.158
CO	Center	1997	2348	38.00	106.00	178	5.62											1.000	0.998	1.001	0.970	1.002	1.002	1.001	1.207	1.062	1.000
CO	Center	1999	2348	38.00	106.00	178	5.96											1.000	0.998	1.001	0.975	1.001	1.001	1.001	1.224	1.066	0.925
CO	Colton	1982	2743	39.00	106.00	279	4.65											1.000	0.998	1.003	0.958	1.004	1.004	1.003	1.171	1.051	1.075
CO	Colton	1983	2743	39.00	106.00	279	4.69											1.000	0.998	1.003	0.965	1.005	1.005	1.003	1.164	1.027	1.048
CO	Fort Collins	1995	1527	40.60	105.00	383	5.58	1.000	0.998	1.000	0.974	0.991	0.991	0.986	1.109	1.013	1.032	1.000	0.998	1.000	0.967	0.992	0.992	0.989	1.159	1.047	1.115
CO	Fruita	1997	1274	38.00	104.00	228	7.83											1.000	0.998	0.998	0.981	1.001	1.001	0.999	1.211	1.038	0.922
CO	Fruita	1999	1274	38.00	104.00	228	6.75											1.000	0.999	0.999	0.974	1.002	1.002	1.000	1.183	1.043	1.059
CO	Loveland	1997	1540	40.40	105.11	406	5.59	1.000	0.999	1.001	0.969	0.996	0.996	0.995	1.161	1.073	1.063	1.000	0.999	1.000	0.965	0.996	0.996	0.995	1.175	1.079	1.092
CO	Loveland	1998	1540	40.40	105.11	406	5.30	1.000	0.999	1.001	0.970	0.995	0.995	0.994	1.138	1.070	1.041	1.000	0.999	1.000	0.965	0.995	0.995	0.994	1.158	1.081	1.083
CO	Ovid	1998	1089	40.97	102.45	448	5.5	1.000	0.998	0.999	0.979	0.978	0.978	0.978	1.144	1.007	0.942	1.000	0.998	0.998	0.976	0.982	0.982	0.982	1.223	1.051	0.997
CO	Ovid	1999	1089	40.97	102.45	448	6.08	1.000	0.998	0.999	0.978	0.978	0.978	0.978	1.136	0.999	0.931	1.000	0.998	0.999	0.973	0.982	0.982	0.982	1.191	1.042	1.007
CO	Portis	1982	2895	39	106	279	4.03											1.000	0.998	1.003	0.957	1.006	1.006	0.998	1.196	1.075	1.028
CO	Portis	1983	2895	39	106	279	4.21											1.000	0.998	1.003	0.961	1.006	1.006	0.999	1.206	1.084	1.039
CO	Rocky Ford	1997	1274	38	104	279	7.08											1.000	0.999	0.998	0.978	1.000	1.000	0.998	1.098	1.016	0.960
CO	Rocky Ford	1999	1274	38	104	279	8.02											1.000	0.999	0.999	0.973	0.999	0.999	0.998	1.059	1.044	0.918
CO	Wiggins	1997	1367	40.31	104.06	353	5.88	1.000	0.998	1.000	0.977	0.980	0.980	0.980	1.134	1.004	0.957	1.000	0.998	0.999	0.974	0.983	0.983	0.982	1.171	1.025	1.002
CO	Wiggins	1998	1367	40.31	104.06	353	5.93	1.000	0.998	1.000	0.979	0.980	0.980	0.980	1.138	0.998	0.951	1.000	0.998	0.999	0.976	0.983	0.983	0.982	1.191	1.028	0.991
CO	Yellow Jacket	1997	2252	37.00	109.00	406	5.94											1.000	0.999	1.000	0.969	0.997	0.997	0.994	1.156	1.080	0.993
CO	Yellow Jacket	1999	2252	37.00	109.00	406	6.01											1.000	0.998	1.000	0.971	0.997	0.997	0.994	1.171	1.089	0.907
FL	Lake Alfred	1998	46	28.03	80.89	1250	6.08	1.000	0.999	0.996	0.984	0.996	0.996	0.997	1.145	1.043	1.071	1.000	0.999	0.995	0.981	0.995	0.995	0.996	1.167	1.047	1.069
FL	Lake Alfred	1999	46	28.03	80.89	1250	5.23	1.000	0.999	0.996	0.984	0.997	0.997	0.997	1.150	1.041	1.094	1.000	0.999	0.996	0.982	0.996	0.996	0.997	1.162	1.046	1.102
FL	St. Pierce	1999	7	27.57	80.44	1422	4.99	1.000	0.998	0.996	0.987	0.997	0.997	0.997	1.180	1.078	1.056	1.000	0.999	0.996	0.982	0.996	0.996	0.997	1.195	1.083	1.077
GA	Attapulgus	1997	37	30.761	84.4853	1460	4.54	1.000	0.999	0.998	0.974	0.999	0.999	0.998	1.197	1.104	1.261	1.000	0.999	0.997	0.975	0.998	0.998	0.998	1.213	1.108	1.266
GA	Attapulgus	1998	37	30.761	84.4853	1460	6.29	1.000	0.999	0.997	0.971	0.998	0.998	0.998	1.202	1.100	1.295	1.000	0.999	0.996	0.973	0.996	0.996	0.997	1.221	1.098	1.264
GA	Blairsville	1997	584.3	34.839	83.928	1307	4.48	1.000	0.999	1.001	0.955	1.004	1.004	1.001	1.196	1.126	1.309	1.000	0.999	1.001	0.961	1.003	1.003	1.001	1.215	1.131	1.326
GA	Blairsville	1998	584.3	34.839	83.928	1307	4.63	1.000	0.999	1.000	0.960	1.002	1.002	1.000	1.188	1.092	1.241	1.000	0.999	0.999	0.965	1.001	1.001	0.999	1.209	1.096	1.242
GA	Griffin	1997	281.9	33.262	84.284	1447	5.05	1.000	0.998	0.999	0.972	1.001	1.001	0.999	1.213	1.091	1.092	1.000	0.999	0.998	0.975	0.999	0.999	0.998	1.231	1.095	1.107
GA	Griffin	1998	281.9	33.262	84.284	1447	5.99	1.000	0.999	0.998	0.973	0.998	0.998	0.998	1.228	1.103	1.157	1.000	0.999	0.997	0.974	0.998	0.998	0.998	1.239	1.103	1.151
ID	Ashton	1997	1615	44.03	111.47	430	4.96	1.000	0.998	1.001	0.967	0.998	0.998	0.997	1.196	1.078	0.929	1.000	0.998	1.001	0.966	0.998	0.998	0.997	1.208	1.071	0.946
ID	Ashton	1998	1615	44.03	111.47	430	5.70	1.000	0.998	1.001	0.967	0.998	0.998	0.997	1.167	1.053	0.966	1.000	0.998	1.001	0.970	0.998	0.998	0.997	1.183	1.043	0.971
ID	Parma	1997	703	43.80	116.93	237	5.66	1.000	0.999	1.000	0.977	0.997	0.997	0.997	1.181	1.074	1.037	1.000	0.999	1.000	0.977	0.997	0.997	0.997	1.195	1.075	1.036
ID	Parma	1998	703	43.80	116.93	237	6.10	1.000	0.999	1.000	0.972	0.997	0.997	0.997	1.187	1.080	1.054	1.000	0.999	1.000	0.976	0.997	0.997	0.997	1.207	1.082	1.069
ID	Twin Falls	1997	1195	42.61	114.35	222	5.69	1.000	0.998	1.000	0.977	0.996	0.996	0.996	1.184	1.055	0.899	1.000	0.998	0.999	0.975	0.996	0.996	0.996	1.208	1.057	0.927
ID	Twin Falls	1998	1195	42.61	114.35	222	6.44	1.000	0.998	1.000	0.970	0.996	0.996	0.996	1.175	1.056	0.922	1.000	0.998	0.999	0.971	0.997	0.997	0.996	1.200	1.057	0.952
IL	Belleville	1999	133	38.52	89.88	974	5.53	1.000	0.999	0.999	0.980	1.000	0.998	0.998	1.207	1.107	1.093	1.000	0.999	0.998	0.972	0.998	0.998	0.998	1.235	1.118	1.099
IL	Bondville	1999	213	40.05	88.37	1008	5.18	1.000	0.998	0.998	0.978	1.001	1.001	0.998	1.210	1.091	1.038	1.000	0.999	0.998	0.972	0.998	0.998	0.998	1.249	1.110	1.093

Table F-3. Ratio of method Daily ETo to Daily ASCE-PM ETo, continued.

								YEARLY SUMMARY										GROWING SEASON									
State	Site	Year	Elevation (m)	Latitude	Longitude	Mean Annual Precip (mm)	Peak-Month Mean Daily ETo (ASCE PM) - mm	ASCE PM (YR)	ASCE PMD (YR)	ASCE PMDL (YR)	ASCE PMDR (YR)	ASCE PMrf (YR)	ETos (YR)	F56 PM (YR)	F24 Pen (YR)	1963 Pen (YR)	1985 Harg (YR)	ASCE PM (GS)	ASCE PMD (GS)	ASCE PMDL (GS)	ASCE PMDR (GS)	ASCE PMrf (GS)	ETos (GS)	F56 PM (GS)	F24 Pen (GS)	1963 Pen (GS)	1985 Harg (GS)
IL	Monmouth	1999	229	40.92	90.73	942	5.23	1.000	0.998	0.999	0.979	1.001	1.001	0.998	1.206	1.085	0.981	1.000	0.998	0.998	0.969	0.999	0.999	0.998	1.245	1.106	1.054
MT	Creston	1997	899	48.19	114.13	390	4.16	1.000	0.999	1.002	0.948	1.001	1.001	0.999	1.170	1.107	1.090	1.000	0.999	1.001	0.955	1.000	1.000	0.999	1.188	1.098	1.108
MT	Creston	1998	899	48.19	114.13	390	4.73	1.000	0.999	1.001	0.955	1.000	1.000	0.998	1.155	1.078	1.109	1.000	0.999	1.001	0.965	0.999	0.999	0.998	1.176	1.072	1.138
MT	Ronan	1997	927	47.54	114.28	380	4.31	1.000	0.999	1.002	0.948	1.001	1.001	0.999	1.178	1.122	1.096	1.000	0.999	1.001	0.955	1.001	1.001	1.000	1.193	1.113	1.117
MT	Ronan	1998	927	47.54	114.28	380	4.70	1.000	0.999	1.001	0.952	1.000	1.000	0.999	1.174	1.117	1.146	1.000	0.999	1.001	0.961	1.000	1.000	0.999	1.195	1.114	1.175
MT	St. Ignatius	1997	896	47.31	114.10	360	4.52	1.000	0.999	1.002	0.951	1.000	1.000	0.999	1.173	1.097	1.058	1.000	0.999	1.001	0.959	1.000	1.000	0.999	1.196	1.094	1.080
MT	St. Ignatius	1998	896	47.31	114.10	360	5.27	1.000	0.999	1.001	0.958	0.998	0.998	0.997	1.154	1.066	1.004	1.000	0.999	1.000	0.967	0.998	0.998	0.997	1.173	1.060	1.036
NE	Champion	1997	1029	40.22	101.43	482	6.64	1.000	0.998	0.998	0.978	0.985	0.985	0.985	1.144	0.993	0.906	1.000	0.998	0.998	0.972	0.988	0.988	0.987	1.208	1.031	0.986
NE	Champion	1998	1029	40.22	101.43	482	6.18	1.000	0.998	0.999	0.973	0.986	0.986	0.986	1.110	0.978	0.929	1.000	0.998	0.998	0.973	0.987	0.987	0.987	1.179	1.012	0.980
NE	Clay Center	1997	552	40.31	98.08	685	5.46	1.000	0.998	0.998	0.971	0.989	0.989	0.988	1.157	1.035	1.008	1.000	0.998	0.998	0.967	0.991	0.991	0.990	1.229	1.075	1.081
NE	Clay Center	1998	552	40.31	98.08	685	5.15	1.000	0.998	0.998	0.967	0.989	0.989	0.989	1.122	1.030	1.053	1.000	0.998	0.997	0.968	0.990	0.990	0.990	1.184	1.055	1.091
NE	Mead	1997	366	41.08	96.30	743	5.15	1.000	0.998	0.998	0.968	0.989	0.989	0.989	1.165	1.056	1.080	1.000	0.998	0.998	0.966	0.990	0.990	0.990	1.209	1.075	1.130
NE	Mead	1998	366	41.08	96.30	743	4.57	1.000	0.998	0.998	0.967	0.990	0.990	0.989	1.129	1.047	1.094	1.000	0.998	0.997	0.967	0.991	0.991	0.991	1.180	1.068	1.125
NY	Ithaca	1997	123	42.45	76.45	914	3.9	1.000	0.998	1.000	0.944	1.005	1.005	0.999	1.176	1.117	1.221	1.000	0.998	1.000	0.953	1.003	1.003	1.000	1.201	1.117	1.259
NY	Ithaca	1998	123	42.45	76.45	914	3.89	1.000	0.998	1.000	0.948	1.003	1.003	0.999	1.162	1.107	1.223	1.000	0.998	1.000	0.955	1.002	1.002	0.999	1.192	1.113	1.263
NY	Valatie	1997	76	42.43	73.68	914	3.82	1.000	0.999	1.001	0.939	1.005	1.005	1.001	1.185	1.153	1.329	1.000	0.999	1.001	0.947	1.003	1.003	1.001	1.198	1.148	1.356
NY	Valatie	1998	76	42.43	73.68	914	3.88	1.000	0.999	1.001	0.944	1.004	1.004	1.001	1.160	1.129	1.328	1.000	0.999	1.000	0.951	1.002	1.002	1.000	1.172	1.121	1.336
NY	Willsboro	1998	43	44.38	73.38	762	3.79	1.000	0.998	1.001	0.944	1.004	1.004	1.000	1.171	1.123	1.155	1.000	0.999	1.000	0.951	1.002	1.002	1.000	1.194	1.126	1.188
OK	Apache	1997	440	34.91	98.29	757	6.59	1.000	0.998	0.997	0.982	0.988	0.988	0.988	1.223	1.070	0.878	1.000	0.998	0.996	0.976	0.989	0.989	0.989	1.272	1.089	0.923
OK	Apache	1998	440	34.91	98.29	757	8.60	1.000	0.998	0.996	0.983	0.985	0.985	0.984	1.187	1.044	0.839	1.000	0.998	0.994	0.982	0.985	0.985	0.983	1.213	1.043	0.832
OK	Goodwell	1997	996	36.60	101.60	447	8.56	1.000	0.998	0.997	0.984	0.984	0.984	0.984	1.143	0.993	0.792	1.000	0.998	0.996	0.978	0.986	0.986	0.985	1.191	1.014	0.848
OK	Goodwell	1998	996	36.60	101.60	447	9.68	1.000	0.998	0.997	0.986	0.983	0.983	0.982	1.105	0.975	0.758	1.000	0.998	0.996	0.982	0.983	0.983	0.982	1.142	0.995	0.791
OK	Marena	1997	331	36.06	97.21	889	5.63	1.000	0.998	0.998	0.977	0.989	0.989	0.989	1.208	1.075	0.963	1.000	0.998	0.997	0.973	0.991	0.991	0.991	1.253	1.093	0.992
OK	Marena	1998	331	36.06	97.21	889	6.84	1.000	0.999	0.996	0.977	0.987	0.987	0.986	1.184	1.064	0.960	1.000	0.999	0.995	0.976	0.986	0.986	0.986	1.215	1.068	0.960
OK	Wister	1997	143	34.98	94.68	1188	5.13	1.000	0.999	0.999	0.965	0.994	0.994	0.993	1.181	1.105	1.249	1.000	0.999	0.997	0.966	0.994	0.994	0.994	1.203	1.104	1.231
OK	Wister	1998	143	34.98	94.68	1188	6.09	1.000	0.999	0.997	0.973	0.990	0.990	0.990	1.196	1.100	1.209	1.000	0.999	0.996	0.975	0.990	0.990	0.989	1.224	1.096	1.200
OR	Haga	1999	9	42.50	124.50	1778	3.32	1.000	1.000	1.004	0.933	1.008	1.008	1.004	1.058	1.063	1.125	1.000	1.000	1.004	0.948	1.007	1.007	1.004	1.062	1.043	1.051
SC	Florence	1986	40	34.24	79.81	1120	5.91	1.000	0.999	0.998	0.971	0.998	0.998	0.998	1.189	1.116	0.985	1.000	0.999	0.997	0.974	0.998	0.998	0.997	1.195	1.110	0.999
TX	Bushland	1997	1170	35.11	102.05	505	7.36	1.000	0.997	0.998	0.983	0.993	0.993	0.993	1.203	1.039	0.815	1.000	0.998	0.997	0.976	0.994	0.994	0.994	1.259	1.060	0.892
TX	Bushland	1998	1170	35.11	102.05	505	9.34	1.000	0.998	0.997	0.985	0.992	0.992	0.992	1.162	1.010	0.793	1.000	0.998	0.996	0.983	0.992	0.992	0.992	1.186	1.019	0.811
TX	Dalhart	1997	1228	36.20	102.32	467	6.44	1.000	0.998	0.999	0.980	0.998	0.998	0.994	1.178	1.016	0.948	1.000	0.998	0.998	0.980	0.997	0.997	0.994	1.211	1.031	0.974
TX	Dalhart	1998	1228	36.20	102.32	467	7.30	1.000	0.998	0.998	0.980	0.996	0.996	0.994	1.138	0.990	0.948	1.000	0.998	0.998	0.979	0.995	0.995	0.993	1.170	1.007	0.967
UT	Logan	1989	1350	41.60	111.80	433	6.21											1.000	0.999	1.000	0.974	0.997	0.997	0.996	1.189	1.029	1.102
UT	Logan	1990	1350	41.60	111.80	433	5.77											1.000	0.999	1.000	0.971	0.998	0.998	0.997	1.156	1.022	1.182
WA	Gramling	1998	386	46.29	119.73	178	7.42											1.000	0.998	0.997	0.980	0.988	0.988	0.987	1.197	1.045	0.878
WA	Grayland	1998	2	46.78	124.00	2032	2.78											1.000	0.998	1.001	0.957	1.003	1.003	1.000	1.213	1.201	1.166
WA	Paterson	1998	109	45.94	119.49	152	6.65											1.000	0.998	0.998	0.979	0.990	0.990	0.990	1.236	1.068	1.072
WA	Puyallup	1998	61	47.10	122.30	1016	3.48											1.000	0.999	1.001	0.943	0.999	0.999	0.998	1.151	1.119	1.430
WA	Roza	1998	343	46.29	119.73	178	5.96											1.000	0.999	0.999	0.978	0.991	0.991	0.991	1.233	1.083	1.048
	Average							1.000	0.998	0.999	0.971	0.994	0.994	0.993	1.171	1.065	1.041	1.000	0.999	0.999	0.971	0.995	0.995	0.994	1.195	1.072	1.057
	Minimum							1.000	0.997	0.995	0.933	0.978	0.978	0.978	1.058	0.975	0.758	1.000	0.998	0.994	0.943	0.982	0.982	0.982	1.059	0.995	0.791
	Maximum							1.000	1.000	1.004	0.994	1.008	1.008	1.004	1.228	1.153	1.329	1.000	1.000	1.004	0.991	1.007	1.007	1.004	1.272	1.201	1.430

Table F-4. Ratio of Hourly Sum ETo to Daily ETo (within Method)

								YEARLY									GROWING SEASON								
State	Site	Year	Elevation (m)	Latitude	Longitude	Mean Annual Precip (mm)	Peak-Month Mean Daily ETo (ASCE PM) - mm	ASCE PM (YR)	ASCE PMD (YR)	ASCE PMDL (YR)	ASCE PMDR (YR)	ASCE PMrf (YR)	ASCE PMrfh (YR)	ETos (YR)	F56 PM (YR)	1963 Pen (YR)	ASCE PM (GS)	ASCE PMD (GS)	ASCE PMDL (GS)	ASCE PMDR (GS)	ASCE PMrf (GS)	ASCE PMrfh (GS)	ETos (GS)	F56 PM (GS)	1963 Pen (GS)
AZ	Phoenix	1997	335	33.48	112.10	175	7.49	1.005	1.033	1.031	1.028	1.003	1.042	1.031	1.003	1.069	0.992	1.018	1.015	1.013	0.990	1.027	1.016	0.990	1.052
AZ	Phoenix	1998	335	33.48	112.10	175	7.60	0.994	1.027	1.024	1.021	0.993	1.034	1.025	0.993	1.059	0.984	1.013	1.011	1.009	0.982	1.020	1.012	0.982	1.042
AZ	Tucson	1997	713	32.28	110.94	300	8.54	0.988	1.020	1.017	1.012	0.987	1.041	1.019	0.987	1.073	0.992	1.021	1.018	1.015	0.991	1.042	1.019	0.991	1.057
AZ	Tucson	1998	713	32.28	110.94	300	8.21	0.980	1.016	1.013	1.009	0.979	1.032	1.015	0.979	1.069	0.986	1.020	1.017	1.015	0.984	1.035	1.018	0.984	1.052
CA	Davis	1998	18	38.50	121.80	461	6.71	0.938	0.998	0.995	0.997	0.938	1.014	0.997	0.938	1.047	0.940	0.997	0.994	0.994	0.939	1.007	0.996	0.940	1.042
CA	Fresno	1998	103	36.80	119.70	269	7.11	0.970	1.014	1.011	1.014	0.969	1.024	1.013	0.969	1.052	0.973	1.014	1.011	1.011	0.972	1.024	1.012	0.972	1.043
CA	Santa Maria	1998	82	35.00	120.40	314	4.42	0.939	1.006	1.004	1.003	0.939	1.005	1.006	0.940	1.055	0.948	1.017	1.015	1.014	0.948	1.012	1.016	0.949	1.046
CO	Center	1997	2348	38.00	106.00	178	5.62										0.967	1.018	1.016	1.011	0.964	1.028	1.015	0.964	1.066
CO	Center	1999	2348	38.00	106.00	178	5.96										0.967	1.023	1.021	1.014	0.964	1.038	1.020	0.965	1.084
CO	Colton	1982	2743	39.00	106.00	279	4.65																		
CO	Colton	1983	2743	39.00	106.00	279	4.69																		
CO	Fort Collins	1995	1527	40.60	105.00	383	5.58																		
CO	Fruita	1997	1274	38.00	104.00	228	7.83										0.985	1.033	1.029	1.012	0.978	1.031	1.026	0.977	1.107
CO	Fruita	1999	1274	38.00	104.00	228	6.75										0.995	1.034	1.031	1.014	0.989	1.033	1.028	0.991	1.102
CO	Loveland	1997	1540	40.40	105.11	406	5.59	0.995	1.027	1.024	1.021	0.993	1.041	1.025	0.993	1.087	0.987	1.016	1.014	1.010	0.985	1.026	1.014	0.985	1.057
CO	Loveland	1998	1540	40.40	105.11	406	5.30	0.992	1.024	1.021	1.019	0.990	1.039	1.022	0.991	1.082	0.989	1.021	1.018	1.016	0.987	1.029	1.019	0.987	1.055
CO	Ovid	1998	1089	40.97	102.45	448	5.5	0.930	0.984	0.981	0.981	0.933	1.008	0.987	0.933	1.088	0.956	1.009	1.006	1.006	0.957	1.024	1.010	0.958	1.053
CO	Ovid	1999	1089	40.97	102.45	448	6.08	0.918	0.976	0.973	0.972	0.922	1.000	0.979	0.922	1.088	0.946	1.003	1.001	1.002	0.947	1.017	1.004	0.947	1.042
CO	Portis	1982	2895	39	106	279	4.03																		
CO	Portis	1983	2895	39	106	279	4.21																		
CO	Rocky Ford	1997	1274	38	104	279	7.08										1.047	1.079	1.075	1.052	1.041	1.081	1.073	1.043	1.182
CO	Rocky Ford	1999	1274	38	104	279	8.02										1.032	1.060	1.057	1.039	1.028	1.064	1.055	1.037	1.142
CO	Wiggins	1997	1367	40.31	104.06	353	5.88	0.950	0.995	0.993	0.988	0.954	1.021	1.000	0.954	1.104	0.956	0.999	0.997	0.992	0.959	1.019	1.002	0.959	1.074
CO	Wiggins	1998	1367	40.31	104.06	353	5.93	0.947	0.996	0.993	0.990	0.951	1.015	1.000	0.951	1.103	0.961	1.007	1.004	1.001	0.962	1.020	1.009	0.963	1.071
CO	Yellow Jacket	1997	2252	37.00	109.00	406	5.94										0.959	1.002	1.000	0.998	0.960	1.014	1.003	0.962	1.056
CO	Yellow Jacket	1999	2252	37.00	109.00	406	6.01										0.968	1.019	1.017	1.014	0.965	1.016	1.016	0.967	1.063
FL	Lake Alfred	1998	46	28.03	80.89	1250	6.08	0.899	0.944	0.941	0.943	0.895	0.942	0.940	0.896	0.998	0.904	0.946	0.943	0.944	0.900	0.943	0.942	0.901	0.993
FL	Lake Alfred	1999	46	28.03	80.89	1250	5.23	0.905	0.947	0.944	0.942	0.901	0.943	0.942	0.902	1.000	0.909	0.948	0.945	0.943	0.905	0.945	0.944	0.905	0.994
FL	St. Pierce	1999	7	27.57	80.44	1422	4.99	0.947	1.006	1.004	0.981	0.943	1.008	1.001	0.945	1.052	0.942	0.999	0.997	0.980	0.938	1.001	0.994	0.939	1.038
GA	Attapulgus	1997	37	30.7612	84.4853	1460	4.54	0.903	0.944	0.943	0.946	0.899	0.943	0.940	0.900	0.967	0.909	0.947	0.945	0.946	0.905	0.945	0.943	0.906	0.958
GA	Attapulgus	1998	37	30.7612	84.4853	1460	6.29	0.903	0.942	0.940	0.946	0.899	0.941	0.938	0.900	0.960	0.906	0.943	0.941	0.944	0.902	0.941	0.938	0.903	0.955
GA	Blairsville	1997	584.3	34.8388	83.928	1307	4.48	0.959	0.993	0.990	0.994	0.954	0.992	0.988	0.956	1.002	0.973	1.005	1.002	1.004	0.968	1.002	1.000	0.970	1.000
GA	Blairsville	1998	584.3	34.8388	83.928	1307	4.63	0.921	0.965	0.962	0.968	0.916	0.963	0.960	0.918	0.993	0.927	0.971	0.968	0.971	0.923	0.968	0.966	0.925	0.987
GA	Griffin	1997	281.9	33.2623	84.284	1447	5.05	0.899	0.945	0.943	0.944	0.896	0.945	0.941	0.897	0.990	0.905	0.950	0.948	0.949	0.901	0.949	0.946	0.902	0.983
GA	Griffin	1998	281.9	33.2623	84.284	1447	5.99	0.916	0.958	0.956	0.961	0.912	0.957	0.954	0.913	0.985	0.918	0.960	0.957	0.960	0.914	0.958	0.956	0.915	0.983
ID	Ashton	1997	1615	44.03	111.47	430	4.96	0.968	1.024	1.022	1.017	0.967	1.047	1.022	0.967	1.087	0.961	1.013	1.011	1.009	0.959	1.034	1.011	0.959	1.070
ID	Ashton	1998	1615	44.03	111.47	430	5.70	0.942	1.001	0.998	0.997	0.941	1.010	0.999	0.941	1.068	0.941	0.997	0.994	0.992	0.939	1.005	0.995	0.939	1.064
ID	Parma	1997	703	43.80	116.93	237	5.66	0.990	1.027	1.024	1.028	0.987	1.039	1.024	0.987	1.088	0.985	1.020	1.017	1.017	0.982	1.031	1.017	0.982	1.075
ID	Parma	1998	703	43.80	116.93	237	6.10	0.980	1.019	1.016	1.022	0.977	1.029	1.016	0.977	1.076	0.982	1.021	1.018	1.020	0.978	1.027	1.017	0.979	1.073
ID	Twin Falls	1997	1195	42.61	114.35	222	5.69	0.956	1.000	0.997	0.995	0.954	1.024	0.999	0.954	1.074	0.958	0.999	0.996	0.994	0.956	1.018	0.997	0.956	1.058
ID	Twin Falls	1998	1195	42.61	114.35	222	6.44	0.946	0.987	0.984	0.984	0.945	1.011	0.985	0.945	1.061	0.951	0.992	0.990	0.989	0.949	1.008	0.990	0.949	1.050
IL	Belleville	1999	133	38.52	89.88	974	5.53	0.997	1.040	1.037	1.031	0.993	1.037	1.036	0.994	1.062	0.988	1.028	1.025	1.023	0.984	1.025	1.024	0.985	1.026
IL	Bondville	1999	213	40.05	88.37	1008	5.18	0.957	1.012	1.010	1.007	0.953	1.009	1.008	0.955	1.060	0.961	1.016	1.014	1.014	0.958	1.014	1.012	0.959	1.027

Table F-4. Ratio of Hourly Sum ETo to Daily ETo (within Method), continued.

								YEARLY									GROWING SEASON								
State	**Site**	**Year**	**Elevation (m)**	**Latitude**	**Longitude**	**Mean Annual Precip (mm)**	**Peak-Month Mean Daily ETo (ASCE PM) - mm**	**ASCE PM (YR)**	**ASCE PMD (YR)**	**ASCE PMDL (YR)**	**ASCE PMDR (YR)**	**ASCE PMrf (YR)**	**ASCE PMrfh (YR)**	**ETos (YR)**	**F56 PM (YR)**	**1963 Pen (YR)**	**ASCE PM (GS)**	**ASCE PMD (GS)**	**ASCE PMDL (GS)**	**ASCE PMDR (GS)**	**ASCE PMrf (GS)**	**ASCE PMrfh (GS)**	**ETos (GS)**	**F56 PM (GS)**	**1963 Pen (GS)**
IL	Monmouth	1999	229	40.92	90.73	942	5.23	0.940	0.988	0.986	0.983	0.937	0.986	0.984	0.938	1.049	0.944	0.995	0.993	0.994	0.940	0.994	0.991	0.941	1.017
MT	Creston	1997	899	48.19	114.13	390	4.16	0.969	1.020	1.019	1.030	0.966	1.026	1.018	0.967	1.048	0.970	1.019	1.017	1.021	0.967	1.023	1.016	0.968	1.048
MT	Creston	1998	899	48.19	114.13	390	4.73	0.971	1.019	1.017	1.027	0.969	1.024	1.017	0.969	1.062	0.975	1.024	1.021	1.024	0.972	1.023	1.021	0.972	1.063
MT	Ronan	1997	927	47.54	114.28	380	4.31	0.996	1.037	1.035	1.047	0.993	1.042	1.033	0.994	1.057	0.997	1.035	1.033	1.037	0.994	1.037	1.032	0.995	1.055
MT	Ronan	1998	927	47.54	114.28	380	4.70	1.001	1.035	1.033	1.042	0.997	1.041	1.032	0.999	1.063	1.002	1.038	1.035	1.037	0.999	1.037	1.035	1.000	1.060
MT	St. Ignatius	1997	896	47.31	114.10	360	4.52	0.978	1.012	1.010	1.017	0.976	1.024	1.010	0.977	1.037	0.979	1.014	1.012	1.014	0.977	1.020	1.012	0.977	1.034
MT	St. Ignatius	1998	896	47.31	114.10	360	5.27	0.965	0.987	0.985	0.990	0.963	1.009	0.985	0.964	1.036	0.966	0.992	0.990	0.989	0.963	1.003	0.990	0.964	1.038
NE	Champion	1997	1029	40.22	101.43	482	6.64	0.931	0.991	0.989	0.982	0.932	1.019	0.992	0.932	1.116	0.945	1.003	1.000	0.997	0.944	1.018	1.002	0.944	1.068
NE	Champion	1998	1029	40.22	101.43	482	6.18	0.917	0.971	0.968	0.961	0.918	0.996	0.971	0.918	1.106	0.934	0.989	0.986	0.982	0.934	1.004	0.988	0.934	1.070
NE	Clay Center	1997	552	40.31	98.08	685	5.46	0.907	0.975	0.973	0.974	0.907	0.993	0.975	0.907	1.075	0.929	0.996	0.994	0.996	0.928	1.004	0.995	0.928	1.038
NE	Clay Center	1998	552	40.31	98.08	685	5.15	0.886	0.950	0.948	0.953	0.886	0.965	0.950	0.886	1.047	0.906	0.967	0.964	0.967	0.906	0.977	0.966	0.906	1.025
NE	Mead	1997	366	41.08	96.30	743	5.15	0.936	0.998	0.996	0.995	0.936	1.021	0.998	0.936	1.080	0.943	1.006	1.003	1.002	0.942	1.017	1.005	0.943	1.049
NE	Mead	1998	366	41.08	96.30	743	4.57	0.921	0.978	0.976	0.975	0.921	0.998	0.977	0.921	1.066	0.928	0.983	0.981	0.981	0.927	0.994	0.982	0.927	1.035
NY	Ithaca	1997	123	42.45	76.45	914	3.9	0.977	1.031	1.029	1.038	0.972	1.035	1.026	0.975	1.077	0.983	1.044	1.041	1.045	0.978	1.043	1.039	0.981	1.071
NY	Ithaca	1998	123	42.45	76.45	914	3.89	0.976	1.029	1.027	1.033	0.972	1.032	1.025	0.974	1.071	0.979	1.037	1.035	1.036	0.975	1.037	1.033	0.977	1.059
NY	Valatie	1997	76	42.43	73.68	914	3.82	1.017	1.046	1.044	1.055	1.014	1.045	1.042	1.015	1.064	1.018	1.045	1.043	1.048	1.014	1.042	1.041	1.015	1.053
NY	Valatie	1998	76	42.43	73.68	914	3.88	1.001	1.035	1.033	1.046	0.997	1.034	1.031	0.998	1.055	0.997	1.031	1.029	1.034	0.994	1.029	1.027	0.995	1.042
NY	Willsboro	1998	43	44.38	73.38	762	3.79	0.985	1.019	1.017	1.027	0.983	1.022	1.016	0.983	1.046	0.985	1.022	1.020	1.023	0.982	1.023	1.019	0.983	1.033
OK	Apache	1997	440	34.91	98.29	757	6.59	0.925	0.977	0.975	0.974	0.925	1.010	0.977	0.925	1.047	0.935	0.987	0.985	0.986	0.933	1.007	0.986	0.934	1.016
OK	Apache	1998	440	34.91	98.29	757	8.60	0.933	0.977	0.975	0.976	0.932	1.007	0.976	0.933	1.039	0.943	0.982	0.980	0.981	0.942	1.008	0.981	0.942	1.020
OK	Goodwell	1997	996	36.60	101.60	447	8.56	0.920	0.972	0.969	0.962	0.921	1.008	0.972	0.921	1.085	0.924	0.975	0.972	0.971	0.923	1.000	0.974	0.923	1.042
OK	Goodwell	1998	996	36.60	101.60	447	9.68	0.922	0.967	0.964	0.957	0.922	1.007	0.967	0.922	1.085	0.935	0.976	0.973	0.971	0.934	1.010	0.976	0.934	1.047
OK	Marena	1997	331	36.06	97.21	889	5.63	0.938	0.992	0.990	0.993	0.938	1.012	0.991	0.938	1.055	0.943	0.994	0.992	0.994	0.941	1.006	0.992	0.942	1.024
OK	Marena	1998	331	36.06	97.21	889	6.84	0.946	0.992	0.989	0.995	0.945	1.014	0.991	0.945	1.050	0.949	0.991	0.988	0.991	0.948	1.007	0.989	0.948	1.026
OK	Wister	1997	143	34.98	94.68	1188	5.13	1.004	1.043	1.040	1.047	1.002	1.050	1.040	1.002	1.076	0.989	1.026	1.022	1.028	0.986	1.026	1.022	0.987	1.041
OK	Wister	1998	143	34.98	94.68	1188	6.09	1.013	1.053	1.050	1.056	1.010	1.064	1.050	1.010	1.079	1.002	1.043	1.039	1.042	0.999	1.045	1.039	0.999	1.053
OR	Haga	1999	9	42.50	124.50	1778	3.32																		
SC	Florence	1986	40	34.24	79.81	1120	5.91	0.973	1.007	1.005	1.008	0.970	1.025	1.004	0.970	1.060	0.975	1.010	1.008	1.007	0.972	1.022	1.008	0.973	1.051
TX	Bushland	1997	1170	35.11	102.05	505	7.36	0.894	0.944	0.942	0.935	0.894	0.982	0.944	0.893	1.036	0.903	0.956	0.954	0.953	0.902	0.979	0.955	0.902	1.002
TX	Bushland	1998	1170	35.11	102.05	505	9.34	0.904	0.951	0.949	0.941	0.903	0.987	0.950	0.902	1.045	0.917	0.961	0.959	0.954	0.915	0.995	0.959	0.915	1.033
TX	Dalhart	1997	1228	36.20	102.32	467	6.44	0.913	0.976	0.973	0.967	0.909	0.970	0.971	0.911	1.084	0.917	0.977	0.974	0.971	0.912	0.971	0.972	0.915	1.059
TX	Dalhart	1998	1228	36.20	102.32	467	7.30	0.920	0.979	0.976	0.973	0.915	0.973	0.974	0.918	1.091	0.931	0.986	0.983	0.982	0.926	0.979	0.981	0.928	1.072
UT	Logan	1989	1350	41.60	111.80	433	6.21										0.996	1.042	1.039	1.037	0.993	1.045	1.039	0.994	1.112
UT	Logan	1990	1350	41.60	111.80	433	5.77										0.987	1.036	1.032	1.032	0.984	1.032	1.033	0.984	1.110
WA	Gramling	1998	386	46.29	119.73	178	7.42										0.910	0.944	0.942	0.941	0.910	0.976	0.944	0.910	1.003
WA	Grayland	1998	2	46.78	124.00	2032	2.78										0.930	1.017	1.016	1.014	0.927	1.009	1.014	0.928	1.020
WA	Paterson	1998	109	45.94	119.49	152	6.65										0.947	0.991	0.988	0.990	0.946	1.006	0.990	0.946	1.041
WA	Puyallup	1998	61	47.10	122.30	1016	3.48										1.007	1.049	1.046	1.050	1.005	1.047	1.046	1.006	1.064
WA	Roza	1998	343	46.29	119.73	178	5.96										0.984	1.021	1.018	1.019	0.983	1.033	1.020	0.984	1.058
	Average							0.951	0.997	0.995	0.995	0.949	1.009	0.995	0.950	1.057	0.960	1.005	1.002	1.001	0.957	1.012	1.002	0.958	1.047
	Minimum							0.886	0.942	0.940	0.935	0.886	0.941	0.938	0.886	0.960	0.903	0.943	0.941	0.941	0.900	0.941	0.938	0.901	0.955
	Maximum							1.017	1.053	1.050	1.056	1.014	1.064	1.050	1.015	1.116	1.047	1.079	1.075	1.052	1.041	1.081	1.073	1.043	1.182

Table F-5. Ratio of Hourly Sum ETo to Daily ASCE-PM ETo

								YEARLY SUMMARY										GROWING SEASON									
Site	Year	State	Elevation (m)	Latitude	Longitude	Mean Annual Precip (mm)	Peak-Month Mean Daily ETo (ASCE PM) - mm	ASCE PM (YR)	ASCE PMD (YR)	ASCE PMDL (YR)	ASCE PMDR (YR)	ASCE PMrf (YR)	ASCE PMrfh (YR)	ETos (YR)	F56 PM (YR)	1963 Pen (YR)	CIM Pen (YR)	ASCE PM (GS)	ASCE PMD (GS)	ASCE PMDL (GS)	ASCE PMDR (GS)	ASCE PMrf (GS)	ASCE PMrfh (GS)	ETos (GS)	F56 PM (GS)	1963 Pen (GS)	CIM Pen (GS)
Phoenix	1997	AZ	335	33.48	112.10	175	7.49	1.005	1.032	1.025	1.022	0.990	1.028	1.016	0.989	1.196	1.074	0.992	1.017	1.009	1.004	0.976	1.013	1.001	0.976	1.161	1.061
Phoenix	1998	AZ	335	33.48	112.10	175	7.60	0.994	1.026	1.019	1.015	0.981	1.021	1.012	0.981	1.171	1.064	0.984	1.012	1.005	0.998	0.970	1.008	0.998	0.969	1.144	1.059
Tucson	1997	AZ	713	32.28	110.94	300	8.54	0.988	1.019	1.013	1.002	0.973	1.027	1.003	0.973	1.100	1.001	0.992	1.020	1.013	1.003	0.977	1.027	1.004	0.976	1.093	1.008
Tucson	1998	AZ	713	32.28	110.94	300	8.21	0.980	1.015	1.009	1.000	0.966	1.019	1.000	0.966	1.103	1.008	0.986	1.019	1.012	1.002	0.972	1.021	1.004	0.971	1.099	1.021
Davis	1998	CA	18	38.50	121.80	461	6.71	0.938	0.996	0.993	0.981	0.927	0.996	0.984	0.927	1.115	1.044	0.940	0.995	0.992	0.980	0.929	0.995	0.983	0.929	1.107	1.050
Fresno	1998	CA	103	36.80	119.70	269	7.11	0.970	1.012	1.009	0.996	0.959	1.013	1.001	0.959	1.119	1.050	0.973	1.012	1.008	0.995	0.962	1.013	1.000	0.962	1.113	1.060
Santa Maria	1998	CA	82	35.00	120.40	314	4.42	0.939	1.004	1.004	0.984	0.933	0.999	0.998	0.933	1.136	1.087	0.948	1.015	1.014	0.991	0.943	1.007	1.010	0.944	1.149	1.127
Center	1997	CO	2348	38.00	106.00	178	5.62											0.967	1.017	1.017	0.980	0.966	1.030	1.016	0.966	1.132	1.097
Center	1999	CO	2348	38.00	106.00	178	5.96											0.967	1.021	1.022	0.989	0.966	1.039	1.020	0.965	1.156	1.124
Colton	1982	CO	2743	39.00	106.00	279	4.65																				
Colton	1983	CO	2743	39.00	106.00	279	4.69																				
Fort Collins	1995	CO	1527	40.60	105.00	383	5.58																				
Fruita	1997	CO	1274	38.00	104.00	228	7.83											0.985	1.031	1.028	0.993	0.979	1.031	1.025	0.977	1.149	1.132
Fruita	1999	CO	1274	38.00	104.00	228	6.75											0.995	1.033	1.030	0.987	0.991	1.035	1.029	0.991	1.150	1.116
Loveland	1997	CO	1540	40.40	105.11	406	5.59	0.995	1.026	1.025	0.989	0.989	1.037	1.020	0.988	1.167	1.084	0.987	1.015	1.014	0.975	0.981	1.022	1.009	0.980	1.141	1.089
Loveland	1998	CO	1540	40.40	105.11	406	5.30	0.992	1.023	1.022	0.988	0.985	1.033	1.016	0.985	1.158	1.061	0.989	1.020	1.018	0.980	0.982	1.024	1.013	0.982	1.141	1.076
Ovid	1998	CO	1089	40.97	102.45	448	5.5	0.930	0.982	0.980	0.960	0.913	0.986	0.964	0.913	1.096	1.024	0.956	1.007	1.004	0.982	0.940	1.006	0.990	0.940	1.107	1.066
Ovid	1999	CO	1089	40.97	102.45	448	6.08	0.918	0.974	0.972	0.951	0.901	0.978	0.956	0.902	1.087	1.020	0.946	1.001	0.999	0.971	0.931	1.000	0.986	0.931	1.108	1.074
Portis	1982	CO	2895	39	106	279	4.03																				
Portis	1983	CO	2895	39	106	279	4.21																				
Rocky Ford	1997	CO	1274	38	104	279	7.08											1.047	1.078	1.074	1.029	1.041	1.080	1.071	1.041	1.201	1.152
Rocky Ford	1999	CO	1274	38	104	279	8.02											1.032	1.058	1.055	1.011	1.027	1.063	1.053	1.034	1.192	1.135
Wiggins	1997	CO	1367	40.31	104.06	353	5.88	0.950	0.993	0.992	0.965	0.935	1.000	0.978	0.935	1.109	1.046	0.956	0.998	0.996	0.966	0.942	1.001	0.983	0.942	1.101	1.065
Wiggins	1998	CO	1367	40.31	104.06	353	5.93	0.947	0.994	0.993	0.969	0.932	0.995	0.979	0.932	1.101	1.037	0.961	1.005	1.003	0.978	0.946	1.003	0.990	0.946	1.100	1.063
Yellow Jacket	1997	CO	2252	37.00	109.00	406	5.94											0.959	1.001	1.000	0.968	0.957	1.011	0.998	0.957	1.141	1.093
Yellow Jacket	1999	CO	2252	37.00	109.00	406	6.01											0.968	1.017	1.017	0.985	0.962	1.012	1.011	0.961	1.158	1.099
Lake Alfred	1998	FL	46	28.03	80.89	1250	6.08	0.899	0.943	0.938	0.929	0.892	0.938	0.935	0.894	1.041	1.002	0.904	0.944	0.938	0.926	0.896	0.938	0.936	0.898	1.039	1.016
Lake Alfred	1999	FL	46	28.03	80.89	1250	5.23	0.905	0.946	0.941	0.927	0.898	0.940	0.938	0.900	1.041	1.017	0.909	0.947	0.941	0.926	0.901	0.941	0.939	0.903	1.040	1.028
St. Pierce	1999	FL	7	27.57	80.44	1422	4.99	0.947	1.004	1.000	0.968	0.940	1.005	0.996	0.942	1.135	1.142	0.942	0.997	0.993	0.963	0.934	0.997	0.989	0.936	1.124	1.143
Attapulgus	1997	GA	37	30.761	84.4853	1460	4.54	0.903	0.943	0.941	0.921	0.898	0.942	0.938	0.899	1.067	1.027	0.909	0.946	0.942	0.922	0.903	0.943	0.940	0.904	1.061	1.043
Attapulgus	1998	GA	37	30.761	84.4853	1460	6.29	0.903	0.941	0.937	0.919	0.897	0.939	0.935	0.898	1.056	1.022	0.906	0.942	0.937	0.918	0.899	0.937	0.934	0.900	1.049	1.029
Blairsville	1997	GA	584.3	34.839	83.928	1307	4.48	0.959	0.992	0.991	0.950	0.958	0.996	0.991	0.957	1.128	1.080	0.973	1.004	1.003	0.964	0.970	1.005	1.002	0.970	1.131	1.105
Blairsville	1998	GA	584.3	34.839	83.928	1307	4.63	0.921	0.964	0.962	0.929	0.918	0.965	0.961	0.918	1.084	1.037	0.927	0.970	0.967	0.936	0.924	0.969	0.966	0.924	1.082	1.055
Griffin	1997	GA	281.9	33.262	84.284	1447	5.05	0.899	0.943	0.942	0.918	0.896	0.945	0.940	0.896	1.080	1.022	0.905	0.949	0.947	0.925	0.900	0.948	0.944	0.901	1.076	1.038
Griffin	1998	GA	281.9	33.262	84.284	1447	5.99	0.916	0.957	0.953	0.935	0.911	0.955	0.951	0.912	1.087	1.043	0.918	0.959	0.955	0.935	0.912	0.956	0.953	0.913	1.084	1.052
Ashton	1997	ID	1615	44.03	111.47	430	4.96	0.968	1.022	1.023	0.984	0.966	1.044	1.019	0.964	1.171	1.111	0.961	1.011	1.012	0.974	0.957	1.032	1.007	0.956	1.145	1.103
Ashton	1998	ID	1615	44.03	111.47	430	5.70	0.942	0.999	0.998	0.964	0.939	1.008	0.996	0.938	1.125	1.065	0.941	0.995	0.994	0.962	0.937	1.003	0.991	0.937	1.110	1.066
Parma	1997	ID	703	43.80	116.93	237	5.66	0.990	1.026	1.025	1.004	0.984	1.036	1.020	0.984	1.168	1.067	0.985	1.019	1.017	0.993	0.979	1.028	1.012	0.979	1.155	1.076
Parma	1998	ID	703	43.80	116.93	237	6.10	0.980	1.018	1.016	0.994	0.974	1.026	1.012	0.974	1.163	1.073	0.982	1.020	1.017	0.996	0.976	1.024	1.014	0.976	1.161	1.090
Twin Falls	1997	ID	1195	42.61	114.35	222	5.69	0.956	0.998	0.997	0.973	0.951	1.020	0.993	0.951	1.133	1.050	0.958	0.997	0.995	0.969	0.953	1.014	0.991	0.953	1.118	1.062
Twin Falls	1998	ID	1195	42.61	114.35	222	6.44	0.946	0.985	0.984	0.955	0.942	1.008	0.980	0.941	1.120	1.038	0.951	0.991	0.989	0.961	0.946	1.005	0.985	0.946	1.110	1.053
Belleville	1999	IL	133	38.52	89.88	974	5.53	0.997	1.039	1.036	1.010	0.993	1.038	1.035	0.993	1.176	1.124	0.988	1.027	1.023	0.994	0.982	1.023	1.021	0.983	1.147	1.138
Bondville	1999	IL	213	40.05	88.37	1008	5.18	0.957	1.011	1.009	0.985	0.954	1.010	1.007	0.953	1.157	1.099	0.961	1.015	1.012	0.985	0.956	1.012	1.009	0.957	1.140	1.123

Table F-5. Ratio of Hourly Sum ETo to Daily ASCE-PM ETo, continued.

								YEARLY SUMMARY										GROWING SEASON									
Site	Year	State	Elevation (m)	Latitude	Longitude	Mean Annual Precip (mm)	Peak-Month Mean Daily ETo (ASCE PM) - mm	ASCE PM (YR)	ASCE PMD (YR)	ASCE PMDL (YR)	ASCE PMDR (YR)	ASCE PMrf (YR)	ASCE PMrfh (YR)	ETos (YR)	F56 PM (YR)	1963 Pen (YR)	CIM Pen (YR)	ASCE PM (GS)	ASCE PMD (GS)	ASCE PMDL (GS)	ASCE PMDR (GS)	ASCE PMrf (GS)	ASCE PMrfh (GS)	ETos (GS)	F56 PM (GS)	1963 Pen (GS)	CIM Pen (GS)
Monmouth	1999	IL	229	40.92	90.73	942	5.23	0.940	0.986	0.985	0.963	0.938	0.987	0.984	0.936	1.137	1.072	0.944	0.993	0.991	0.963	0.939	0.992	0.989	0.939	1.125	1.102
Creston	1997	MT	899	48.19	114.13	390	4.16	0.969	1.019	1.020	0.977	0.967	1.026	1.017	0.966	1.160	1.086	0.970	1.018	1.019	0.975	0.967	1.023	1.015	0.967	1.151	1.106
Creston	1998	MT	899	48.19	114.13	390	4.73	0.971	1.018	1.018	0.981	0.968	1.024	1.015	0.968	1.145	1.070	0.975	1.023	1.022	0.988	0.971	1.022	1.019	0.971	1.140	1.089
Ronan	1997	MT	927	47.54	114.28	380	4.31	0.996	1.036	1.037	0.992	0.994	1.043	1.033	0.993	1.186	1.110	0.997	1.034	1.035	0.990	0.995	1.038	1.031	0.994	1.174	1.125
Ronan	1998	MT	927	47.54	114.28	380	4.70	1.001	1.034	1.034	0.991	0.998	1.041	1.031	0.997	1.187	1.100	1.002	1.037	1.036	0.996	0.999	1.037	1.033	0.998	1.181	1.118
St. Ignatius	1997	MT	896	47.31	114.10	360	4.52	0.978	1.010	1.011	0.968	0.977	1.024	1.009	0.976	1.138	1.061	0.979	1.013	1.013	0.972	0.977	1.020	1.011	0.976	1.131	1.081
St. Ignatius	1998	MT	896	47.31	114.10	360	5.27	0.965	0.986	0.985	0.948	0.962	1.007	0.982	0.961	1.105	1.016	0.966	0.991	0.990	0.957	0.962	1.002	0.987	0.961	1.101	1.034
Champion	1997	NE	1029	40.22	101.43	482	6.64	0.931	0.989	0.987	0.961	0.919	1.003	0.975	0.918	1.108	1.037	0.945	1.001	0.998	0.970	0.932	1.006	0.988	0.932	1.101	1.062
Champion	1998	NE	1029	40.22	101.43	482	6.18	0.917	0.968	0.966	0.935	0.905	0.981	0.955	0.905	1.082	1.017	0.934	0.987	0.983	0.955	0.922	0.991	0.974	0.922	1.084	1.044
Clay Center	1997	NE	552	40.31	98.08	685	5.46	0.907	0.973	0.971	0.945	0.897	0.982	0.962	0.897	1.112	1.045	0.929	0.994	0.991	0.963	0.919	0.994	0.984	0.919	1.115	1.082
Clay Center	1998	NE	552	40.31	98.08	685	5.15	0.886	0.948	0.946	0.921	0.876	0.955	0.938	0.876	1.078	1.017	0.906	0.965	0.962	0.936	0.897	0.967	0.955	0.897	1.081	1.053
Mead	1997	NE	366	41.08	96.30	743	5.15	0.936	0.996	0.994	0.964	0.926	1.009	0.985	0.925	1.140	1.084	0.943	1.004	1.001	0.968	0.933	1.007	0.993	0.933	1.127	1.102
Mead	1998	NE	366	41.08	96.30	743	4.57	0.921	0.976	0.974	0.943	0.912	0.988	0.966	0.912	1.116	1.059	0.928	0.981	0.978	0.948	0.919	0.985	0.972	0.919	1.105	1.079
Ithaca	1997	NY	123	42.45	76.45	914	3.9	0.977	1.030	1.030	0.980	0.977	1.041	1.030	0.975	1.203	1.140	0.983	1.042	1.042	0.996	0.981	1.047	1.041	0.980	1.196	1.159
Ithaca	1998	NY	123	42.45	76.45	914	3.89	0.976	1.027	1.027	0.980	0.975	1.036	1.027	0.973	1.186	1.134	0.979	1.035	1.034	0.989	0.977	1.039	1.032	0.976	1.179	1.154
Valatie	1997	NY	76	42.43	73.68	914	3.82	1.017	1.045	1.045	0.991	1.019	1.050	1.046	1.016	1.227	1.147	1.018	1.045	1.044	0.992	1.017	1.045	1.044	1.016	1.208	1.160
Valatie	1998	NY	76	42.43	73.68	914	3.88	1.001	1.035	1.034	0.987	1.001	1.038	1.035	0.999	1.191	1.122	0.997	1.030	1.029	0.983	0.996	1.031	1.028	0.995	1.168	1.133
Willsboro	1998	NY	43	44.38	73.38	762	3.79	0.985	1.017	1.018	0.969	0.987	1.027	1.019	0.984	1.175	1.094	0.985	1.021	1.020	0.973	0.984	1.025	1.020	0.983	1.164	1.117
Apache	1997	OK	440	34.91	98.29	757	6.59	0.925	0.975	0.973	0.957	0.914	0.998	0.964	0.914	1.120	1.057	0.935	0.985	0.981	0.962	0.924	0.997	0.973	0.924	1.106	1.077
Apache	1998	OK	440	34.91	98.29	757	8.60	0.933	0.975	0.970	0.959	0.919	0.992	0.960	0.918	1.084	1.015	0.943	0.981	0.974	0.963	0.927	0.992	0.964	0.927	1.064	1.011
Goodwell	1997	OK	996	36.60	101.60	447	8.56	0.920	0.969	0.967	0.947	0.906	0.992	0.955	0.906	1.078	1.003	0.924	0.973	0.969	0.950	0.910	0.986	0.958	0.909	1.057	1.010
Goodwell	1998	OK	996	36.60	101.60	447	9.68	0.922	0.965	0.961	0.944	0.906	0.989	0.948	0.905	1.058	0.981	0.935	0.974	0.969	0.953	0.919	0.993	0.957	0.918	1.042	0.984
Marena	1997	OK	331	36.06	97.21	889	5.63	0.938	0.990	0.987	0.971	0.928	1.001	0.979	0.928	1.135	1.070	0.943	0.992	0.988	0.967	0.932	0.996	0.982	0.933	1.119	1.091
Marena	1998	OK	331	36.06	97.21	889	6.84	0.946	0.990	0.986	0.972	0.932	1.000	0.976	0.932	1.117	1.043	0.949	0.990	0.983	0.968	0.935	0.993	0.975	0.935	1.095	1.048
Wister	1997	OK	143	34.98	94.68	1188	5.13	1.004	1.042	1.038	1.011	0.995	1.043	1.033	0.996	1.188	1.131	0.989	1.025	1.020	0.993	0.980	1.020	1.016	0.981	1.149	1.129
Wister	1998	OK	143	34.98	94.68	1188	6.09	1.013	1.053	1.047	1.029	1.000	1.055	1.039	1.000	1.186	1.118	1.003	1.042	1.035	1.017	0.989	1.035	1.028	0.989	1.155	1.117
Haga	1999	OR	9	42.50	124.50	1778	3.32																				
Florence	1986	SC	40	34.24	79.81	1120	5.91	0.973	1.006	1.003	0.979	0.968	1.023	1.001	0.968	1.182	1.086	0.975	1.009	1.005	0.981	0.970	1.020	1.004	0.970	1.167	1.095
Bushland	1997	TX	1170	35.11	102.05	505	7.36	0.894	0.941	0.940	0.919	0.887	0.975	0.935	0.886	1.076	1.005	0.903	0.954	0.951	0.930	0.897	0.973	0.947	0.896	1.062	1.023
Bushland	1998	TX	1170	35.11	102.05	505	9.34	0.904	0.948	0.946	0.927	0.896	0.979	0.940	0.895	1.055	0.980	0.917	0.959	0.955	0.938	0.908	0.987	0.949	0.907	1.053	0.992
Dalhart	1997	TX	1228	36.20	102.32	467	6.44	0.913	0.974	0.972	0.949	0.907	0.968	0.967	0.906	1.101	1.040	0.917	0.975	0.972	0.951	0.909	0.968	0.967	0.910	1.092	1.048
Dalhart	1998	TX	1228	36.20	102.32	467	7.30	0.920	0.977	0.974	0.954	0.912	0.969	0.968	0.912	1.080	1.012	0.931	0.984	0.980	0.961	0.921	0.974	0.974	0.922	1.079	1.026
Logan	1989	UT	1350	41.60	111.80	433	6.21											0.996	1.041	1.039	1.009	0.990	1.042	1.035	0.990	1.144	1.082
Logan	1990	UT	1350	41.60	111.80	433	5.77											0.987	1.035	1.032	1.002	0.982	1.030	1.030	0.982	1.135	1.080
Gramling	1998	WA	386	46.29	119.73	178	7.42											0.910	0.942	0.939	0.922	0.898	0.964	0.930	0.898	1.049	0.969
Grayland	1998	WA	2	46.78	124.00	2032	2.78											0.930	1.015	1.017	0.971	0.929	1.011	1.014	0.927	1.225	1.220
Paterson	1998	WA	109	45.94	119.49	152	6.65											0.947	0.989	0.986	0.969	0.937	0.996	0.979	0.937	1.112	1.042
Puyallup	1998	WA	61	47.10	122.30	1016	3.48											1.007	1.048	1.048	0.990	1.004	1.047	1.045	1.003	1.191	1.157
Roza	1998	WA	343	46.29	119.73	178	5.96											0.984	1.019	1.017	0.996	0.975	1.024	1.009	0.974	1.146	1.072
Average								0.951	0.995	0.993	0.967	0.944	1.003	0.988	0.943	1.127	1.059	0.960	1.004	1.001	0.973	0.952	1.007	0.996	0.952	1.124	1.080
Minimum								0.886	0.941	0.937	0.918	0.876	0.938	0.935	0.876	1.041	0.980	0.903	0.942	0.937	0.918	0.896	0.937	0.930	0.896	1.039	0.969
Maximum								1.017	1.053	1.047	1.029	1.019	1.055	1.046	1.016	1.227	1.147	1.047	1.078	1.074	1.029	1.041	1.080	1.071	1.041	1.225	1.220

Table F-6. Ratio of method Hourly Sum ETo to Hourly Sum ASCE PMD ETo

State	Site	Year	Elevation (m)	Latitude	Longitude	Mean Annual Precip (mm)	Peak-Month Mean Daily ETo (ASCE PM) - mm	YEARLY SUMMARY										GROWING SEASON									
								ASCE PM (YR)	ASCE PMD (YR)	ASCE PMDL (YR)	ASCE PMDR (YR)	ASCE PMrf (YR)	ASCE PMrfh (YR)	ETos (YR)	F56 PM (YR)	1963 Pen (YR)	CIM Pen (YR)	ASCE PM (GS)	ASCE PMD (GS)	ASCE PMDL (GS)	ASCE PMDR (GS)	ASCE PMrf (GS)	ASCE PMrfh (GS)	ETos (GS)	F56 PM (GS)	1963 Pen (GS)	CIM Pen (GS)
AZ	Phoenix	1997	335	33.48	112.10	175	7.49	0.974	1.000	0.993	0.990	0.959	0.996	0.985	0.958	1.158	1.040	0.975	1.000	0.992	0.987	0.960	0.996	0.984	0.959	1.141	1.043
AZ	Phoenix	1998	335	33.48	112.10	175	7.60	0.969	1.000	0.994	0.989	0.957	0.996	0.987	0.956	1.141	1.038	0.971	1.000	0.993	0.985	0.958	0.995	0.986	0.957	1.130	1.046
AZ	Tucson	1997	713	32.28	110.94	300	8.54	0.970	1.000	0.995	0.984	0.956	1.008	0.985	0.955	1.080	0.983	0.973	1.000	0.993	0.983	0.958	1.007	0.984	0.957	1.072	0.989
AZ	Tucson	1998	713	32.28	110.94	300	8.21	0.966	1.000	0.995	0.985	0.952	1.004	0.986	0.952	1.087	0.994	0.968	1.000	0.993	0.983	0.954	1.003	0.985	0.953	1.079	1.003
CA	Davis	1998	18	38.50	121.80	461	6.71	0.942	1.000	0.997	0.985	0.931	1.001	0.988	0.931	1.119	1.048	0.945	1.000	0.997	0.984	0.933	1.000	0.988	0.933	1.112	1.055
CA	Fresno	1998	103	36.80	119.70	269	7.11	0.958	1.000	0.997	0.984	0.947	1.001	0.989	0.947	1.105	1.038	0.962	1.000	0.996	0.983	0.950	1.001	0.988	0.950	1.099	1.047
CA	Santa Maria	1998	82	35.00	120.40	314	4.42	0.935	1.000	0.999	0.980	0.929	0.994	0.994	0.929	1.131	1.082	0.934	1.000	0.999	0.976	0.929	0.992	0.995	0.929	1.132	1.110
CO	Center	1997	2348	38.00	106.00	178	5.62											0.951	1.000	1.000	0.964	0.950	1.013	0.999	0.950	1.114	1.079
CO	Center	1999	2348	38.00	106.00	178	5.96											0.947	1.000	1.001	0.968	0.946	1.018	0.998	0.945	1.132	1.101
CO	Colton	1982	2743	39.00	106.00	279	4.65											0.955	1.000	0.997	0.963	0.949	1.000	0.994	0.947	1.115	1.098
CO	Colton	1983	2743	39.00	106.00	279	4.69																				
CO	Fort Collins	1995	1527	40.60	105.00	383	5.58																				
CO	Fruita	1997	1274	38.00	104.00	228	7.83											0.955	1.000	0.997	0.963	0.949	1.000	0.994	0.947	1.115	1.098
CO	Fruita	1999	1274	38.00	104.00	228	6.75											0.963	1.000	0.997	0.956	0.959	1.002	0.996	0.959	1.113	1.080
CO	Loveland	1997	1540	40.40	105.11	406	5.59	0.970	1.000	0.999	0.965	0.964	1.011	0.994	0.964	1.137	1.057	0.972	1.000	0.998	0.956	0.966	1.005	0.994	0.965	1.119	1.081
CO	Loveland	1998	1540	40.40	105.11	406	5.30	0.970	1.000	0.999	0.966	0.963	1.011	0.993	0.963	1.132	1.037	0.969	1.000	0.997	0.960	0.962	1.003	0.993	0.962	1.114	1.058
CO	Ovid	1998	1089	40.97	102.45	448	5.5	0.947	1.000	0.998	0.978	0.930	1.004	0.982	0.930	1.116	1.043	0.950	1.000	0.997	0.975	0.934	0.999	0.983	0.934	1.099	1.059
CO	Ovid	1999	1089	40.97	102.45	448	6.08	0.943	1.000	0.999	0.977	0.926	1.005	0.982	0.926	1.117	1.047	0.943	1.000	0.998	0.974	0.928	1.002	0.984	0.928	1.112	1.061
CO	Portis	1982	2895	39	106	279	4.03																				
CO	Portis	1983	2895	39	106	279	4.21																				
CO	Rocky Ford	1997	1274	38	104	279	7.08											0.972	1.000	0.997	0.955	0.966	1.003	0.994	0.966	1.115	1.070
CO	Rocky Ford	1999	1274	38	104	279	8.02											0.975	1.000	0.997	0.956	0.970	1.004	0.995	0.970	1.126	1.072
CO	Wiggins	1997	1367	40.31	104.06	353	5.88	0.956	1.000	0.999	0.972	0.941	1.007	0.984	0.941	1.116	1.053	0.958	1.000	0.998	0.965	0.945	1.002	0.986	0.945	1.104	1.078
CO	Wiggins	1998	1367	40.31	104.06	353	5.93	0.952	1.000	0.999	0.975	0.937	1.001	0.984	0.937	1.107	1.043	0.956	1.000	0.997	0.971	0.941	0.997	0.985	0.941	1.093	1.064
CO	Yellow Jacket	1997	2252	37.00	109.00	406	5.94											0.958	1.000	0.999	0.967	0.956	1.010	0.997	0.956	1.139	1.092
CO	Yellow Jacket	1999	2252	37.00	109.00	406	6.01											0.952	1.000	1.000	0.968	0.946	0.995	0.994	0.945	1.139	1.080
FL	Lake Alfred	1998	46	28.03	80.89	1250	6.08	0.954	1.000	0.994	0.985	0.946	0.995	0.992	0.948	1.104	1.063	0.957	1.000	0.994	0.980	0.949	0.993	0.991	0.951	1.100	1.076
FL	Lake Alfred	1999	46	28.03	80.89	1250	5.23	0.957	1.000	0.995	0.980	0.950	0.994	0.992	0.951	1.101	1.076	0.960	1.000	0.994	0.978	0.951	0.993	0.991	0.953	1.098	1.086
FL	St. Pierce	1999	7	27.57	80.44	1422	4.99	0.943	1.000	0.996	0.964	0.936	1.000	0.992	0.938	1.130	1.137	0.945	1.000	0.995	0.966	0.936	0.999	0.991	0.939	1.127	1.146
GA	Attapulgus	1997	37	30.76	84.4853	1460	4.54	0.958	1.000	0.997	0.977	0.952	0.999	0.994	0.953	1.131	1.089	0.961	1.000	0.996	0.975	0.954	0.996	0.993	0.955	1.121	1.102
GA	Attapulgus	1998	37	30.76	84.4853	1460	6.29	0.960	1.000	0.996	0.977	0.953	0.997	0.993	0.954	1.122	1.086	0.962	1.000	0.995	0.975	0.954	0.995	0.992	0.956	1.114	1.093
GA	Blairsville	1997	584.3	34.84	83.928	1307	4.48	0.967	1.000	0.999	0.958	0.966	1.004	0.999	0.965	1.137	1.089	0.969	1.000	0.999	0.960	0.966	1.001	0.998	0.966	1.126	1.100
GA	Blairsville	1998	584.3	34.84	83.928	1307	4.63	0.955	1.000	0.998	0.964	0.953	1.001	0.997	0.952	1.125	1.076	0.957	1.000	0.997	0.966	0.953	0.999	0.996	0.953	1.116	1.088
GA	Griffin	1997	281.9	33.26	84.284	1447	5.05	0.953	1.000	0.998	0.973	0.950	1.002	0.996	0.950	1.144	1.083	0.954	1.000	0.997	0.975	0.949	0.999	0.995	0.949	1.134	1.094
GA	Griffin	1998	281.9	33.26	84.284	1447	5.99	0.957	1.000	0.996	0.977	0.952	0.998	0.994	0.953	1.136	1.090	0.957	1.000	0.996	0.975	0.951	0.997	0.994	0.953	1.131	1.098
ID	Ashton	1997	1615	44.03	111.47	430	4.96	0.948	1.000	1.001	0.963	0.945	1.022	0.997	0.944	1.146	1.087	0.949	1.000	1.000	0.963	0.945	1.017	0.996	0.945	1.130	1.097
ID	Ashton	1998	1615	44.03	111.47	430	5.70	0.943	1.000	1.000	0.965	0.940	1.009	0.997	0.939	1.127	1.067	0.947	1.000	0.999	0.965	0.943	1.007	0.996	0.942	1.114	1.080
ID	Parma	1997	703	43.80	116.93	237	5.66	0.965	1.000	0.999	0.979	0.959	1.009	0.994	0.959	1.139	1.040	0.967	1.000	0.997	0.971	0.960	1.003	0.993	0.961	1.127	1.065
ID	Parma	1998	703	43.80	116.93	237	6.10	0.963	1.000	0.998	0.976	0.957	1.008	0.994	0.957	1.143	1.055	0.964	1.000	0.996	0.972	0.958	1.001	0.993	0.958	1.132	1.076
ID	Twin Falls	1997	1195	42.61	114.35	222	5.69	0.958	1.000	0.999	0.975	0.953	1.022	0.995	0.953	1.135	1.053	0.961	1.000	0.999	0.974	0.955	1.020	0.995	0.955	1.128	1.066
ID	Twin Falls	1998	1195	42.61	114.35	222	6.44	0.961	1.000	0.999	0.969	0.956	1.023	0.995	0.956	1.137	1.054	0.959	1.000	0.999	0.970	0.954	1.016	0.995	0.954	1.126	1.065
IL	Belleville	1999	133	38.52	89.88	974	5.53	0.960	1.000	0.997	0.972	0.956	0.999	0.996	0.956	1.132	1.082	0.961	1.000	0.996	0.968	0.955	0.996	0.994	0.957	1.117	1.107
IL	Bondville	1999	213	40.05	88.37	1008	5.18	0.947	1.000	0.998	0.975	0.944	0.999	0.997	0.943	1.145	1.087	0.947	1.000	0.997	0.971	0.942	0.997	0.994	0.943	1.124	1.107

Table F-6. Ratio of method Hourly Sum ETo to Hourly Sum ASCE PMD ETo, continued.

								YEARLY SUMMARY										GROWING SEASON									
State	Site	Year	Elevation (m)	Latitude	Longitude	Mean Annual Precip (mm)	Peak-Month Mean Daily ETo (ASCE PM) - mm	ASCE PM (YR)	ASCE PMD (YR)	ASCE PMDL (YR)	ASCE PMDR (YR)	ASCE PMrf (YR)	ASCE PMrfh (YR)	ETos (YR)	F56 PM (YR)	1963 Pen (YR)	CIM Pen (YR)	ASCE PM (GS)	ASCE PMD (GS)	ASCE PMDL (GS)	ASCE PMDR (GS)	ASCE PMrf (GS)	ASCE PMrfh (GS)	ETos (GS)	F56 PM (GS)	1963 Pen (GS)	CIM Pen (GS)
IL	Monmouth	1999	229	40.92	90.73	942	5.23	0.953	1.000	0.999	0.976	0.951	1.001	0.998	0.949	1.153	1.087	0.950	1.000	0.997	0.970	0.945	0.999	0.995	0.946	1.133	1.110
MT	Creston	1997	899	48.19	114.13	390	4.16	0.951	1.000	1.001	0.958	0.949	1.007	0.998	0.948	1.139	1.066	0.952	1.000	1.001	0.959	0.949	1.006	0.998	0.949	1.136	1.086
MT	Creston	1998	899	48.19	114.13	390	4.73	0.954	1.000	1.000	0.964	0.951	1.006	0.997	0.950	1.125	1.051	0.952	1.000	1.000	0.966	0.949	1.000	0.997	0.948	1.118	1.065
MT	Ronan	1997	927	47.54	114.28	380	4.31	0.962	1.000	1.001	0.958	0.959	1.007	0.997	0.959	1.145	1.071	0.962	1.000	1.001	0.959	0.960	1.006	0.997	0.959	1.142	1.089
MT	Ronan	1998	927	47.54	114.28	380	4.70	0.967	1.000	1.000	0.958	0.964	1.006	0.997	0.964	1.148	1.063	0.965	1.000	0.999	0.961	0.962	1.001	0.997	0.962	1.141	1.078
MT	St. Ignatius	1997	896	47.31	114.10	360	4.52	0.968	1.000	1.001	0.958	0.967	1.013	0.998	0.966	1.126	1.050	0.966	1.000	1.001	0.960	0.964	1.009	0.998	0.964	1.121	1.065
MT	St. Ignatius	1998	896	47.31	114.10	360	5.27	0.979	1.000	1.000	0.961	0.976	1.022	0.996	0.975	1.121	1.031	0.973	1.000	0.999	0.965	0.969	1.011	0.996	0.969	1.113	1.043
NE	Champion	1997	1029	40.22	101.43	482	6.64	0.942	1.000	0.998	0.972	0.929	1.015	0.986	0.929	1.121	1.049	0.943	1.000	0.997	0.969	0.931	1.004	0.987	0.931	1.100	1.060
NE	Champion	1998	1029	40.22	101.43	482	6.18	0.947	1.000	0.998	0.966	0.934	1.013	0.986	0.934	1.117	1.050	0.947	1.000	0.996	0.968	0.934	1.004	0.987	0.934	1.098	1.058
NE	Clay Center	1997	552	40.31	98.08	685	5.46	0.933	1.000	0.998	0.972	0.922	1.010	0.989	0.922	1.144	1.075	0.935	1.000	0.997	0.969	0.925	1.000	0.989	0.925	1.122	1.089
NE	Clay Center	1998	552	40.31	98.08	685	5.15	0.934	1.000	0.998	0.972	0.924	1.007	0.989	0.924	1.137	1.073	0.939	1.000	0.997	0.970	0.929	1.003	0.989	0.929	1.121	1.091
NE	Mead	1997	366	41.08	96.30	743	5.15	0.939	1.000	0.998	0.968	0.929	1.013	0.989	0.929	1.145	1.088	0.940	1.000	0.997	0.964	0.930	1.003	0.990	0.930	1.123	1.098
NE	Mead	1998	366	41.08	96.30	743	4.57	0.944	1.000	0.998	0.966	0.934	1.012	0.990	0.934	1.144	1.085	0.946	1.000	0.997	0.966	0.936	1.004	0.990	0.936	1.125	1.100
NY	Ithaca	1997	123	42.45	76.45	914	3.9	0.949	1.000	1.000	0.951	0.949	1.011	1.000	0.947	1.168	1.107	0.944	1.000	0.999	0.953	0.943	1.004	0.998	0.942	1.148	1.121
NY	Ithaca	1998	123	42.45	76.45	914	3.89	0.950	1.000	1.000	0.953	0.949	1.008	0.999	0.947	1.155	1.104	0.947	1.000	0.999	0.955	0.945	1.003	0.997	0.944	1.138	1.121
NY	Valatie	1997	76	42.43	73.68	914	3.82	0.974	1.000	1.000	0.948	0.975	1.005	1.001	0.972	1.174	1.097	0.975	1.000	0.999	0.947	0.974	1.000	0.999	0.974	1.154	1.116
NY	Valatie	1998	76	42.43	73.68	914	3.88	0.967	1.000	1.000	0.954	0.967	1.003	1.000	0.966	1.151	1.084	0.969	1.000	0.998	0.952	0.967	1.000	0.998	0.967	1.130	1.106
NY	Willsboro	1998	43	44.38	73.38	762	3.79	0.968	1.000	1.001	0.953	0.970	1.009	1.002	0.967	1.155	1.076	0.964	1.000	1.000	0.952	0.963	1.004	0.999	0.962	1.137	1.103
OK	Apache	1997	440	34.91	98.29	757	6.59	0.949	1.000	0.997	0.981	0.937	1.023	0.988	0.937	1.148	1.084	0.949	1.000	0.996	0.977	0.937	1.012	0.988	0.938	1.123	1.093
OK	Apache	1998	440	34.91	98.29	757	8.60	0.957	1.000	0.995	0.983	0.942	1.018	0.985	0.941	1.112	1.040	0.962	1.000	0.993	0.982	0.946	1.012	0.983	0.945	1.084	1.031
OK	Goodwell	1997	996	36.60	101.60	447	8.56	0.949	1.000	0.997	0.977	0.935	1.023	0.985	0.934	1.112	1.035	0.950	1.000	0.996	0.976	0.935	1.013	0.985	0.935	1.087	1.038
OK	Goodwell	1998	996	36.60	101.60	447	9.68	0.955	1.000	0.997	0.978	0.939	1.026	0.983	0.939	1.097	1.017	0.960	1.000	0.995	0.978	0.943	1.019	0.983	0.942	1.069	1.010
OK	Marena	1997	331	36.06	97.21	889	5.63	0.948	1.000	0.997	0.980	0.937	1.011	0.989	0.937	1.146	1.080	0.950	1.000	0.996	0.975	0.940	1.004	0.989	0.940	1.128	1.100
OK	Marena	1998	331	36.06	97.21	889	6.84	0.955	1.000	0.995	0.982	0.942	1.010	0.986	0.941	1.128	1.054	0.959	1.000	0.993	0.978	0.944	1.003	0.985	0.944	1.106	1.059
OK	Wister	1997	143	34.98	94.68	1188	5.13	0.964	1.000	0.996	0.970	0.955	1.001	0.991	0.956	1.140	1.086	0.965	1.000	0.995	0.969	0.956	0.995	0.991	0.957	1.121	1.102
OK	Wister	1998	143	34.98	94.68	1188	6.09	0.963	1.000	0.995	0.976	0.950	1.002	0.987	0.950	1.127	1.062	0.962	1.000	0.993	0.975	0.949	0.992	0.986	0.949	1.108	1.072
OR	Haga	1999	9	42.50	124.50	1778	3.32	0.904	1.000	1.002	0.955	0.905	1.033	1.001	0.906	1.427	1.425	0.887	1.000	1.001	0.955	0.887	1.011	1.000	0.884	1.418	1.436
SC	Florence	1986	40	34.24	79.81	1120	5.91	0.967	1.000	0.997	0.973	0.963	1.017	0.995	0.963	1.175	1.080	0.966	1.000	0.996	0.972	0.961	1.011	0.995	0.961	1.156	1.085
TX	Bushland	1997	1170	35.11	102.05	505	7.36	0.950	1.000	0.999	0.976	0.943	1.036	0.993	0.942	1.143	1.068	0.947	1.000	0.996	0.975	0.940	1.019	0.992	0.939	1.113	1.073
TX	Bushland	1998	1170	35.11	102.05	505	9.34	0.953	1.000	0.997	0.978	0.944	1.033	0.991	0.944	1.113	1.034	0.957	1.000	0.996	0.979	0.947	1.030	0.990	0.947	1.099	1.035
TX	Dalhart	1997	1228	36.20	102.32	467	6.44	0.937	1.000	0.998	0.974	0.931	0.994	0.993	0.930	1.131	1.068	0.940	1.000	0.997	0.975	0.933	0.993	0.992	0.933	1.120	1.075
TX	Dalhart	1998	1228	36.20	102.32	467	7.30	0.941	1.000	0.997	0.976	0.933	0.991	0.991	0.933	1.105	1.036	0.945	1.000	0.996	0.977	0.936	0.989	0.990	0.936	1.097	1.043
UT	Logan	1989	1350	41.60	111.80	433	6.21											0.956	1.000	0.998	0.970	0.950	1.001	0.994	0.950	1.100	1.041
UT	Logan	1990	1350	41.60	111.80	433	5.77											0.954	1.000	0.997	0.969	0.949	0.995	0.995	0.949	1.097	1.043
WA	Gramling	1998	386	46.29	119.73	178	7.42											0.966	1.000	0.997	0.979	0.954	1.023	0.988	0.953	1.113	1.029
WA	Grayland	1998	2	46.78	124.00	2032	2.78											0.916	1.000	1.002	0.957	0.916	0.997	1.000	0.914	1.208	1.202
WA	Paterson	1998	109	45.94	119.49	152	6.65											0.957	1.000	0.997	0.980	0.947	1.007	0.989	0.947	1.124	1.053
WA	Puyallup	1998	61	47.10	122.30	1016	3.48											0.961	1.000	1.000	0.944	0.958	0.998	0.997	0.957	1.136	1.104
WA	Roza	1998	343	46.29	119.73	178	5.96											0.966	1.000	0.997	0.977	0.956	1.005	0.990	0.956	1.124	1.052
	Average							0.954	1.000	0.998	0.971	0.947	1.008	0.992	0.947	1.136	1.069	0.955	1.000	0.997	0.969	0.948	1.003	0.992	0.948	1.123	1.082
	Minimum							0.904	1.000	0.993	0.948	0.905	0.991	0.982	0.906	1.080	0.983	0.887	1.000	0.992	0.944	0.887	0.989	0.983	0.884	1.069	0.989
	Maximum							0.979	1.000	1.002	0.990	0.976	1.036	1.002	0.975	1.427	1.425	0.975	1.000	1.002	0.987	0.974	1.030	1.000	0.974	1.418	1.436

Table F-7. Ratio of Daily ETr to Daily ASCE PM ETr

State	Site	Year	Elevation (m)	Latitude	Longitude	Mean Annual Precip (mm)	Peak-Month Mean Daily ETr (ASCE PM) - mm	YEARLY SUMMARY							GROWING SEASON						
								ASCE PM (YR)	ASCE PMD (YR)	ASCE PMDL (YR)	ASCE PMDR (YR)	ASCE PMrf (YR)	ETrs (YR)	1982 Kpen (YR)	ASCE PM (GS)	ASCE PMD (GS)	ASCE PMDL (GS)	ASCE PMDR (GS)	ASCE PMrf (GS)	ETrs (GS)	1982 Kpen (GS)
AZ	Phoenix	1997	335	33.48	112.10	175	9.50	1.000	0.999	0.995	0.996	0.984	0.984	0.948	1.000	0.999	0.994	0.993	0.983	0.983	0.972
AZ	Phoenix	1998	335	33.48	112.10	175	9.67	1.000	0.999	0.996	0.995	0.986	0.986	0.954	1.000	0.999	0.995	0.991	0.985	0.985	0.979
AZ	Tucson	1997	713	32.28	110.94	300	11.37	1.000	0.999	0.997	0.993	0.986	0.986	0.858	1.000	0.999	0.996	0.992	0.985	0.985	0.892
AZ	Tucson	1998	713	32.28	110.94	300	10.93	1.000	0.999	0.997	0.993	0.988	0.988	0.876	1.000	0.999	0.996	0.990	0.987	0.987	0.914
CA	Davis	1998	18	38.50	121.80	461	8.55	1.000	0.999	0.999	0.988	0.989	0.989	0.962	1.000	0.999	0.998	0.989	0.989	0.989	0.975
CA	Fresno	1998	103	36.80	119.70	269	9.09	1.000	0.999	0.998	0.986	0.989	0.989	0.963	1.000	0.999	0.997	0.988	0.988	0.988	0.984
CA	Santa Maria	1998	82	35.00	120.40	314	5.11	1.000	0.999	1.000	0.986	1.000	1.000	0.959	1.000	0.999	1.000	0.982	0.996	0.996	1.017
CO	Center	1997	2348	38.00	106.00	178	7.24								1.000	0.999	1.002	0.977	1.002	1.002	0.973
CO	Center	1999	2348	38.00	106.00	178	7.73								1.000	0.998	1.001	0.982	1.003	1.003	0.976
CO	Colton	1982	2743	39.00	106.00	279	5.85								1.000	0.999	1.003	0.968	1.006	1.006	1.007
CO	Colton	1983	2743	39.00	106.00	279	5.91								1.000	0.999	1.003	0.973	1.006	1.006	1.006
CO	Fort Collins	1995	1527	40.60	105.00	383	6.76	1.000	0.999	1.001	0.980	0.986	0.986	0.905	1.000	0.999	1.000	0.970	0.988	0.988	0.999
CO	Fruita	1997	1274	38.00	104.00	228	10.45								1.000	0.999	0.999	0.986	0.994	0.994	0.966
CO	Fruita	1999	1274	38.00	104.00	228	9.06								1.000	0.999	0.999	0.980	0.994	0.994	0.950
CO	Loveland	1997	1540	40.40	105.11	406	6.68	1.000	0.999	1.001	0.975	1.002	1.002	0.952	1.000	0.999	1.000	0.971	1.000	1.000	1.008
CO	Loveland	1998	1540	40.40	105.11	406	6.45	1.000	0.999	1.001	0.976	1.001	1.001	0.936	1.000	0.999	1.000	0.972	0.998	0.998	0.996
CO	Ovid	1998	1089	40.97	102.45	448	7.12	1.000	0.999	1.000	0.985	0.974	0.974	0.886	1.000	0.999	0.999	0.982	0.974	0.974	0.953
CO	Ovid	1999	1089	40.97	102.45	448	7.55	1.000	0.998	1.000	0.984	0.975	0.975	0.876	1.000	0.999	0.999	0.980	0.976	0.976	0.948
CO	Portis	1982	2895	39	106	279	4.74								1.000	0.999	1.003	0.967	1.008	1.008	1.021
CO	Portis	1983	2895	39	106	279	5								1.000	0.999	1.004	0.969	1.009	1.009	1.040
CO	Rocky Ford	1997	1274	38	104	279	9.44								1.000	0.999	0.999	0.984	1.007	1.007	0.944
CO	Rocky Ford	1999	1274	38	104	279	11.37								1.000	0.999	0.999	0.981	1.007	1.007	0.924
CO	Wiggins	1997	1367	40.31	104.06	353	7.30	1.000	0.999	1.000	0.983	0.975	0.975	0.893	1.000	0.999	1.000	0.980	0.975	0.975	0.950
CO	Wiggins	1998	1367	40.31	104.06	353	7.67	1.000	0.999	1.000	0.984	0.975	0.975	0.897	1.000	0.999	1.000	0.982	0.975	0.975	0.954
CO	Yellow Jacket	1997	2252	37.00	109.00	406	7.60								1.000	0.999	1.000	0.976	0.997	0.997	0.989
CO	Yellow Jacket	1999	2252	37.00	109.00	406	7.70								1.000	0.999	1.001	0.978	0.999	0.999	0.961
FL	Lake Alfred	1998	46	28.03	80.89	1250	7.51	1.000	0.999	0.996	0.988	1.004	1.004	0.942	1.000	0.999	0.996	0.985	1.002	1.002	0.977
FL	Lake Alfred	1999	46	28.03	80.89	1250	6.12	1.000	0.999	0.997	0.987	1.004	1.004	0.924	1.000	0.999	0.996	0.985	1.003	1.003	0.949
FL	St. Pierce	1999	7	27.57	80.44	1422	5.81	1.000	0.999	0.997	0.990	1.005	1.005	0.960	1.000	0.999	0.996	0.986	1.003	1.003	0.992

Table F-7. Ratio of Daily ETr to Daily ASCE PM ETr, continued.

								YEARLY SUMMARY							GROWING SEASON						
State	Site	Year	Elevation (m)	Latitude	Longitude	Mean Annual Precip (mm)	Peak-Month Mean Daily ETr (ASCE PM) - mm	ASCE PM (YR)	ASCE PMD (YR)	ASCE PMDL (YR)	ASCE PMDR (YR)	ASCE PMrf (YR)	ETrs (YR)	1982 Kpen (YR)	ASCE PM (GS)	ASCE PMD (GS)	ASCE PMDL (GS)	ASCE PMDR (GS)	ASCE PMrf (GS)	ETrs (GS)	1982 Kpen (GS)
GA	Attapulgus	1997	37	30.76	84.485	1460	5.02	1.000	0.999	0.998	0.979	1.005	1.005	0.959	1.000	0.999	0.998	0.979	1.003	1.003	1.007
GA	Attapulgus	1998	37	30.76	84.485	1460	7.68	1.000	0.999	0.997	0.976	1.003	1.003	0.984	1.000	0.999	0.997	0.978	1.002	1.002	1.018
GA	Blairsville	1997	584.3	34.84	83.928	1307	4.85	1.000	0.999	1.001	0.962	1.009	1.009	0.993	1.000	0.999	1.001	0.965	1.007	1.007	1.051
GA	Blairsville	1998	584.3	34.84	83.928	1307	5.27	1.000	0.999	1.000	0.968	1.008	1.008	0.958	1.000	0.999	0.999	0.971	1.006	1.006	1.005
GA	Griffin	1997	281.9	33.26	84.284	1447	5.9	1.000	0.999	0.999	0.978	1.008	1.008	0.921	1.000	0.999	0.998	0.980	1.006	1.006	0.966
GA	Griffin	1998	281.9	33.26	84.284	1447	7.27	1.000	0.999	0.998	0.978	1.005	1.005	0.981	1.000	0.999	0.997	0.978	1.004	1.004	1.002
ID	Ashton	1997	1615	44.03	111.47	430	6.01	1.000	0.998	1.001	0.976	1.010	1.010	0.969	1.000	0.998	1.001	0.974	1.008	1.008	0.984
ID	Ashton	1998	1615	44.03	111.47	430	7.04	1.000	0.999	1.001	0.976	1.009	1.009	0.973	1.000	0.999	1.001	0.978	1.007	1.007	0.987
ID	Parma	1997	703	43.80	116.93	237	6.89	1.000	0.999	1.000	0.982	1.004	1.004	0.966	1.000	0.999	1.000	0.982	1.003	1.003	0.988
ID	Parma	1998	703	43.80	116.93	237	7.29	1.000	0.999	1.000	0.978	1.004	1.004	0.971	1.000	0.999	1.000	0.981	1.003	1.003	1.006
ID	Twin Falls	1997	1195	42.61	114.35	222	7.53	1.000	0.999	1.000	0.984	1.008	1.008	0.938	1.000	0.999	1.000	0.982	1.005	1.005	0.978
ID	Twin Falls	1998	1195	42.61	114.35	222	8.19	1.000	0.999	1.000	0.978	1.006	1.006	0.931	1.000	0.999	1.000	0.979	1.004	1.004	0.975
IL	Belleville	1999	133	38.52	89.88	974	5.76	1.000	0.999	0.999	0.983	1.007	1.007	0.980	1.000	0.999	0.998	0.975	1.003	1.003	1.049
IL	Bondville	1999	213	40.05	88.37	1008	5.66	1.000	0.999	0.999	0.983	1.010	1.010	0.944	1.000	0.999	0.998	0.977	1.006	1.006	0.996
IL	Monmouth	1999	229	40.92	90.73	942	5.87	1.000	0.999	0.999	0.984	1.011	1.011	0.953	1.000	0.999	0.998	0.976	1.007	1.007	1.016
MT	Creston	1997	899	48.19	114.13	390	4.84	1.000	0.999	1.002	0.958	1.009	1.009	0.978	1.000	0.999	1.002	0.964	1.007	1.007	1.017
MT	Creston	1998	899	48.19	114.13	390	5.78	1.000	0.999	1.001	0.965	1.007	1.007	0.961	1.000	0.999	1.001	0.972	1.005	1.005	1.009
MT	Ronan	1997	927	47.54	114.28	380	4.89	1.000	0.999	1.002	0.957	1.008	1.008	0.998	1.000	0.999	1.002	0.962	1.006	1.006	1.041
MT	Ronan	1998	927	47.54	114.28	380	5.42	1.000	0.999	1.001	0.961	1.006	1.006	0.993	1.000	0.999	1.001	0.968	1.004	1.004	1.047
MT	St. Ignatius	1997	896	47.31	114.10	360	5.40	1.000	0.999	1.002	0.962	1.008	1.008	0.956	1.000	0.999	1.001	0.967	1.007	1.007	1.006
MT	St. Ignatius	1998	896	47.31	114.10	360	6.43	1.000	0.999	1.001	0.968	1.005	1.005	0.936	1.000	0.999	1.000	0.975	1.004	1.004	0.989
NE	Champion	1997	1029	40.22	101.43	482	8.71	1.000	0.998	0.999	0.984	0.991	0.991	0.882	1.000	0.998	0.998	0.979	0.989	0.989	0.949
NE	Champion	1998	1029	40.22	101.43	482	8.19	1.000	0.998	0.999	0.981	0.990	0.990	0.876	1.000	0.999	0.998	0.980	0.988	0.988	0.939
NE	Clay Center	1997	552	40.31	98.08	685	6.69	1.000	0.998	0.999	0.979	0.995	0.995	0.921	1.000	0.999	0.998	0.975	0.993	0.993	0.986
NE	Clay Center	1998	552	40.31	98.08	685	6.52	1.000	0.998	0.999	0.976	0.994	0.994	0.925	1.000	0.999	0.998	0.976	0.992	0.992	0.973
NE	Mead	1997	366	41.08	96.30	743	6.50	1.000	0.999	0.999	0.976	0.993	0.993	0.921	1.000	0.999	0.998	0.974	0.992	0.992	0.978
NE	Mead	1998	366	41.08	96.30	743	5.54	1.000	0.999	0.999	0.975	0.993	0.993	0.926	1.000	0.999	0.998	0.974	0.992	0.992	0.977
NY	Ithaca	1997	123	42.45	76.45	914	4.44	1.000	0.999	1.001	0.954	1.013	1.013	0.971	1.000	0.999	1.001	0.961	1.010	1.010	1.032
NY	Ithaca	1998	123	42.45	76.45	914	4.39	1.000	0.999	1.001	0.957	1.011	1.011	0.970	1.000	0.999	1.000	0.962	1.008	1.008	1.036
NY	Valatie	1997	76	42.43	73.68	914	4.03	1.000	0.999	1.002	0.945	1.009	1.009	1.042	1.000	0.999	1.001	0.951	1.006	1.006	1.107
NY	Valatie	1998	76	42.43	73.68	914	4.14	1.000	0.999	1.001	0.950	1.008	1.008	1.014	1.000	0.999	1.001	0.955	1.006	1.006	1.069
NY	Willsboro	1998	43	44.38	73.38	762	4.24	1.000	0.999	1.001	0.953	1.011	1.011	0.962	1.000	0.999	1.001	0.958	1.008	1.008	1.029

Table F-7. Ratio of Daily ETr to Daily ASCE PM ETr, continued.

								YEARLY SUMMARY							GROWING SEASON						
State	Site	Year	Elevation (m)	Latitude	Longitude	Mean Annual Precip (mm)	Peak-Month Mean Daily ETr (ASCE PM) - mm	ASCE PM (YR)	ASCE PMD (YR)	ASCE PMDL (YR)	ASCE PMDR (YR)	ASCE PMrf (YR)	ETrs (YR)	1982 Kpen (YR)	ASCE PM (GS)	ASCE PMD (GS)	ASCE PMDL (GS)	ASCE PMDR (GS)	ASCE PMrf (GS)	ETrs (GS)	1982 Kpen (GS)
OK	Apache	1997	440	34.91	98.29	757	8.36	1.000	0.998	0.998	0.987	0.991	0.991	0.920	1.000	0.998	0.996	0.982	0.989	0.989	0.986
OK	Apache	1998	440	34.91	98.29	757	11.47	1.000	0.999	0.996	0.988	0.985	0.985	0.882	1.000	0.999	0.995	0.987	0.981	0.981	0.908
OK	Goodwell	1997	996	36.60	101.60	447	12.07	1.000	0.998	0.998	0.989	0.989	0.989	0.878	1.000	0.999	0.997	0.984	0.986	0.986	0.934
OK	Goodwell	1998	996	36.60	101.60	447	14.03	1.000	0.998	0.998	0.991	0.986	0.986	0.858	1.000	0.998	0.996	0.987	0.983	0.983	0.894
OK	Marena	1997	331	36.06	97.21	889	6.67	1.000	0.999	0.998	0.983	0.991	0.991	0.917	1.000	0.999	0.997	0.979	0.990	0.990	0.993
OK	Marena	1998	331	36.06	97.21	889	8.64	1.000	0.999	0.997	0.983	0.986	0.986	0.908	1.000	0.999	0.995	0.982	0.983	0.983	0.955
OK	Wister	1997	143	34.98	94.68	1188	5.59	1.000	0.999	0.999	0.971	0.994	0.994	0.985	1.000	0.999	0.998	0.971	0.993	0.993	1.056
OK	Wister	1998	143	34.98	94.68	1188	7.40	1.000	0.999	0.997	0.979	0.988	0.988	0.949	1.000	0.999	0.996	0.980	0.986	0.986	0.998
OR	Haga	1999	9	42.50	124.50	1778	3.33	1.000	1.000	1.004	0.935	1.009	1.009	1.000	1.000	1.000	1.004	0.949	1.008	1.008	1.015
SC	Florence	1986	40	34.24	79.81	1120	7.05	1.000	0.999	0.998	0.978	1.006	1.006	0.925	1.000	0.999	0.997	0.980	1.004	1.004	0.976
TX	Bushland	1997	1170	35.11	102.05	505	9.88	1.000	0.998	0.998	0.988	1.004	1.004	0.902	1.000	0.998	0.997	0.983	1.000	1.000	0.967
TX	Bushland	1998	1170	35.11	102.05	505	13.27	1.000	0.998	0.998	0.989	1.001	1.001	0.887	1.000	0.998	0.997	0.988	0.999	0.999	0.916
TX	Dalhart	1997	1228	36.20	102.32	467	8.33	1.000	0.998	0.999	0.986	1.005	1.005	0.904	1.000	0.999	0.999	0.985	1.003	1.003	0.940
TX	Dalhart	1998	1228	36.20	102.32	467	10.96	1.000	0.999	0.999	0.986	1.003	1.003	0.887	1.000	0.999	0.998	0.985	1.001	1.001	0.923
UT	Logan	1989	1350	41.60	111.80	433	7.69								1.000	0.999	1.000	0.980	1.003	1.003	0.990
UT	Logan	1990	1350	41.60	111.80	433	7.06								1.000	0.999	1.000	0.978	1.003	1.003	1.013
WA	Gramling	1998	386	46.29	119.73	178	10.21								1.000	0.999	0.998	0.986	0.991	0.991	0.951
WA	Grayland	1998	2	46.78	124.00	2032	2.96								1.000	0.999	1.002	0.963	1.025	1.025	1.118
WA	Paterson	1998	109	45.94	119.49	152	8.65								1.000	0.999	0.998	0.985	0.992	0.992	0.993
WA	Puyallup	1998	61	47.10	122.30	1016	3.92								1.000	0.999	1.001	0.951	1.000	1.000	1.050
WA	Roza	1998	343	46.29	119.73	178	7.40								1.000	0.999	0.999	0.983	0.992	0.992	0.989
	Average							1.000	0.999	0.999	0.977	0.999	0.999	0.939	1.000	0.999	0.999	0.977	0.998	0.998	0.988
	Minimum							1.000	0.998	0.995	0.935	0.974	0.974	0.858	1.000	0.998	0.994	0.949	0.974	0.974	0.892
	Maximum							1.000	1.000	1.004	0.996	1.013	1.013	1.042	1.000	1.000	1.004	0.993	1.025	1.025	1.118

Table F-8. Ratio of Hourly Sum ETr to Daily ETr (within method)

State	Site	Year	Elevation (m)	Latitude	Longitude	Mean Annual Precip (mm)	Peak-Month Mean Daily ETr (ASCE PM) - mm	YEARLY SUMMARY								GROWING SEASON							
								ASCE PM (YR)	ASCE PMD (YR)	ASCE PMDL (YR)	ASCE PMDR (YR)	ASCE PMrf (YR)	ASCE PMrfh (YR)	ETrs (YR)	1982 Kpen (YR)	ASCE PM (GS)	ASCE PMD (GS)	ASCE PMDL (GS)	ASCE PMDR (GS)	ASCE PMrf (GS)	ASCE PMrfh (GS)	ETrs (GS)	1982 Kpen (GS)
AZ	Phoenix	1997	335	33.48	112.10	175	9.50	0.976	1.004	1.001	0.998	1.002	1.051	1.031	1.003	0.975	1.001	0.998	0.996	1.002	1.049	1.028	0.998
AZ	Phoenix	1998	335	33.48	112.10	175	9.67	0.966	1.000	0.997	0.993	0.990	1.041	1.024	0.996	0.969	1.000	0.997	0.995	0.994	1.043	1.025	0.993
AZ	Tucson	1997	713	32.28	110.94	300	11.37	0.957	0.982	0.979	0.974	0.983	1.052	1.009	0.997	0.973	0.995	0.992	0.989	1.001	1.067	1.023	0.999
AZ	Tucson	1998	713	32.28	110.94	300	10.93	0.948	0.982	0.978	0.974	0.972	1.039	1.007	0.989	0.970	1.001	0.998	0.996	0.995	1.060	1.028	0.994
CA	Davis	1998	18	38.50	121.80	461	8.55	0.905	0.975	0.973	0.973	0.922	1.010	0.994	0.953	0.912	0.979	0.977	0.976	0.930	1.016	0.998	0.953
CA	Fresno	1998	103	36.80	119.70	269	9.09	0.945	0.993	0.991	0.990	0.962	1.032	1.011	0.970	0.955	0.998	0.995	0.994	0.973	1.040	1.016	0.970
CA	Santa Maria	1998	82	35.00	120.40	314	5.11	0.905	0.991	0.989	0.984	0.911	0.994	0.998	0.978	0.930	1.024	1.021	1.018	0.940	1.023	1.034	0.986
CO	Center	1997	2348	38.00	106.00	178	7.24									0.934	0.995	0.993	0.988	0.945	1.028	1.006	0.968
CO	Center	1999	2348	38.00	106.00	178	7.73									0.930	0.994	0.992	0.986	0.940	1.034	1.005	0.977
CO	Colton	1982	2743	39.00	106.00	279	5.85																
CO	Colton	1983	2743	39.00	106.00	279	5.91																
CO	Fort Collins	1995	1527	40.60	105.00	383	6.76																
CO	Fruita	1997	1274	38.00	104.00	228	10.45									0.954	1.007	1.004	0.992	0.952	1.010	1.005	0.999
CO	Fruita	1999	1274	38.00	104.00	228	9.06									0.964	1.006	1.003	0.991	0.962	1.011	1.004	0.997
CO	Loveland	1997	1540	40.40	105.11	406	6.68	0.967	0.999	0.997	0.992	0.978	1.036	1.010	0.997	0.975	1.005	1.003	0.999	0.986	1.037	1.016	0.984
CO	Loveland	1998	1540	40.40	105.11	406	6.45	0.965	0.995	0.993	0.989	0.979	1.037	1.010	0.993	0.979	1.013	1.010	1.008	0.993	1.045	1.027	0.988
CO	Ovid	1998	1089	40.97	102.45	448	7.12	0.896	0.953	0.951	0.949	0.914	1.007	0.973	0.968	0.942	1.000	0.997	0.997	0.961	1.045	1.020	0.981
CO	Ovid	1999	1089	40.97	102.45	448	7.55	0.885	0.947	0.945	0.943	0.903	1.001	0.967	0.960	0.934	1.001	0.999	1.000	0.951	1.040	1.019	0.971
CO	Portis	1982	2895	39	106	279	4.74																
CO	Portis	1983	2895	39	106	279	5																
CO	Rocky Ford	1997	1274	38	104	279	9.44									1.013	1.041	1.038	1.022	1.007	1.046	1.035	1.042
CO	Rocky Ford	1999	1274	38	104	279	11.37									1.001	1.022	1.019	1.007	0.996	1.030	1.017	1.054
CO	Wiggins	1997	1367	40.31	104.06	353	7.30	0.907	0.954	0.951	0.946	0.925	1.009	0.973	0.970	0.928	0.973	0.970	0.967	0.946	1.022	0.992	0.965
CO	Wiggins	1998	1367	40.31	104.06	353	7.67	0.903	0.956	0.954	0.949	0.921	1.001	0.976	0.964	0.932	0.984	0.981	0.978	0.951	1.024	1.003	0.967
CO	Yellow Jacke	1997	2252	37.00	109.00	406	7.60									0.932	0.981	0.979	0.977	0.955	1.024	1.005	0.991
CO	Yellow Jacke	1999	2252	37.00	109.00	406	7.70									0.944	0.999	0.997	0.995	0.942	0.993	0.997	0.999
FL	Lake Alfred	1998	46	28.03	80.89	1250	7.51	0.872	0.928	0.925	0.924	0.868	0.924	0.923	0.920	0.889	0.939	0.936	0.936	0.884	0.935	0.934	0.919
FL	Lake Alfred	1999	46	28.03	80.89	1250	6.12	0.877	0.928	0.925	0.922	0.872	0.923	0.922	0.944	0.887	0.935	0.933	0.930	0.882	0.931	0.930	0.945
FL	St. Pierce	1999	7	27.57	80.44	1422	5.81	0.944	1.015	1.012	0.994	0.940	1.019	1.010	0.994	0.945	1.016	1.014	1.001	0.941	1.020	1.012	0.988

Table F-8. Ratio of Hourly Sum ETr to Daily ETr (within method), continued.

								YEARLY SUMMARY								GROWING SEASON							
State	Site	Year	Elevation (m)	Latitude	Longitude	Mean Annual Precip (mm)	Peak-Month Mean Daily ETr (ASCE PM) - mm	ASCE PM (YR)	ASCE PMD (YR)	ASCE PMDL (YR)	ASCE PMDR (YR)	ASCE PMrf (YR)	ASCE PMrfh (YR)	ETrs (YR)	1982 Kpen (YR)	ASCE PM (GS)	ASCE PMD (GS)	ASCE PMDL (GS)	ASCE PMDR (GS)	ASCE PMrf (GS)	ASCE PMrfh (GS)	ETrs (GS)	1982 Kpen (GS)
GA	Attapulgus	1997	37	30.76	84.485	1460	5.02	0.873	0.925	0.923	0.924	0.869	0.924	0.921	0.922	0.891	0.940	0.938	0.939	0.887	0.938	0.936	0.918
GA	Attapulgus	1998	37	30.76	84.485	1460	7.68	0.875	0.925	0.922	0.926	0.870	0.924	0.920	0.917	0.887	0.935	0.932	0.935	0.883	0.933	0.930	0.912
GA	Blairsville	1997	584	34.84	83.928	1307	4.85	0.926	0.971	0.968	0.970	0.921	0.971	0.965	0.950	0.954	0.999	0.996	0.998	0.949	0.997	0.993	0.952
GA	Blairsville	1998	584	34.84	83.928	1307	5.27	0.885	0.941	0.939	0.942	0.880	0.940	0.936	0.934	0.902	0.959	0.956	0.959	0.898	0.957	0.954	0.932
GA	Griffin	1997	282	33.26	84.284	1447	5.9	0.869	0.919	0.917	0.916	0.866	0.918	0.915	0.934	0.884	0.936	0.935	0.934	0.880	0.933	0.933	0.934
GA	Griffin	1998	282	33.26	84.284	1447	7.27	0.896	0.947	0.944	0.947	0.892	0.945	0.942	0.942	0.904	0.955	0.953	0.954	0.900	0.953	0.951	0.944
ID	Ashton	1997	1615	44.03	111.47	430	6.01	0.933	0.992	0.990	0.985	0.942	1.042	1.002	0.979	0.936	0.993	0.991	0.990	0.947	1.043	1.004	0.974
ID	Ashton	1998	1615	44.03	111.47	430	7.04	0.898	0.963	0.961	0.958	0.906	0.993	0.972	0.941	0.903	0.966	0.963	0.961	0.912	0.995	0.975	0.938
ID	Parma	1997	703	43.80	116.93	237	6.89	0.954	0.994	0.991	0.991	0.968	1.035	1.008	0.982	0.959	0.995	0.992	0.992	0.973	1.037	1.009	0.980
ID	Parma	1998	703	43.80	116.93	237	7.29	0.951	0.993	0.990	0.992	0.962	1.030	1.005	0.982	0.958	1.003	1.000	1.001	0.970	1.032	1.015	0.981
ID	Twin Falls	1997	1195	42.61	114.35	222	7.53	0.918	0.959	0.957	0.953	0.929	1.017	0.970	0.963	0.930	0.968	0.965	0.963	0.942	1.021	0.980	0.961
ID	Twin Falls	1998	1195	42.61	114.35	222	8.19	0.911	0.946	0.944	0.943	0.923	1.008	0.959	0.957	0.923	0.963	0.961	0.960	0.936	1.012	0.977	0.956
IL	Belleville	1999	133	38.52	89.88	974	5.76	0.994	1.044	1.042	1.034	0.989	1.041	1.040	1.028	1.011	1.065	1.062	1.060	1.007	1.062	1.061	1.022
IL	Bondville	1999	213	40.05	88.37	1008	5.66	0.936	0.999	0.997	0.993	0.931	0.991	0.995	1.008	0.962	1.032	1.029	1.030	0.958	1.026	1.027	1.020
IL	Monmouth	1999	229	40.92	90.73	942	5.87	0.916	0.964	0.962	0.958	0.912	0.957	0.959	0.968	0.939	1.000	0.997	0.998	0.935	0.996	0.995	0.974
MT	Creston	1997	899	48.19	114.13	390	4.84	0.949	1.017	1.015	1.022	0.957	1.035	1.025	0.987	0.961	1.026	1.024	1.028	0.968	1.042	1.034	0.986
MT	Creston	1998	899	48.19	114.13	390	5.78	0.947	1.005	1.003	1.010	0.957	1.029	1.015	0.983	0.956	1.019	1.016	1.019	0.966	1.031	1.029	0.977
MT	Ronan	1997	927	47.54	114.28	380	4.89	0.977	1.029	1.027	1.035	0.985	1.051	1.037	1.004	0.987	1.038	1.035	1.039	0.994	1.053	1.045	0.999
MT	Ronan	1998	927	47.54	114.28	380	5.42	0.978	1.021	1.019	1.025	0.987	1.045	1.031	0.995	0.987	1.034	1.031	1.033	0.996	1.047	1.044	0.988
MT	St. Ignatius	1997	896	47.31	114.10	360	5.40	0.945	0.979	0.977	0.980	0.954	1.016	0.988	0.967	0.954	0.992	0.990	0.990	0.962	1.017	1.000	0.965
MT	St. Ignatius	1998	896	47.31	114.10	360	6.43	0.924	0.937	0.935	0.935	0.937	0.995	0.949	0.945	0.927	0.950	0.947	0.945	0.939	0.990	0.961	0.938
NE	Champion	1997	1029	40.22	101.43	482	8.71	0.899	0.963	0.960	0.955	0.916	1.022	0.981	0.969	0.926	0.993	0.990	0.989	0.944	1.037	1.012	0.968
NE	Champion	1998	1029	40.22	101.43	482	8.19	0.883	0.941	0.938	0.933	0.900	0.997	0.959	0.954	0.914	0.976	0.973	0.970	0.932	1.021	0.995	0.961
NE	Clay Center	1997	552	40.31	98.08	685	6.69	0.880	0.959	0.957	0.956	0.893	1.000	0.973	0.958	0.920	1.002	1.000	1.002	0.933	1.029	1.017	0.966
NE	Clay Center	1998	552	40.31	98.08	685	6.52	0.857	0.935	0.933	0.934	0.870	0.969	0.949	0.930	0.892	0.966	0.964	0.965	0.906	0.996	0.981	0.941
NE	Mead	1997	366	41.08	96.30	743	6.50	0.919	0.992	0.990	0.988	0.934	1.042	1.008	0.992	0.942	1.018	1.016	1.016	0.957	1.053	1.034	0.989
NE	Mead	1998	366	41.08	96.30	743	5.54	0.904	0.966	0.964	0.962	0.918	1.014	0.981	0.972	0.926	0.991	0.990	0.990	0.939	1.026	1.006	0.975
NY	Ithaca	1997	123	42.45	76.45	914	4.44	0.976	1.035	1.034	1.040	0.971	1.041	1.031	1.021	0.989	1.061	1.059	1.063	0.984	1.061	1.056	1.018
NY	Ithaca	1998	123	42.45	76.45	914	4.39	0.977	1.037	1.035	1.039	0.972	1.041	1.033	1.020	0.989	1.060	1.057	1.059	0.985	1.060	1.055	1.012
NY	Valatie	1997	76	42.43	73.68	914	4.03	1.028	1.061	1.059	1.070	1.023	1.060	1.057	1.037	1.042	1.076	1.074	1.079	1.037	1.072	1.072	1.028
NY	Valatie	1998	76	42.43	73.68	914	4.14	1.006	1.051	1.048	1.060	1.002	1.051	1.047	1.024	1.016	1.062	1.059	1.065	1.013	1.060	1.058	1.011
NY	Willsboro	1998	43	44.38	73.38	762	4.24	0.985	1.018	1.016	1.023	0.982	1.024	1.015	1.012	0.995	1.036	1.034	1.037	0.992	1.038	1.033	1.004

Table F-8. Ratio of Hourly Sum ETr to Daily ETr (within method), continued.

State	Site	Year	Elevation (m)	Latitude	Longitude	Mean Annual Precip (mm)	Peak-Month Mean Daily ETr (ASCE PM) - mm	YEARLY SUMMARY								GROWING SEASON							
								ASCE PM (YR)	ASCE PMD (YR)	ASCE PMDL (YR)	ASCE PMDR (YR)	ASCE PMrf (YR)	ASCE PMrfh (YR)	ETrs (YR)	1982 Kpen (YR)	ASCE PM (GS)	ASCE PMD (GS)	ASCE PMDL (GS)	ASCE PMDR (GS)	ASCE PMrf (GS)	ASCE PMrfh (GS)	ETrs (GS)	1982 Kpen (GS)
OK	Apache	1997	440	34.91	98.29	757	8.36	0.904	0.953	0.951	0.949	0.920	1.028	0.971	0.971	0.930	0.985	0.982	0.983	0.947	1.043	1.003	0.974
OK	Apache	1998	440	34.91	98.29	757	11.47	0.916	0.955	0.953	0.952	0.938	1.035	0.979	0.977	0.937	0.971	0.969	0.969	0.962	1.048	0.998	0.982
OK	Goodwell	1997	996	36.60	101.60	447	12.07	0.885	0.933	0.931	0.925	0.904	1.013	0.954	0.950	0.902	0.954	0.952	0.950	0.924	1.022	0.976	0.945
OK	Goodwell	1998	996	36.60	101.60	447	14.03	0.887	0.927	0.924	0.918	0.908	1.015	0.950	0.955	0.912	0.948	0.945	0.943	0.936	1.033	0.974	0.958
OK	Marena	1997	331	36.06	97.21	889	6.67	0.923	0.982	0.979	0.982	0.939	1.036	0.999	0.998	0.947	1.008	1.005	1.007	0.963	1.049	1.025	0.993
OK	Marena	1998	331	36.06	97.21	889	8.64	0.934	0.982	0.979	0.983	0.955	1.044	1.004	0.996	0.950	0.994	0.992	0.995	0.973	1.051	1.018	0.991
OK	Wister	1997	143	34.98	94.68	1188	5.59	1.015	1.062	1.059	1.068	1.025	1.093	1.073	1.057	1.020	1.068	1.065	1.071	1.028	1.084	1.077	1.023
OK	Wister	1998	143	34.98	94.68	1188	7.40	1.021	1.069	1.066	1.072	1.039	1.113	1.088	1.061	1.026	1.079	1.075	1.079	1.044	1.108	1.098	1.052
OR	Haga	1999	9	42.50	124.50	1778	3.33																
SC	Florence	1986	40	34.24	79.81	1120	7.05	0.957	0.989	0.987	0.988	0.975	1.045	1.008	1.005	0.966	1.003	1.000	1.000	0.984	1.049	1.022	1.002
TX	Bushland	1997	1170	35.11	102.05	505	9.88	0.859	0.904	0.903	0.896	0.875	0.985	0.921	0.921	0.882	0.936	0.934	0.932	0.899	0.997	0.953	0.925
TX	Bushland	1998	1170	35.11	102.05	505	13.27	0.870	0.910	0.908	0.902	0.889	0.994	0.930	0.927	0.891	0.929	0.927	0.924	0.912	1.013	0.951	0.933
TX	Dalhart	1997	1228	36.20	102.32	467	8.33	0.873	0.944	0.942	0.935	0.868	0.934	0.940	0.950	0.886	0.955	0.952	0.948	0.881	0.944	0.950	0.946
TX	Dalhart	1998	1228	36.20	102.32	467	10.96	0.882	0.948	0.945	0.942	0.877	0.937	0.943	0.952	0.903	0.965	0.962	0.961	0.898	0.953	0.960	0.954
UT	Logan	1989	1350	41.60	111.80	433	7.69									0.943	0.987	0.983	0.981	0.955	1.021	0.999	0.961
UT	Logan	1990	1350	41.60	111.80	433	7.06									0.935	0.987	0.984	0.982	0.944	1.006	0.997	0.951
WA	Gramling	1998	386	46.29	119.73	178	10.21									0.875	0.900	0.899	0.897	0.895	0.979	0.921	0.910
WA	Grayland	1998	2	46.78	124.00	2032	2.96									0.931	1.048	1.047	1.048	0.915	1.017	1.030	1.003
WA	Paterson	1998	109	45.94	119.49	152	8.65									0.922	0.973	0.970	0.970	0.939	1.019	0.991	0.951
WA	Puyallup	1998	61	47.10	122.30	1016	3.92									1.011	1.073	1.070	1.077	1.019	1.077	1.081	1.024
WA	Roza	1998	343	46.29	119.73	178	7.40									0.958	0.994	0.991	0.991	0.976	1.041	1.012	0.980
	Average							0.926	0.977	0.975	0.974	0.936	1.010	0.987	0.975	0.944	0.996	0.993	0.992	0.953	1.022	1.005	0.976
	Minimum							0.857	0.904	0.903	0.896	0.866	0.918	0.915	0.917	0.875	0.900	0.899	0.897	0.880	0.931	0.921	0.910
	Maximum							1.028	1.069	1.066	1.072	1.039	1.113	1.088	1.061	1.042	1.079	1.075	1.079	1.044	1.108	1.098	1.054

Table F-9. Ratio of Hourly Sum ETr to Daily ASCE-PM ETr

								YEARLY SUMMARY								GROWING SEASON							
State	Site	Year	Elevation (m)	Latitude	Longitude	Mean Annual Precip (mm)	Peak-Month Mean Daily ETr (ASCE PM) - mm	ASCE PM (YR)	ASCE PMD (YR)	ASCE PMDL (YR)	ASCE PMDR (YR)	ASCE PMrf (YR)	ASCE PMrfh (YR)	ETrs (YR)	1982 Kpen (YR)	ASCE PM (GS)	ASCE PMD (GS)	ASCE PMDL (GS)	ASCE PMDR (GS)	ASCE PMrf (GS)	ASCE PMrfh (GS)	ETrs (GS)	1982 Kpen (GS)
AZ	Phoenix	1997	335	33.48	112.10	175	9.50	0.976	1.003	0.996	0.994	0.986	1.034	1.014	0.951	0.975	1.000	0.992	0.988	0.985	1.031	1.009	0.971
AZ	Phoenix	1998	335	33.48	112.10	175	9.67	0.966	0.999	0.993	0.988	0.976	1.026	1.010	0.950	0.969	0.999	0.992	0.986	0.979	1.027	1.009	0.972
AZ	Tucson	1997	713	32.28	110.94	300	11.37	0.957	0.981	0.976	0.967	0.970	1.037	0.995	0.855	0.973	0.994	0.987	0.981	0.986	1.051	1.007	0.891
AZ	Tucson	1998	713	32.28	110.94	300	10.93	0.948	0.981	0.975	0.967	0.961	1.026	0.994	0.867	0.970	1.000	0.994	0.986	0.982	1.046	1.013	0.908
CA	Davis	1998	18	38.50	121.80	461	8.55	0.905	0.974	0.972	0.961	0.912	0.999	0.982	0.916	0.912	0.978	0.975	0.965	0.919	1.004	0.985	0.928
CA	Fresno	1998	103	36.80	119.70	269	9.09	0.945	0.992	0.989	0.976	0.951	1.021	0.999	0.934	0.955	0.996	0.992	0.982	0.961	1.027	1.003	0.955
CA	Santa Maria	1998	82	35.00	120.40	314	5.11	0.905	0.990	0.990	0.970	0.911	0.995	0.997	0.938	0.930	1.023	1.021	1.000	0.936	1.018	1.029	1.003
CO	Center	1997	2348	38.00	106.00	178	7.24									0.934	0.993	0.994	0.965	0.946	1.030	1.006	0.942
CO	Center	1999	2348	38.00	106.00	178	7.73									0.930	0.993	0.994	0.968	0.942	1.037	1.006	0.953
CO	Colton	1982	2743	39.00	106.00	279	5.85																
CO	Colton	1983	2743	39.00	106.00	279	5.91																
CO	Fort Collins	1995	1527	40.60	105.00	383	6.76																
CO	Fruita	1997	1274	38.00	104.00	228	10.45									0.954	1.006	1.003	0.978	0.947	1.005	0.999	0.966
CO	Fruita	1999	1274	38.00	104.00	228	9.06									0.964	1.005	1.002	0.971	0.957	1.006	0.997	0.947
CO	Loveland	1997	1540	40.40	105.11	406	6.68	0.967	0.998	0.998	0.967	0.980	1.038	1.011	0.949	0.975	1.004	1.003	0.971	0.986	1.037	1.015	0.991
CO	Loveland	1998	1540	40.40	105.11	406	6.45	0.965	0.994	0.994	0.965	0.980	1.038	1.009	0.929	0.979	1.012	1.010	0.979	0.992	1.043	1.025	0.984
CO	Ovid	1998	1089	40.97	102.45	448	7.12	0.896	0.952	0.950	0.935	0.890	0.981	0.946	0.858	0.942	0.999	0.996	0.979	0.936	1.018	0.993	0.935
CO	Ovid	1999	1089	40.97	102.45	448	7.55	0.885	0.946	0.945	0.928	0.880	0.975	0.941	0.842	0.934	1.000	0.997	0.976	0.929	1.016	0.995	0.942
CO	Portis	1982	2895	39.00	106.00	279	4.74																
CO	Portis	1983	2895	39.00	106.00	279	5																
CO	Rocky Ford	1997	1274	38.00	104.00	279	9.44									1.013	1.040	1.037	1.005	1.014	1.054	1.041	0.984
CO	Rocky Ford	1999	1274	38.00	104.00	279	11.37									1.001	1.021	1.018	0.987	1.003	1.038	1.024	0.974
CO	Wiggins	1997	1367	40.31	104.06	353	7.30	0.907	0.952	0.952	0.930	0.902	0.983	0.947	0.866	0.928	0.972	0.970	0.948	0.923	0.996	0.966	0.916
CO	Wiggins	1998	1367	40.31	104.06	353	7.67	0.903	0.955	0.954	0.934	0.898	0.975	0.950	0.865	0.932	0.983	0.981	0.961	0.927	0.998	0.977	0.922
CO	Yellow Jacke	1997	2252	37.00	109.00	406	7.60									0.932	0.980	0.979	0.954	0.952	1.022	1.001	0.980
CO	Yellow Jacke	1999	2252	37.00	109.00	406	7.70									0.944	0.998	0.998	0.973	0.941	0.992	0.995	0.960
FL	Lake Alfred	1998	46	28.03	80.89	1250	7.51	0.872	0.927	0.922	0.912	0.871	0.927	0.925	0.866	0.889	0.938	0.932	0.922	0.886	0.937	0.936	0.898
FL	Lake Alfred	1999	46	28.03	80.89	1250	6.12	0.877	0.927	0.922	0.910	0.875	0.927	0.925	0.872	0.887	0.935	0.929	0.916	0.885	0.933	0.932	0.897
FL	St. Pierce	1999	7	27.57	80.44	1422	5.81	0.944	1.014	1.009	0.984	0.944	1.024	1.014	0.954	0.945	1.015	1.010	0.987	0.944	1.024	1.014	0.981

Table F-9. Ratio of Hourly Sum ETr to Daily ASCE-PM ETr, continued.

								YEARLY SUMMARY								GROWING SEASON							
State	Site	Year	Elevation (m)	Latitude	Longitude	Mean Annual Precip (mm)	Peak-Month Mean Daily ETr (ASCE PM) - mm	ASCE PM (YR)	ASCE PMD (YR)	ASCE PMDL (YR)	ASCE PMDR (YR)	ASCE PMrf (YR)	ASCE PMrfh (YR)	ETrs (YR)	1982 Kpen (YR)	ASCE PM (GS)	ASCE PMD (GS)	ASCE PMDL (GS)	ASCE PMDR (GS)	ASCE PMrf (GS)	ASCE PMrfh (GS)	ETrs (GS)	1982 Kpen (GS)
GA	Attapulgus	1997	37	30.76	84.49	1460	5.02	0.873	0.925	0.922	0.904	0.873	0.929	0.925	0.884	0.891	0.939	0.936	0.919	0.890	0.941	0.938	0.925
GA	Attapulgus	1998	37	30.76	84.49	1460	7.68	0.875	0.924	0.920	0.904	0.873	0.927	0.923	0.902	0.887	0.934	0.929	0.914	0.885	0.935	0.932	0.928
GA	Blairsville	1997	584	34.84	83.93	1307	4.85	0.926	0.970	0.970	0.934	0.930	0.980	0.974	0.943	0.954	0.999	0.997	0.964	0.955	1.004	1.000	1.001
GA	Blairsville	1998	584	34.84	83.93	1307	5.27	0.885	0.940	0.939	0.912	0.888	0.948	0.943	0.894	0.902	0.958	0.956	0.931	0.903	0.963	0.959	0.937
GA	Griffin	1997	282	33.26	84.28	1447	5.9	0.869	0.918	0.917	0.896	0.873	0.925	0.922	0.860	0.884	0.936	0.933	0.915	0.886	0.939	0.937	0.903
GA	Griffin	1998	282	33.26	84.28	1447	7.27	0.896	0.946	0.942	0.926	0.896	0.950	0.946	0.925	0.904	0.954	0.950	0.934	0.903	0.957	0.954	0.947
ID	Ashton	1997	1615	44.03	111.47	430	6.01	0.933	0.991	0.991	0.961	0.951	1.052	1.010	0.949	0.936	0.992	0.992	0.964	0.954	1.052	1.011	0.958
ID	Ashton	1998	1615	44.03	111.47	430	7.04	0.898	0.962	0.962	0.935	0.914	1.002	0.979	0.916	0.903	0.964	0.964	0.940	0.919	1.003	0.981	0.925
ID	Parma	1997	703	43.80	116.93	237	6.89	0.954	0.993	0.991	0.973	0.971	1.039	1.011	0.949	0.959	0.994	0.992	0.974	0.975	1.040	1.011	0.968
ID	Parma	1998	703	43.80	116.93	237	7.29	0.951	0.992	0.990	0.970	0.966	1.034	1.008	0.954	0.958	1.002	1.000	0.982	0.972	1.035	1.017	0.987
ID	Twin Falls	1997	1195	42.61	114.35	222	7.53	0.918	0.957	0.957	0.938	0.936	1.025	0.976	0.903	0.930	0.966	0.965	0.946	0.946	1.026	0.984	0.940
ID	Twin Falls	1998	1195	42.61	114.35	222	8.19	0.911	0.945	0.945	0.922	0.929	1.014	0.964	0.892	0.923	0.962	0.960	0.939	0.940	1.016	0.980	0.933
IL	Belleville	1999	133	38.52	89.88	974	5.76	0.994	1.043	1.041	1.016	0.996	1.048	1.046	1.008	1.011	1.064	1.060	1.033	1.009	1.064	1.063	1.072
IL	Bondville	1999	213	40.05	88.37	1008	5.66	0.936	0.998	0.996	0.977	0.941	1.001	1.003	0.952	0.962	1.031	1.028	1.006	0.963	1.032	1.032	1.016
IL	Monmouth	1999	229	40.92	90.73	942	5.87	0.916	0.962	0.961	0.943	0.922	0.967	0.968	0.923	0.939	0.998	0.996	0.974	0.941	1.002	1.001	0.990
MT	Creston	1997	899	48.19	114.13	390	4.84	0.949	1.015	1.017	0.980	0.965	1.045	1.033	0.965	0.961	1.025	1.025	0.990	0.975	1.049	1.040	1.002
MT	Creston	1998	899	48.19	114.13	390	5.78	0.947	1.004	1.004	0.975	0.963	1.036	1.021	0.945	0.956	1.018	1.017	0.991	0.971	1.037	1.034	0.985
MT	Ronan	1997	927	47.54	114.28	380	4.89	0.977	1.028	1.029	0.991	0.992	1.059	1.044	1.001	0.987	1.037	1.037	1.000	1.001	1.060	1.051	1.040
MT	Ronan	1998	927	47.54	114.28	380	5.42	0.978	1.020	1.020	0.985	0.993	1.052	1.036	0.988	0.987	1.033	1.032	0.999	1.000	1.051	1.047	1.034
MT	St. Ignatius	1997	896	47.31	114.10	360	5.40	0.945	0.978	0.979	0.942	0.962	1.024	0.995	0.924	0.954	0.991	0.991	0.957	0.968	1.024	1.005	0.971
MT	St. Ignatius	1998	896	47.31	114.10	360	6.43	0.924	0.936	0.935	0.905	0.942	1.000	0.953	0.885	0.927	0.949	0.947	0.922	0.942	0.993	0.964	0.928
NE	Champion	1997	1029	40.22	101.43	482	8.71	0.899	0.961	0.959	0.940	0.908	1.013	0.970	0.855	0.926	0.991	0.988	0.968	0.934	1.026	0.999	0.919
NE	Champion	1998	1029	40.22	101.43	482	8.19	0.883	0.940	0.938	0.915	0.891	0.987	0.948	0.836	0.914	0.975	0.971	0.951	0.920	1.009	0.982	0.903
NE	Clay Center	1997	552	40.31	98.08	685	6.69	0.880	0.957	0.956	0.936	0.889	0.995	0.966	0.882	0.920	1.001	0.998	0.976	0.927	1.021	1.008	0.952
NE	Clay Center	1998	552	40.31	98.08	685	6.52	0.857	0.933	0.931	0.911	0.865	0.963	0.941	0.860	0.892	0.965	0.962	0.942	0.898	0.988	0.972	0.916
NE	Mead	1997	366	41.08	96.30	743	6.50	0.919	0.991	0.989	0.965	0.928	1.035	1.000	0.913	0.942	1.017	1.014	0.989	0.949	1.045	1.024	0.967
NE	Mead	1998	366	41.08	96.30	743	5.54	0.904	0.965	0.963	0.938	0.911	1.007	0.973	0.900	0.926	0.990	0.987	0.964	0.932	1.017	0.997	0.953
NY	Ithaca	1997	123	42.45	76.45	914	4.44	0.976	1.034	1.035	0.992	0.984	1.055	1.043	0.991	0.989	1.060	1.060	1.021	0.994	1.072	1.066	1.051
NY	Ithaca	1998	123	42.45	76.45	914	4.39	0.977	1.036	1.035	0.994	0.983	1.053	1.043	0.989	0.989	1.059	1.057	1.019	0.993	1.068	1.062	1.048
NY	Valatie	1997	76	42.43	73.68	914	4.03	1.028	1.061	1.061	1.011	1.033	1.070	1.066	1.081	1.042	1.076	1.075	1.027	1.044	1.079	1.078	1.138
NY	Valatie	1998	76	42.43	73.68	914	4.14	1.006	1.050	1.050	1.007	1.011	1.060	1.055	1.038	1.016	1.061	1.060	1.017	1.018	1.066	1.063	1.081
NY	Willsboro	1998	43	44.38	73.38	762	4.24	0.985	1.017	1.018	0.974	0.993	1.035	1.025	0.974	0.995	1.035	1.035	0.993	0.999	1.046	1.040	1.034

Table F-9. Ratio of Hourly Sum ETr to Daily ASCE-PM ETr, continued.

State	Site	Year	Elevation (m)	Latitude	Longitude	Mean Annual Precip (mm)	Peak-Month Mean Daily ETr (ASCE PM) - mm	YEARLY SUMMARY ASCE PM (YR)	ASCE PMD (YR)	ASCE PMDL (YR)	ASCE PMDR (YR)	ASCE PMrf (YR)	ASCE PMrfh (YR)	ETrs (YR)	1982 Kpen (YR)	GROWING SEASON ASCE PM (GS)	ASCE PMD (GS)	ASCE PMDL (GS)	ASCE PMDR (GS)	ASCE PMrf (GS)	ASCE PMrfh (GS)	ETrs (GS)	1982 Kpen (GS)
OK	Apache	1997	440	34.91	98.29	757	8.36	0.904	0.952	0.949	0.937	0.912	1.019	0.961	0.893	0.930	0.983	0.978	0.965	0.937	1.032	0.991	0.960
OK	Apache	1998	440	34.91	98.29	757	11.47	0.916	0.954	0.949	0.941	0.924	1.019	0.963	0.882	0.937	0.970	0.963	0.957	0.944	1.029	0.978	0.908
OK	Goodwell	1997	996	36.60	101.60	447	12.07	0.885	0.932	0.930	0.915	0.894	1.002	0.942	0.834	0.902	0.952	0.948	0.936	0.911	1.008	0.961	0.883
OK	Goodwell	1998	996	36.60	101.60	447	14.03	0.887	0.925	0.922	0.910	0.895	1.001	0.934	0.819	0.912	0.947	0.942	0.932	0.920	1.015	0.955	0.856
OK	Marena	1997	331	36.06	97.21	889	6.67	0.923	0.980	0.978	0.965	0.931	1.027	0.989	0.913	0.947	1.007	1.002	0.986	0.953	1.038	1.013	0.985
OK	Marena	1998	331	36.06	97.21	889	8.64	0.934	0.981	0.976	0.966	0.941	1.029	0.988	0.905	0.950	0.993	0.987	0.976	0.956	1.033	1.000	0.947
OK	Wister	1997	143	34.98	94.68	1188	5.59	1.015	1.061	1.058	1.037	1.019	1.086	1.066	1.025	1.020	1.068	1.062	1.039	1.021	1.076	1.069	1.081
OK	Wister	1998	143	34.98	94.68	1188	7.40	1.021	1.069	1.066	1.072	1.039	1.113	1.088	1.061	1.026	1.079	1.075	1.079	1.044	1.108	1.098	1.052
OR	Haga	1999	9	42.50	124.50	1778	3.33																
SC	Florence	1986	40	34.24	79.81	1120	7.05	0.957	0.988	0.985	0.966	0.981	1.052	1.013	0.929	0.966	1.002	0.998	0.980	0.988	1.053	1.025	0.978
TX	Bushland	1997	1170	35.11	102.05	505	9.88	0.859	0.902	0.902	0.885	0.879	0.989	0.923	0.831	0.882	0.934	0.931	0.916	0.899	0.997	0.952	0.894
TX	Bushland	1998	1170	35.11	102.05	505	13.27	0.870	0.909	0.906	0.892	0.890	0.996	0.930	0.823	0.891	0.927	0.924	0.912	0.911	1.012	0.948	0.855
TX	Dalhart	1997	1228	36.20	102.32	467	8.33	0.873	0.943	0.941	0.922	0.872	0.938	0.943	0.859	0.886	0.953	0.951	0.934	0.884	0.947	0.951	0.889
TX	Dalhart	1998	1228	36.20	102.32	467	10.96	0.882	0.947	0.944	0.929	0.880	0.939	0.944	0.845	0.903	0.964	0.960	0.947	0.899	0.954	0.960	0.881
UT	Logan	1989	1350	41.60	111.80	433	7.69									0.943	0.986	0.984	0.961	0.958	1.024	1.001	0.952
UT	Logan	1990	1350	41.60	111.80	433	7.06									0.935	0.986	0.984	0.959	0.947	1.009	0.999	0.963
WA	Gramling	1998	386	46.29	119.73	178	10.21									0.875	0.899	0.897	0.885	0.886	0.970	0.911	0.865
WA	Grayland	1998	2	46.78	124.00	2032	2.96									0.931	1.047	1.049	1.009	0.938	1.043	1.055	1.121
WA	Paterson	1998	109	45.94	119.49	152	8.65									0.922	0.971	0.969	0.955	0.932	1.011	0.982	0.944
WA	Puyallup	1998	61	47.10	122.30	1016	3.92									1.011	1.072	1.071	1.024	1.019	1.077	1.080	1.075
WA	Roza	1998	343	46.29	119.73	178	7.40									0.958	0.993	0.990	0.974	0.968	1.033	1.003	0.969
	Average							0.926	0.976	0.974	0.952	0.935	1.009	0.984	0.917	0.944	0.995	0.992	0.970	0.951	1.020	1.002	0.963
	Minimum							0.857	0.902	0.902	0.885	0.865	0.925	0.922	0.819	0.875	0.899	0.897	0.885	0.884	0.933	0.911	0.855
	Maximum							1.028	1.069	1.066	1.072	1.039	1.113	1.088	1.081	1.042	1.079	1.075	1.079	1.044	1.108	1.098	1.138

Table F-10. Ratio of Hourly Sum ETr to Hourly Sum ASCE PMD ETr

								YEARLY SUMMARY								GROWING SEASON							
State	Site	Year	Elevation (m)	Latitude	Longitude	Mean Annual Precip (mm)	Peak-Month Mean Daily ETr (ASCE PM) - mm	ASCE PM (YR)	ASCE PMD (YR)	ASCE PMDL (YR)	ASCE PMDR (YR)	ASCE PMrf (YR)	ASCE PMrfh (YR)	ETrs (YR)	1982 Kpen (YR)	ASCE PM (GS)	ASCE PMD (GS)	ASCE PMDL (GS)	ASCE PMDR (GS)	ASCE PMrf (GS)	ASCE PMrfh (GS)	ETrs (GS)	1982 Kpen (GS)
AZ	Phoenix	1997	335	33.48	112.10	175	9.50	0.972	1.000	0.993	0.990	0.983	1.030	1.010	0.948	0.975	1.000	0.992	0.988	0.985	1.031	1.010	0.971
AZ	Phoenix	1998	335	33.48	112.10	175	9.67	0.967	1.000	0.994	0.989	0.977	1.027	1.010	0.951	0.970	1.000	0.993	0.987	0.979	1.028	1.010	0.973
AZ	Tucson	1997	713	32.28	110.94	300	11.37	0.975	1.000	0.995	0.986	0.989	1.057	1.014	0.872	0.979	1.000	0.993	0.987	0.992	1.057	1.013	0.896
AZ	Tucson	1998	713	32.28	110.94	300	10.93	0.967	1.000	0.995	0.986	0.980	1.047	1.014	0.884	0.969	1.000	0.993	0.986	0.982	1.046	1.013	0.908
CA	Davis	1998	18	38.50	121.80	461	8.55	0.929	1.000	0.998	0.987	0.936	1.026	1.008	0.941	0.933	1.000	0.997	0.987	0.940	1.027	1.008	0.949
CA	Fresno	1998	103	36.80	119.70	269	9.09	0.952	1.000	0.997	0.984	0.959	1.029	1.007	0.942	0.959	1.000	0.996	0.985	0.965	1.031	1.006	0.958
CA	Santa Maria	1998	82	35.00	120.40	314	5.11	0.913	1.000	0.999	0.979	0.920	1.004	1.007	0.947	0.910	1.000	0.999	0.978	0.916	0.996	1.006	0.981
CO	Center	1997	2348	38.00	106.00	178	7.24									0.940	1.000	1.001	0.972	0.952	1.036	1.013	0.948
CO	Center	1999	2348	38.00	106.00	178	7.73									0.936	1.000	1.001	0.975	0.949	1.044	1.013	0.960
CO	Colton	1982	2743	39.00	106.00	279	5.85																
CO	Colton	1983	2743	39.00	106.00	279	5.91																
CO	Fort Collins	1995	1527	40.60	105.00	383	6.76																
CO	Fruita	1997	1274	38.00	104.00	228	10.45									0.948	1.000	0.997	0.972	0.941	0.999	0.993	0.960
CO	Fruita	1999	1274	38.00	104.00	228	9.06									0.959	1.000	0.997	0.967	0.952	1.001	0.993	0.942
CO	Loveland	1997	1540	40.40	105.11	406	6.68	0.969	1.000	1.000	0.969	0.982	1.040	1.013	0.951	0.970	1.000	0.998	0.963	0.980	1.029	1.010	0.997
CO	Loveland	1998	1540	40.40	105.11	406	6.45	0.971	1.000	0.999	0.971	0.985	1.044	1.015	0.935	0.968	1.000	0.998	0.967	0.979	1.029	1.012	0.979
CO	Ovid	1998	1089	40.97	102.45	448	7.12	0.941	1.000	0.998	0.982	0.935	1.030	0.994	0.901	0.943	1.000	0.997	0.981	0.937	1.020	0.994	0.936
CO	Ovid	1999	1089	40.97	102.45	448	7.55	0.935	1.000	0.999	0.981	0.930	1.031	0.994	0.890	0.934	1.000	0.998	0.980	0.929	1.023	0.995	0.918
CO	Portis	1982	2895	39	106	279	4.74																
CO	Portis	1983	2895	39	106	279	5																
CO	Rocky Ford	1997	1274	38	104	279	9.44									0.974	1.000	0.997	0.966	0.976	1.014	1.001	0.946
CO	Rocky Ford	1999	1274	38	104	279	11.37									0.980	1.000	0.997	0.967	0.982	1.016	1.002	0.953
CO	Wiggins	1997	1367	40.31	104.06	353	7.30	0.952	1.000	0.999	0.976	0.947	1.033	0.995	0.910	0.954	1.000	0.998	0.973	0.949	1.023	0.995	0.952
CO	Wiggins	1998	1367	40.31	104.06	353	7.67	0.945	1.000	0.999	0.978	0.940	1.021	0.994	0.906	0.949	1.000	0.998	0.977	0.944	1.015	0.994	0.944
CO	Yellow Jacket	1997	2252	37.00	109.00	406	7.60									0.951	1.000	0.999	0.973	0.971	1.042	1.021	1.000
CO	Yellow Jacket	1999	2252	37.00	109.00	406	7.70									0.946	1.000	1.000	0.975	0.943	0.994	0.997	0.962
FL	Lake Alfred	1998	46	28.03	80.89	1250	7.51	0.941	1.000	0.994	0.984	0.940	1.001	0.999	0.935	0.947	1.000	0.993	0.982	0.945	0.999	0.997	0.957
FL	Lake Alfred	1999	46	28.03	80.89	1250	6.12	0.946	1.000	0.995	0.982	0.944	1.000	0.998	0.941	0.950	1.000	0.994	0.981	0.947	0.999	0.997	0.960
FL	St. Pierce	1999	7	27.57	80.44	1422	5.81	0.931	1.000	0.996	0.970	0.931	1.010	1.000	0.941	0.931	1.000	0.995	0.972	0.930	1.008	0.999	0.966

Table F-10. Ratio of Hourly Sum ETr to Hourly Sum ASCE PMD ETr, continued.

								YEARLY SUMMARY								GROWING SEASON							
State	Site	Year	Elevation (m)	Latitude	Longitude	Mean Annual Precip (mm)	Peak-Month Mean Daily ETr (ASCE PM) - mm	ASCE PM (YR)	ASCE PMD (YR)	ASCE PMDL (YR)	ASCE PMDR (YR)	ASCE PMrf (YR)	ASCE PMrfh (YR)	ETrs (YR)	1982 Kpen (YR)	ASCE PM (GS)	ASCE PMD (GS)	ASCE PMDL (GS)	ASCE PMDR (GS)	ASCE PMrf (GS)	ASCE PMrfh (GS)	ETrs (GS)	1982 Kpen (GS)
GA	Attapulgus	1997	37	30.76	84.485	1460	5.02	0.944	1.000	0.997	0.978	0.944	1.004	1.001	0.956	0.949	1.000	0.996	0.978	0.947	1.001	0.999	0.984
GA	Attapulgus	1998	37	30.76	84.485	1460	7.68	0.946	1.000	0.995	0.978	0.945	1.003	0.998	0.976	0.950	1.000	0.994	0.978	0.947	1.000	0.997	0.993
GA	Blairsville	1997	584.3	34.84	83.928	1307	4.85	0.955	1.000	0.999	0.962	0.958	1.010	1.004	0.972	0.956	1.000	0.999	0.965	0.957	1.006	1.001	1.002
GA	Blairsville	1998	584.3	34.84	83.928	1307	5.27	0.941	1.000	0.998	0.969	0.944	1.008	1.003	0.951	0.942	1.000	0.997	0.971	0.943	1.005	1.001	0.977
GA	Griffin	1997	281.9	33.26	84.284	1447	5.9	0.947	1.000	0.998	0.976	0.951	1.008	1.004	0.937	0.945	1.000	0.997	0.978	0.947	1.004	1.002	0.965
GA	Griffin	1998	281.9	33.26	84.284	1447	7.27	0.947	1.000	0.996	0.979	0.947	1.004	1.000	0.978	0.948	1.000	0.996	0.979	0.947	1.003	0.999	0.992
ID	Ashton	1997	1615	44.03	111.47	430	6.01	0.941	1.000	1.001	0.970	0.960	1.062	1.020	0.958	0.942	1.000	1.000	0.972	0.960	1.054	1.018	0.971
ID	Ashton	1998	1615	44.03	111.47	430	7.04	0.934	1.000	1.000	0.972	0.951	1.042	1.018	0.953	0.937	1.000	0.999	0.973	0.953	1.038	1.017	0.967
ID	Parma	1997	703	43.80	116.93	237	6.89	0.961	1.000	0.998	0.980	0.978	1.047	1.018	0.956	0.962	1.000	0.997	0.977	0.976	1.033	1.015	0.999
ID	Parma	1998	703	43.80	116.93	237	7.29	0.959	1.000	0.998	0.978	0.974	1.043	1.016	0.962	0.957	1.000	0.996	0.976	0.969	1.026	1.013	1.005
ID	Twin Falls	1997	1195	42.61	114.35	222	7.53	0.959	1.000	1.000	0.979	0.978	1.071	1.020	0.944	0.962	1.000	0.999	0.979	0.980	1.067	1.019	0.962
ID	Twin Falls	1998	1195	42.61	114.35	222	8.19	0.963	1.000	0.999	0.976	0.983	1.073	1.020	0.943	0.958	1.000	0.999	0.976	0.976	1.059	1.019	0.963
IL	Belleville	1999	133	38.52	89.88	974	5.76	0.952	1.000	0.998	0.974	0.954	1.004	1.002	0.966	0.950	1.000	0.996	0.971	0.949	1.000	0.999	1.007
IL	Bondville	1999	213	40.05	88.37	1008	5.66	0.938	1.000	0.999	0.979	0.943	1.003	1.005	0.954	0.933	1.000	0.997	0.976	0.934	1.001	1.001	0.985
IL	Monmouth	1999	229	40.92	90.73	942	5.87	0.952	1.000	0.999	0.979	0.958	1.005	1.006	0.959	0.940	1.000	0.997	0.975	0.943	1.004	1.002	0.991
MT	Creston	1997	899	48.19	114.13	390	4.84	0.935	1.000	1.001	0.965	0.951	1.029	1.017	0.951	0.936	1.000	1.001	0.967	0.951	1.027	1.016	0.973
MT	Creston	1998	899	48.19	114.13	390	5.78	0.943	1.000	1.000	0.971	0.959	1.032	1.017	0.941	0.937	1.000	1.000	0.973	0.952	1.018	1.016	0.963
MT	Ronan	1997	927	47.54	114.28	380	4.89	0.950	1.000	1.001	0.963	0.965	1.029	1.015	0.973	0.951	1.000	1.000	0.965	0.964	1.026	1.014	0.994
MT	Ronan	1998	927	47.54	114.28	380	5.42	0.958	1.000	1.000	0.965	0.973	1.031	1.015	0.969	0.953	1.000	0.999	0.967	0.966	1.017	1.014	0.993
MT	St. Ignatius	1997	896	47.31	114.10	360	5.40	0.967	1.000	1.001	0.964	0.984	1.047	1.017	0.946	0.963	1.000	1.001	0.966	0.978	1.039	1.016	0.965
MT	St. Ignatius	1998	896	47.31	114.10	360	6.43	0.988	1.000	1.000	0.967	1.006	1.069	1.019	0.946	0.975	1.000	0.999	0.971	0.991	1.046	1.016	0.973
NE	Champion	1997	1029	40.22	101.43	482	8.71	0.936	1.000	0.998	0.979	0.945	1.054	1.010	0.890	0.935	1.000	0.997	0.977	0.942	1.036	1.008	0.927
NE	Champion	1998	1029	40.22	101.43	482	8.19	0.940	1.000	0.998	0.974	0.948	1.050	1.009	0.889	0.937	1.000	0.997	0.976	0.944	1.035	1.007	0.926
NE	Clay Center	1997	552	40.31	98.08	685	6.69	0.919	1.000	0.999	0.977	0.928	1.039	1.009	0.921	0.919	1.000	0.997	0.976	0.926	1.021	1.008	0.952
NE	Clay Center	1998	552	40.31	98.08	685	6.52	0.918	1.000	0.998	0.976	0.926	1.032	1.009	0.922	0.924	1.000	0.997	0.976	0.931	1.024	1.007	0.949
NE	Mead	1997	366	41.08	96.30	743	6.50	0.928	1.000	0.998	0.974	0.937	1.045	1.009	0.922	0.927	1.000	0.997	0.973	0.934	1.028	1.008	0.951
NE	Mead	1998	366	41.08	96.30	743	5.54	0.937	1.000	0.998	0.972	0.945	1.044	1.008	0.933	0.935	1.000	0.997	0.973	0.941	1.027	1.007	0.962
NY	Ithaca	1997	123	42.45	76.45	914	4.44	0.943	1.000	1.000	0.959	0.951	1.020	1.008	0.959	0.934	1.000	0.999	0.961	0.939	1.010	1.005	0.998
NY	Ithaca	1998	123	42.45	76.45	914	4.39	0.943	1.000	1.000	0.960	0.949	1.016	1.006	0.955	0.935	1.000	0.998	0.962	0.938	1.008	1.003	0.998
NY	Valatie	1997	76	42.43	73.68	914	4.03	0.969	1.000	1.000	0.953	0.974	1.009	1.005	1.019	0.970	1.000	0.999	0.951	0.971	1.003	1.002	1.065
NY	Valatie	1998	76	42.43	73.68	914	4.14	0.958	1.000	0.999	0.959	0.962	1.009	1.004	0.988	0.960	1.000	0.999	0.957	0.961	1.005	1.001	1.028
NY	Willsboro	1998	43	44.38	73.38	762	4.24	0.969	1.000	1.000	0.958	0.976	1.018	1.008	0.957	0.958	1.000	0.999	0.958	0.962	1.009	1.004	1.009

Table F-10. Ratio of Hourly Sum ETr to Hourly Sum ASCE PMD ETr, continued.

								YEARLY SUMMARY								GROWING SEASON							
State	Site	Year	Elevation (m)	Latitude	Longitude	Mean Annual Precip (mm)	Peak-Month Mean Daily ETr (ASCE PM) - mm	ASCE PM (YR)	ASCE PMD (YR)	ASCE PMDL (YR)	ASCE PMDR (YR)	ASCE PMrf (YR)	ASCE PMrfh (YR)	ETrs (YR)	1982 Kpen (YR)	ASCE PM (GS)	ASCE PMD (GS)	ASCE PMDL (GS)	ASCE PMDR (GS)	ASCE PMrf (GS)	ASCE PMrfh (GS)	ETrs (GS)	1982 Kpen (GS)
OK	Apache	1997	440	34.91	98.29	757	8.36	0.950	1.000	0.997	0.984	0.959	1.071	1.010	0.939	0.946	1.000	0.996	0.982	0.954	1.050	1.008	0.977
OK	Apache	1998	440	34.91	98.29	757	11.47	0.960	1.000	0.995	0.986	0.969	1.068	1.009	0.924	0.966	1.000	0.993	0.986	0.973	1.060	1.008	0.936
OK	Goodwell	1997	996	36.60	101.60	447	12.07	0.949	1.000	0.997	0.982	0.959	1.075	1.011	0.894	0.947	1.000	0.996	0.982	0.956	1.058	1.009	0.927
OK	Goodwell	1998	996	36.60	101.60	447	14.03	0.958	1.000	0.996	0.983	0.968	1.082	1.010	0.885	0.963	1.000	0.994	0.984	0.971	1.072	1.009	0.904
OK	Marena	1997	331	36.06	97.21	889	6.67	0.942	1.000	0.997	0.984	0.949	1.048	1.008	0.932	0.941	1.000	0.996	0.980	0.947	1.031	1.007	0.979
OK	Marena	1998	331	36.06	97.21	889	8.64	0.952	1.000	0.996	0.985	0.960	1.050	1.008	0.923	0.956	1.000	0.994	0.983	0.963	1.040	1.006	0.953
OK	Wister	1997	143	34.98	94.68	1188	5.59	0.956	1.000	0.996	0.977	0.960	1.023	1.004	0.966	0.955	1.000	0.995	0.974	0.956	1.008	1.001	1.012
OK	Wister	1998	143	34.98	94.68	1188	7.40	0.955	1.000	0.995	0.982	0.961	1.030	1.006	0.941	0.951	1.000	0.993	0.980	0.955	1.013	1.003	0.974
OR	Haga	1999	9	42.50	124.50	1778	3.33	0.881	1.000	1.003	0.966	0.891	1.051	1.011	1.213	0.854	1.000	1.002	0.966	0.860	1.013	1.007	1.238
SC	Florence	1986	40	34.24	79.81	1120	7.05	0.968	1.000	0.997	0.978	0.993	1.065	1.026	0.940	0.964	1.000	0.996	0.978	0.986	1.051	1.023	0.976
TX	Bushland	1997	1170	35.11	102.05	505	9.88	0.952	1.000	0.999	0.981	0.974	1.096	1.022	0.921	0.945	1.000	0.996	0.980	0.963	1.067	1.019	0.957
TX	Bushland	1998	1170	35.11	102.05	505	13.27	0.957	1.000	0.997	0.982	0.980	1.096	1.023	0.906	0.961	1.000	0.996	0.984	0.983	1.092	1.023	0.922
TX	Dalhart	1997	1228	36.20	102.32	467	8.33	0.925	1.000	0.998	0.978	0.925	0.995	1.000	0.911	0.929	1.000	0.998	0.980	0.927	0.994	0.998	0.933
TX	Dalhart	1998	1228	36.20	102.32	467	10.96	0.931	1.000	0.997	0.981	0.929	0.992	0.997	0.892	0.937	1.000	0.996	0.982	0.933	0.989	0.996	0.913
UT	Logan	1989	1350	41.60	111.80	433	7.69									0.956	1.000	0.998	0.975	0.971	1.039	1.016	0.962
UT	Logan	1990	1350	41.60	111.80	433	7.06									0.948	1.000	0.998	0.973	0.960	1.023	1.013	0.976
WA	Gramling	1998	386	46.29	119.73	178	10.21									0.973	1.000	0.997	0.984	0.986	1.079	1.013	0.962
WA	Grayland	1998	2	46.78	124.00	2032	2.96									0.889	1.000	1.002	0.964	0.896	0.996	1.008	1.072
WA	Paterson	1998	109	45.94	119.49	152	8.65									0.949	1.000	0.997	0.984	0.959	1.040	1.011	0.972
WA	Puyallup	1998	61	47.10	122.30	1016	3.92									0.944	1.000	1.000	0.956	0.951	1.005	1.008	1.003
WA	Roza	1998	343	46.29	119.73	178	7.40									0.965	1.000	0.998	0.981	0.975	1.041	1.010	0.976
	Average							0.948	1.000	0.998	0.976	0.956	1.034	1.009	0.942	0.948	1.000	0.997	0.975	0.955	1.025	1.007	0.972
	Minimum							0.881	1.000	0.993	0.953	0.891	0.992	0.994	0.872	0.854	1.000	0.992	0.951	0.860	0.989	0.993	0.896
	Maximum							0.988	1.000	1.003	0.990	1.006	1.096	1.026	1.213	0.980	1.000	1.002	0.988	0.992	1.092	1.023	1.238

APPENDIX B

ASAE EP505 APR04, MEASUREMENT AND REPORTING PRACTICES FOR AUTOMATIC AGRICULTURAL WEATHER STATIONS

SITING AND INSTRUMENT SPECIFICATIONS FOR TEXAS AGRICULTURAL METEOROLOGICAL NETWORKS

ASAE EP505 APR04, Measurement and Reporting Practices for Automatic Agricultural Weather Stations

Developed by the ASAE SW-244 Irrigation Management Subcommittee; approved by the ASAE Soil and Water Division Standards Committee April 2004.

1 Purpose and scope

1.1 Purpose: The purpose of this Engineering Practice is to establish minimum recommendations for measurement, reporting, siting, operation, maintenance, and data management procedures for automatic agricultural weather stations. Additionally, these recommended procedures are intended to assist in the planning of automatic agricultural weather station installation and operation.

1.2 Scope: This Engineering Practice applies to automatic weather stations installed individually, or as part of a network of stations, for the measurement and reporting of specific weather variables in agricultural environments. This Engineering Practice also addresses a recommended core set of measurements and general siting considerations for agricultural weather stations. It is recognized that special purpose agricultural weather stations may deviate from the recommendations herein, particularly with respect to sensor deployment and station siting conditions. This Engineering Practice does not specifically address these special purpose stations.

2 Normative references

The following standard contains provisions that, through reference in this text, constitute provisions of this Engineering Practice. At the time of publication, the editions indicated were valid. All standards are subject to revision, and parties to agreements based on this Engineering Practice are encouraged to investigate the possibility of applying the most recent editions of the standards indicated below. Standards organizations maintain registers of currently valid standards.

ASAE S526.2 JAN01, *Soil and Water Terminology*

3 Definitions

3.1 Definitions. For the purpose of this Engineering Practice only, the following definitions are defined herein. Additional terminology is defined in ASAE Standard S526, Soil and Water Terminology.

3.2 adiabatic lapse rate. The decrease in temperature of a parcel of air with height above the surface when lifted in elevation adiabatically, that is, without the addition or withdrawal of heat from the surrounding air. The adiabatic lapse rate of dry air is about 1°C/100 m.

3.3 anemometer: Instrument for measuring the speed of the wind.

3.4 atmospheric (barometric) pressure: The pressure exerted by the weight of air (dry air and water vapor mixture) above a given point.

3.5 automatic agricultural weather station: A stand-alone set of equipment designed to automatically measure and record agriculturally significant weather variables, as specified in clause 4, for agricultural purposes. The station is based on an electronic data logger and includes associated sensing devices, power supplies, environmental enclosures, and support structures, normally operated on a year-round basis at a fixed location and it may be part of a network of similar stations. It collects data at a specified sampling interval(s), stores intermediate measurements in memory, processes summary values at a specified reporting interval, and stores the summary values in memory. Finally, it incorporates some means of data telemetry for access to, or transfer of, summary values, typically on a near-real time basis, to a central location for more general processing, long-term storage and dissemination, or to alternative on-site exchangeable storage media.

3.6 climate day: A 24-hour period (e.g., midnight to midnight, 8 am to 8 am, local standard time) for which a statistical summary of the measured weather values is prepared (means, maximums, minimums, totals, etc.)

3.7 data logger: An electronic, microprocessor-based device that can be programmed to make measurements of specific sensors, to process the measurements, and to store intermediate measurements and summary data values.

3.8 dew-point temperature: The temperature to which moist air at a specific barometric pressure, relative humidity, and temperature must be cooled to reach moisture saturation.

3.9 dry-bulb temperature: Ambient air temperature.

3.10 evaporation: The process by which a liquid changes into a gas.

3.11 fetch: The extent of homogeneous area surrounding a given point.

3.12 fully adjusted layer: Approximately the lowest 10% of the internal boundary layer that is in complete equilibrium with new surface boundary conditions caused by a transition in surface conditions.

3.13 internal boundary layer: The layer of air downwind of a transition in surface characteristics such as surface roughness; its thickness increases with distance downwind, or down fetch.

3.14 psychrometer: Instrument used to measure the water vapor content of the air by measuring the wet-bulb and dry-bulb temperature of the air.

3.15 radiation shield: A device used for housing air temperature sensors that reduces the temperature effects of radiation on the sensor.

3.16 resistance temperature detector: A length of pure metal (wire), carefully wound in a stress free form, that increases in resistance as the temperature of the metal (wire) increases.

3.17 sampling interval: The time interval between successive measurements of a sensor, or sensors, by a data logger.

3.18 saturation vapor pressure: The partial pressure exerted by water vapor when it is in equilibrium with a plane surface of pure water.

3.19 sensor: A device that provides a measurable signal output in response to a physical stimulus or variable.

3.20 soil heat flux: The flow of heat energy per unit cross-sectional area into, or out of, the soil.

3.21 solar radiation (irradiance) (direct, diffuse, global, longwave, net, shortwave): Direct solar radiation is the radiation coming from the solid angle of the sun's disc; irradiance is the property that is measured. Diffuse, or sky radiation, is downward, scattered and reflected solar radiation coming from the whole hemisphere. Global radiation is the sum of direct and diffuse solar radiation. Longwave radiation is the infrared energy emitted by the earth and the atmosphere. Net radiation is the sum of net shortwave radiation and net longwave radiation. Shortwave radiation is the radiant energy emitted from the sun at wavelengths less than 4 microns.

3.22 surface roughness: Aerodynamic roughness of a surface; a parameter affecting the downward transport of horizontal momentum from airflow to a surface.

3.23 telemetry: The transmission of data collected at a remote location to a central station, using one or more means of communication.

3.24 thermal stability: A concept describing the variation of temperature with elevation in the atmosphere. When the actual air temperature decreases with height above the surface at a rate greater than the dry adiabatic lapse rate (about 1°C/100 m), the atmosphere is unstable, the temperature is termed a lapse profile, air is buoyant, and turbulence or mixing is enhanced. When the actual air temperature decreases with height above the surface at a rate less than the dry adiabatic lapse rate, the atmosphere is stable, the temperature profile is termed an inversion, air tends to hold its position vertically, and turbulence or mixing is suppressed. When the actual air temperature profile equals the dry adiabatic lapse rate, the atmosphere is neutral.

3.25 thermistor: An electrical resistance device for measuring temperature that exhibits rapid and large changes in resistance for relatively small changes in temperature.

3.26 thermocouple: A device consisting of two dissimilar metals joined together at their end that produces a thermoelectric voltage proportional to the temperature difference between the two junctions.

3.27 time constant: The time required for an instrument to make a 63.2 percent adjustment to new environmental conditions, in which the measurement system is a linear, first-order, time-invariant, step function input. This percentage is equal to the quantity (1-1/e) where e is the base of the natural logarithm, 2.7182.

3.28 vapor pressure (actual): The pressure exerted by the water vapor molecules in air at a given temperature.

3.29 wet-bulb temperature: The temperature to which moist air can be cooled adiabatically (without any gain or loss of heat) by evaporation.

3.30 wind speed: Horizontal movement of air in distance per unit time.

3.31 wind direction: The direction from which air is moving.

3.32 wind vane: Instrument used to indicate wind direction.

3.33 zero plane displacement: The mean level, or height, at which momentum is absorbed by individual elements on a surface, e.g., plant leaves.

4 Measurements

4.1 Variables

4.1.1 Core variables. The recommended core variable set to be measured on an agricultural weather station should include solar radiation, air temperature, relative humidity, wind speed, wind direction, rainfall (total and intensity), and soil temperature (Table 1).

4.1.2 Derived variables. Variables derived from the core set of measured variables and applicable formulae for their derivation should include (see Table 1):

4.1.2.1 Saturation vapor pressure. Saturation vapor pressure should be calculated and logged with each sampling of air temperature and may be determined using an equation such as that of Tetens (1930) or Murray (1967):

$$e^o = \exp[(16.78\ T - 117)/(T + 237.3)]$$

Allen et al. (1994) give the Tetens (1930) equation as:

$$e^o = 0.611 \text{ EXP } [17.27 \text{ T}/(\text{T} + 237.3)]$$

and Allen et al. (1998) give the Tetens (1930) equation as:

$$e^o = 0.6108 \text{ EXP } [17.27 \text{ T}/(\text{T} + 237.3)]$$

where:

e^o = saturation vapor pressure (kPa)
T = air temperature (°C).

Lowe (1977) gives an equation for saturation vapor pressure as,

$$e^o = a_0 + T(a_1 + T(a_2 + T(a_3 + T(a_4 + T(a_5 + a_6\, T)))))$$

where:

e^o = saturation vapor pressure (kPa)
T = air temperature (K)
a_0 = 698.450 529 4
a_1 = -18.890 393 10
a_2 = 0.213.335 767 5
$a_3 = -1.288\ 580\ 973 \times 10^{-3}$
$a_4 = 4.393\ 587\ 233 \times 10^{-6}$
$a_5 = -8.023\ 923\ 082 \times 10^{-9}$
$a_6 = 6.136\ 820\ 929 \times 10^{-12}$.

Note that a different formula for saturation vapor pressure with respect to an ice surface should be used. The definition of relative humidity requires the use of saturation vapor pressure with respect to a water surface at all temperatures.

4.1.2.2 Actual vapor pressure. Actual vapor pressure of the air should be calculated and logged with each sampling of air temperature and relative humidity, and is determined by:

$$e_a = e^o\ (RH/100)$$

where:

e_a = actual air vapor pressure (kPa)
RH = relative humidity (%).

4.1.2.3 Vapor pressure deficit. Vapor pressure deficit should be calculated and logged with each sampling of air temperature and relative humidity, and computed using:

$$VPD = e^o - e_a$$

where:

VPD = vapor pressure deficit (kPa).

4.1.2.4 Wind data reduction. Scalar mean wind speed, unit vector mean wind direction, resultant mean wind speed and direction, and standard deviation of wind direction may be computed using raw sampled data values in the following relationships:

$$W = \Sigma\ (w_i)/n$$

$$\theta_u = \tan^{-1} (w_x/w_y)$$

$$w_x = \sum (w_i \sin \theta_i)/n$$
$$w_y = \sum (w_i \cos \theta_i)/n$$

$$U = (w_x + w_y)^{0.5}$$

$$\theta_1 = \tan^{-1} (w_{x1}/w_{y1})$$

$$w_{x1} = \sum (\sin \theta_i)/n$$
$$w_{y1} = \sum (\cos \theta_i)/n$$

$$\sigma(\theta_u) = 81\ (1\text{-}U/W)^{0.5}$$

$$\sigma(\theta_1) = \sin^{-1} (\varepsilon)[1+0.1547\ \varepsilon^3]$$

$$\varepsilon = [1 - (w_{x1}^{\ 2} + w_{y1}^{\ 2})]^{0.5}$$

where:

W = scalar mean horizontal wind speed (m s^{-1})
w_i = sampled wind speed data values (m s^{-1})
n = number of samples
θ_u = resultant mean wind vector direction (degrees)
w_x = speed weighted mean wind vector component in East-West direction
w_y = speed weighted mean wind vector component in North-South direction
θ_i = sampled wind direction data values (degrees)
U = resultant mean wind vector magnitude (m s^{-1})
θ_1 = unit vector mean wind direction (degrees)
w_{x1} = mean unit vector component in East-West direction
w_{y1} = mean unit vector component in North-South direction
$\sigma(\theta_u)$ = standard deviation of wind direction, Campbell Scientific algorithm (CSI, 1987)
$\sigma(\theta_1)$ = standard deviation of wind direction, Yamartino algorithm (US EPA, 1987).
x,y = coordinate system in the horizontal plane with x-axis aligned with East.

4.1.3 Supplemental variables. Supplemental and additional variables which may be measured or derived on an automatic agricultural weather station include: net radiation; photosynthetically active radiation; air temperature, relative humidity, and wind speed at heights other than those specified in Table 1; soil temperature at depths other than those specified in Table 1; soil temperatures under other surface conditions; standard deviation of wind speed (see clause 4.1.2.4); dew-point temperature; soil water content; soil heat flux; leaf wetness; barometric pressure; surface temperature; evaporation (by Class A Pan or atmometry if successfully automated, otherwise evapotranspiration is calculated); solid precipitation (snow fall and snow depth). Suitable algorithms exist for the estimation of some of these variables using the measured standard variable set, e.g., net radiation, soil heat flux, evapotranspiration, photosynthetically active radiation.

4.2 Units. All measured and derived variables should be reported in SI (metric) units. See Table 1 for recommended units for each variable.

4.3 Deployment. Recommended deployment heights and depths for each standard measurement given in clause 4.1 are listed in Table 1. For purposes of reference evapotranspiration computation using a Penman model, daily average wind speed at 2-m height above the surface is required. Daily average wind speed at 2 m may be estimated from the measured data at height z using the following general relationship (Jensen et al., 1990):

$$W_2 = W_z (2/z)^{0.2}$$

where:

W_2 = estimated wind speed at 2-m height (m s^{-1}),
W_z = wind speed (m s^{-1}) measured at height z (m).

Or, to account for measurement surface roughness:

$$W_2 = W_z [\ln((2-d)/z_o)/\ln((z-d)/z_o)]$$

where W_2, W_z, and z are as previously given and:

d = zero plane displacement height of the measurement surface (m),
z_o = surface roughness height for momentum transfer (m).

d and z_o may be approximated as:

$$d = 0.7\ h_c$$

$$z_o = 0.1\ h_c$$

where:

h_c = vegetation height (m).

4.4 Sampling interval. Recommended data logger sampling intervals for each measurement given in clause 4.1 are listed in Table 1. It is probable the data logger will be programmed to sample at the smallest sampling interval and thus all sensors will be sampled at that rate. The World Meteorological Organization (WMO) standard for wind measurements is a 3-s sampling interval. The Office of the Federal Coordinator for Meteorological Services and Supporting Research (OFCM) has issued a standard method for characterizing surface wind that requires a 3-s sampling interval (OFCM, 1992). When characterization of wind is an important component of the automatic agricultural weather station program, it is advisable to follow the OFCM wind standards. The OFCM standard data output includes additional parameters to those listed in Table 1 for wind speed and direction. Note that a more frequent sampling rate will drain batteries more quickly, making battery maintenance a more important factor for battery-powered stations without solar panels.

4.5 Reporting. Reporting interval and values to be reported for each of the core and derived variables are listed in Table 1. The hourly reporting interval of values specified in Table 1 allows data users to generate summaries for different climate days, i.e., midnight to midnight, 0800 to 0800, etc., as desired. A midnight to midnight daily reporting interval is recommended. Data should always be collected and reported in local standard time.

5 Types of equipment

5.1 Data loggers. A microprocessor-based electronic data logger is the necessary basis of an automatic agricultural weather station. This device must be user-programmable to allow, at a minimum, readings of instruments listed in Table 1 at the recommended sampling intervals listed in Table 1. Additionally the data logger must be capable of intermediate processing of data such as computation of the derived variables listed in clause 4.1.2, storage of intermediate values, computation of the statistical summary values listed in Table 1, and storage of summary values. Finally, the data logger must have appropriate communications interfaces for data transfer to storage media or data telemetry equipment.

5.2 Solar radiation (irradiance) sensors. Total or global solar radiation may be measured with pyranometers or total hemispherical radiometers. Pyranometers may be of the thermopile or photocell types. Instruments should have compensation for temperature dependence. The instrument should have sensitivity across the entire spectral range affecting biological activity. The typical short-wave spectrum is 0.3 to 3 microns.

5.3 Temperature sensors. Air and soil temperature may be measured with thermistors, resistance temperature detectors (RTD,) or thermocouples. Thermocouples measure the temperature difference between a measuring junction and reference junction; the reference junction will typically be at a data logger or multiplexer wiring.

Table 1 - Core variable set, units, deployment heights, sampling intervals, and values reported for automatic agricultural weather stations

Variable	Derived variables	Units	Deployment height (m)	Sampling interval (s)	Values reported each hour
Solar radiation	---	W m^{-2}	[1]	≤ 10	average
Air temperature [2]	---	˚C	1.5 to 3	≤ 60	average instantaneous max/min
Sat. vapor pressure		kPa	---	[3]	---
Relative humidity [2]	---	%	co-located with air temperature	≤ 60	average instantaneous max/min
	Vapor pressure	kPa	---	[4]	average
	Vapor pressure deficit	kPa	---	[4]	average
Wind speed [5]	---	m s^{-1}	2 to 3	≤ 10	scalar mean maximum during interval and time of occurrence
Wind direction [6]	---	deg	co-located with wind speed	≤ 10	unit vector or resultant mean magnitude and direction standard deviation
Rainfall [7]	---	mm h^{-1}[8]	≤ 1	[8]	total rate or intensity [8]
Soil temperature [9]	---	ºC	-0.10 to –0.20[10]	≤ 60	average instantaneous max/min

Notes for Table 1:
1) Deploy to avoid shading by and reflection from nearby objects. Practical considerations for height include ease of maintenance, i.e., routine cleaning and checking instrument level.
2) Supplemental data, which may be reported, are times of occurrence of maximum and minimum values.
3) Saturation vapor pressure is calculated with each sample of air temperature (see text for equation) and may be reported as supplemental data. See clause 4.1.2.1.
4) Vapor pressure and vapor pressure deficit are calculated with each sample of relative humidity and air temperature. Supplemental data that may be reported are times of occurrence of maximum and minimum values. See clauses 4.1.2.2 and 4.1.2.3.
5) See clause 4.1.2.4. WMO and OFCM standard is 3-second sampling rate for wind speed and direction, see clause 4.4. WMO standard height for wind measurements is 10 m.
6) Azimuth direction referenced to true North. See clause 4.1.2.4 for algorithms for calculating hourly mean wind direction (magnitude and direction) and standard deviation of wind direction from sampled values.
7) Liquid precipitation only.
8) Sampling is event driven for tipping bucket rain gages. To obtain the rainfall rate or intensity, record the time of each tip for tipping bucket gages; for weighing gages, record the total weight and time for each 0.254 mm (0.01 in.) of rainfall to obtain both total rainfall and intensity. Hydrologists recommend a minimum sampling interval of 15 min; 1-min sampling intervals are often used.
9) Measure under bare soil surface conditions. Soil moisture at probe depth should be maintained at levels equivalent to the environment being represented (i.e., irrigated vs. dryland sites).
10) Soil temperature deployment is often dependent on the intended use of the data; the values of –0.10 m and –0.20 m are typical depths of installation.

panel, requiring a temperature measurement at the panel. Air temperature sensors must be deployed in a minimum of a naturally-ventilated radiation shield. Soil temperature sensors must be environmentally sealed to prevent moisture penetration and to allow for direct burial in the soil.

5.4 Relative humidity sensors. The most common types of relative humidity sensors used on automated agricultural weather stations measure changes in physical, chemical, or electrical properties of a material upon absorption of water vapor by, or adsorption of water vapor to, the material. These may include strain measurements, or measurements of the change in electrical resistance or capacitance. Psychrometers are generally not used on remote stations due to the high power requirements of the aspirating mechanism and the problem of providing a continuous water supply to the wet-bulb temperature device.

5.5 Wind instruments

5.5.1 Wind speed. Wind speed is typically measured on an automatic weather station using a cup or propeller anemometer; horizontal wind speed is typically the only component measured. Devices may be of switch closure type, optical type, or the type that generates an AC signal or a DC signal.

5.5.2 Wind direction. Wind direction is measured with a wind vane. The measurement will be the direction from which the air is moving. Wind vanes should be aligned relative to true north, i.e., 0 degrees is true north, 90 degrees is east, etc.

5.6 Rain gages

5.6.1 Tipping bucket gages. Tipping bucket rain gages operate on a switch closure principle generating electrical pulses with each tip of a small bucket that receives liquid from a funnel. Knowing the depth represented by each tip and counting the number of tips, the depth of rainfall over a specified time interval can be determined. Rainfall intensity can be determined by recording the time of each tip in addition to counting the tips. Unless heated, tipping buckets are limited to measurement of liquid precipitation.

5.6.2 Weighing gages. Weighing gages weigh and record all forms of precipitation as soon as they fall into the gage. Anti-freeze may be used to avoid ice formation in the bucket and oil may be used to retard evaporation. Weighing gages are sensitive to strong winds, which often cause erroneous readings.

5.7 Data storage/telemetry

5.7.1 On-site data storage. On-site data storage requirements are dependent upon the method and frequency of data retrieval. Data loggers should be equipped with adequate memory to store data for a minimum of several days. Transfer of data to on-site memory or to recording devices (solid state memory, cassette tape, etc.) should occur hourly and daily as per the reporting intervals in Table 1. Frequency of exchange of on-site data storage media is dependent on capacity, data utilization requirements, etc.

5.7.2 Telemetry equipment. Data telemetry to a central computing facility may be accomplished via telephone (standard or cellular) and modem connection, land-based radio frequency telemetry, satellite telemetry, meteor burst technology, etc.

5.8 Other equipment

5.8.1 Station power. Most data loggers operate on direct current (DC) power. Power requirements of the data logger for measurement, and processing and storage of data should be minimal, allowing for extended operation before it becomes necessary to replace batteries. AC power at the weather station site may be used for trickle charging the battery with an appropriate voltage transformer and adequate surge protection. Solar panels may also be used to trickle charge batteries with appropriate voltage regulation. Batteries of the sealed gel-cell type may be housed in the same enclosure as the data logger and telemetry equipment. Wet cell batteries should be housed in a separate enclosure to minimize the risk of hydrogen gas buildup and possible explosion within the data logger enclosure, as well as to avoid corrosion of electronic equipment terminals.

5.8.2 Enclosures. All enclosures should be rainproof. Enclosures housing the data logger should be National Electrical Manufacturer's Association (NEMA) type 4 with a gasket type seal on the door. Ports for sensor leads should be sealed with electrician's putty. Desiccant packs should be kept within the data logger enclosure and maintained according to clause 9.3.5.

5.8.3 Structure. Data logger enclosures, battery enclosures, all sensor mounting arms, etc. should be rigidly attached to the weather station structure. The weather station structure may be a tripod, a free-standing tower, or a guyed tower. The weather station structure should be firmly anchored to the ground and should be equipped with an electrical grounding system connected to an earth ground and a lightning rod. All instruments, the entire tower/structure, and all connections leading to the tower should be connected to a common ground. This ensures that there are no ground loops in the system, where voltage differentials between the instruments and data logger or tower can develop. Sensors not directly mounted on the main station structure should be mounted on their own rigid and anchored structure. Provisions should be made to bring the sensor leads to the data logger in buried moisture-and rodent-proof conduit.

6 Measurement requirement and uncertainty

6.1 General. A fundamental objective of this engineering practice is to define requirements and practices necessary to:

- characterize the uncertainty in measurements obtained;
- obtain measurements of sufficient quality to be useful for the intended agricultural applications or products.

The quality of measurements obtained requires a compromise between the cost of instrumentation and maintenance, and the need for long-term operation. Estimates of the measurement uncertainty one can expect using sensors and practices commonly employed in long-term weather station operation, are given in Table 2. Sensitivity analyses of various agricultural applications (ET estimation, crop modeling, pest and disease prediction) to expected measurement uncertainty are required to determine the usefulness of measured variables for such applications. If the level of uncertainty reduces the usefulness of the measurements, additional or tighter specifications for both sensors and practices must be considered.

Flexibility in the choice of sensors and instrumentation by weather station operators is desirable. The intent of this section is to provide guidance on desirable measurement ranges and measurement resolution. The choice of sensors influences the maintenance and calibration schedules needed to maintain a desired level of measurement quality.

Types of sensors commonly used in agricultural and climatic networks are listed in Table 2. A number of other sensor options exist beyond those shown. Higher quality sensors may exist, but the information in Table 2 is intended to assist in the selection of a sensor type capable of obtaining the desired quality of measurement. The minimum acceptable quality of data is in part determined by the measurement capability for a given sensor type. The quality of measurement may differ greatly between sensors of the same type, but from different manufacturers.

6.2 Measurement range. The desired measurement range for an individual variable should be specified or known. Table 2 provides general guidance, however, certain regions of the world may not require ranges as broad as those given for some variables (e.g., air temperature).

6.3 Measurement resolution. Two columns are listed under measurement resolution in Table 2; variable resolution is that needed for the specific application(s) of the data. To avoid ambiguity, the resolution should be specified for an individual measurement as opposed to the time-averaged, recorded value. Values given in Table 2 are suggested initial values for evaluation.

Digital resolution is the resolution required of the measurement electronics for a particular type of sensor signal, in order to obtain the accompanying specified variable resolution. Values given in Table 2 are for information purposes only.

Table 2 - Typical measurement range, resolution, and estimated field accuracy of sensors used on automatic agricultural weather stations

Variable	Range	Resolution Variable	Resolution Digital	Specified accuracy	Estimated field accuracy
Solar Radiation	0 to 1500 W m^{-2}	5 W m^{-2}	(33 μV)	typical: ±3% OR[1] max: ±5% OR	same as specified
Air temperature thermistor (resistance)	-30ºC to 50ºC	0.1ºC	(1 mV V^{-1})[2]	±0.3ºC	aspirated: ±0.5ºC unaspirated: +0.5 to 2.5ºC -0.5 to -1ºC
PRT (resistance)	---	---	(100 μV V^{-1})	±0.2ºC±0.15%OR[3] ±0.35ºC±0.4%OR[4]	---
Thermocouple	---	---	(4 to 6 μV)	±0.75% of (T_m-T_R)[5] ±T_R error	---
Soil Temperature	---	---	---	---	±0.5ºC
Relative humidity	10 to 100% RH	1% RH	(10 mV)	±3% to ±5% RH	±5% RH
Wind speed (frequency)	0.5 to 40 m s^{-1}	0.5 m s^{-1}	---	±0.3 m s^{-1} or ±2% OR	---
Wind direction (vane)	0 to 360 deg	5 deg	(14 mV V^{-1})	±3 to 5 deg	10 deg
Rainfall	0 to 200 mm h^{-1}	0.25 mm h^{-1}	---	---	-10% at 100 mm h^{-1}

Notes for Table 2:

1) OR: Of Reading
2) Units of mV V^{-1} in the digital resolution column reflect resolution required per volt of excitation to resistance of sensor.
3) Class A
4) Class B
5) Specified accuracy for thermocouples is in terms of T_m and T_R, the measurement and reference temperatures.

6.4 Accuracy

6.4.1 Manufacturer's specifications. Values shown in Table 2 in the specified accuracy column refer to manufacturer's specified accuracy. In some cases the values reflect a specific manufacturer, and in others, a typical value from a distribution provided by several manufacturers of the same type of sensors. The accuracies should be regarded as representative of bench top environments rather than achievable field operational accuracies. Values given in Table 2 are given for information purposes only.

6.4.2 Operational field accuracy. Values shown in Table 2 are representative of the uncertainty of measurements made under field conditions. The values are provided as first estimates for determining their usefulness for agricultural applications.

7 Documentation

7.1 General. Each automatic agricultural weather station site installation should have a station history document developed and maintained for the duration of the installation. This station history file must be available to all potential users of data collected at the weather station. Station grounds conditions and maintenance; sensor condition, maintenance, calibration, and replacement; etc.; should all be included in the station history file. The station history file is important documentation needed for such activities as investigation of data anomalies, etc. The station history file should contain physical information about the site and surrounding area, information about the array of sensors deployed at the site (clause 7.2), site and sensor maintenance information, sensor calibration data (clause 7.3), and descriptions of electronic data retrieval and storage (archival) formats (clause 7.4).

7.2 Site documentation. Each weather station site should be identified with a unique identification label. Written documentation describing the weather station installation site should be developed and periodically updated. Constant geographic data such as station elevation above mean sea level, latitude and longitude to the nearest 30 seconds of arc, and land slope and aspect should be included.

7.2.1 Site description. Site characteristics to be described include: ground cover characteristics (type and height), soil type, and irrigated or rainfed conditions under the station and in the immediate vicinity (radius out to 200 m) of the station. Terrain features (hills, trees, bodies of water, buildings, etc.) of the surrounding local area (radius out to 5000 m) should be described by distance, height, and sector. Written descriptions of the immediate vicinity of the site and local surrounding area should be supplemented with photographs taken in a minimum of each of 8 coordinate directions (45º sectors), and preferably 12 coordinate directions (30º sectors), several times per year (at least twice during the growing season; beginning and mid-season). Average surface roughness in each sector should be characterized and recorded using the roughness classifications given in Table 3.

General comments about the agriculture (irrigated or rainfed, crop types, growing seasons, etc.) in the region of the station (radius up to 50 km) should be included. Descriptions should include natural and anthropogenic-based changes to the area surrounding the site as a function of time during the calendar year (e.g., cropping patterns, growth cycles, etc.).

7.2.2 Sensor exposure description. Written documentation describing the array of sensors deployed at a site and their deployment characteristics (height, depth, orientation, etc.) should be developed and maintained. Sensors should be described by name of manufacturer, serial number, or other identification number. Dates of installation, maintenance and/or calibration activity (clause 7.3), and removal or replacement should be recorded. All changes in sensor deployment characteristics should be documented when they occur.

7.3 Calibration and maintenance documentation

7.3.1 Calibration. All calibration activities should be recorded on a standard form showing part or sensor name or other identifier, serial number, date, and a checklist of activities performed. Deviations of sensor performance from calibration sensors should be noted, both before and after the calibration. Completed forms should be maintained in at least a paper filing system, and preferably, also in an electronic database file. All calibration records should provide a trace of the sensor or part history, and should be cross-referenced with station/sensor maintenance record keeping.

7.3.2 Maintenance. All maintenance activities, whether scheduled routine maintenance or unscheduled emergency maintenance, should be recorded on a standard form showing station name or other identifier, date of visit, and a checklist of activities performed. Record notes on these forms detailing "as found" and "as left" conditions. The form should also contain a checklist for ensuring the station and data logger are left in proper operational state upon completion of the maintenance visit. Completed forms should be maintained in at least a paper filing system for each station, and preferably, also in an electronic database file. All station/sensor maintenance records should be cross-referenced with all calibration records.

Table 3 - Average surface roughness classification (after Wieringa, 1992)

No.	z_o (m)	Landscape description
1	0.0002 "Sea"	Open sea or lake (irrespective of the wave size), tidal flat, snow-covered flat plain, featureless desert, tarmac and concrete, with a free fetch of several kilometers.
2	0.005 "Smooth"	Featureless land surface without any noticeable obstacles and with negligible vegetation; e.g., beaches, pack ice without large ridges, morass, and snow-covered or fallow open country.
3	0.03 "Open"	Level country with low vegetation (e.g., grass) and isolated obstacles with separations of at least 50 obstacle heights; e.g., grazing land without windbreaks, heather, moor and tundra, runway area of airports.
4	0.10 "Roughly open"	Cultivated area with regular cover of low crops, or moderately open country with occasional obstacles (e.g., low hedges, single rows of trees, isolated farms) at relative horizontal distances of at least 20 obstacle heights.
5	0.25 "Rough"	Recently-developed "young" landscape with high crops or crops of varying heights, and scattered obstacles (e.g., dense shelterbelts, vineyards) at relative distance of about 15 obstacle heights.
6	0.5 "Very rough"	"Old" cultivated landscape with many rather large obstacle groups (large farms, clumps of forest) separated by open spaces of about 10 obstacle heights. Also low large vegetation with small interspaces, such as bushland, orchards, young densely-planted forest.
7	1.0 "Closed"	Landscape totally and quite regularly covered with similar-size large obstacles, with open spaces comparable to the obstacle heights; e.g., mature regular forests, homogeneous cities or villages.
8	≥ 2 "Chaotic"	Center of large towns with mixture of low-rise and high-rise buildings. Also irregular large forests with many clearings.

7.4 Data documentation. All data should have written documentation, electronic or otherwise, developed and maintained describing means for data access and retrieval. Additionally all data sets should be accompanied with documentation describing storage (archival) formats (see clause 10).

8 Station siting

8.1 Exposure. Ideally, agricultural weather stations should be sited in level, open terrain representative of the local agricultural environment. Stations should be sited away from the influence of obstructions such as buildings, trees, small hills, etc. and the influence of non-homogeneous surface conditions (paved or graveled areas, large open water surfaces, etc.) to the greatest extent possible. The extent to which measurements are representative on a spatial scale depends on the uniformity of the surface, topography, and on soil characteristics such as moisture, color, etc.
In all cases, obvious micro-environments (tops of ridges, steep slopes, narrow valley bottoms, sheltered hollows, sites significantly influenced by diurnal atmospheric patterns, etc.) should be avoided unless the characterization of that micro-environment is the specific purpose of the weather measurements. In such cases, station site documentation (clause 7.2) should explicitly state the purpose of the measurements.

8.1.1 Wind. Recommended anemometer and wind vane exposure calls for separation distances between sensors and obstructions of a minimum of 10 times the height of the obstruction, and preferably greater than 50 times the height of the obstruction. The influence of vegetative crop growth and development through the growing season should be considered. Wind instruments are preferably mounted on top of masts, but if side-mounted on a boom, the boom length should be at least three times the mast or tower width and the boom should be mounted on the prevailing wind direction side of the mast. Instruments must be installed and maintained in a level position.

8.1.2 Air temperature and relative humidity. Generally these sensors will be co-located or integrated into one unit where one of each measurement is made at a weather station. The sensor should be protected from thermal radiation from all sources and directions using a radiation shield. Any additional air temperature sensors at other heights on the weather station should use an identical radiation shield. At a minimum, a naturally ventilated radiation shield that allows free circulation of air around all sides of the sensor should be used. The shield should be reflective (white) to avoid extraneous heat build up. The recommended separation distance between sensors and nearby obstructions is 4 times the height of the obstruction, and at least 30 m from large paved or graveled areas. Temperature/RH sensors installed on towers should be installed on booms, with the boom length equal to at least the width of the tower.

8.1.3 Solar radiation. The site should be free of obstructions above the plane of the radiation sensing element. Care must be taken that no part of the weather station structure or tower casts a shadow across the radiation sensor at any time of day or year. Reflections from nearby objects and artificial sources of radiation should be avoided. The instrument must be installed and maintained in a level position.

8.1.4 Precipitation. Rain gages should be sited on open ground with the top of the opening level and open to the sky. The separation distance between obstructions and the instrument should be at least twice, and preferably four times the height of the obstruction. Some sheltering may be desirable to reduce turbulence around the gage. Windshields can be used to reduce wind speed at the mouth of the gage.

8.1.5 Soil temperature. Soil temperature probes should be installed at the desired depths and under the desired surface conditions with soil water contents maintained at levels equivalent to the soil environment being represented (i.e., irrigated vs. rainfed). In the case of a single soil temperature measurement, it is recommended in Table 1 to install the probe under bare surface soil conditions at a depth of 0.10 m.

8.2 Measurement surface. The station should be installed over uniform, low-cover vegetation such as grass. In arid areas, natural rainfed cover is acceptable, although it may be preferable to establish and maintain a drought tolerant grass species beneath the station. The preferred installation will be over green grass vegetation having adequate soil water to support reference evapotranspiration rates. The underlying measurement surface should be homogeneous with respect to surface roughness, surface temperature, and surface moisture, particularly in the prevailing wind direction.

8.3 Fetch. The extent of the homogeneous area surrounding a station (or fetch) is traditionally recommended to be 100 times the height of the measurement above ground surface. This "ensures" that sensors (wind, temperature, and relative humidity) are placed within the fully adjusted layer of a newly developing internal boundary layer caused by any surface nonhomogeneities. The purpose(s) for which the weather station data is intended to be used may relax or tighten the degree to which this requirement is followed. For example, if the intended use of the weather station is for computing reference evapotranspiration, the fetch surrounding the station is recommended to be a minimum of 100 m for each 1 m of instrument height and to consist of a green, well-irrigated crop of uniform height. On the other hand, stations intended for integrated pest management (IPM) should be located in, or among, crops of interest, which might not necessarily be of uniform height or might not be well-irrigated all season e.g., orchards or groves.

LeClerc and Thurtell (1990) showed that the "footprint", or the upwind surface area affecting fluxes measured at downwind heights, changes dramatically with surface roughness and thermal stability. The fetch to height ratio of 100:1 may be much too small when measurements are made over smooth surfaces, or during stable thermal conditions.

8.4 Other considerations. Siting considerations should include the availability of local personnel, or cooperators, who may regularly (weekly) perform a visual inspection of station equipment, possibly carry out basic maintenance tasks, and report any problems to station operators.

8.4.1 Access. The site should be accessible by vehicle on a year-round basis for routine maintenance and calibration activities. The site should be away from roads to minimize problems of dust and vandalism.

8.4.2 Power. Automatic remote weather stations configured with the standard array of measurements given in clause 4.1 may be operated independent of any need for AC power at the site. These stations are equipped with DC power and may include a solar panel for trickle charging a rechargeable battery. Certain instrumentation beyond the standard set of measurements may require AC power at the site.

8.4.3 Telemetry. If telemetry is used for transfer of data from the remote station to a central collection facility station, siting may be constrained. For instance, if telephone telemetry is used, economics of standard telephone line installation may constrain station siting. Telephone telemetry using cellular service may eliminate some station siting constraints, however, connection and usage fees may be expensive.

For radio frequency (RF) telemetry, the proximity of the station to the RF base station, or to an RF repeater station will constrain siting. Line-of-sight between antennae of the weather station and the base station, or between the weather station and repeater station is generally recommended. This constraint becomes a necessity in the UHF band, unless stations are very close. Satellite telemetry generally imparts few siting constraints.

8.4.4 Security. Site security is a secondary, but important, consideration. When considered necessary to protect facilities and/or instrumentation, protective fencing surrounding a weather station site should not exceed 2 m in height, and should be installed to maintain the recommended separation distances for sensors given in clause 8.1.

9 Calibration and maintenance

9.1 General maintenance and calibration guidelines

9.1.1 Personnel. Only properly trained personnel should perform all maintenance and calibration activities.

9.1.2 Frequency. Routine maintenance at weather station sites should be performed on at least a quarterly basis. (See clause 9.3)

9.1.3 Spare parts. A spare parts inventory (data loggers, power supplies (battery packs and solar panels), sensors, telemetry equipment, hardware, etc.) of at least 10-15% of total equipment inventory should be maintained in ready-to-install condition. This decreases lost data and downtime by allowing immediate replacement of parts that cannot be repaired or brought into proper operation through maintenance and calibration. Also, sensors can be rotated through a laboratory-based calibration and maintenance procedure.

9.1.4 Quality control. Crucial to successful collection and retrieval of high quality data from automatic remote weather stations is the routine processing of incoming data through quality assurance and quality control (QA/QC) algorithms and the regular review of data by experienced, qualified, trained personnel. These reviews are useful for checking reasonableness of data, for flagging of unusual values, and for spotting data values showing unusual consistency or fluctuation. These reviews are preferably performed daily and are an extremely important adjunct to routine scheduled maintenance (clause 10).

9.2 Calibration tests

9.2.1 Data logging equipment. Data loggers should be rotated through a laboratory calibration procedure on an annual basis. Data loggers should be replaced and calibrated in the laboratory or by the manufacturer in the event of electrical transients, or other electrical damage to the data logger or to individual channels. I/O channels on programmable data loggers may be tested with a digital multimeter (DMM) and a program designed to test each channel.

9.2.2 Weather station sensors

9.2.2.1 General considerations. Sensor type and on-site environmental conditions will affect calibration schedules. Detailed, systematic maintenance activities and record keeping will provide considerable insight into the rates of deterioration of sensor calibrations. Physical inspections and cleaning specified in clause 9.3 can be considered a minimal level of effort to ensure sensors operate according to their calibration specifications. Sensors should not be field calibrated, but should be rotated on an annual basis from the weather station to the base for laboratory or manufacturer calibration. The preferable approach is for all sensors to be periodically rotated through a laboratory calibration procedure. Laboratory calibration involves the evaluation of current calibration coefficients and/or derivation of new calibration coefficients through the comparison of sensor output with a known standard at several (minimum of three) points across the operating range of the sensor.

Field sensor performance/intercomparison tests may be performed through accuracy tests using a known input or characteristic, or through side by side comparisons with sensors that are calibrated against a known standard (i.e., preferably against an instrument traceable to the National Bureau of Standards). These standard sensors used for side-by-side comparisons should be used sparingly and only for field intercomparison purposes. They should be either replaced periodically with new, calibrated sensors or routinely subjected to calibration against the known standard to maintain their validity. When sensors are tested side by side with calibration sensors, or against a known characteristic, simultaneous readings are taken over a specified period of time. The percent difference between the averages of the two sets of readings should be computed and compared to previously determined criteria of acceptability or rejection specific to each sensor.

$$\%\ \text{difference} = \frac{(\text{station sensor value}) - (\text{standard sensor value})}{(\text{standard sensor value})} \times 100$$

Side by side comparisons assume the standard sensor is of the same type as the weather station sensor to the extent possible.

All sensors should be subjected to calibration tests upon receipt and before field deployment to ensure proper and accurate operation.

Field tests of a new weather station as a unit should be performed immediately after installation to ensure proper operation of the system. Incoming data from the new station should be carefully screened during the first week of operation to ensure proper operation. Once a new station is operating satisfactorily, routine sensor performance tests should occur at least once a year and preferably every six months.

9.2.2.2 Solar radiation. The standard sensor should be placed at the same height and directly adjacent to the station sensor. The % difference between the two sensors should be less than, or equal to 5%. If this is not obtained, clean the station sensor and repeat the test. If the % difference is still greater than 5%, the station sensor should be replaced and subjected to a thorough laboratory calibration over a complete range of sunlight conditions. A completely opaque cover over the sensor may be used to perform a zero check.

9.2.2.3 Air temperature. Place an aspirated psychrometer at the same level as the temperature sensor in the radiation shield with the psychrometer's thermometers shaded and facing north. Compare temperature readings of the weather station sensor with readings from the dry-bulb thermometer of the psychrometer when maximum depression of wet bulb is achieved. Some difference is expected due to differences in shielding of the two temperature sensors and the fact the sensors are of two different designs.

If differences are greater than instrument accuracy specifications and the tests are being conducted under warm, calm conditions, repeat the test with the weather station sensor removed from the radiation shield, but with both sensors shaded. If the difference is still unacceptable replace the weather station temperature sensor.

Lab calibration of temperature sensors may be accomplished using a stable thermal mass of known temperature, having a time constant of more than 1 hour and design such that there are no thermal sources or sinks to create local gradients within the mass. Alternatively, calibrations may be performed against a precision laboratory thermometer in a temperature controlled water bath, or in a temperature controlled environmental chamber.

Resistance temperature devices (RTD) tend to be very stable and generally do not require calibration.

9.2.2.4 Relative humidity. Use a battery-powered aspirated psychrometer or an Assmann psychrometer (with clean wicking on the wet-bulb thermometer, wetted with distilled water, and a calibrated thermometer pair that matches ambient temperature before wetting of the wet-bulb) to obtain several readings of wet- and dry-bulb temperature. Determine relative humidity from these wet-/dry-bulb pairs using a computer or hand-held calculator program with elevation correction for atmospheric pressure or tables that can be corrected for elevation. Ensure wicking on the wet-bulb remains wet throughout the entire test. Record sensor RH values simultaneously with psychrometer readings.

Deviations of greater than 5-10% between the paired readings indicate a calibration or other problem with the weather station RH sensor. Remove the station sensor from the radiation shield and repeat test. If no improvement occurs, clean the sensor as thoroughly as possible (a few sensors allow water immersion, but subsequently require considerable time to "dry-down" to ambient conditions) and repeat test. If the % difference is unacceptable, the sensor should be replaced and subjected to laboratory calibration or the sensing element replaced if it is replaceable.

Lab calibrations of relative humidity sensors may be developed using saturated salt solutions, or against a standard device such as a calibrated dew-point hygrometer in an environmental chamber having temperature/relative humidity control. At least three known humidities should be used to determine a new set of calibration coefficients.

9.2.2.5 Wind speed. Place the standard sensor at the same height as the station sensor and such that there is no interference of the streams of air from the devices. The percent difference between sensor readings should be less than, or equal to, 5%. Test devices are available to drive the anemometer or propeller shaft at known rates of rotation. The station sensor should be tested at three representative rates equivalent to typical wind speeds at the station (e.g., 2, 5, and 10 m s^{-1}). The anemometer or propeller transfer function should produce a quantity (wind speed value) within one increment of resolution (0.1 m s^{-1}) of the known speed.

Starting torque of the wind speed sensor is tested with a torque wrench. If the starting torque is outside the manufacturer's specifications, the result is a higher starting threshold and loss of accuracy in determination of total wind run. Replace bearings and repeat test.

9.2.2.6 Wind direction. Upon installation, ensure station sensor is oriented to provide readings with respect to true north. Templates that resemble the faceplate of a compass can be constructed to fit around the sensor base. Oriented to true north, readings of the wind vane can be taken at each of many azimuth positions after aligning with the template (see clause 9.3.2.5).

9.2.2.7 Precipitation. Tipping bucket type gages with buckets of known tipping depth may be calibrated based on a measurement of the funnel orifice area, from which a volume of water may be computed that produces one tip of the bucket (e.g., 0.25 mm (0.01 in.) per tip).

A more reliable test is to slowly introduce a volume to produce 10 tips, or 100 tips, and to count the number of tips. Using adjusting mechanisms (set screws, etc.) typically found on most tipping bucket rain gages, it is possible to adjust the gage to operate within 1% to 2% difference.

Weighing gages should be calibrated by placing a series of known weights on the gage. The calibration of the gage should cover the total weighing range of the gage and each weight increment should be no greater than 10% of the total weighing range. The weighing gage should be protected from wind during all calibrations.

9.2.2.8 Soil temperature. See clause 9.2.2.3 for lab calibration. In-field reliability of soil temperature sensors may be checked using a laboratory-calibrated insertion type soil temperature probe of appropriate length.

9.3 Maintenance

9.3.1 Site. Perform the following maintenance during each station visit. Security equipment should be maintained in working order through visual inspection and through annual refurbishing as needed. The grounds surrounding the site should be maintained in a condition similar to the surrounding vegetation, but with the additional condition that plant growth should not interfere with operation of the sensors; this should involve weed control, grass mowing, etc. as appropriate. Trash should be picked up and removed as needed. If local personnel are available, the site should be inspected weekly.

9.3.2 Sensors. The following maintenance duties should be performed during each station visit. All leads from the sensors to the data logger should be secured to station structure (if not routed through the interior of the structure) using black UV resistant cable ties. Check the condition of wire/cable ties. Check the condition of all exposed cables and wire leads for signs of UV breakdown, mechanical damage, etc. The length of exposed cable may be minimized by pulling it through flexible plastic conduit.

9.3.2.1 Solar radiation. Carefully clean sensor surface and check instrument mount to ensure the instrument is level.

9.3.2.2 Air temperature. Clean radiation shield(s) housing the sensor. Gently clean sensor of dust, cobwebs, etc. If sensor is housed within a filter element, remove and gently clean filter.

9.3.2.3 Relative humidity. Clean radiation shield housing the sensor. Gently clean sensor of dust, cobwebs, etc. If sensor is housed within a filter element, remove and gently clean filter.

9.3.2.4 Wind speed. Clean anemometer cups or propeller vanes of dust and cobwebs. Check for dents or cracks. Check instrument level. Check anemometer starting torque for bearing condition. Simple checks such as listening for noise in bearings and/or temporarily shielding the anemometer from wind to visually monitor startup and stop responsiveness are valuable diagnostics in determining bearing fatigue and fouling. In dusty environments replace bearings semi-annually.

9.3.2.5 Wind direction. Clean sensor surfaces of dust, cobwebs, etc. Check instrument level. Verify orientation of vane relative to true north and proceed to check sensor output at a minimum of each of the four coordinate directions (N-0 or 360, E-90, S-180, and W-270). Simple checks such as listening for noise in bearings and temporarily shielding the vane from wind to visually monitor startup and stop responsiveness are valuable diagnostics in determining bearing fatigue and fouling. Significant deviations between sensor output and known compass direction may occur when winds are predominantly from a narrow sector of the compass, this indicates the potentiometer is worn in that area and should be replaced, even though the readings from other directions may be acceptable.

9.3.2.6 Precipitation. Clean all components of gage of dust, cobwebs, insects, etc. Install screens over all ports to the interior of the gage to minimize entry of spiders and insects. Check that drainage ports are clean and functional. Check instrument level (funnel orifice opening and instrument base). For tipping buckets, ensure pulse output is received at data logger correctly for each manual tip of the bucket. Verify movement of bucket over entire range of movement. When gage is installed away from the main station structure, leads from the gage to the data logger should be buried below ground surface in a moisture- and rodent-proof conduit to prevent mechanical damage by grounds maintenance equipment and rodent chewing damage. Conduit encasement should extend above ground to the entry point of the leads to the interior of the gage and up the station structure a minimum of 0.4 m. Each end of the conduit should be sealed. If a windscreen is used, check to ensure it is level and no more than 12.5 mm above the level of the orifice, with the orifice centered within the screen.

Weighing type gages should be serviced at least once each year by washing all moving parts of the weighing mechanism with a solvent to remove grease. If the moving parts of the gage are lubricated, a dry graphite lubricant should be used. If freezing temperatures are not expected, lightweight oil with a specific gravity of 0.8 to 0.9 should be placed in the bucket to retard evaporation. If freezing temperatures or snow are expected, an oil-ethyl glycol antifreeze solution should be placed in the bucket to melt snow by chemical action, to prevent freezing of the solution, and to retard evaporation.

9.3.2.7 Soil temperature. When a sensor is installed away from the main station structure, wire leads from the sensor to the data logger should be buried below ground surface in a moisture- and rodent-proof conduit to prevent mechanical damage by grounds maintenance equipment and rodent chewing damage. Conduit encasement should extend a minimum of 0.4 m above ground at the station structure. The bare soil surface specification for this measurement (see Table 1) requires that a soil sterilant be used, or periodic weeding be performed, to keep the surface above the sensor (approximately 1 square meter) free of vegetation. A laboratory-calibrated bimetallic dial-type insertion thermometer of appropriate length(s) may be used to check sensor output.

9.3.3 Data logging and telemetry equipment. Inspect equipment during each station visit. Check all connections, plugs, etc., including wiring panel for sensor inputs, wire/cable connections to data storage device or to data telemetry equipment. Inspect data telemetry equipment as follows:

9.3.3.1 Telephone communications. The external telephone lines are the responsibility of the telephone company providing service to the site, and procedures for contacting the company when data can not be retrieved and when other potential sources of difficulty have been eliminated should be clearly established. Any internal phone lines and switching equipment (if applicable) should be inspected annually and repaired or replaced as necessary. Modems should be replaced annually and whenever data storage equipment is replaced due to damage/failure. These units should then be tested under laboratory conditions and repaired as necessary to bring them up to specifications.

9.3.3.2 RF Telemetry and satellite telemetry. Check antenna/cable (each station visit). The proper orientation of directional antennae should be verified. All cable connections at the antenna must be maintained in waterproof condition. The cable path to the transceiver should be secure. Inspect cable connections at the transceiver.

Transceiver performance should be checked semi-annually. Use a watt meter to check forward and reflected power. Take corrective action as needed to reduce any reflected power to acceptable levels. The transceiver transmit frequency must be maintained within federal agency guidelines. Check for frequency drift on the transmit side and check receive-side sensitivity. Check the power supply to the transceiver and verify it is within operational specifications for the transceiver.

Appurtenant telemetry equipment (repeaters for RF systems, base station receiving equipment, etc.) should be checked and tests performed as outlined above.

9.3.4 Power supply. During each station visit, perform the following inspections and clean and/or repair as needed.

9.3.4.1. Stations on AC power. Check all power connections. Check and verify output of power transformers with a DMM.

9.3.4.2. Stations on DC power. On stations operated with battery power and no solar panel, check for corrosion at all battery terminals and power cable connectors. Check voltage output of battery pack with a DMM. Maintain a comprehensive written record of battery replacement. On stations with battery power and a solar panel, check for corrosion at all terminals and power cable connectors. Check voltage output of battery with a DMM. Check voltage output of solar panel with a DMM (this may require connection of an artificial load to obtain realistic steady readings). Clean the surface of the solar panel. If the battery is a wet cell type, it should be housed in a separate enclosure. Check fluid levels and refill as needed. Clean and maintain the enclosure as needed. Maintain a written record of battery maintenance and replacement schedule.

9.3.4.3 Cables. Secure all power cables, ground wires, etc. to the station structure using black UV resistant wire/cable ties.

9.3.5 Station structure. Instrument support structures (towers, tripods, etc.)and instrument/electronic equipment enclosures should be inspected semi-annually and painted, repaired, and/or replaced as necessary to keep them functioning properly. Check and tighten all clamps, nuts, bolts, etc. Lightning protection in the form of fully grounded, heavy-duty lightning rods should be provided with these support structures. Support structures and the electronic equipment enclosures must be properly grounded to the lightning rods.

Maintain fresh desiccant inside data logger enclosure. Inspect the desiccant at each station visit and replace as needed with a fresh supply. Check the cable and wire ports into the enclosure to ensure they are sealed.

All cables should be secured neatly to convenient support structures using black UV resistant cable ties and protected from accidental damage by lawn mowers, etc., where necessary. Inspection for damaged or deteriorating cables should be carried out yearly, and cables should be replaced as necessary. Similarly, panels and any other electrical connection devices should be inspected annually for proper performance and maintained in a suitable state of repair.

10 Data management

10.1 Data quality assurance/quality control. Weather data collected by automatic agricultural weather stations or networks of stations should be subjected to quality assurance/quality control (QA/QC) programs for validation before dissemination or archival. A quality assurance plan of action should be formulated that contains all of the information specified in clause 7, Documentation, as well as summary documentation indicating compliance with the QA plan and appropriate updating of the recommended documentation on a regular basis.

10.2 Data validation and flagging. Data validation consists of routine review of data by experienced or trained personnel, screening of data to identify possible erroneous values, and random comparisons of data with other available data. Manual data reviews should be conducted on a frequency relative to the frequency with which data are retrieved at the central processing facility, i.e., daily reviews for data retrieved hourly or daily, etc. Data sets should be scanned for obvious incorrect values, missing data, etc.

Automatic data screening is easily performed by passing incoming data through a computer program that will check the data against specified screening criteria such as the allowable ranges for the data , historical maxima or minima, allowable rates of change, etc. Screening criteria may be based on historical data and physically realistic values. Site-specific screening criteria should be developed for each weather station. Data that do not meet screening criteria limits should be flagged for later investigation.

Data from adjacent stations should be randomly compared to assess whether instrumentation operation/calibration are changing over time. This is often done most expeditiously by using graphical techniques. Discrepancies that cannot be explained by geographic differences or regional climate variability should be flagged for further investigation.

Trained personnel should further evaluate any data flagged by the above procedures. Anomalous flagged data may be left as measured and received, but should be re-flagged with a flag indicating questionable values. Flagged data should be saved. Flagged data values that are replaced with back-up data, nearest-neighbor data, or interpolated values should remain flagged, indicating the action taken. All data changes occurring during the data validation process should be fully documented.

10.3 Data format and archival. Data storage formats for intermediate and long term storage (archival) to be used by the personnel operating a weather station, or a network of stations are not specified here due to the variety of commercial and privately developed database systems in use.

Procedures should be implemented to make all data available upon request to all potential users in a minimum of a fully documented, concise ASCII format . This documentation should include station location data (latitude, longitude and elevation); instrument exposure and deployment heights; and descriptions of the variables (order, format, units). Each record of daily data should be date stamped with the year and day of the year. Each record of data collected on a finer time scale (e.g., hourly or 15-minute) should be time stamped with the year, day of the year, and time of day.

Weather station history (site documentation, maintenance and calibration documentation, etc.) should be made available to all users upon request.

A plan for long term storage or archival of all data collected by automatic agricultural weather stations is recommended. The State Climatologist or the nearest Regional Climate Center should be contacted for advice. Archival formats and procedures are not specified here, however, procedures to produce the minimum recommended ASCII format described above should be implemented.

Annex A
(informative)
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Siting and Instrument Specifications for Texas Agricultural Meteorological Networks
By
Howell, T., Marek, T., and Dusek, D.

Siting

Location sites of weather stations can be in dry land pastures or mowed CRP fields which represent as much as possible the surrounding, representative agricultural area. Specific siting of a station can also be dependent on the intended use of the data. Thus, sites can also within irrigated production regions such as within the corners of center pivots or adjacent to production fields; however, the data may be altered from other typical dry land sites and as such these siting locations should be noted. Sites are to be free of trees or buildings or other major obstructions from the prevailing wind direction for at least 1/4 mile and preferably further. Topography of the area should also be considered. If the general area is rolling, a rolling area station site can be acceptable. However, locating sites downwind or adjacent to valleys or gullies should be avoided, as humidity readings particularly will be temporally affected during morning periods. Similarly, hilltops are not desirable due to wind variations. If livestock are in the pasture or field a square 2 to 3 wire electric fence with a solar source is suggested to be constructed approximately 100 feet by 100 feet with the station tower centered within the fenced area. A second interior fence of approximately 35 feet square with a personnel gate to allow easy access for maintenance is constructed and centered within the electric fence. Both areas and a 10-foot region outside the outer fence is to be maintained several times a year by mowing with weed and ant hill and other non-desirable critter eradication as needed. The maintained height of the mowed grass should be 4.5 inches tall. The inner fence can be constructed of electromechanical metal tubing (EMT) framing with 3 rebar intermediate posts and 2 inch by 4 inch welded wire fencing and is to be no more then 4 feet high. The interior fence is designed to prevent intrusion by animals such as rabbits that chew on the instrumentation wire leads at the tower base.

Meteorological Station

The meteorological stations should adhere to the ASAE engineering practice proposed for agricultural weather stations that collect data for calculations or ETo. (A copy of the proposed standard is attached in Appendix G). The station tower can typically be mounted on a concrete block approximately 2 feet square by 5.5 inches in depth. The concrete block is buried to ground level and leveled as much as possible. Tower height should be capable of holding topmost instrumentation to a maximum height of 6 feet -6 inches (2 meters). Additionally, a 2 feet high grounding rod is suggested to be mounted atop the tower for lighting protection and is to be firmly grounded to an 8 feet – ¾ inch diameter copper coated, steel grounding rod driven into the soil a minimum of 7 feet deep.

The instrumentation should include the following and be at these heights:

Solar radiation	Li-Cor LI-200 silicon pyranometer	1.5 -2.0m
Temperature	Thermistor type Viasala HMP-35C or HMP-45C	1.8m
RH	Capacitance type Viasala HMP-35C or HMP-45C	1.8m
Wind speed	Cup type RM Young Anemometer starting threshold @ .2m/s	2.0m

Wind Direction	RM Young Vane potentiometer starting threshold @ .8m/s	2.0m
Precipitation	Tipping bucket .0l-inch (typically 6 inch diameter)	2.0m
Soil Temperature	Thermistor type @ 2 and 6 inches	
Radiation shield	Gill type with l2 plates	
Barometric Pressure	Silicon capacitive type Viasala	
Leaf Wetness Sensor	Electrical resistance type CSI model 237	

A soil ring, approximately 1 meter in diameter by 4 inches deep, is set and the soil temperature thermistors are inserted horizontally at 2 and 6-inch depths below the nominal soil surface in a horizontal plane from a vertically dug trench. (Vertical insertion of the sensors can cause rainfall to run down the wire or developing crack from a vertical passing wire and is easy to dislodge from the expected depth through swelling and shrinking by the soil). All wires leading to the soil ring are to be placed underground in ¾ inch diameter PVC pipe to protect from burrowing rodent damage. A drip loop is established at the tower with PVC fittings and the tubing extends to and beneath the soil ring into the soil temperature placement trench. The soil ring is installed 2 inches into the soil, leaving a 2-inch freeboard above the nominal ground surface. The interior of the soil ring should be treated annually with a soil sterilant herbicide to provide a vegetation free surface (i.e., bare ground). Full maintenance on the station sensor should occur annually before the summer cropping season. Wind anemometer and direction sensors should have bearings replaced at that time. If the station is located in blowing sand prone areas, bearings will typically have to be replaced twice during the year. Temp and RH sensors will need replacement and recalibration annually.

Data loggers are suggested to be obtained from Campbell Scientific Inc. Several models such as the CR-10, CR- !0X, or CR-2IX with 2k programming memory have been satisfactorily used over time. Campbell Scientific data loggers and sensors are recommended for the reasons of sustainable performance and stability of the units and the company, recalibration of sensors, and technical support of both. Data loggers should be powered by battery and solar panels or by AC with battery backup. The CR-10X has analog sensitivity of 13 bits over 2.5mV to 2.5V with 12 single ended (6 double) analog channels, 2 pulse counting channels, 3 excitation channels, 2-5V control output channels, and 8 digital I/O ports. Communications for data collection is by either landline telephone or cellular telephone or more recently, short haul radio transmission. Remote cellular telephone sites require a second standard car battery and charger for the cellular operating amperage. The cellular phone typically also has to be programmed to activate and deactivate the phone at set times to prevent battery depletion or a larger, more costly solar panel must be provided.

Data collection is suggested at an interval of once daily by multi-computers for backup purposes. The main data computer should typically collect data and maintain data logger clock time starting at 12:05 AM, calculate all data for computation and output formats. Automated forwarding and uploading to web sites should occur before 6:00 AM. All these operations can be accomplished with scripts in multiple operating systems. An error file should also be logged to notify administrators of malfunctions.

Data logger programs

Data logger programming for output should be constant for all stations within a network, even if an individual instrument is not available for a particular station (for instance, in the North Plains ET network, leaf wetness or barometric pressure are only at select locations).

Outputs of the North Plains ET network which are processed daily are as follows:

Hourly Outputs (24 each day)

1	id	129
2	month	Month
3	dom	Day of Month
4	year	Year
5	doy	Day of Year
6	time	Time
7	sig	Site program signature (CRC)
8	battery	Battery Voltage
9	temp	Internal Temperature (C)
10	soil2	2" Soil Temperature (C)
11	soil6	6" Soil Temperature (C)
12	air	Air Temperature (C)
13	dew	Dew Temperature (C)
14	rh	Relative Humidity (%)
15	svp	Saturation Vapor Pressure (kPa)
16	vp	Actual Vapor Pressure (kPa)
17	vpd	Vapor Pressure Deficit (kPa)
18	Rs	Solar Radiation (Watts)
19	ws	Wind Speed (m/s)
20	dir	Wind Direction (degrees)
21	sd	Standard Deviation Wind Dir (degrees)
22	precip	Hourly Precipitation (.01 inches)
23	0-15	Precipitation 1-15 minute into hour
24	15-30	Precipitation 16-30 minute into hour
25	30-45	Precipitation 31-45 minute into hour
26	45-60	Precipitation 46-60 minute into hour
27	Iwet	Leaf Wetness (voltage output)
28	bp	Barometer Pressure (kPa)

Daily Summary

1	id	139
2	year	year
3	doy	day
4	time	2400
5	sig	Site Signature
6	soil2	24 hour average 2" soil temperature

7	soil6	24 hour average 6" soil temperature
8	max2	24 hour maximum 2" soil temperature
9	time	Time of previous event
10	max6	24 hour maximum 6" soil temperature
11	time	Time of previous event
12	min2	24 hour minimum 2" soil temperature
13	time	Time of previous event
14	min6	24 hour minimum 6" soil temperature
15	time	Time of previous event
16	airT	24 hour average air temperature
17	maxT	24 hour maximum air temperature
18	time	Time of previous event
19	minT	24 hour minimum air temperature
20	time	Time of previous event
21	dewT	24 hour average dew temperature
22	maxdewT	24 hour maximum dew temperature
23	time	Time of previous event
24	mindewT	24 hour minimum dew temperature
25	time	Time of previous event
26	RH	24 hour average RH
27	maxRH	24 hour maximum RH
28	time	Time of previous event
29	minRH	24 hour minimum RH
30	time	Time of previous event
31	VP	24 hour average VP
32	maxVP	24 hour maximum VP
33	time	Time of previous event
34	minVP	24 hour minimum VP
35	time	Time of previous event
36	VPD	24 hour average VPD
37	maxVPD	24 hour maximum VPD
38	time	Time of previous event
39	minVPD	24 hour minimum VPD
40	time	Time of previous event
41	SR	24 hour average Solar Radiation
42	maxSR	24 hour maximum Solar Radiation
43	time	Time of previous event
44	maxWS	24 hour maximum wind speed
45	time	Time of previous event
46	WS	24 hour average wind speed
47	dir	24 hour average wind direction
48	wsSD	24 hour standard deviation of wind direction
49	precip	24 hour precipitation
50	Lwet	24 hour leaf wetness
51	bp	24 hour barometric pressure
52	bpmax	24 hour maximum barometric pressure

53	time	Time of previous event
54	bpmin	24 hour minimum barometric pressure
55	time	Time of previous event

Data quality control

All original data from the data loggers are maintained as is and additional data files are created during QA/QC. Thus no destruction of the original data takes place if problems or questions are encountered in the future.

Primary data scanning is in the main network program that makes all calculations and writes the files for the web database and faxing sheet outputs. Extremes in all outputs are checked and if problems or out of range numbers are detected, -99999 is written into the data set and an error log is additionly output denoting location, date and time (if applicable) and instrument problem.

Secondary QA/QC is done as time allows, generally by 10 day periods when archiving normally takes place, and is by manual review of visual graphics using scripts and spreadsheet macros to load the original 'raw' data and display the graphics. The spreadsheet loads the hourly and daily data and graphically compares the hourly averages, sums, maximums and minimums to the daily outputs of the same. Spikes in the values are manually located and decisions made to correct the data for possible data logger spikes, if that is determined. If other problems are detected (such as RH > 100% over several days) on site visits are scheduled for instrument replacement. Otherwise if no recourse can be found the -99999 data is maintained and the data is declared missing (for example, frozen anemometer or wind vane for long periods of time). Spread sheet macros then rewrite the 'corrected data' into a new corrected file and the programs which are used on the original real time outputs are then rerun and corrected web updates are uploaded to provide the best possible data generally within 10-15 days of the original posting. For illustrative purposes, a fax sheet and daily meteorological output file are shown below with -9's for missing data. Other files for importation to other ET network sites and locations can be processed and forwarded similarly once the data integrity has been checked and verified. The format of the suggested format to the Spatial Sciences Laboratory (SSL) will be addressed below.

North Plains ET Network Weather Station, Dalhart, TX

Date	ETo in.	Temperatures (F) ---Air-- Max	Min	Soil Min 2in.	6in.	Prec. in.	Growing Degrees Days (F) Crn	Srg	Pnt	Cot	Soy	Wht
07/24/2001	.27	99	60	73	85	0.00	23	30	23	20	27	0
07/25/2001	.28	98	66	77	86	0.00	26	32	26	22	30	0
07/26/2001	.25	95	64	76	86	0.00	25	29	24	19	29	0

10-day avg min soil temp 73 85 Wind 4.7 mph from 83 deg.

CORN Seed Date	Acc GDD	Short Season Var. Water Use Growth Stage	Day	3day	7day	Seas. in.	Long Season Var. Water Use Growth Stage	Day	3day	7day	Seas. in.
04/01	2089	Dent	.25	.30	.32	25.4	Milk	.32	.35	.36	25.4
04/15	1924	Dough	.30	.34	.36	22.5	Blister	.32	.35	.36	22.3
05/01	1717	Milk	.32	.35	.36	18.5	Silk,	.32	.35	.36	18.3
05/15	1552	Blister	.32	.35	.36	15.6	14-leaf	.31	.33	.35	15.4

SORGHUM Seed Date	Acc GDD	Short Season Var. Water Use Growth Stage	Day	3day	7day	Seas. in.	Long Season Var. Water Use Growth Stage	Day	3day	7day	Seas. in.
05/01	1905	Flower	.25	.28	.30	15.1	Boot	.27	.29	.29	14.0
05/15	1755	Boot	.27	.28	.27	13.0	Flag	.23	.25	.26	12.0
06/01	1466	Flag	.23	.25	.25	9.6	GPD	.20	.21	.20	8.8
06/15	1158	GPD	.20	.21	.22	6.7	5-leaf	.17	.19	.19	6.3

COTTON Seed Date	Acc GDD	North Plains Area Water Use Growth Stage	Day	3day	7day	Seas. in.	South Plains Area Water Use Growth Stage	Day	3day	7day	Seas. in.
05/01	1027	1st Sqr	.24	.26	.27	10.7	1st Sqr	.24	.26	.27	11.2
05/15	987	1st Sqr	.24	.26	.27	9.7	1st Sqr	.24	.26	.27	10.2
06/01	889	1st Sqr	.24	.26	.27	7.8	1st Sqr	.24	.26	.27	8.4
06/15	721	Emerged	.12	.13	.14	4.9	1st Sqr	.24	.26	.19	5.3

SOYBEANS Seed Date	Acc GDD	Late Group 4-Var. Water Use Growth Stage	Day	3day	7day	Seas. in.
05/15	1806	R_4	.28	.30	.31	14.6
06/01	1495	R-2	.21	.22	.23	10.3
06/15	1153	V-6	.21	.22	.23	7.3
07/01	757	V-2	.15	.16	.17	4.0

Corn Rootworm Estimated Hatch 100.0%
Corn Rootworm Estimated Adults 100.0%
Fescue/Bluegrass lawn water use 0.24 inch
Bermuda grass lawn water use 0.18 inch
Buffalo grass lawn water use 0.12 inch

Last data calculation 01-13-2003 23:55

Station:DALHART, TX Long 102 deg 32 min Lat 36 deg 20 min
Date:07/26/2001 Year/DOY:2001207 Elev: 1223 m   Bar. Corr: 13.8
Sunrise 551 Sunset 2000   Daylight time = 14 hours 8 minutes

Time CST	Rs W/m^2	Ts2 C	Ts6 C	Tair C	TDew C	RH %	AVP kPa	VPD kPa	WSpd m/s	Wdir deg	SDd deg	PREC mm	BP kPa	ETo mm
100	0.0	28.2	33.3	20.8	17.1	79	1.95	0.51	1.1	359	29	0.00	-99.9	0.00
200	0.0	27.5	32.7	20.3	16.7	80	1.90	0.48	1.1	55	16	0.00	-99.9	0.00
300	0.0	26.8	32.2	20.9	16.8	77	1.92	0.56	2.3	326	25	0.00	-99.9	0.01
400	0.0	26.6	31.7	21.8	16.9	74	1.93	0.68	2.5	29	15	0.00	-99.9	0.02
500	0.0	25.7	31.2	20.3	16.3	78	1.86	0.52	1.4	30	19	0.00	-99.9	0.00
600	0.8	24.8	30.8	18.5	16.2	86	1.84	0.29	0.5	33	22	0.00	-99.9	0.00
700	68.0	24.3	30.4	18.5	16.2	87	1.85	0.28	0.6	83	18	0.00	-99.9	0.03
800	251.9	26.0	30.1	21.7	16.7	74	1.90	0.70	1.6	75	11	0.00	-99.9	0.16
900	452.3	29.3	30.1	24.9	16.3	59	1.85	1.30	2.5	94	18	0.00	-99.9	0.34
1000	635.6	33.4	30.4	26.8	16.2	52	1.84	1.68	2.1	105	21	0.00	-99.9	0.48
1100	766.4	38.3	31.0	28.6	16.4	48	1.87	2.03	1.3	75	38	0.00	-99.9	0.58
1200	778.2	42.5	32.1	30.0	16.6	45	1.89	2.34	1.5	44	44	0.00	-99.9	0.62
1300	930.2	45.7	33.4	31.5	16.0	39	1.82	2.81	1.5	39	44	0.00	-99.9	0.74
1400	818.9	47.6	34.8	32.7	16.6	38	1.89	3.05	2.6	70	26	0.00	-99.9	0.72
1500	599.6	44.8	36.0	33.5	15.6	34	1.78	3.41	3.8	104	13	0.00	-99.9	0.63
1600	522.6	43.7	36.6	33.7	15.5	34	1.76	3.47	4.2	114	13	0.00	-99.9	0.59
1700	439.1	41.9	36.8	33.4	13.8	31	1.58	3.58	4.4	140	17	0.00	-99.9	0.55
1800	209.7	39.0	36.8	30.5	13.5	35	1.55	2.83	4.5	158	19	0.00	-99.9	0.37
1900	31.3	34.6	36.4	26.2	12.7	44	1.47	1.94	5.7	130	23	0.00	-99.9	0.25
2000	26.6	31.6	35.6	25.1	13.8	50	1.58	1.61	1.9	92	18	0.00	-99.9	0.10
2100	0.3	30.3	34.7	23.4	15.3	60	1.73	1.14	1.0	135	16	0.00	-99.9	0.00
2200	0.0	28.9	34.0	23.1	16.2	65	1.84	0.99	1.2	162	13	0.00	-99.9	0.01
2300	0.0	28.3	33.3	23.2	15.6	63	1.78	1.06	1.5	278	41	0.00	-99.9	0.02
2400	0.0	27.3	32.6	20.3	16.2	77	1.84	0.55	0.5	255	48	0.00	-99.9	0.00
Sum	23.5 MJ											0.00		6.22
Avg		33.2	33.2	25.4	15.8	59	1.80	1.58	2.1	83	62		-99.9	
Max	1092.3	48.1	36.9	35.0	18.4	90	2.11	3.95	11.9				-99.9	
Time	1342	1343	1636	1535	1335	628	1335	1621	1844				9999	
Min		24.2	30.0	17.8	10.7	28	1.29	0.21					-99.9	
Time		623	810	621	1832	1636	1832	626					9999	

APPENDIX C

SELECTED PROJECT PRESENTATIONS
TAMA GROUP

Review and Discussion of Water Methodologies Used in Other States

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Division of Agriculture
West Texas A&M University
Canyon, Texas

Water Used for Irrigation in US

- Total water use 153 maf (137, 000 Mgal/d)
- 65 % of total freshwater withdrawals
- 61.9 million acres irrigated in 2000
  - 29.4 ma surface (flood) systems
  - 28.3 ma sprinklers systems
  - 4.2 ma micro-irrigation systems
- Average application rate 2.48 af/acre

Irrigation Water Use in 2000 in Selected States

State	Irrigated Land Acre (000)	Water Use Ac-ft (000)	Application Rate Ac-ft/acre
California	10,100	34,200	3.37
Idaho	3,750	19,100	5.10
Colorado	3,400	12,800	3.76
Nebraska	7,820	9,860	1.26
Texas	6,490	9,680	1.49
Arkansas	4,510	8,870	1.97
Kansas	3,310	4,160	1.26
New Mexico	998	3,210	3.22
Oklahoma	507	804	1.59

Irrigation Water Sources

- Irrigation is the largest user of ground water 63.8 million acre-feet (maf)
- 89.7 maf surface water
- Increasing withdrawal from groundwater for irrigation (23 percent in 1950 to 42 percent in 2000

Irrigation Water Use Estimation Key Factors

- Methods vary by geographic areas
- Climatic variables, crop composition, application efficiencies, conveyance losses, and other irrigation practices influence irrigation water demand
- Comparison and analyses of methodologies act as a baseline for developing water management plans and addressing water related policy issues

Estimation Methods in Use

- Evaportranspiration (ET) based method
- Crop growth simulation model
- Remote sensing or geographic information system (GIS) based method
- Most of them require ground based meteorological data, usually with a daily time step
- Application of a specific method on a large irrigation area needs an access to a network of meteorological stations with a suitable spatial density

Evapotranspiration (ET) Based Method

- Amount of water needed by the various crops under an optimal crop growth condition
- Modified Penman method - most commonly used
  - Combination method
  - Overestimate ET, even by up to 20% for low evaporative conditions
  - local calibration of the wind function is required (CIMIS)
- The Blanley-Criddle method
  - amount of consumptive water used by plants during their normal growing season
  - Closely related with mean monthly temperatures and daylight hours
  - Inaccuracy, long-term records required

Evapotranspiration (ET) Based Method

- Other methods
  - the Lowry-Johnson, Jensen-Haise and Thornthwait
  - Jensen-Haise is claimed to be the most accurate but needs solar radiation data
- The standardization of reference ET
  - Developed by ASCE ET in Irrigation and Hydrology Committee in cooperation with the Water Management Committee of Irrigation Association
  - Provide common national basis in calculation of ET

Plant Growth Models

- Relationship between crop productivity and environmental factors
- EPIC, CERES, GAPS, SOYGRO and IBSNAT
- When introducing such crop models into new regions, their applicability should be evaluated
- Crop Environment Resource Synthesis (CERES) – maize
  - simulate crop (maize) growth, soil, water and temperature and soil nitrogen dynamics at a field scale for one growing season
  - related to other CERES models
  - immense spatial data as inputs required

Remote Sensing and Geographic Information System (GIS) Technology

- The GIS : analyze, model, and display multiple sets of information using computerized maps as the primary form of system output
- Images and other remotely sensed information with GIS computer programs
- A synoptic perspective critical for understanding biophysical relationships at a regional scale
- Timing of the photographs or images is critical
- Additional field surveys required
- Limitations
  - data availability, length of recording period, limited mapping capability, requirement of expertise, availability of computer facilities, and cost

Advantages and Disadvantages

Method	Advantage	Disadvantage
ET	1. Easy to apply using commonly available weather data 2. Easy to understand and visualize 3. High acceptance rate 4. Has been conventionally used and applied in agricultural water use estimation across country	1. Site-specific data requirement 2. Long-term data is required 3. Requires calibration for a specific area or region.
Crop Growth Model	1. Determine the response of crop plants to changes in weather and climate 2. Better performance with rain fed than irrigated water use 3. Integrate daily effects of temporal stress on growth and yield	1. Requires lot of spatial data as inputs 2. Site specific and crop specific 3. Discrepancy between predicted water use and observed one later in the growing season
Remote Sensing/ GIS	1. More successful in arid and semiarid land 2. Useful in identifying crop types and crop acreage in areas where crop calendars are more diverse 3. Cost effective way to provide maps to GIS models	1. Limited mapping capacity 2. Requires expertise and computer facility 3. Data limitation due to discrete time events 4. Lack of information on plant growth and environment status

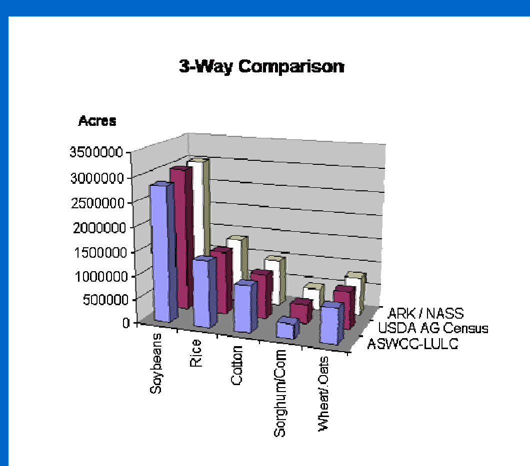
Water Use and Estimation Methods

State	Irrigated Land (000 ac.)	Water Used for Irrigation (000 acre-feet)			Estimation Methodologies
		GRD.	SUR.	Total	
Arkansas	**4,510**	**7,290**	**1,580**	**8,870**	**GIS-Landsat Theuamatic Mapper, Digital Land Use/Land Cover (LULC)**
California	**10,100**	**13,100**	**21,100**	**34,200**	**ET (SIMETAW, CUP), GIS**
Colorado	**3,400**	**2,420**	**10,400**	**12,820**	**ET (Modified Blanley-Criddle, Penman-Montieth), State CU Model, Colorado Decision Support System**
Idaho	**3,750**	**4,170**	**15,000**	**19,170**	**FAO-MBC, Kimberly Penman Equation, Remote Sensing (SEBAL)**
Kansas	**3,310**	**3,840**	**323**	**4,163**	**Regional Standard ac-ft/ac, County Standard, Hydro Data Software**
Nebraska	**7,820**	**8,320**	**1,540**	**9,860**	**PET, Crop ET, Conveyance Losses**
New Mexico	**998**	**1,380**	**1,830**	**3,210**	**ET (Blanley-Criddle), Effective Rainfall**
Oklahoma	**507**	**635**	**170**	**804**	**General Irrigation Rate (Region Specific), Irrigated Base Acres**
Texas	**6,490**	**7,290**	**2,390**	**9,680**	**ET, TAMA Model, Crop Growth Models, GIS**
Total	**40,882**	**48,445**	**54,333**	**102,778**	

Arkansas

- The Mississippi Alluvial Valley (MAV)
- Digital land-use/land-cover (LULC) maps focuses on agricultural land-use for the 27 Arkansas counties within MAV
- Landsat Theumatic Mapper (TM) satellite imagery used to develop LULC
- The planting patterns and phenologies of the major crops were examined in the land image selection work
- Informal interviews
- LULC depicts season to season land-use/land-cover patterns

Arkansas



California

- Statewide Water Planning Branch of Department Water Resources estimates of crop ET and applied water with irrigated acreage data collected through Land Use Survey Program
- Effects of change in irrigation methods, geographic variation in ET and cultural practices are considered
- CUP and SIMETAW
  - CUP : determine crop coefficient and crop ET, computes reference ET using daily Penman-Monteith equation, accounting for rainfall, cover crops and immaturity factors for estimating crop ET
  - SIMETAW : simulate many years of weather data from monthly climate data to estimate reference ET, crop ET, effective rainfall and ET of applied water

Colorado

- Colorado Water Conservation Board
- Irrigation Water Requirement (IWR) with climate data of State's Consumptive Use Model
- Based on the modified Blanley-Criddle and the Penman-Montieth method
- Wide application of State's CU model is restricted by the lack of adequate climate data
- For projected water demand in 2030, CWCR assumed that irrigated acres in 2030 would remain constant

Idaho

- The Blanley-Criddle equation, the FAO-modified Blanley-Criddle method, and Remote sensing and GIS tools
- SEBAL : developed by the University of Idaho (UI) and The Idaho Department of Water Resources (IDWR)
- SEBAL (Surface Energy Balance Algorithm for Land)
  - an image-processing model comprised of twenty-five computational steps that calculate ET and other energy exchanges at the earth's surface using digital image data
  - accurate prediction of past, current and future ET
  - does not require intensive ground, meteorological or land use information
  - provides an independent means to identify and confirm lysimeter ET data

Kansas

- KWA approved assessment of the high irrigation water use
  - Measure inefficient irrigation water use
  - Reduce high irrigation use or an amount of water that exceeds the reasonable irrigation level of applied water for a specific area by 2010
- Two ways to measure high irrigation use
  - the number of points of diversions and the amount of water applied in acre-feet per acre
  - the number of irrigation water rights
- Regional AF/A standards used to decide appropriate water for irrigation use (1.0 for eastern, 1.5 for central, and 2.0 western)
- New county-based standards -- benchmark amounts considered reasonable for irrigation
- Monthly rainfall was obtained from Hydrodata software of Hydrosphere Data Products Inc for the comparison reason

Nebraska

- Four categories of crops : high water consumptive crops, low water consumptive crops, hay and small grains
- Potential ET and precipitation data
- A network of automated weather stations by University of Nebraska
- The relationship between PET and crop ET during crop growth has been examined and ET for each crop was estimated from PET
- Crop irrigation requirement was also calculated for the four categories at all stations to calculate the irrigation demand
- Crop water use per county : the use by sprinkler system and the use of other water application methods

New Mexico

- OSE, New Mexico Water Planning
- The Blanley-Criddle model used
- Climatic Data : temperature, monthly percentage of annual daylight hours based on the latitude of the area under study, seasonal consumptive use coefficients, and length of growing season
- Some components were added to explain discrepancies between USDA and NMASS estimates
- A large degree of year-to-year variability in water use by irrigated agriculture
- Additional survey to evaluate the crop consumptive water use

Oklahoma

- Okalahoma Water Resource Board
- Potential irrigated acreage and the general irrigation rate to project the future irrigation water demand
- Potential irrigated acreage: number of actual irrigated acres and acres potentially available for irrigation
- General irrigation rate
  - Lands in the east one acre-foot per acre
  - 1.5 acre-feet in the mid-region counties and
  - 2 acre-feet in the western counties
- Total water demand of each region estimation by multiplying the potential irrigated acres by the general irrigation rate of the region

Texas

- The PET based water application of individual crop by TWDB for comparing the NRCS estimates
- The ET methodology has been used for developing irrigation water demand model for Texas Panhandle Water Planning Area
- TAMA group utilized calibrated crop ET values from the North Plains Evapotranspiration (NPET) network
- Due to the excellent agreement for the baseline year of 1997, Irrigation water demand model was employed in a subsequent project
- A crop growth model approach by the TAES-Temple group
- Cropping distribution for the 50-year planning period needs to be determined
- Changes in irrigated acreage and conveyance loss of surface water also need consideration
- Remote sensing study of irrigated acreage and metering crop water application for better projection of irrigation water demand

Comments/Questions

Development of an Agricultural Water Use Estimating Methodology – TAMA ET Network Based Model

Thomas Marek, P.E.
Research Engineer & Superintendent
Amarillo/Etter, TX

TAMA Model Project Team

Thomas Marek
Steve Amosson
Leon New
Terry Howell
Fran Bretz
Lal Almas

Texas A&M -Amarillo (TAMA) Crop Water Use Model Approach - What is it?

- The Texas A&M - Amarillo irrigation water use demand estimate model is a model based on a categorized crop water use approach for multiple crops on a county by county basis.

The TAMU Model

…really a simple model

Methodology

TAMA Model

is basically
a water balance model!

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Texas A&M -Amarillo (TAMA) Crop Water Use Approach

Irrigation Water Pumped =
Crop PET x (% Applied)
- Effective Rainfall
- Soil Profile Water Used

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TAMA Model

$$P_T(ET_C) = IRR_C + ER + SSM_D$$

where:

P_T =Percentage of crop ET pumped on a seasonal basis, (in),

ET_C =Crop ET (or water use) for maximum production potential, (in),

IRR_C =Irrigation applied (pumped) on a seasonal basis to a crop, (in),

ER =Effective rainfall computed from seasonal rainfall occurring during the crop season, (in),

SMM_D=Differential seasonal soil moisture used in crop production which is extracted from the soil profile, (in).

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TAMA Model

Rearranging:

$$IRR_C = ET_C(P_T) - ER - SSM_D$$

TAMA Model

$$IRR_{CTY} = \sum_{1}^{n} IRR_C$$

where:

IRR_{CTY}=Total quantity of irrigation volume applied (pumped) to the crops grown within a in a given year or growing season, (ac-ft), per county .

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TAMA Model

$$IRR_{REG} = \sum_{1}^{n} IRR_{CTY}$$

where:

IRR_{REG}=Total quantity of irrigation volume applied (pumped) to the region or area of interest per given year or growing season, (ac-ft).

TAMA type model

- **Sets up very well for use in spreadsheet form**

TAMA type Advantages

- Simple model
- Spreadsheet oriented
- Model id county based
- Accurate – FSA acreage, crop distribution
- Crop ET representative – ET network based
- Rain representative –TWDB quad based
- Multiple crops model – all ET based
- Soil Water – county soil(s) based
- Yield levels reflect actual grower production

TAMA type disadvantages

- Acreage data per crop per county required
- Requires ET based crop data per crop per county –(must be accurate as multiplier is large)
- Requires grower factors
- Requires soil moisture assessments

Data Requirements

Data Requirements:

- Crop Acreage. Crop acreages should be used from the now available FSA county offices. These represent the “best” acreage values since producers are paid form these figures on their farms.

Data Requirements:

- Crop Evapotranspiration (ETc). Actual crop ET needs to be derived and updated from lysimeters throughout Texas and obtained through the use of ET networks.
- Monthly Effective Rainfall. A modified monthly effective rainfall is utilized from the procedure described in the NRCS National Engineering Handbook.

Data Requirements:

- Grower Factor. The percent crop ET pumped should be based on Texas Cooperative Extension (TCE) demonstration data or other data gathered from actual producers' fields (no a true "pumpage factor").
- Soil Moisture. Soil moisture levels assessed in the profile used by the plant over the season.

…regarding the question of non ET networked counties?

NPET Meteorological Station Correlation Matrix Identifying Station Attribution in Computing ET

County Met Station	Armstrong	Collingsworth	Donley	Roberts
Dalhart	-	-	-	-
Dimmitt	0.25	-	0.07	-
Etter	-	-	-	-
JBF	0.50	-	0.13	-
Morse	-	-	-	0.33
Perryton	-	-	-	0.33
Wellington	0.25	1.00	0.80	-
White Deer	-	-	-	0.34

…regarding the questions of rainfall representation and crop seasons?

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Effective Rainfall??

Calculated by method from NRCS , Chapter 2, National Engineering Handbook on Irrigation Water Requirements

Technique was mean monthly precipitation, average crop ET, and soil water storage factor to calculate effective precipitation.

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Actual Effective Rainfall Equations are:

$$SF = (0.531747 + 0.295164\ D - 0.057697\ D^2 + 0.003804\ D^3)$$

$$P_e = SF(0.70917 P_t^{0.82416} - 0.11556)\ (10^{0.02426 ET_c})$$

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Seasonal Periods and Crop Categories Used in Effective Rainfall Calculations

Crop	Season Used in Crop ET Calculations	Season Used in Effective Rainfall (ER)	# of Months Used in ER Calculations
Corn	April 15-October 15	April 15-August 15	4
Cotton	May 15-October 15	May 15-October 15	5
Sorghum	May 15-October 15	May 15-October 15	5
Hay	April 1-November 1	April 1-November 1	7
Pasture	April 1-November 1	April 1-November 1	7
Peanuts	May 1-November 1	May 1-November 1	6
Soybeans	June 1-November 1	June 1-November 1	5
Wheat	October 1-July 1	October 1-July 1	9

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…regarding the questions of crop ET and soil moisture?

Annual Seasonal SM and Crop ET%

Crop	Differential Seasonal Soil Moisture (in)	Percent ET Applied
Corn	2.00	0.84
Cotton	5.00	0.93
Sorghum	2.50	0.77
Hay	1.50	0.95
Pasture	2.50	0.80
Peanuts	2.50	1.00
Soybeans	3.00	0.78
Wheat	3.50	0.60

Feasibility of Implementation

Implementation Feasibility?

- *Relatively good*
- *Relatively easy*
- *Data is partially available in state*
- *Some good ET networks already in place*
- *Relatively low costs*
- *A "can doable " effort – tech. people in places*
- *Potential opportunity to utilize university and other agencies networks with conformity to QA/QC standards.*

GAMS Interfacing

- ***Relatively good & promising***
- ***Relatively easy task– preprocessor needed***
- ***Data to do so is partially available in state***
- ***Envisioned "low" cost effort for preprocessor work***
- ***A "doable " programming effort – tech. people in places***
- ***Potential opportunity to utilize university and other agencies.***

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Costs of Startup Implementation

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TAMA type Methodology Startup Costs

Irrigated Area of Texas	Proposed minimum number of base ET stations	Estimated cost of met. hardware	Estimated personnel expenses	Estimated computing & acquisition equipment	Estimated support & installation expenses
High Plains	24	$ 180,000	-	$ 5,000	-
Rolling Plains	3	$ 22,500	-	$ 5,000	-
West Texas Area	6	$ 45,000	-	$ 5,000	-
Winter Garden	6	$ 45,000	-	$ 5,000	-
Rio Grande Valley	10	$ 75,000	-	$ 5,000	-
Gulf Coast Area	4	$ 30,000	-	$ 5,000	-
Central Computing & Acquisition Site	-	-	$ 100,000	$ 35,000	-
Subtotals	**53**	**$ 397,500**	**$ 304,800***	**$ 65,000**	**$ 188,500**
Estimated State Totals	**53**	**$ 955,800**			

Costs of Continuing Operation

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TAMA type Methodology On-Going Costs

Irrigated Area of Texas	Anticipated number of base ET stations	Replacement & calibration estimate of met. sensors	Estimated personnel expenses	Estimated computing & acquisition upgrades	Estimated support expense
High Plains	24	$ 48,000	-	$ 10,000	-
Rolling Plains	3	$ 6,000	-	$ 2,000	-
West Texas Area	6	$ 12,000	-	$ 3,000	-
Winter Garden	6	$ 12,000	-	$ 3,000	-
Rio Grande Valley	10	$ 20,000	-	$ 6,000	-
Gulf Coast Area	4	$ 8,000	-	$ 3,500	-
Central Computing & Acquisition Site	-	-	$ 275,000	$ 25,000	$ 77,592-
Subtotals	**53**	**$ 106,000**	**$ 275,000**	**$ 52,000$**	**$ 161,592***
Annual Estimated State Totals	**53**	**$ 594,592**			

TAMA type model benefits

- Benefits state water planning efforts
- Provides user data to other agencies
- Can provide trigger data for drought, etc

…that's it for today…

Assessment of Reliable Weather Station Data in Texas

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Research Engineer & Superintendent
Texas Agricultural Experiment Station
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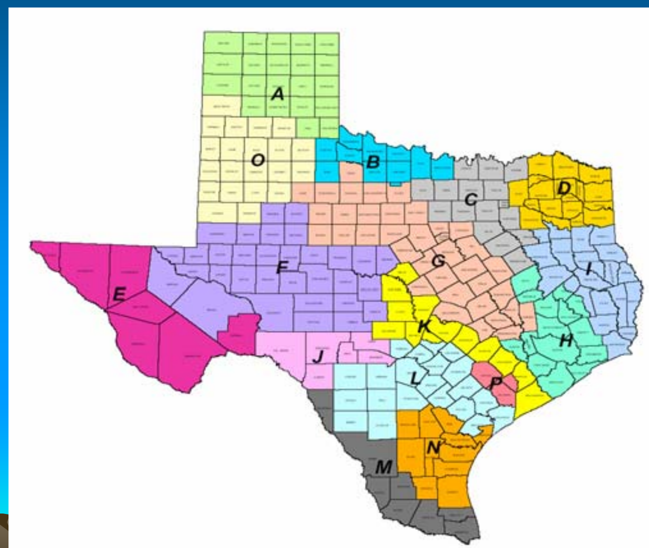
Type of Data Available Varies by Region of the State

Texas Water Planning Regions



Data Acquisition & Availability

1) Air Temperature

2) Relative Humidity
   - compute Dewpoint and VPD

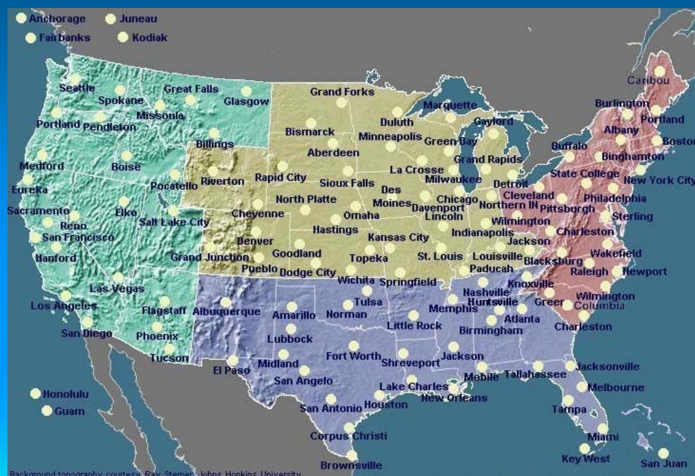
3) Wind Speed - @2 meter height

4) Rainfall – Site & Quads for average

Type of Data Stations Available in Texas

- Metar Units
- National Weather Station (NWS)
- Forest Service
- USDA-NRCS
- University-based, TAMUS
- Texas Water Development Board
- Federal Research Units
- Texas Department of Transportation (DOT)
- Commercial TV Stations
- Airports
- Safety Services network
- Groundwater Districts
- Cities

National Weather Station (NWS) Offices and Forecast Offices



Metar/Surface Weather Observations

METAR is the Aviation Routine Weather Observation created at thousands of locations (primarily, airports) around the world every hour. It provides insight on a number of weather elements being observed at the airport or observing location. This represents weather conditions that exist at a one particular time at one specific location.

- Wind speed and direction
- Visibility
- Air temperature including maximum and minimum temperature in the last 6 hours
- Dew point
- Precipitation in the previous 6 hours
- Current weather such as thunderstorms

Federal Aviation Administration (FAA) Weather Station

- Air temperature including minimum and maximum
- Average dew point
- Precipitation
- Relative humidity
- Wind speed
- Solar radiation

Army Corps of Engineers

- Uses data primarily for river forecasting
- Links to National Weather Service

National Oceanic and Atmospheric Administration (NOAA)

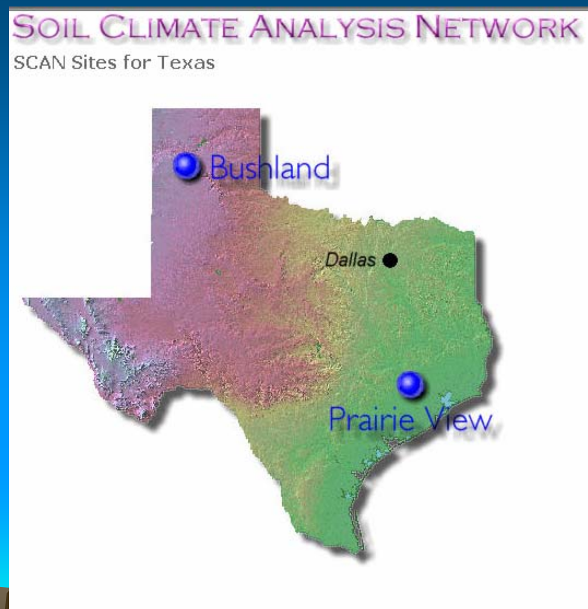
- Air temperature including maximum and minimum
- Mean number of days below 32 degrees F and above 90 degrees F
- Mean number of days with more than .01 in precipitation
- Amount of snowfall and hail
- Average and maximum wind speed
- Sunshine
- Cloudiness
- Average relative humidity in the morning and afternoon

National Weather Station (NWS) Data Collected

- Essentially same as NOAA sanctioned sites

USDA-NRCS SCAN

Data Collected



USDA-NRCS SCAN

Data Collected

April 14, 2004 Data

DATA REPORT
for last 0 complete days

BUSHLAND #1 TX GCDC0 2006.1 Elev. 3820 Lat. 3510 Long. 10206
****

Date	Time #	BAT1	BAD	ATC1	SR1A1	WR1A1	RH1C1	RH1X1	RH1N1	ATX1	ATN1	ATA1	ETID	ETIL
0404140000	1	12.39	-99.90	5.36	4.98	7.54	100.00	100.00	0.17	5.90	4.90	5.33	12.03	0.03
0404140100	2	12.36	-99.90	4.79	4.98	8.13	2.61	100.00	2.61	5.36	4.14	4.65	12.02	0.03
0404140200	3	12.35	-99.90	4.21	4.98	9.46	0.17	100.00	0.17	5.15	4.00	4.57	12.00	0.03
0404140300	4	12.33	-99.90	4.00	4.98	8.21	0.17	100.00	0.17	4.39	3.82	4.11	11.99	0.03
0404140400	5	12.31	-99.90	4.07	4.98	8.23	0.17	100.00	0.17	4.29	3.17	3.78	11.98	0.03
0404140500	6	12.31	-99.90	3.32	4.98	8.33	0.17	100.00	0.17	4.11	3.17	3.46	11.97	0.03
0404140600	7	12.28	-99.90	3.17	4.98	9.51	0.17	100.00	0.17	3.32	2.85	3.06	11.96	0.03
0404140700	8	12.29	-99.90	4.97	14.61	9.69	0.17	0.17	0.17	4.97	2.88	3.64	11.96	0.03
0404140800	9	12.51	-99.90	8.67	117.20	10.87	0.17	0.17	0.17	8.67	5.00	6.98	12.10	0.03
04041409001	0	12.84	-99.90	12.16	274.91	13.81	0.20	0.20	0.17	12.16	8.63	10.29	12.76	0.03
04041410001	1	13.09	-99.90	15.75	414.69	14.68	0.20	0.20	0.20	15.75	12.12	14.06	13.13	0.03
04041411001	2	13.29	-99.90	18.41	519.27	15.42	0.20	0.20	0.20	18.48	15.82	17.29	13.10	0.03
04041412001	3	13.37	-99.90	19.56	580.69	16.75	0.20	0.20	0.20	20.10	18.12	19.05	13.17	0.03
04041413001	4	13.43	-99.90	21.53	601.28	16.01	0.20	0.20	0.20	21.53	19.74	20.38	13.14	0.03

BUSHLAND #2 TX GCDC0 2006.2 Elev. 3820 Lat. 3510 Long. 10206
****

Date	Time #	v1smv	v1tmp	v1sal	v1rdc	v2smv	v2tmp	v2sal	v2rdc	v3smv	v3tmp	v3sal	v3rdc	v4smv	v4tmp	v4sal	v4rdc
0404140000	1	34.10	10.51	0.33	21.41	33.55	10.79	0.36	20.82	37.38	10.94	0.45	25.84	25.65	10.63	0.35	14.65
0404140100	2	34.00	10.27	0.33	21.32	33.56	10.65	0.36	20.83	37.38	10.94	0.45	25.84	25.72	10.65	0.34	14.70
0404140200	3	34.00	10.04	0.33	21.32	33.60	10.51	0.36	20.88	37.43	10.92	0.45	25.92	25.72	10.65	0.34	14.70
0404140300	4	33.90	9.83	0.33	21.23	33.46	10.40	0.36	20.74	37.42	10.88	0.45	25.92	25.73	10.67	0.34	14.70
0404140400	5	33.86	9.65	0.34	21.20	33.50	10.29	0.36	20.79	37.35	10.83	0.45	25.79	25.73	10.67	0.34	14.70
0404140500	6	33.78	9.49	0.34	21.11	33.36	10.17	0.37	20.65	37.39	10.79	0.45	25.86	25.80	10.70	0.34	14.74
0404140600	7	33.74	9.33	0.34	21.08	33.50	10.06	0.36	20.80	37.43	10.76	0.45	25.94	25.70	10.70	0.34	14.68
0404140700	8	33.80	9.19	0.33	21.15	33.36	9.95	0.36	20.66	37.27	10.72	0.45	25.66	25.70	10.72	0.34	14.68
0404140800	9	33.77	9.10	0.33	21.12	33.40	9.86	0.36	20.71	37.39	10.63	0.45	25.88	25.78	10.72	0.34	14.73
04041409001	0	33.77	9.12	0.33	21.12	33.37	9.79	0.36	20.68	37.28	10.56	0.45	25.68	25.78	10.74	0.34	14.73
04041410001	1	33.75	9.33	0.33	21.09	33.29	9.76	0.36	20.59	37.20	10.51	0.45	25.56	25.56	10.74	0.34	14.59
04041411001	2	33.74	9.74	0.33	21.06	33.13	9.81	0.37	20.44	37.05	10.47	0.46	25.31	25.63	10.74	0.34	14.64
04041412001	3	33.71	10.45	0.34	20.99	33.17	9.97	0.36	20.46	37.12	10.47	0.45	25.42	25.63	10.74	0.34	14.64
04041413001	4	33.84	11.31	0.34	21.09	32.88	10.24	0.37	20.17	37.02	10.54	0.45	25.26	25.75	10.74	0.34	14.71

BUSHLAND #3 TX GCDC0 2006.3 Elev. 3820 Lat. 3510 Long. 10206
****

Date	Time #	v5smv	v5tmp	v5sal	v5rdc	STC6
0404140000	1	25.62	14.85	0.50	14.49	10.72
0404140100	2	25.62	14.89	0.50	14.50	10.72

USDA-NRCS SCAN

Data Labels

Sensor and Element Descriptions for site 2006, Bushland, Texas

(As of: Wed Apr 14 13:24:42 PDT 2004)

Label	Elem Code	Description	Units	Depth
BAT1	BATT	Battery-system	volt	N/A
ATC1	TOBS	Air temperature-standard	degC	N/A
SR1A1	SRADV	Solar radiation-SM/ST,prev.hour	watt/m2	N/A
WR1A1	WDMVV	Wind run-previous hour	mile	N/A
RH1C1	RHUM	Relative humidity-SM/ST,previous hour	pct	N/A
RH1X1	RHUMX	Relative humidity-SM/ST,previous hour	pct	N/A
RH1N1	RHUMN	Relative humidity-SM/ST,previous hour	pct	N/A
ATX1	TMAX	Air temperature-standard	degC	N/A
ATN1	TMIN	Air temperature-standard	degC	N/A
ATA1	TAVG	Air temperature-standard	degC	N/A
ETIB	ETIB	Battery-ETI precipitation gauge	volt	N/A
ETIL	ETIL	Pulse line monitor-ETI gauge	volt	N/A
v1smv	SMS	Soil moisture - percent water by volume	pct	N/A
v1tmp	STO	Soil temperature	degC	2 inches
v1sal	SAL	Soil salinity	gram/l	2 inches
v1rdc	RDC	Soil real dielectric constant	unitless	2 inches
v2smv	SMS	Soil moisture - percent water by volume	pct	2 inches
v2tmp	STO	Soil temperature	degC	4 inches
v2sal	SAL	Soil salinity	gram/l	4 inches
v2rdc	RDC	Soil real dielectric constant	unitless	4 inches
v3smv	SMS	Soil moisture - percent water by volume	pct	4 inches
v3tmp	STO	Soil temperature	degC	8 inches
v3sal	SAL	Soil salinity	gram/l	8 inches
v3rdc	RDC	Soil real dielectric constant	unitless	8 inches
v4smv	SMS	Soil moisture - percent water by volume	pct	8 inches
v4tmp	STO	Soil temperature	degC	20 inches
v4sal	SAL	Soil salinity	gram/l	20 inches
v4rdc	RDC	Soil real dielectric constant	unitless	20 inches
v5smv	SMS	Soil moisture - percent water by volume	pct	20 inches
v5tmp	STO	Soil temperature	degC	40 inches
v5sal	SAL	Soil salinity	gram/l	40 inches
v5rdc	RDC	Soil real dielectric constant	unitless	40 inches
STC6	STO	Soil temperature, SM/ST	degC	40 inches

Forest Service Data Collected

- Links to National Weather Service

USDA-NRCS Stations

- Limited coverage
- Geostationary Satellite Server (GOES) network transmission
- Availability sporadic

Texas High Plains (TXHPET) Network

Consists of:

- North Plains ET network
  - 7 stations in Region A
  - 6 stations in Region O
  - 2 stations in Region B
- South Plains ET network
  - 3 stations in Region O

North Plains and South Plains Evapotranspiration Network

- Daily air temperature including minimum and maximum
- Relative humidity including minimum and maximum
- Solar radiation
- Precipitation
- Wind speed and direction
- Dew point including minimum and maximum
- Heat units
- Growing degree days for corn, cotton, peanuts, sorghum, and soybeans for the South Plains ET Network and corn, cotton, peanuts, sorghum, soybeans, and wheat for the North Plains ET Network
- Soil temperature including minimum, maximum and average at 2 inches and 6 inches depths

Texas Evapotranspiration Network

- Temperature including minimum and maximum
- Relative humidity
- Solar radiation
- Precipitation
- Wind speed at 4:00 a.m. and 4:00 p.m.
- Dew point including minimum and maximum
- Heat units

TXHPET Network Daily “fax” sheet

North Plains ET Network   Weather Station, Etter, TX

Date	ETo in.	Temperatures (F) Air Max	Air Min	Soil Min 2in.	Soil Min 6in.	Prec. in.	Growing Degrees Days (F) Crn	Srg	Pnt	Cot	Soy	Wht
06/17/2003	.23	85	58	69	71	0.02	21	21	16	11	25	36
06/18/2003	.13	76	61	70	71	0.15	19	19	14	9	23	37
06/19/2003	.21	82	61	69	70	0.01	22	22	17	12	26	38
10-day avg min soil temp				67	69	Wind	5.8	mph from 199 deg.				

CORN

Seed Date	Acc GDD	Short Season Var. Water Use Growth Stage	Day (in/d)	3day (in/d)	7day (in/d)	Seas. in.	Long Season Var. Water Use Growth Stage	Day (in/d)	3day (in/d)	7day (in/d)	Seas. in.
04/01	1192	12-leaf	.25	.22	.24	11.6	12-leaf	.25	.22	.24	11.6
04/15	1042	10-leaf	.24	.22	.22	8.8	10-leaf	.24	.22	.22	8.8
05/01	855	6-leaf	.18	.16	.17	5.8	6-leaf	.18	.16	.17	5.8
05/15	646	4-leaf	.14	.13	.13	3.3	4-leaf	.14	.13	.13	3.3

SORGHUM

Seed Date	Acc GDD	Short Season Var. Water Use Growth Stage	Day (in/d)	3day (in/d)	7day (in/d)	Seas. in.	Long Season Var. Water Use Growth Stage	Day (in/d)	3day (in/d)	7day (in/d)	Seas. in.
05/01	878	5-leaf	.14	.13	.14	5.9	4-leaf	.12	.11	.12	5.6
05/15	680	4-leaf	.12	.11	.12	3.7	4-leaf	.12	.11	.12	3.7
06/01	366	Emerged	.08	.08	.08	1.7	Emerged	.08	.08	.08	1.7
06/15	116	Seeded	.08	.08	.07	0.5	Seeded	.08	.08	.07	0.5

COTTON

Seed Date	Acc GDD	North Plains Area Water Use Growth Stage	Day (in/d)	3day (in/d)	7day (in/d)	Seas. in.	South Plains Area Water Use Growth Stage	Day (in/d)	3day (in/d)	7day (in/d)	Seas. in.
05/01	352	Emerged	.10	.09	.10	3.6	Emerged	.10	.09	.10	3.6
05/15	310	Emerged	.10	.09	.10	2.8	Emerged	.10	.09	.10	2.8
06/01	167	Emerged	.10	.09	.08	0.9	Emerged	.10	.09	.08	0.9
06/15	56	Seeded	.02	.02	.02	0.1	Seeded	.02	.02	.02	0.1

SOYBEANS   Late Group 4-Var. Water Use

TXHPET Network Daily “prt” sheet

Station:ETTER, TX Long 102 deg 0 min Lat 36 deg 0 min
Date:06/19/2003 Year/DOY:2003170 Elev: 1103 m Bar. Corr: 12.5
Sunrise 531 Sunset 2008 Daylight time = 14 hours 37 minutes

Time CST	Rs W/m^2	Ts2 C	Ts6 C	Tair C	TDew C	RH %	AVP kPa	VPD kPa	WSpd m/s	Wdir deg	SDd deg	PREC mm	BP kPa	ETo mm
100	0.0	21.7	22.4	17.4	15.6	89	1.77	0.22	2.6	271	23	0.25	-99.9	0.00
200	0.0	21.4	22.2	17.4	15.8	91	1.80	0.18	0.8	301	17	0.00	-99.9	0.00
300	0.0	21.1	22.0	17.1	15.8	92	1.79	0.16	0.7	266	17	0.00	-99.9	0.00
400	0.0	20.9	21.9	16.9	15.9	94	1.81	0.12	0.6	126	11	0.00	-99.9	0.00
500	0.0	20.8	21.7	16.6	15.6	94	1.77	0.11	1.0	182	14	0.00	-99.9	0.00
600	3.6	20.6	21.6	16.5	15.5	94	1.77	0.11	1.1	209	16	0.00	-99.9	0.01
700	71.2	20.4	21.4	17.0	15.7	92	1.78	0.16	1.6	217	13	0.00	-99.9	0.04
800	202.4	20.4	21.3	18.4	16.3	88	1.85	0.26	2.7	229	14	0.00	-99.9	0.12
900	243.0	20.6	21.2	19.2	16.3	83	1.85	0.38	2.4	241	14	0.00	-99.9	0.17
1000	490.4	21.0	21.2	20.9	15.9	73	1.81	0.66	3.4	244	18	0.00	-99.9	0.33
1100	344.1	21.5	21.2	20.5	14.9	70	1.69	0.71	2.5	250	16	0.00	-99.9	0.26
1200	625.9	22.0	21.3	21.9	14.6	63	1.67	0.97	2.0	228	24	0.00	-99.9	0.44
1300	786.3	22.8	21.4	24.1	15.1	57	1.71	1.30	2.1	216	34	0.00	-99.9	0.57
1400	829.2	23.9	21.7	25.2	14.3	51	1.63	1.56	3.2	204	21	0.00	-99.9	0.62
1500	789.8	24.8	22.1	25.9	14.7	50	1.67	1.67	2.8	208	26	0.00	-99.9	0.60
1600	403.9	25.4	22.5	25.8	14.2	49	1.62	1.70	3.2	200	22	0.00	-99.9	0.38
1700	539.2	25.3	22.9	26.7	13.1	43	1.51	2.00	2.8	199	22	0.00	-99.9	0.45
1800	474.4	25.3	23.2	23.4	14.3	57	1.64	1.26	5.1	167	22	0.00	-99.9	0.38
1900	369.6	24.9	23.3	22.8	14.0	58	1.60	1.17	3.9	156	17	0.00	-99.9	0.29
2000	102.7	24.5	23.4	20.8	14.7	68	1.67	0.79	3.3	155	17	0.00	-99.9	0.09
2100	2.0	23.9	23.4	19.1	16.3	84	1.85	0.36	3.0	134	11	0.00	-99.9	0.00
2200	0.0	23.3	23.3	18.4	16.2	87	1.84	0.27	3.7	126	11	0.00	-99.9	0.01
2300	0.0	22.8	23.1	17.9	15.6	87	1.78	0.27	4.4	133	13	0.00	-99.9	0.01
2400	0.0	22.3	22.9	17.7	15.7	88	1.79	0.24	4.4	159	17	0.00	-99.9	0.01
Sum	22.6 MJ											0.25		4.77
Avg		22.6	22.2	20.3	15.3	75	1.74	0.69	2.6	199	49		-99.9	
Max	1381.1	25.4	23.5	27.9	17.2	95	1.96	2.34	9.4				-99.9	
Time	1213	1534	1953	1630	1239	328	1239	1632	1711				9999	
Min		20.3	21.1	16.3	11.0	37	1.31	0.10					-99.9	
Time		703	951	448	1653	1632	1653	328					9999	

Done

TXHPET Network

TXHPET Network

TXHPET Network

TXHPET Network

Average Seasonal Corn Water Requirements (ET)
SW Texas Panhandle

Date	Season Rainfall	Corn Rainfall	ET	Irrigation Required
04/15	1.7	0.0	0.1	0
05/01	2.3	0.6	1.0	0
05/15	3.1	1.4	2.4	1
06/01	4.2	2.6	5.3	3
06/15	5.7	4.0	9.3	5
07/01	6.6	5.0	14.8	10
07/15	7.7	6.0	19.7	14
08/01	8.7	7.1	25.9	19
08/15	9.6	7.9	29.9	22
09/01	10.7	9.0	33.9	25

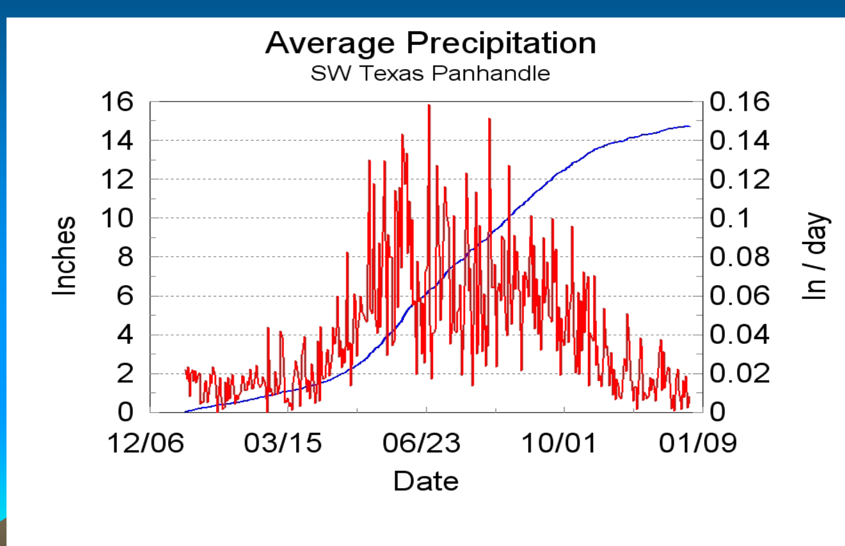
TXHPET Network

Average Seasonal Sorghum Water Requirements (ET)
SW Texas Panhandle

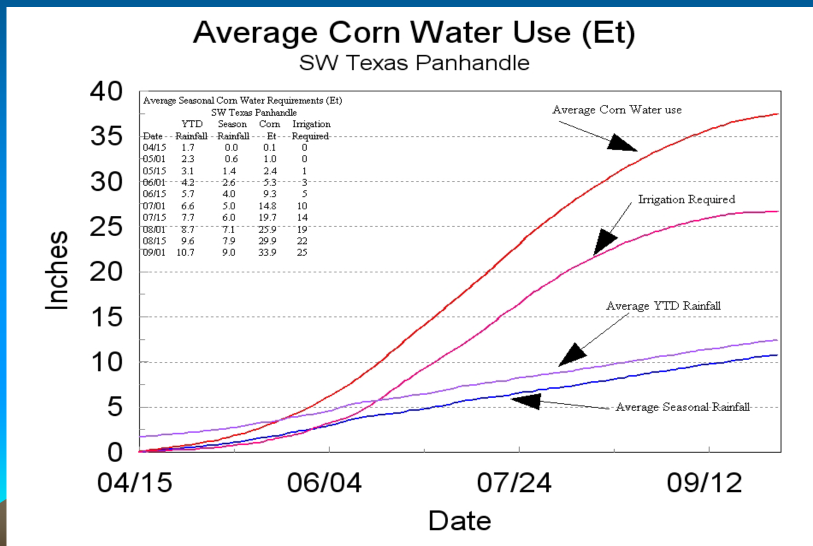
YTD Date	Season Rainfall	Sorghum Rainfall	ET	Irrigation Required
05/15	3.1	0.1	0.1	0
06/01	4.3	1.3	2.0	1
06/15	5.7	2.6	3.9	1
07/01	6.6	3.6	6.9	3
07/15	7.7	4.6	9.8	5
08/01	8.7	5.7	14.5	9
08/15	9.6	6.5	17.9	11
09/01	10.7	7.7	21.6	14
09/15	11.6	8.5	24.2	16

Sorghum ET as % of corn 71.5%

TXHPET Network



TXHPET Network



Date	YTD Rainfall	Season Rainfall	Corn Et	Irrigation Required
04/15	1.7	0.0	0.1	0
05/01	2.3	0.6	1.0	0
05/15	3.1	1.4	2.4	1
06/01	4.2	2.6	5.3	3
06/15	5.7	4.0	9.3	5
07/01	6.6	5.0	14.8	10
07/15	7.7	6.0	19.7	14
08/01	8.7	7.1	25.9	19
08/15	9.6	7.9	29.9	22
09/01	10.7	9.0	33.9	25

Central Texas (Uvalde) Evapotranspiration Network

- Daily air temperature including minimum and maximum
- Relative humidity including minimum and maximum
- Solar radiation
- Precipitation
- Wind speed and direction
- Dew point including minimum and maximum
- Heat units
- Growing degree days for corn, cotton, peanuts, sorghum, spinach, and wheat
- Soil temperature including minimum, maximum and average at 2 inches and 6 inches depths

West Central Texas (San Angelo) Evapotranspiration Network

- Daily air temperature including minimum and maximum
- Relative humidity including minimum and maximum
- Solar radiation
- Precipitation
- Wind speed and direction
- Dew point including minimum and maximum
- Heat units
- Growing degree days for corn, cotton, peanuts, sorghum, spinach, and wheat
- Soil temperature including minimum, maximum and average at 2 inches and 6 inches depths

Texas Tech – West Texas Mesonet Data Collected

Standard Measurements

- Wind speed and direction at 10 meters every 15 minutes
- Air temperature at 1.5 meters every 15 minutes
- Relative humidity at 1.5 meters every 15 min
- Barometric pressure every 15 minutes
- Precipitation every 15 minutes
- Solar radiation every 15 minutes

Texas Tech – West Texas Mesonet Data Collected

Supplemental Measurements for Inland and Coastal Sites

- Wind speed at 2 meters every 15 minutes
- Air temperature at 9 meters every 15 minutes
- Soil temperatures at various depths every 15 minutes
- Leaf wetness every 15 minutes
- Pan evaporation every 15 minutes
- Soil moisture at various depths every 15 minutes

Texas Tech – West Texas Mesonet Data Collected

Supplemental Measurements for Inland and Coastal Sites

- Supplemental Measurements for Offshore Sites
- Sea surface temperature
- Wave height
- Current speed and direction
- Salinity
- Tide

Texas A&M University System

Office of the State Climatologist

- Daily temperature including maximum, minimum and average
- Solar radiation
- Daily precipitation
- Number of days of precipitation and percent of average precipitation
- Heating degree days

Texas Natural Resources Information System (TNRIS)

The mission of TNRIS is to provide a centralized information system incorporating all Texas natural resource data, socioeconomic data related to natural resources, and indexes related to that data that are collected by state agencies or other entities.

Texas Water Development Board Data Collected

Lake evaporation and precipitation rates are provided at this site for each one-degree quadrangle in Texas. The quadrangle data were determined from all available data collection sites operated by the National Weather Service and the Texas Water Development Board. Monthly and annual gross lake surface evaporation data are available from 1954 through 2002, and precipitation data are available from 1940 through 2002. This data is provided by TNRIS.

Federal Research Units Data Collected

- Varies at most locations compared to USDA-ARS Bushland, Texas
- Archived data sets are housed from several locations at Oakridge National Laboratories
- USDA-ARS Bushland superset of North Plains ET network since NPET is somewhat of an applied derivative

Commercial TV Stations Data Collected

- Varies by station and includes:
  - **Wind speed and direction**
  - **Dew point**
  - **Barometric pressure**
  - **Relative humidity**
  - **Visibility**

Texas Department of Transportation (TxDOT)

Current weather including:

- **Temperature**
- **Humidity**
- **Wind**
- **Dew point**
- **15 minute update intervals**
- **Primary use of data is for the automated control of new de-icing systems. Not of much value to agriculture due to poor location.**

Safety Services Network Data Collected

Generally, linked to Advanced Very High Resolution Radiometer (AVHRR) systems data for severe weather concerns.

Groundwater Districts Data Collected

- Provides water quality data
- Provides water quantity data by monitoring the water well permitting program and well depletion program
- Some provide radar imagery for cloud seeding programs

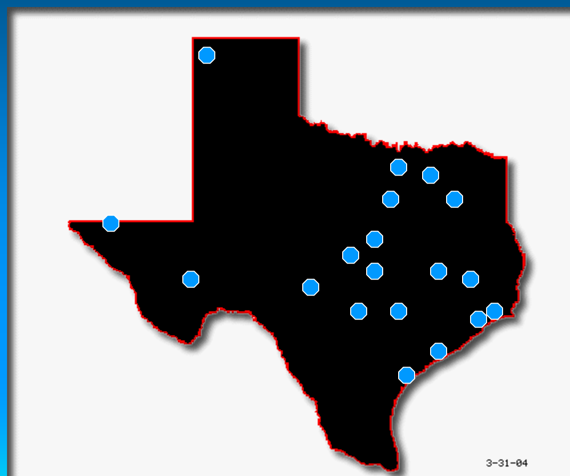
Cities
Data Collected

Cities provide data on water quality, water conservation tips, and water services available to the public. Most cities rely on commercial TV stations and airport for data stream and records.

Interactive Weather Information Network (IWIN) Data Collected

- **Current temperature, wind speed, sky conditions, dew point, and relative humidity**
- **Maximum and minimum temperature at 6 and 24 hours**
- **Precipitation in preceding 24 hours**
- **24 hour summary including temperature, dew point, pressure, and wind speed**

NOAA IWIN Stations in Texas



Location of IWIN Stations

http://iwin.nws.noaa.gov/iwin/tx/tx.
html

Texas IWIN Stations

- KDHT-Dalhart, Dalhart Municipal Airport, TX
  - 36-01-24N/102-32-50W/1217M
- KGDP-Pine Springs, Guadalupe Mountains National Park, TX,
  - 31-49-52N/104-48-32W/1692M
- KFST-Fort Stockton, Fort Stockton-Pecos County Airport, TX,
  - 30-54-43N/102-55-00W/918M
- KGYI-Sherman/Denison, Grayson County Airport, TX
  - 33-43N /096-40
- KGVT-Greenville / Majors, TX,
  - 33-04N/096-04W
- KTRL-Terrell, Terrell Municipal Airport, TX,
  - 32-42-49N/096-16-06W/144M

Texas IWIN Stations

- KTRL-Terrell, Terrell Municipal Airport, TX,
  - 32-42-49N/096-16-06W/144M
- KFTW-Fort Worth, Meacham International Airport, TX,
  - 32-49-31N/097-21-51W/214M
- KTPL-Temple / Miller Automatic Weather Observing / Reporting System, TX,
  - 31-09N/097-24W
- KILE-Killeen Municipal Automatic Weather Observing / Reporting System, TX,
  - 31-05N/097-41W
- KSSF-San Antonio, Stinson Municipal Airport, TX,
  - 29-20-20N/098-28-18W/176M

Texas IWIN Stations

- KJCT-Junction, Kimble County Airport, TX,
  - 30-30-39N/099-45-59W/523M
- KGTU-Georgetown Automatic Weather Observing / Reporting System, TX,
  - 30-41N/097-41W
- KEFD-Houston / Ellington, TX,
  - 29-36N/095-10W
- KIAH-Houston, Houston Intercontinental Airport, TX,
  - 29-59-33N/095-21-50W/36M
- KDWH-Houston, Hooks Memorial Airport, TX,
  - 30-04-03N/095-33-22W/46M

Texas IWIN Stations

- KIAH-Houston, Houston Intercontinental Airport, TX,
  - 29-59-33N/095-21-50W/36M
- KBPT-Beaumont / Port Arthur, Southeast Texas Regional Airport, TX,
  - 29-57-03N/094-01-15W/5M
- KRPE-Sabine Pass, TX,
  - 29-42N/093-57W
- KRKP-Rockport, Aransas County Airport, TX,
  - 28-05-01N/097-02-47W/6M
- KNGP-Corpus Christi, Naval Air Station, TX,
  - 27-41-19N/097-17-30W/4M

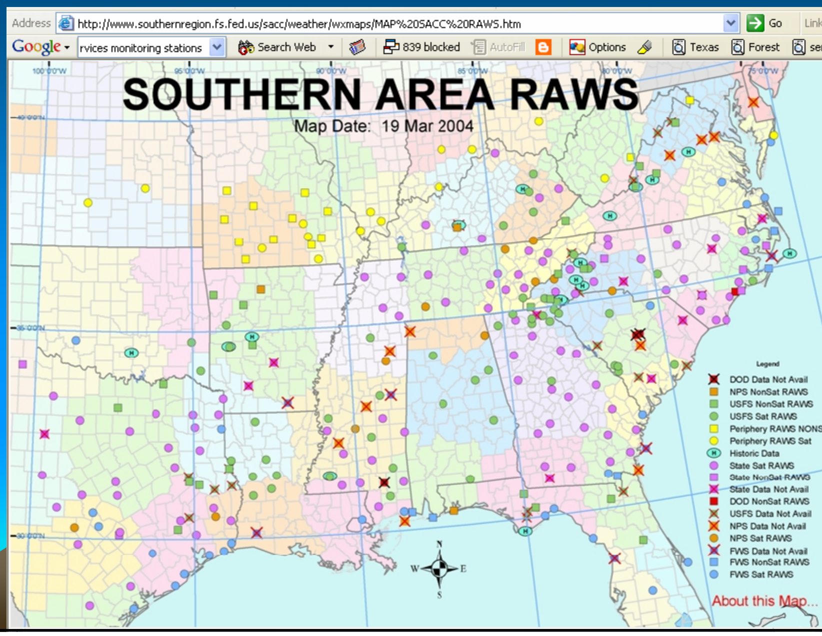
Basic Meteorological Data Desired (for Ag purposes)

- Air temperature including maximum, minimum and average
- Wind speed
- Dew point – need RH
- Solar radiation
- Rainfall – site specific

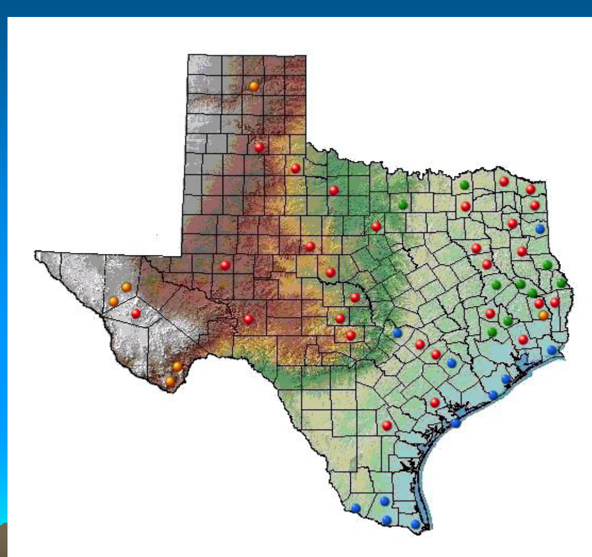
Forest Service Data Collected

Links to National Weather Service

US Forest Service



Remote Automated Weather Stations (RAWS)
Hourly Observations



Texas (combined) RAWS Sites

Operated by:

- Texas Forest Service
- US Forest Service
- US Fish & Wildlife Service
- National Park Service

Guadalupe River RAWS

Station

Texas (combined) RAWS Sites

- http://raws.boi.noaa.gov/obs/TX_zz_CAPROCK_SP.txt (TFS)
- http://raws.boi.noaa.gov/obs/TX_zz_MATADOR_WMA.txt (TFS)
- http://raws.boi.noaa.gov/obs/TX_MILLER_CREEK.txt (TFS)
- http://raws.boi.noaa.gov/obs/TX_zz_HAMBY.txt (TFS)
- http://raws.boi.noaa.gov/obs/TX_POSSUME_KINGDOM.txt (TFS)
- http://raws.boi.noaa.gov/obs/TX_zz_HAMBY.txt (TFS)
- http://raws.boi.noaa.gov/obs/TX_zz_MIDLAND.txt (TFS)
- http://raws.boi.noaa.gov/obs/TX_BARNHART.txt (TFS)
- http://raws.boi.noaa.gov/obs/TX_zz_MIDLAND.txt (TFS)
- http://raws.boi.noaa.gov/obs/TX_BARNHART.txt (TFS)
- http://raws.boi.noaa.gov/obs/TX_zz_DAVIS.txt (TFS)
- http://raws.boi.noaa.gov/obs/TX_KIRBYVILLE,_TX.txt (TFS)
- http://raws.boi.noaa.gov/obs/TX_WOODVILLE.txt (TFS)

Texas (combined) RAWS Sites

- http://raws.boi.noaa.gov/obs/TX_COLEMAN.txt (TFS)
- http://raws.boi.noaa.gov/obs/TX_COLORADO_BEND.txt (TFS)
- http://raws.boi.noaa.gov/obs/TX_BIRD.txt (TFS)
- http://raws.boi.noaa.gov/obs/TX_GREENVILLE.txt (TFS)
- http://raws.boi.noaa.gov/obs/TX_TEXARKANA.txt (TFS)
- http://raws.boi.noaa.gov/obs/TX_LINDEN.txt (TFS)
- http://raws.boi.noaa.gov/obs/TX_GILMER.txt (TFS)
- http://raws.boi.noaa.gov/obs/TX_PALESTINE.txt (TFS)
- http://raws.boi.noaa.gov/obs/TX_HUNTSVILLE.txt (TFS)
- http://raws.boi.noaa.gov/obs/TX_BASTROP.txt (TFS)
- http://raws.boi.noaa.gov/obs/TX_VICTORIA.txt (TFS)
- http://raws.boi.noaa.gov/obs/TX_GEORGE_WEST.txt (TFS)

Texas (combined) RAWS Sites

- http://raws.boi.noaa.gov/obs/TX_DAYTON.txt (TFS)
- http://raws.boi.noaa.gov/obs/TX_zz_LAGRANGE.txt (TFS)
- http://raws.boi.noaa.gov/obs/TX_zz_DREKA.txt (USFS)
- http://raws.boi.noaa.gov/obs/TX_zz_LUFKIN.txt (USFS)
- http://raws.boi.noaa.gov/obs/TX_zz_RATCLIFF.txt (USFS)
- http://raws.boi.noaa.gov/obs/TX_zz_CONROE.txt (USFS)
- http://raws.boi.noaa.gov/obs/TX_CADDO_LAKE.txt (USFWS)
- http://raws.boi.noaa.gov/obs/TX_MCFADDEN.txt (USFWS)
- http://raws.boi.noaa.gov/obs/TX_BALCONES.txt (USFWS)
- http://raws.boi.noaa.gov/obs/TX_ATTWATER_NWR.txt (USFWS)
- http://raws.boi.noaa.gov/obs/TX_BRAZORIA_NWR.txt (USFWS)
- http://raws.boi.noaa.gov/obs/TX_SAN_BERNARD.txt (USFWS)
- Note: Two dead links of USFS Sites.

Texas (combined) RAWS Sites

- http://raws.boi.noaa.gov/obs/TX_ARANSAS.txt (USFWS)
- http://raws.boi.noaa.gov/obs/TX_LAGUNA_ATASCOSA.txt (USFWS)
- http://raws.boi.noaa.gov/obs/TX_SANTA_ANA_NWR.txt (USFWS)
- http://raws.boi.noaa.gov/obs/TX_LINN-SAN_MANUEL.txt (USFWS)
- http://raws.boi.noaa.gov/obs/TX_FALCON_LAKE.txt (USFWS)
- http://raws.boi.noaa.gov/obs/TX_CEDAR.txt (NPS)
- http://raws.boi.noaa.gov/obs/TX_SOUTHERN_ROUGH_-_FT.txt (NPS)
- http://raws.boi.noaa.gov/obs/TX_PANTHER_JUNCTION_-.txt (NPS)
- http://raws.boi.noaa.gov/obs/TX_CHISOS_BASIN_-_FTS.txt (NPS)
- http://raws.boi.noaa.gov/obs/TX_THE_BOWL.txt (NPS)
- http://raws.boi.noaa.gov/obs/TX_THE_BOWL.txt (NPS)

Texas (combined) RAWS Sites Web Sites

http://www.southernregion.fs.fed.us/sacc/weather/wxmaps/MAP SACC RAWS.htm

http://www.fs.fed.us/r3/fire/swapredictive/swaweather/swa-raws.htm

Remote Automated Weather Stations (RAWS) Hourly Observations

```
-------------------------------------------------------------------
TX CEDAR                   FA62CODC 3052    35:40:00   101:34:00

                                            Dew                       Fuel    Peak   Bat   Fuel
                           Day/Time     Tmp Pt   Wind     Pcpn Rh     Temp    Wind   Volt  Moist
==============================================================================================
TX CEDAR                    14/0137Z    56/  33/0205/  19.71 RH 43  FT  50/  15G06  13.0  FM   7 SR   MM
TX CEDAR                    14/0037Z    66/  31/1803/  19.71 RH 27  FT  69/  26G09  13.1  FM   7 SR   MM
TX CEDAR                    13/2337Z    68/  31/2405/  19.71 RH 26  FT  81/  30G15  13.5  FM   7 SR   MM
TX CEDAR                    13/2237Z    68/  31/3104/  19.71 RH 26  FT  92/  25G10  14.0  FM   7 SR   MM
TX CEDAR                    13/2137Z    67/  34/2706/  19.71 RH 30  FT  95/  29G10  14.0  FM   7 SR   MM
TX CEDAR                    13/2037Z    66/  35/2904/  19.71 RH 32  FT100/  30G09  13.6  FM   7 SR   MM
TX CEDAR                    13/1937Z    63/  34/2504/  19.71 RH 34  FT  96/  30G09  14.0  FM   8 SR   MM
TX CEDAR                    13/1837Z    60/  32/2805/  19.71 RH 35  FT  86/  25G14  13.6  FM  11 SR   MM
TX CEDAR                    13/1737Z    56/  34/2908/  19.71 RH 45  FT  66/  20G15  13.6  FM  17 SR   MM
TX CEDAR                    13/1637Z    50/  32/2608/  19.71 RH 50  FT  57/  22G13  13.3  FM  24 SR   MM
TX CEDAR                    13/1537Z    44/  28/2308/  19.71 RH 55  FT  44/  21G15  13.0  FM  21 SR   MM

TX CEDAR                    12/2337Z    45/  22/3520/  19.71 RH 41  FT  54/  33G30  13.5  FM  10 SR   MM
TX CEDAR                    12/2237Z    45/  23/3519/  19.71 RH 43  FT  61/  MMG29  14.0  FM  10 SR   MM
TX CEDAR                    12/2137Z    46/  24/3517/  19.71 RH 43  FT  62/  34G27  13.5  FM  10 SR   MM
TX CEDAR                    12/2037Z    46/  30/3514/  19.71 RH 55  FT  65/  MMG28  13.6  FM  17 SR   MM
TX CEDAR                    12/1937Z    43/  30/MM15/  19.71 RH 62  FT  57/  MMG29  13.4  FM  16 SR   MM
TX CEDAR                    12/1837Z    41/  31/MM17/  19.71 RH 70  FT  52/  MMG27  13.3  FM  21 SR   MM
TX CEDAR                    12/1737Z    38/  32/0116/  19.71 RH 80  FT  46/  35G32  13.5  FM  27 SR   MM

========================================================================
Disclaimer: the National Weather Service does not own or operate any
RAWS site.  The data passes through this system from Bureau of Land
Management computer systems.  Some of the sites are periodically moved,
especially those called portable or those with a q after the longitude.
Location information and weather data might be incorrect.  No quality
control is done on the data or the location information. Use with
caution and at your own risk.
========================================================================
```

RAWS Network Data

- Transmitted by Geostationary Satellite Server (GOES) network
- Available hourly
- Limited data availability
- Purpose – primarily fire
- Data – Includes dew point, temperature, wind speed, relative humidity, precipitation, fuel temperature, peak wind, and fuel moisture

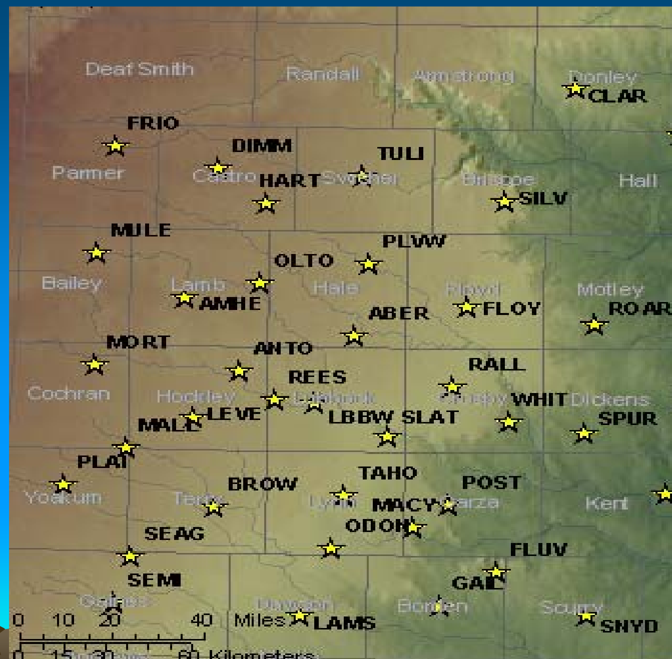
RAWS Network

Part of the
Texas Interagency Coordination Center

http://www.tamu.edu/ticc/

Rt 5 Box 3650/Hwy 94W, Lufkin, TX 75904 (936) 875-4786

TTU Mesonet Sites



TTU Mesonet Locations

Location	Area	Latitude	Longitude	Elevati	ID	4 Letter ID	LDM ID
5NE Abernathy	Abernathy/Hale County	N33° 52' 31.38"	W101° 45' 25.86"	3333 ft.	ABER	KARS	XARS
1NE Amherst	Amherst/Lamb County	N34° 01' 18.40"	W102° 24' 16.30"	3647 ft.	AMHE	KAMH	XAMH
6S Anton	Hockley County	N33° 43' 30.90"	W102° 11' 26.95"	3405 ft.	ANTO	KAOS	XAOS
3NE Aspermont	Aspermont/Stonewall County	N33° 10' 04.65"	W100° 11' 45.6"	1743 ft.			
2S Brownfield	Brownfield/Terry County	N33° 09' 06.78"	W102° 16' 15.66"	3314 ft.	BROW	KBWS	XBWS
2W Clarendon	Clarendon/Donley County	N34° 55' 29.70"	W100° 55' 48.00"	2836 ft.	CLAR	KCES	XCES
2NE Dimmitt	Dimmitt/Castro County	N34° 34' 03.05"	W102° 17' 35.40"	3876 ft.	DIMM	KDMS	XDMS
2NE Floydada	Floydada/Floyd County	N34° 00' 05.70"	W101° 19' 33.18"	3179 ft.	FLOY	KFLS	XFLS
3W Fluvanna	Borden County	N32° 53' 56.50"	W101° 12' 06.80"	2707 ft.	FLUV	KFVS	XFVS
2NE Friona	Friona/Parmer County	N34° 39' 16.20"	W102° 41' 27.50"	4009 ft.	FRIO	KFAS	XFAS
2 SE Gail	Gail/Borden County	N32° 45' 18.30"	W101° 24' 51.80"	2552 ft.	GAIL	KGGS	XGGS
5SW Graham	Graham/Garza County	N33° 04' 53.50"	W101° 30' 58.10"	2851 ft.	MACY	KGHS	XGHS
10W Guthrie	Guthrie/King County	N33° 34' 01.30"	W100° 28' 50.20"	1998 ft.	PITC	KPFS	XPFS
3N Hart	Hart/Castro County	N34° 25' 23.50"	W102° 06' 26.45"	3694 ft.	HART	KHRS	XHRS
1S Jayton	Jayton (Kent Co. Airport)	N33° 13' 56.691"	W100° 34' 03.992"	2010 ft.	JAYT	KJTS	XJTS
3W Lubbock	Lubbock County Micronet	N33° 35' 29.30"	W101° 53' 56.25"	3232 ft.	LBBW	KLBW	XLBW
2SE Lamesa	Lamesa/Dawson County	N32° 42' 21.30"	W101° 56' 10.20"	2956 ft.	LAMS	KLES	XLES
4S Levelland	Levelland/Hockley County	N33° 31' 35.40"	W102° 21' 36.00"	3496 ft.	LEVE	KLDS	XLDS
1NE Memphis	Memphis/Hall County	N34° 43' 52.90"	W100° 31' 31.55"	2057 ft.	MEMP	KMES	XMES
1NE Morton	Morton/Cochran County	N33° 44' 05.16"	W102° 44' 23.22"	3754 ft.	MORT	KMNS	XMNS
2S Muleshoe	Muleshoe/Bailey County	N34° 12' 22.86"	W102° 44' 32.64"	3806 ft.	MULE	KMUS	XMUS
1N O'Donnell	O'Donnell/Lynn County	N32° 59' 06.90"	W101° 49' 30.30"	3054 ft.	ODON	KOES	XOES
6S of Olton	Olton/Lamb County	N34° 05' 37.63"	W102° 07' 05.09"	3566 ft.	OLTO	KONS	XONS
10SW Paducah	Paducah/Cottle County	N33° 53' 25.90"	W100° 23' 55.90"	2021 ft.	PADU	KPAD	XPAD
2E Pampa	Pampa/Gray County	N35° 32' 22.20"	W100° 55' 39.80"	3216 ft.	PAMP	KPMS	XPMS
3N Plains	Plains/Yoakum County	N33° 13' 41.30"	W102° 50' 21.70"	3711 ft.	PLAI	KPPS	XPPS
1S Plainview	Plainview/Hale County	N34° 10' 43.38"	W101° 42' 28.38"	3358 ft.	PLVW	KPVS	XPVS

TTU Mesonet Locations (cont.)

1S Post	Post/Garza County	N33° 10' 18.40"	W101° 23' 07.60"	2618 ft.	POST	KPTS	XPTS
1SE Ralls	Ralls/Crosby County	N33° 40' 06.24"	W101° 22' 32.76"	3097 ft.	RALL	KRAS	XRAS
12W Lubbock (Reese)	Reese Center/Lubbock County	N33° 36' 27.00"	W102° 02' 56.52"	3347 ft.	REES	KREE	XREE
3N Roaring Springs	Roaring S./Motley County	N33° 56' 10.86"	W100° 50' 43.38"	2615 ft.	ROAR	KRRS	XRRS
1SW Seagraves	Seagraves/Gaines County	N32° 56' 11.20"	W102° 34' 27.90"	3360 ft.	SEAG	KSGV	XSGV
2N Seminole	Seminole/Gaines County	N32° 44' 26.70"	W102° 38' 08.90"	3313 ft.	SEMI	KSMS	XSMS
7E Silverton	Silverton/Briscoe County	N34° 26' 43.60"	W101° 11' 25.68"	3202 ft.	SILV	KSVS	XSVS
2NE Slaton	Slaton/Lubbock County	N33° 27' 24.84"	W101° 37' 02.04"	3065 ft.	SLAT	KSLS	XSLS
3E Snyder	Snyder/Scurry County	N32° 42' 58.10"	W100° 51' 42.00"	2431 ft.	SNYD	KSYS	XSYS
1W Spur	Spur/Dickens County	N33° 28' 51.05"	W100° 52' 34.90"	2287 ft.	SPUR	KSPR	XSPR
8SW Sundown	Southeast Cochran County	N33° 23' 21.00"	W102° 36' 35.80"	3625 ft.	MALL	KSDS	XSDS
3NE Tahoka	Tahoka/Lynn County	N33° 12' 26.88"	W101° 46' 48.90"	3104 ft.	TAHO	KTAS	XTAS
2NE Tulia	Tulia/Swisher County	N34° 32' 34.60"	W101° 44' 25.80"	3478 ft.	TULI	KTIS	XTIS
6 NW White River Lake	White River Lake/Crosby County	N33° 31' 31.20"	W101° 09' 54.20"	2704 ft.	WHIT	KWVS	XWVS

: station collecting data
: station under construction
Blue font : surveyed elevation
Red font : cell phone station
Orange font : land-line phone station
Yellow font: : network connection station

Plains Repeater	Plains/Yoakum			
Reese Base	Reese Base Station	N33° 36' 41.06"	W102° 02' 58.03"	REESE BASE
Reese Data	Reese Data Collection	N33° 35' 23.50"	W102° 01' 54.30"	REESE DATA

NODE ID < 256 = MASTER
NODE ID ≥ 256 = REMOTE

35 Proposed Stations in West Texas Mesonet
29 Primary, 6 Alternate/Repeater Sites

TTU Mesonet Data

West Texas Mesonet Daily Summary of Data for 04-13-2004

Note: This is not an official climatology database. Data is occasionally lost due to power or transmission problems, and they are therefore not included in this summary. Climatology files will be periodically produced using all data collected at the sites.

Station	Number of Obs	Max Temp	Min Temp	Peak Wind (Speed)	Peak Wind (Dir)	Total Precip	Frost Duration	Accum Solar Rad	Max Soil Temp	Min Soil Temp
Reese Center	288 /288	65 F	28 F	23 mph	229°	0.01 "	06:35	0	---	---
Abernathy	288 /288	65 F	26 F	19 mph	258°	0.00 "	07:25	93932	---	---
Plainview	287 /288	65 F	29 F	20 mph	281°	0.01 "	05:45	88389	---	---
Tahoka	272 /288	65 F	28 F	19 mph	267°	0.00 "	04:15	93631	---	---
Slaton	288 /288	64 F	29 F	19 mph	204°	0.00 "	04:10	91892	---	---
Levelland	288 /288	65 F	29 F	18 mph	253°	0.00 "	05:05	92947	---	---
Roaring Springs	286 /288	65 F	28 F	21 mph	274°	0.00 "	06:50	89657	---	---
Floydada	286 /288	65 F	25 F	18 mph	270°	0.00 "	07:30	94519	---	---
Ralls	288 /288	62 F	28 F	18 mph	250°	0.00 "	07:10	93169	---	---
Brownfield	288 /288	65 F	33 F	21 mph	225°	0.00 "	00:00	92860	---	---
Muleshoe	288 /288	66 F	26 F	19 mph	263°	0.00 "	06:45	87272	---	---
Morton	286 /288	66 F	31 F	17 mph	222°	0.00 "	01:30	88323	---	---
Olton	288 /288	67 F	26 F	19 mph	237°	0.00 "	07:40	87696	---	---
O'Donnell	288 /288	65 F	30 F	20 mph	228°	0.00 "	03:30	87851	---	---

TTU Mesonet Data

White River Lake	288 /288	65 F	30 F	18 mph	283°	0.00 "	04:05	87971	---	---
Graham	288 /288	66 F	31 F	19 mph	188°	0.00 "	03:25	88390	---	---
Sundown	288 /288	65 F	31 F	25 mph	261°	0.00 "	01:50	88217	---	---
Anton	288 /288	66 F	27 F	18 mph	236°	0.00 "	06:25	89081	---	---
Fluvanna	288 /288	65 F	28 F	18 mph	235°	0.00 "	03:50	89723	---	---
Spur	287 /288	65 F	29 F	17 mph	279°	0.00 "	05:10	87074	---	---
Lubbock 3W	288 /288	65 F	30 F	21 mph	204°	0.00 "	05:30	88565	---	---
Guthrie	287 /288	67 F	31 F	21 mph	244°	0.00 "	03:00	88195	---	---
Clarendon	286 /288	65 F	23 F	23 mph	287°	0.00 "	07:40	88562	---	---
Paducah	286 /288	66 F	31 F	18 mph	320°	0.00 "	03:15	87014	---	---
Snyder	288 /288	65 F	29 F	18 mph	309°	0.00 "	03:05	91583	---	---
Memphis	287 /288	66 F	30 F	15 mph	246°	0.00 "	03:55	87608	---	---
Jayton	287 /288	65 F	29 F	18 mph	297°	0.00 "	04:00	90825	---	---
Pampa	288 /288	64 F	21 F	15 mph	225°	0.00 "	07:45	89291	---	---

* Frost Duration: Length of time the temperature was at or below 32F during the day (in hours:min)

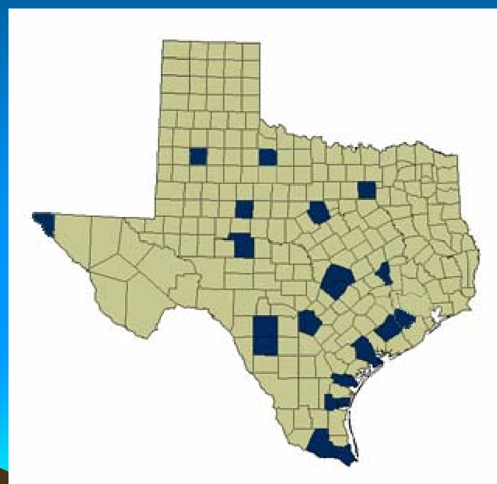
Accumulated Solar Radiation is measured in watts per square meter

* Number of Observations: Maximum number of observations in a day is 288 (one observation every five minutes)

Data as collected from the Texas Tech West Texas Mesonet

Texas ET Weather (ITC)

Texas ET Weather (ITC)



Texas ET Weather (ITC)

Art Ivey Farms	Communication Error
Austin	Communication Error
Calhoun	Invalid Data : RH=231
Capistrano	Updated
Deputy Farms	Updated
Fort Bend	Communication Error
Georgetown	Updated
Irving	Updated
Jackson	Invalid Data : RH=112
Knippa	Updated
La Pryor	Invalid Data : Temp=-40
Lubbock	Invalid Data : Rain=39
Monte Christo	Invalid Data : Temp=-12566
Rio Farms-Tres Corales	Communication Error
San Angelo	Invalid Data :
San Antonio	Updated
Seymour Aquifer	Updated
Sinton	Invalid Data : RH=118
TAMU Golf Course	Updated
Uvalde Center	Updated
Weslaco Annex Farm	Communication Error
Weslaco Center	Communication Error
Weslaco Hiler Farm	Communication Error

9 stations evaluated

Texas ET Weather (ITC)

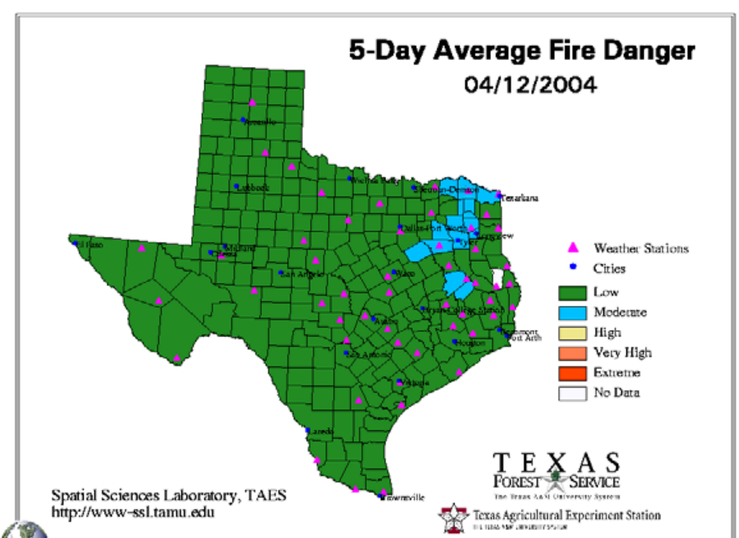
Art Ivey Farms		
Austin	Davis Water Treatment Plant	TCE
Calhoun	Calhoun County Airport	TCE
Capistrano		
Deputy Farms	Deputy Farms-El Paso	
Fort Bend		TCE
Georgetown	County Extension Office	TCE
Irving		
Jackson	Near Edna, intersection of Hwy 111 and Hwy 172	TCE
Knippa	Private Residence	TCE
La Pryor	Private Farm	Private
Lubbock		
Monte Christo		TCE
Rio Farms-Tres Corales		USDA
San Angelo		TCE
San Antonio	Jones-Maltsberger Turfgrass Management Site	TCE
Seymour Aquifer		NRCS
Sinton	East of F.M. 796 on County Rd. 26	TCE
TAMU Golf Course	Texas A&M University Golf Course	TCE
Uvalde Center	Uvalde TAMU Research & Extension Center	TAES
Weslaco Annex Farm	TAMU Annex Farm	TAES
Weslaco Center	TAEX Center in Weslaco	TCE
Weslaco Hiler Farm	Hiler Farm	

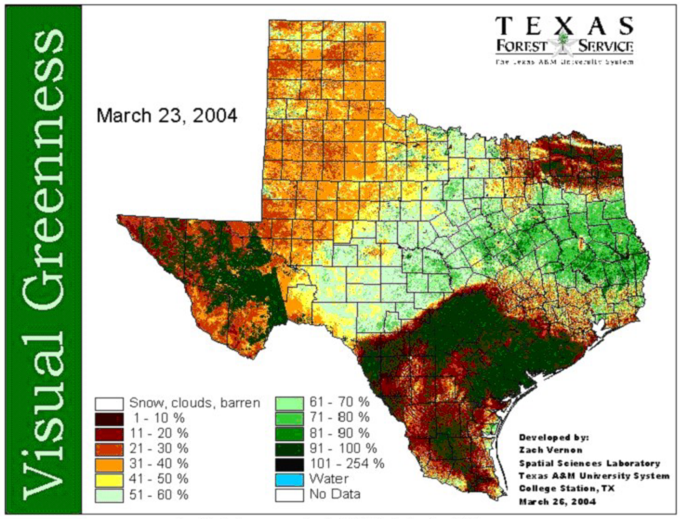
Data Bases and Warehouses Available in Texas

- Texas A&M University- Office of State Climatologist
- Spatial Sciences Lab
- ET Networks
  - Texas High Plains PET – NPET at Amarillo and SPET at Lubbock
  - Texas ET Network - Eastern & Coastal
  - Texas Tech – West Texas MesoNet
  - Central Texas ET Network - Uvalde
  - West Central ET Network - San Angelo
- Texas Water Development Board - TNRIS
- National Oceanic & Atmospheric Administration (NOAA)

Spatial Sciences Lab

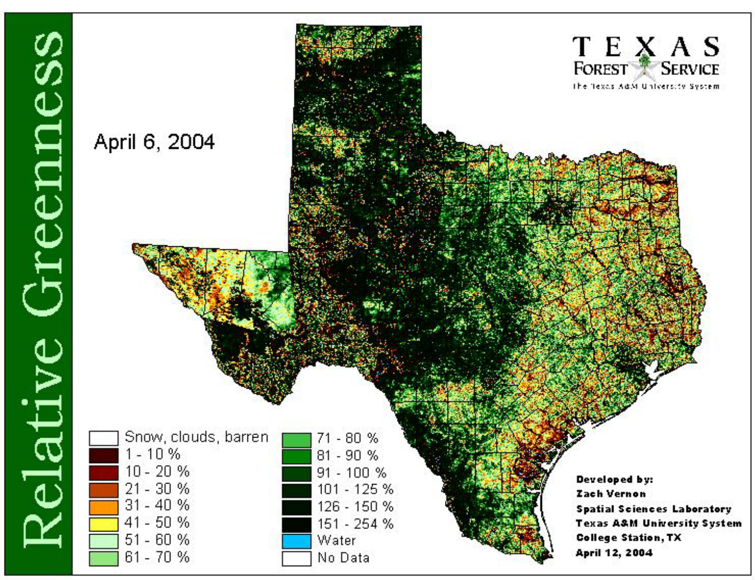
- Uses Weather Information from:
  - –Nexrad
  - –FAA Weather Stations
  - –North Plains Weather Stations
  - –Central Plains Weather Stations

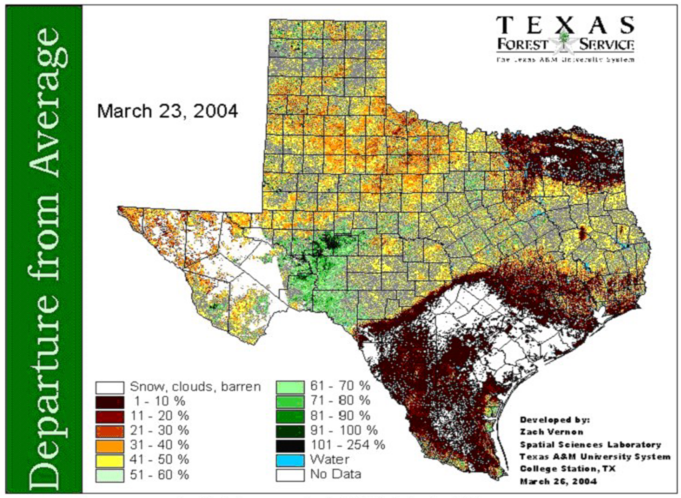




The following is a message from the EROS Data Center, March 2004:

"Due to problems with the NOAA 16 satellite, we have had to reduce the number of observations in the most recent weekly and bi-weekly greenness composites. The composites will likely have more clouds or missing data. NOAA is investigating the problem. The website will be updated as soon as new information is available."





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Texas Forest Service

National Weather Service Weather Forecast Offices:

Southern Area 10-Day Outlook

Amarillo
- fire weather
- local forecast
- current observations
- spot forecast request

Austin/San Antonio
- fire weather
- local forecast
- current observations
- spot forecast request

Brownsville
- fire weather
- local forecast
- current observations
- spot forecast request - *coming soon*

Days Out - 1 3 4

Corpus Christi
- fire weather
- local forecast
- current observations

El Paso
- fire weather
- local forecast
- current observations
- spot forecast request

Fort Worth
- fire weather
- local forecast
- current observations

Houston/Galveston
- fire weather
- local forecast
- current observations
- spot forecast request

Lake Charles
- fire weather
- local forecast
- current observations
- spot forecast request

Lubbock
- fire weather
- local forecast
- current observations
- spot forecast request

Midland
- fire weather
- local forecast
- current observations
- spot forecast request

Norman
- fire weather
- local forecast
- current observations
- spot forecast request

San Angelo
- fire weather
- local forecast
- current observations

Shreveport
- fire weather
- local forecast
- current observations
- spot forecast request

Texas Weather Connection – (SSL) Central Plains Weather Network

Note: Impressive web site, but doesn't work!

…and others

data

Central Plains Weather Network
Data provided by: Office of State Climatology

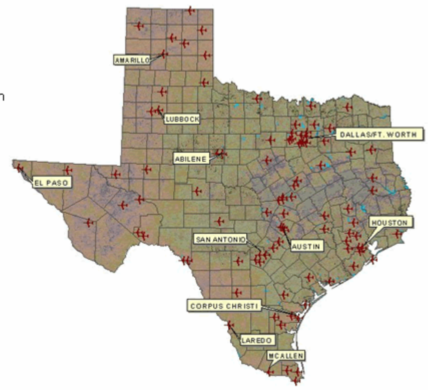
Select a Weather Station:
Weslaco #2

Choose the format in which you want your data.

Metric Units: ◉ English Units: ○

- ◉ View
- ○ Plot
- ○ EPIC/CroPMan
- ○ Download

(Email address required for download):



- ☐ Penman ET
- ☐ Maximum Temperature
- ☐ Minimum Temperature
- ☐ Relative HumidityB
- ☐ Solar Radiation
- ☐ Precipitation
- ☐ Wind

Data Assessment

For agricultural purposes:

- ET network is best due to its derivation and purpose
- Other data sources can be adapted with some loss of accuracy
- Daily computations appear to be better than sub-daily intervals

Data Results

- Lots of data!!
- Variety of purposes – most not ag based
- Unorganized and discontinuous
- Non-standardized
- Some systematically non-maintained
- Funding and personnel shortages

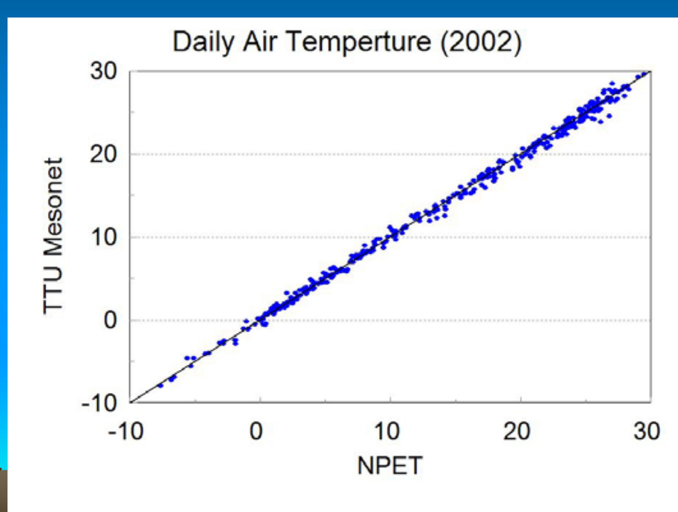
Regions of State by TAMU

- State has no standardization even by our TAMUS agencies
- Attempt made 2 years ago and reference met standardization proposed (Marek, TWRI taskforce project) – no enforcement authority
- Incentives required for change/compliance
- Will require $$$

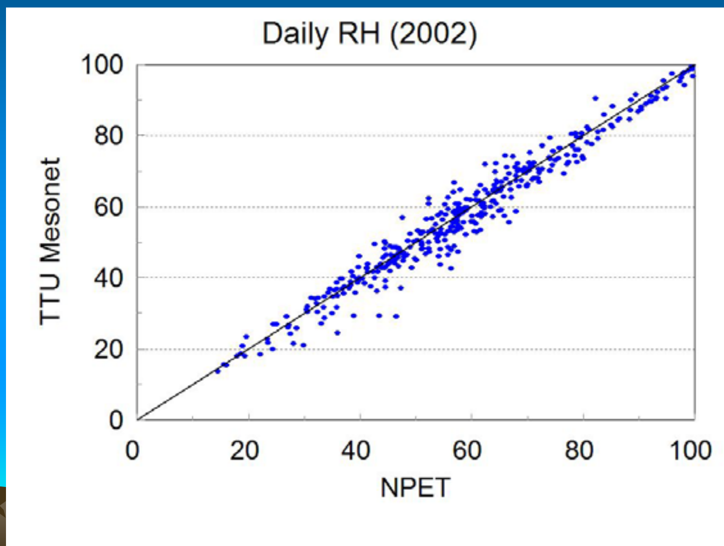
TXHPET/TTU Mesonet

Data comparisons

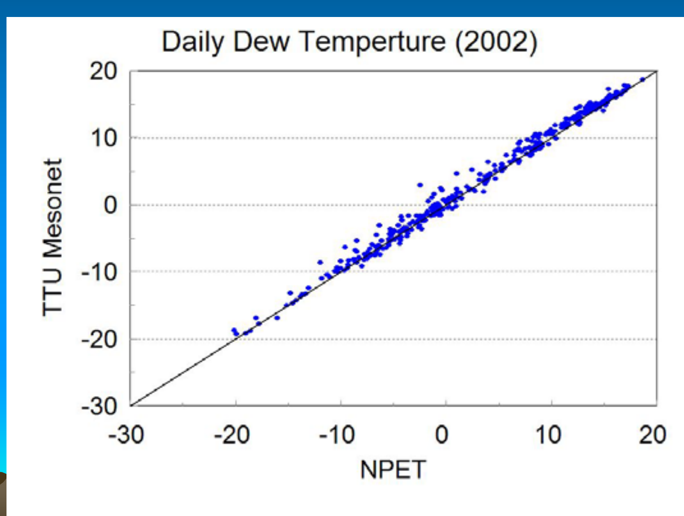
Data QA/QC…



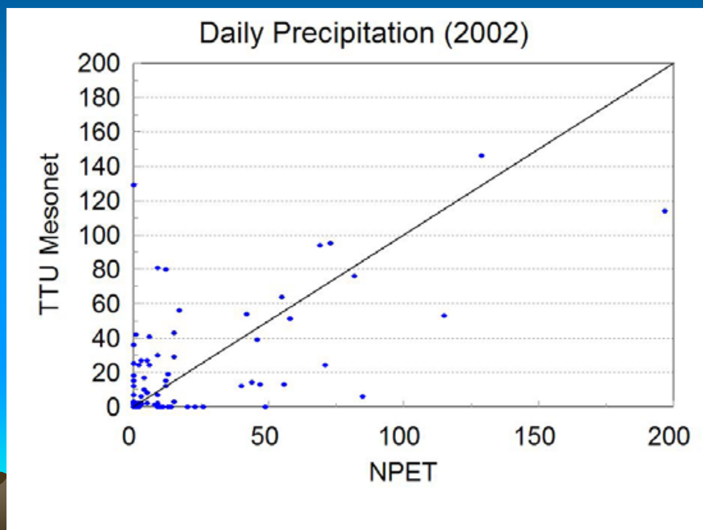
Data QA/QC…



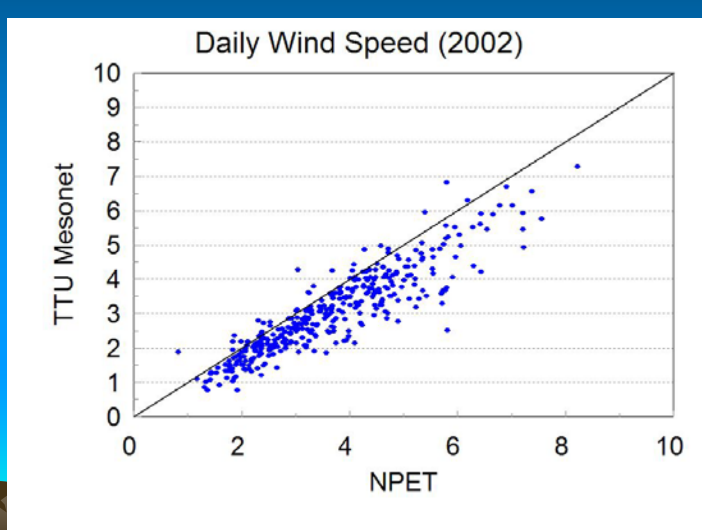
Data QA/QC…



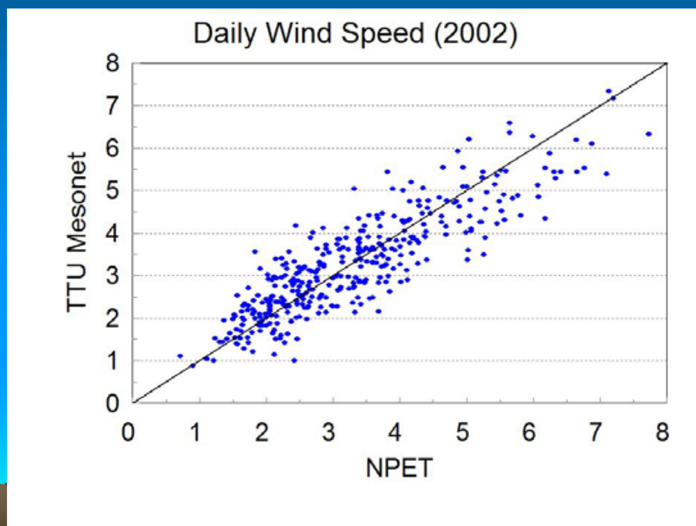
Data QA/QC…



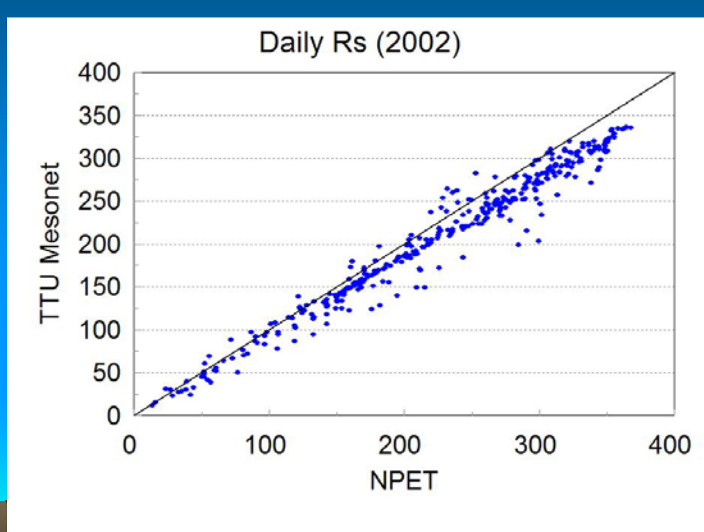
Data QA/QC…



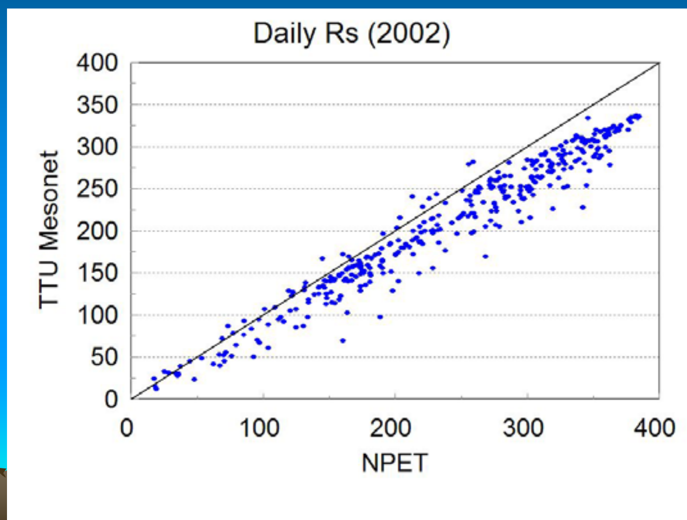
Data QA/QC…



Data QA/QC…



Data QA/QC…



Soooo….

not all created or collected are equal!

No QA/QC is a virtual …GIGO syndrome!

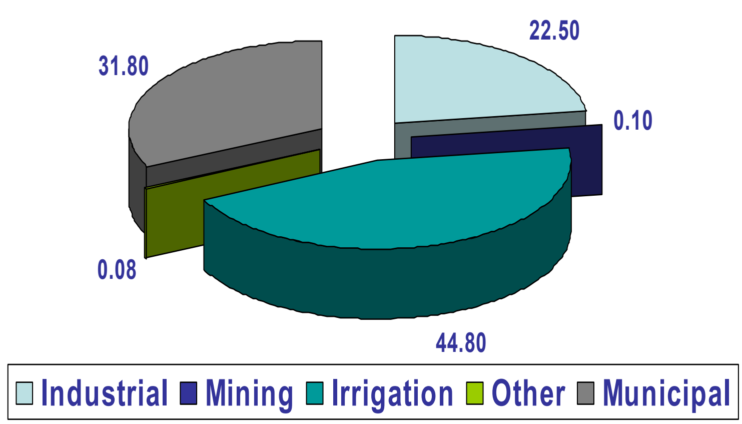
Thus, QA/QC mandatory
+
base standardization in sensors

That’s enough !

Surface Water Irrigation Estimates

Water Methodologies Project Meeting
12-13 August 2004
Texas A&M University
Agricultural Research & Extension Center
Amarillo, Texas

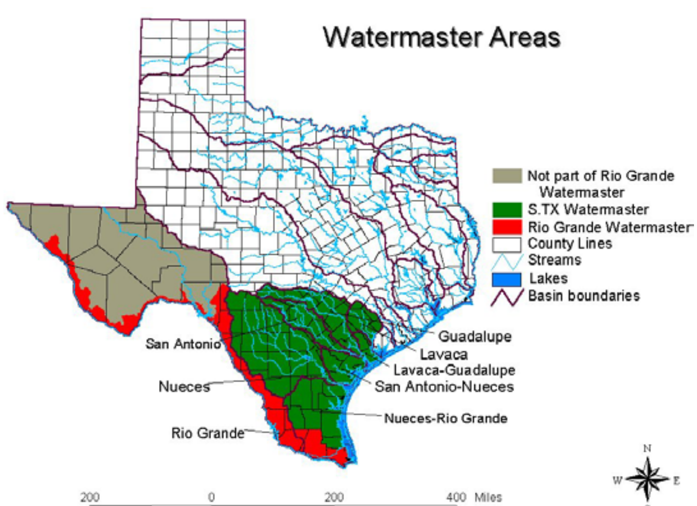
Surface Water Use in Texas (1993-1995 Average) in %



Irrigation with Surface Water in Texas

- All irrigation (*only exemption is domestic gardens and/or landscape*) from surface waters is permitted by Texas Commission on Environmental Quality (TCEQ)
  - Annual Reports *[required]* (calendar year)
    - TCEQ
    - Watermaster

Texas Watermaster Areas



Watermaster Duties

- The TNRCC's [now TCEQ] watermaster programs ensure compliance with water rights by monitoring streamflows, reservoir levels, and water use.
- They also coordinate diversions in the basin. Prior to diverting, water right holders must notify the watermaster and indicate the amount of water they need to divert. This notification allows the watermaster to ensure that the water supply is adequate to meet the needs of all diverters along a stream.
- Only when streamflows diminish, as they did during the summer of 1996, does the watermaster have to allocate flows among users.

Watermaster Duties

- The establishment of a watermaster program does mean additional costs and increased government oversight. By law, the costs associated with watermaster programs are paid by the water right holders. (Domestic and livestock users are exempt from these costs.) In the South Texas Watermaster Program, for example, water right holders are currently charged an annual levy of $50.00 plus a fee based on the amount of water they have the right to use or store. This fee currently ranges from about 13 cents per acre-foot for municipal and industrial uses to slightly over 10 cents per acre-foot for irrigation use. A municipal water right authorized to divert 100 acre-feet of water per year would pay an annual assessment of roughly $63.00.

USDA-Agricultural Research Service

Watermaster Duties

- Watermaster programs also require most water right holders to meter their pumps. However, if a water right authorizes the use of less than 50 acre-feet of water per year or if a water user diverts only a few a times a year, a meter may not be required. Depending on the specific technology, a meter may cost $400 or more, but in many instances metering the water flow actually leads to a savings in water usage, which may offset the cost of the meter.
- The watermaster provides governmental oversight of day-to-day water activities. A watermaster has the authority to lock up pumps for violations of water law and can allocate flows among priority users in times of water shortage.

Water Permits

- Section 11.134(b)(2) of the Texas Water Code allows the TNRCC [now TCEQ] to grant a new water right if there is unappropriated water available in the source of supply. Because river and reservoir levels rise and fall seasonally even in normal years, it can be difficult to determine what it means to have water "available."
- To answer that question, TNRCC [TCEQ] staff members examine the proposed monthly water demand and the monthly flows (in a river) or levels (in a reservoir) over a period of time - decades, if possible. If the historical record suggests that most of the water being requested will be available most of the time it will be needed, the TNRCC [TCEQ] grants the permit.

Water Permits

- In interpreting Section 11.134(b)(2), the TNRCC [TCEQ] follows three *rules of thumb* to determine whether a stream or reservoir has sufficient water to meet the demand of a new permit:
  - for most users, if the record shows that at least 75% of the water can be expected to be available at least 75% of the time, the TNRCC [TCEQ] will usually issue the permit;
  - for municipalities, the TNRCC [TCEQ] will issue a permit only if the record shows that 100% of the water can be expected to be available 100% of the time, unless a backup source is available;
  - for a municipality that has access to a backup supply, the TNRCC [TCEQ] may decide to issue a permit to use water that can be expected to be available less than 100% of the time.

Water Permits

- To obtain information on how to acquire a water right permit, call the TNRCC [TCEQ] Surface Water Uses Section at (512) 239-4730, or call TNRCC [TCEQ] Publications at (512) 239-0028 to order a copy of RG-141, A Regulatory Guidance Document for Applications to Divert, Store, or Use State Water.
  - RG-141, A Regulatory Guidance Document for Applications to Divert, Store, or Use State Water
  - Rights to Surface Water in Texas [Texas Natural Resource Conservation Commission GI-228, PDF version (Revised 5/02)]
    - http://www.tceq.state.tx.us/comm_exec/forms_pubs/pubs/gi/gi-228_167960.pdf

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A Water Right

- Water flowing in Texas creeks, rivers, and bays is state water. This surface water is public property; however, the state confers on individuals and organizations the right to pump water from a stream, creek, pond, or lake or to impound water in a lake or pond.
- In almost all cases, surface waters may be used only with explicit permission of the state. Water for livestock and household uses is exempted from this requirement, so long as the water is diverted by persons who live adjacent to a stream or river. These so-called domestic and livestock (D&L) users may divert surface water for household needs or for irrigating a yard or home garden and may impound in stock tanks up to 200 acre-feet of water for domestic and livestock use. D&L use is a property right that remains attached to the land.

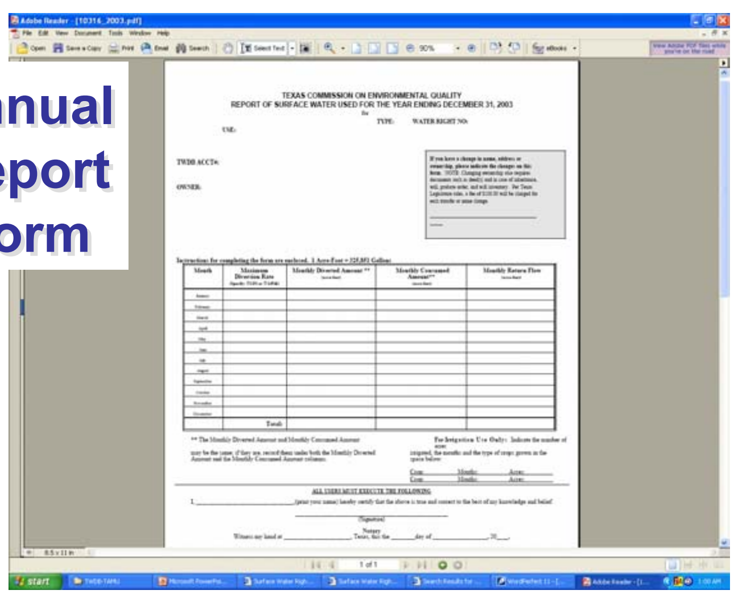
A Water Right

- County and rural community fire departments and other similar services also may divert and use state water from streams and reservoirs for emergency use without first obtaining a permit.
- State law requires a water right document for all other uses of surface water in Texas. None of these documents guarantees that water will always be available, but some of them provide more certainty than others. Each such document has a priority date assigned to it. The various types of water right documents are known as certificates of adjudication, permits, term permits, and temporary permits.

Doctrine of Prior Appropriation

- Domestic and livestock uses ***are always senior*** to any kind of appropriated water right.
- Otherwise, for the documented water rights issued by the state, the legal doctrine of prior appropriation ***("first in time is first in right") [FITFIR]*** applies. This doctrine, common among states west of the Mississippi River, holds that the older water right has first priority during times of low flow or shortage.
- Many people mistakenly believe that municipal use carries a higher priority than other uses, such as irrigation. This situation is true only in the Middle and Lower Rio Grande Basin, where purpose of use determines priority to the water stored in Falcon and Amistad Reservoirs. ***In those reservoirs, municipal and industrial rights have priority over irrigation rights*** if and when water shortages require that supplies be allocated. As a result, no priority dates exist for rights to water stored in Falcon and Amistad Reservoirs. Elsewhere in Texas, the doctrine of prior appropriation governs.

Annual Report Form



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Short Comings

- Monthly data
  - Not necessarily monthly crop irrigation data
  - May not specify crops well
- Diversion data
  - May not be county specific
- Unknown metering accuracy
- Irrigation technology unknown

Recommendation

- Use TCEQ and Watermaster records
- FSA record cross reference
  - When/where possible
  - Query NRCS/County Extension
    - Irrigation technology
    - Seek any on-farm demonstration data
- Use ET based farm factors
  - Future modeling or remote sensing ??

USDA-Agricultural Research Service

Let the Discussing Start !

Water Methodologies Project Meeting
12-13 August 2004
Texas A&M University
Agricultural Research & Extension Center
Amarillo, Texas

Crop Growth Modeling

Ranjan S. Muttiah

- Water infiltration routines
- Root water uptake
- Validation studies

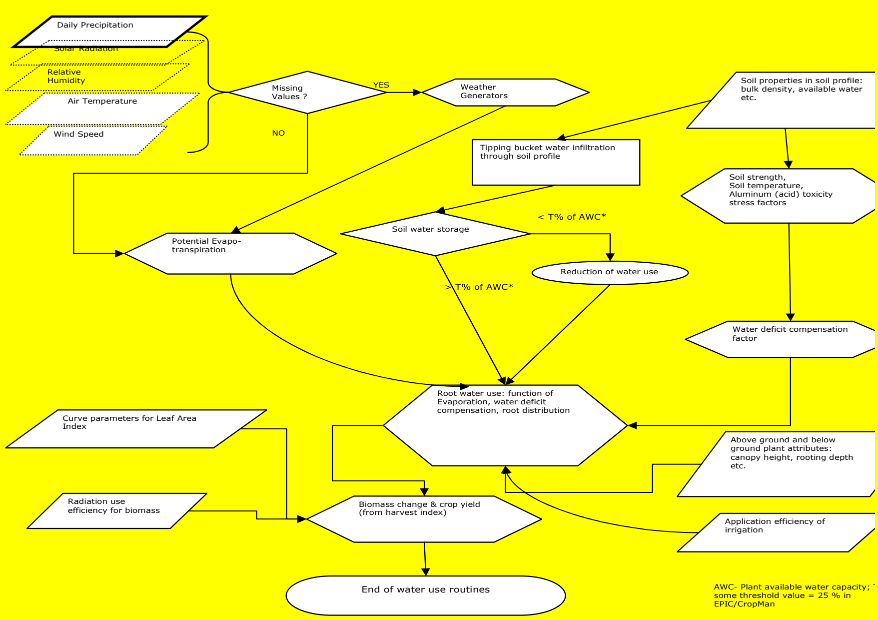


Table 1. Selected crop growth models, tests against measurements, and relevant water uptake routines.

MODELS	Field Testing	Water routines	References
CROPGRO-Soybean (and legumes)	SW content underpredicted 0-60 cm depths 60-120 cm good predictions	- ET from Priestly-Taylor - 1-D soil infiltration through profile (tipping bucket model) - Daily uptake but photosynthesis based on hourly time steps	Boote et al. (1998) Nielsen et al. (2002)
CERES-X x- Barley, wheat, Maize	Barley model soil-water within 4% RMSE of measured on fluvisols and chernozem soils Maize model tests in Kharagpur , India gave Coef. Of determination (R2) for measured SW 0-15,15-30,30-45,45-60,60-90cm respectively: 0.9,0.8,0.83,0.82, and 0.73 Maize model application in Rutigliano, Italy (semi-Arid Mediterranean climate) gave ET predictions within 8% of measured (from water balance via TDR probe)	- Tipping bucket/cascade infiltration in soil layers (infiltration using Field capacity/Wilting point) - Crop uptake a function of potential ET and LAI	Eitzinger et al.(2004) Jones and Kiniry(1986) Panda et al. (2003) Ben Nouna et al.(2000)
RZWQM	water use -12% I. corn, Eastern CO +60% I. Corn Central NE	- Green-Ampt infiltration - Wallace-Shuttelworth ET - Soil evaporation from Richard's equation - Root water uptake function of Nimah & Hanks	Farahani and DeCoursey (2000). Farahani et al., (1999)
EPIC/CropMan	7-9% relative error on Maize in Prosser, WA and Davis,CA	Tipping bucket infiltration potential water use function of LAI,PET Uptake reduced based on soil-water storage	Jara and Stockle (1999) Sharpley and Williams (1990)

1- ET = Soil-water evaporation + plant transpiration; 2-LAI = leaf area cover above a 1 m^2 soil area, Leaf area index.; 3- RMSE = Root mean squared error

Crop Growth Modeling for Texas

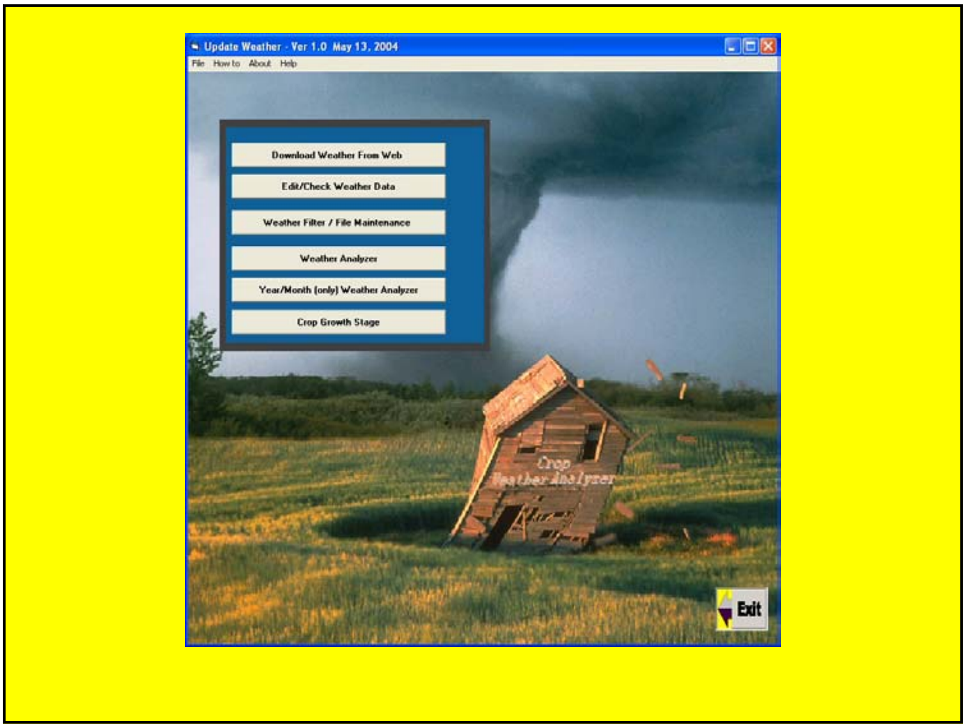
Step 1: State soil survey for each county will be obtained and the soil textural classes (silt, clay, sand) percentages will be assessed to capture at least 60% of the county area. The state soil surveys are available from USDA-NRCS and online for the state at a nominal scale of 1:24,000.

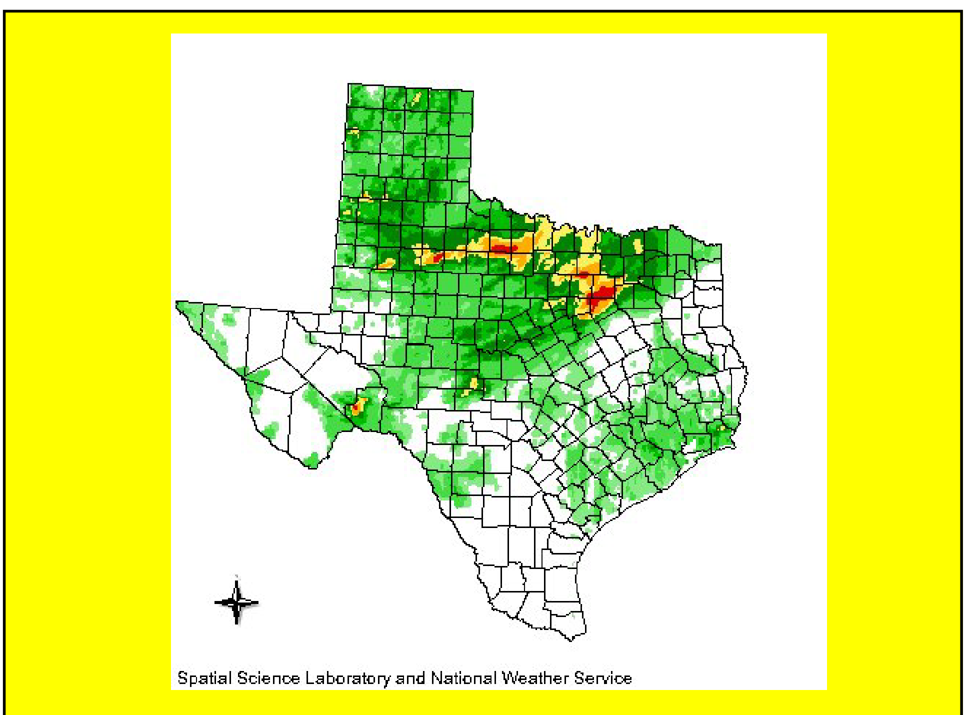
- *Step 2*: Intersect the county soil polygons with the Farm Services Administration (FSA) field maps.
- *Step 3*: Develop unique crop-soil associations to cover 60% of the county based on steps 1-2.
- Step 4: Identify cropping and irrigation management practices by each county.

- *Step 5*: Generate daily historical/real time climate from the Spatial Sciences Lab climate database (processed from satellite, NWS/NOAA, and Doppler radar corrections) for each crop-soil association/county

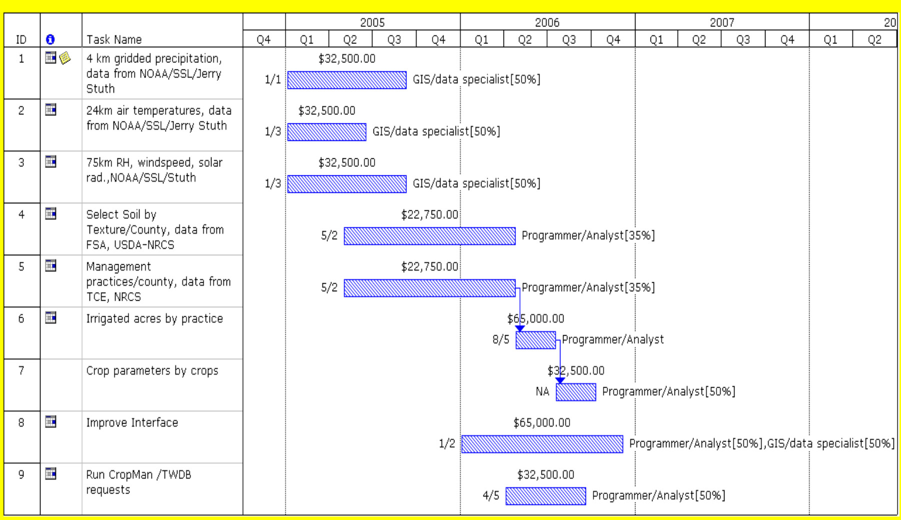
  5.1: 4 km grid precipitation data

  5.2: 24 km grid temperature data
  4.3: 50 km (0.5 degree) grid wind, radiation, relative humidity data from NCEP/NOAA


Update Weather - Ver 1.0 May 13, 2004
File How to About Help
Download Weather From Web
Edit/Check Weather Data
Weather Filter / File Maintenance
Weather Analyzer
Year/Month (only) Weather Analyzer
Crop Growth Stage
Crop Weather Analyzer
Exit


Spatial Science Laboratory and National Weather Service

- *Step 6*: Run the CropMan/EPIC model by soil-crop association by county.
- *Step 7*: Calibrate the crop yields from CropMan to county reported yield estimates by irrigated crop.
- *Step 8*: Aggregate irrigated water demand for entire county based on step 6 runs.
- *Step 9*: Multiply step 7 county water use by irrigation method (furrow, sub-surface etc.) by producer efficiencies.
- *Step 10*: Display GIS maps, tables, and other formats on an interactive website

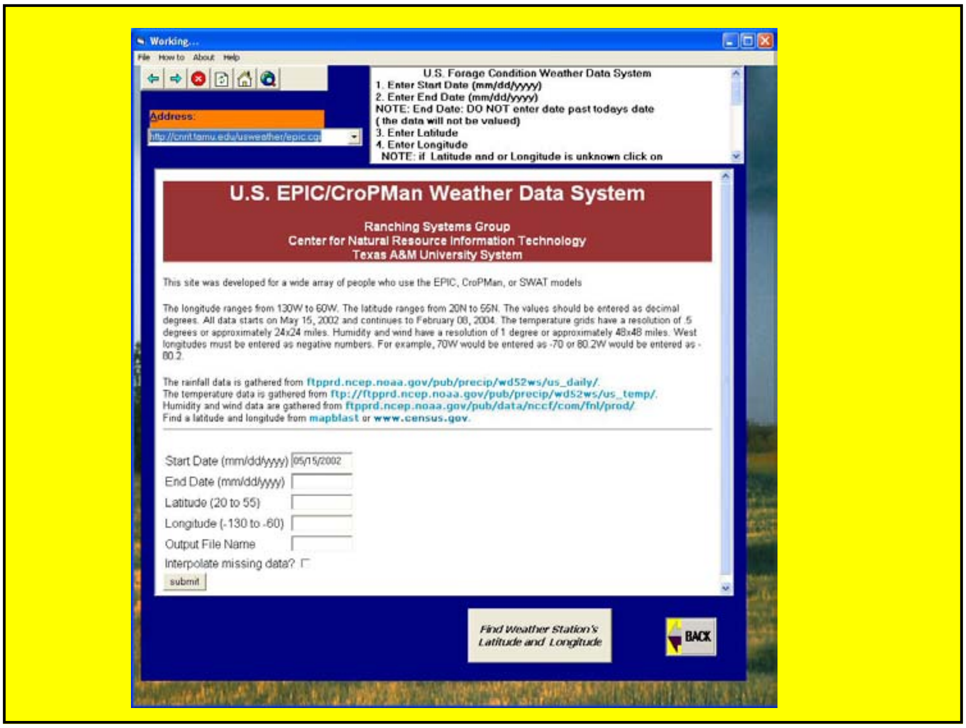


Advantages

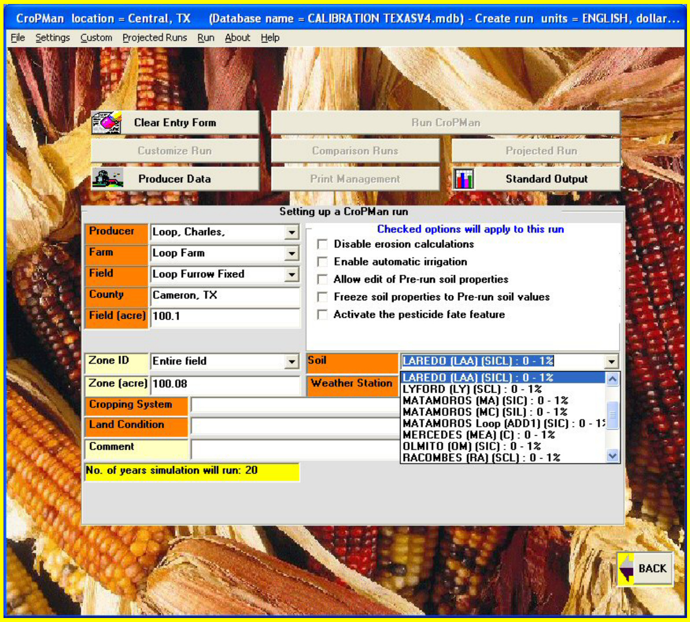
- Cheap (~ $250,000 set up costs, $150,000 maintenance costs)
- Management practices can be modeled
- Interfaces and databases already in place
- Mature decision making technology

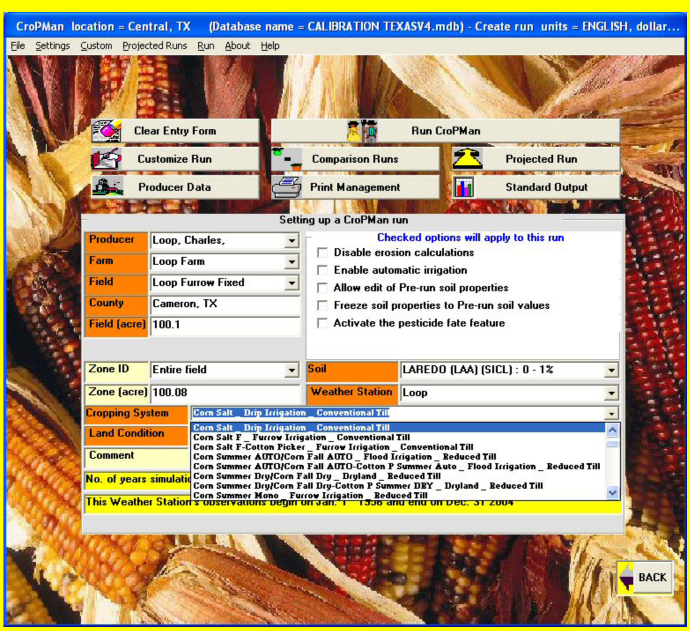
Disadvantages

- Poor at capturing within field variability
- Cumulative water use is reliable
- In-field and delivery efficiencies not part of model
- Well known application for row and close grown crops, many unknowns for vegetables
- Catastrophic events and diseases ignored
- Error 10-20% range


Working...
File How to About Help
Address:
http://cnrit.tamu.edu/usweather/epic.cgi
U.S. Forage Condition Weather Data System
1. Enter Start Date (mm/dd/yyyy)
2. Enter End Date (mm/dd/yyyy)
NOTE: End Date: DO NOT enter date past todays date
(the data will not be valued)
3. Enter Latitude
4. Enter Longitude
NOTE: if Latitude and or Longitude is unknown click on
U.S. EPIC/CroPMan Weather Data System
Ranching Systems Group
Center for Natural Resource Information Technology
Texas A&M University System
This site was developed for a wide array of people who use the EPIC, CroPMan, or SWAT models
The longitude ranges from 130W to 60W. The latitude ranges from 20N to 55N. The values should be entered as decimal degrees. All data starts on May 15, 2002 and continues to February 08, 2004. The temperature grids have a resolution of .5 degrees or approximately 24x24 miles. Humidity and wind have a resolution of 1 degree or approximately 48x48 miles. West longitudes must be entered as negative numbers. For example, 70W would be entered as -70 or 80.2W would be entered as -80.2.
The rainfall data is gathered from ftpprd.ncep.noaa.gov/pub/precip/wd52ws/us_daily/.
The temperature data is gathered from ftp://ftpprd.ncep.noaa.gov/pub/precip/wd52ws/us_temp/.
Humidity and wind data are gathered from ftpprd.ncep.noaa.gov/pub/data/nccf/com/fnl/prod/.
Find a latitude and longitude from mapblast or www.census.gov.
Start Date (mm/dd/yyyy) 05/15/2002
End Date (mm/dd/yyyy)
Latitude (20 to 55)
Longitude (-130 to -60)
Output File Name
Interpolate missing data?
submit
Find Weather Station's Latitude and Longitude
BACK


CroPMan location = Central, TX (Database name = CALIBRATION TEXASV4.mdb) units = ENGLISH, doll...
File Settings/Background Custom Projected Runs Run About Help
Create Run
Analyze
Data/Setup
Delete Runs
BACK


CroPMan location = Central, TX (Database name = CALIBRATION TEXASV4.mdb) - Create run units = ENGLISH, dollar...
File Settings Custom Projected Runs Run About Help
Clear Entry Form
Run CroPMan
Customize Run
Comparison Runs
Projected Run
Producer Data
Print Management
Standard Output
Setting up a CroPMan run
Producer
Loop, Charles,
Farm
Loop Farm
Field
Loop Furrow Fixed
County
Cameron, TX
Field (acre)
100.1
Checked options will apply to this run
Disable erosion calculations
Enable automatic irrigation
Allow edit of Pre-run soil properties
Freeze soil properties to Pre-run soil values
Activate the pesticide fate feature
Zone ID
Entire field
Zone (acre)
100.08
Soil
LAREDO (LAA) (SICL) : 0 - 1%
Weather Station
LAREDO (LAA) (SICL) : 0 - 1%
LYFORD (LY) (SCL) : 0 - 1%
MATAMOROS (MA) (SIC) : 0 - 1%
MATAMOROS (MC) (SIL) : 0 - 1%
MERCEDES (MEA) (C) : 0 - 1%
OLMITO (OM) (SIC) : 0 - 1%
RACOMBES (RA) (SCL) : 0 - 1%
Cropping System
Land Condition
Comment
No. of years simulation will run: 20
BACK


CroPMan location = Central, TX (Database name = CALIBRATION TEXASV4.mdb) - Create run units = ENGLISH, dollar...
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Clear Entry Form
Run CroPMan
Customize Run
Comparison Runs
Projected Run
Producer Data
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Setting up a CroPMan run
Producer
Loop, Charles,
Farm
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Field
Loop Furrow Fixed
County
Cameron, TX
Field (acre)
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Checked options will apply to this run
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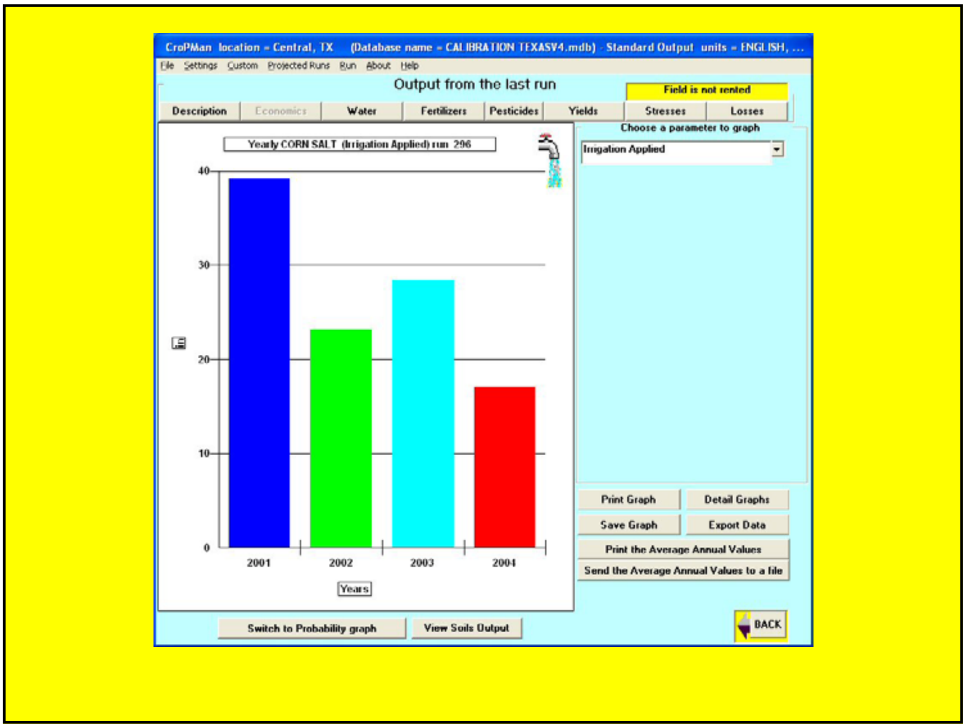
Allow edit of Pre-run soil properties
Freeze soil properties to Pre-run soil values
Activate the pesticide fate feature
Zone ID
Entire field
Zone (acre)
100.08
Soil
LAREDO (LAA) (SICL) : 0 - 1%
Weather Station
Loop
Cropping System
Corn Salt _ Drip Irrigation _ Conventional Till
Corn Salt _ Drip Irrigation _ Conventional Till
Corn Salt F _ Furrow Irrigation _ Conventional Till
Corn Salt F-Cotton Picker _ Furrow Irrigation _ Conventional Till
Corn Summer AUTO/Corn Fall AUTO _ Flood Irrigation _ Reduced Till
Corn Summer AUTO/Corn Fall AUTO-Cotton P Summer Auto _ Flood Irrigation _ Reduced Till
Corn Summer Dry/Corn Fall Dry _ Dryland _ Reduced Till
Corn Summer Dry/Corn Fall Dry-Cotton P Summer DRY _ Dryland _ Reduced Till
Corn Summer Mono _ Furrow Irrigation _ Reduced Till
Land Condition
Comment
BACK


CroPMan location = Central, TX (Database name = CALIBRATION TEXASV4.mdb) Standard Output units = ENGLISH, ...
File Settings Custom Projected Runs Run About Help
Output from the last run
Field is not rented
Description Economics Water Fertilizers Pesticides Yields Stresses Losses
Choose a parameter to graph
Irrigation Applied
Yearly CORN SALT (Irrigation Applied) run 296
40
30
20
10
0
2001 2002 2003 2004
Years
Print Graph
Detail Graphs
Save Graph
Export Data
Print the Average Annual Values
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Texas Water Development Board
Review Comments

TEXAS WATER DEVELOPMENT BOARD
Contract No. 2003-483-009
Draft Final Report Review Comments
"Development of an Agricultural Irrigation Water Use Estimating Methodology"

Task One: Crop Water Use

1. Task one of the scope of work discusses metered wells as a potential source of crop water use data, and indicates that some water districts are currently involved in voluntary well metering programs. It goes on to assert that costs and needs for establishing and maintaining well metering networks should be examined.

   Section 4.0 of the report discusses crop water use. In this section, metering is discussed in the context of existing Texas Cooperative Extension demonstration projects. A cost estimate is given for establishing a statewide "demonstration" metering network, but the report does not discuss other existing metering networks and the potential needs, feasibility and costs of using and/or expanding these networks to obtain crop water use data. This is an important point, considering that the TWDB has been actively involved in promoting metering and providing funding for metering expressly for the purpose of obtaining better data on irrigation water use.

   Other metering network items and needs were addressed and included on pages 8, 27, and 28.

2. Task one of the scope of work discusses satellite imagery as a potential source of irrigated acreage data, with the caveat that that there are questions concerning over accuracy, operation and cost.

   In the report, operational and accuracy issues of satellite imagery are discussed, but costs are not. Some comparison of the cost of using satellite imagery and remote sensing relative to other methods would be helpful, or at least some mention of the costs associated with other programs that have taken this approach.

   Satellite imagery costs are now briefly discussed on pages 60 and 61. Since this was not the selected methodology, an extensive cost analysis was not conducted.

3. The report completes both of the tasks in a thorough, professional manner, however, the report does not clearly state the results.

   The executive summary was revised and implementation tables were added to clarify implementation of the ET based estimation methodology. These items were addressed on pages 1, 9, 10, and 11. The developed methodology was specifically designated in Section 2.0 "Overview of Recommended Methodology" (page 5) and detailed in Section

8.0 “Development of an Agricultural Water Use Estimating Methodology Texas A&M-Amarillo Evapotranspiration Network Based Model” (page 73).

4. The consultant needs to report a methodology from start to finish for estimating irrigation water use.

   In Section 2.0 “Overview of Recommended Methodology” (page 5), it is explicitly stated as to what the estimation methodology developed was, along with the data requirements and costs. However, implementation tables as well as a brief explanation of the tables have been added to Section 2.0 “Overview of Recommended Methodology” pages 9, 10, and 11 and should provide additional clarity.

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