To: Managers of Agricultural Weather Networks and Associated Weather Data Systems

From: Technical Committee on Evapotranspiration in Irrigation and Hydrology of the Environmental and Water Resources Institute (EWRI) of the American Society of Civil Engineers (ASCE)

Date: 1 April, 2009

Subject: Quality Assessment and Control of Automated Weather Data

This memorandum discusses the following topics:

- The need for high quality weather data for calculating reference evapotranspiration (ET_{ref})
- Encouragement to your network to test the visually based QA/QC processes proposed by ASCE-EWRI (2005) for adoption by your QA/QC system
- Encouragement to your network to provide public access to final sets of QA/QC'd weather data to leverage QA/QC efforts and to promote economic efficiency
- To call your attention to the ASCE-EWRI (2005) standardization for the calculation of reference evapotranspiration

In 2005 the American Society of Civil Engineers – Environmental and Water Resources Institute (ASCE-EWRI) published "*The ASCE Standardized Reference Evapotranspiration Equation*[1]" that describes standardized calculation procedures for determining reference evapotranspiration (ET_{ref}). The basis of the standardized ET_{ref} equation and definition is the ASCE Penman-Monteith (ASCE-PM) method. Standardized calculations were recommended for vapor pressure and net radiation determination and for wind speed adjustment. A major impetus for the ASCE report was to improve consistency and quality of calculated ET_{ref} and to provide guidelines on assessing weather data integrity. Reference ET and associated estimates of crop ET are coming under increasing scrutiny in the American courts during water rights cases. The integrity of weather data that form the basis of ET_{ref} calculations is increasingly required to "pass muster."

[1] *The ASCE Standardized Reference Evapotranspiration Equation*. Allen, R.G., I.A. Walter, R.L. Elliott, T.A. Howell, D. Itenfisu, M.E. Jensen, and R.L. Snyder.(eds), Am. Soc. Civ. Engrs., 216 p. ISBN 078440805X. Available at: http://www.asce.org/bookstore/book.cfm?book=5430

State employees and private consultants routinely invest considerable time and expense in identifying and correcting errors and bias in weather data sets. Too often, each side of a water case applies duplicative efforts to QA/QC the same data sets. These efforts are typically repeated by other users of data, including hydrologists, planners and ground-water modelers, constituting large expenditures of financial resources. Application approaches and quality of final data sets vary widely.

ASCE-EWRI (2005) recommended procedures for visual assessment of solar radiation, humidity and wind speed data (appendices D and E). The procedures are straightforward and are intended to streamline and speed QA/QC processes to insure and produce high quality and representative weather data for use in calculating reference ET[2]. *The ASCE-EWRI Committee on Evapotranspiration in Irrigation and Hydrology (ASCE-EWRI-ET) encourages your network to test these QA/QC processes and to consider them to complement other QA/QC means employed by your automated weather data management system.*

Many automated weather station network systems (AWSN) measure the primary variables affecting ET: solar radiation, air temperature, wind speed and humidity, and therefore provide relatively complete data for calculating reference ET. Because the quality and accuracy of the ET_{ref} calculation is dependent on the quality of the weather data, it is important that the weather data are subjected to a QA/QC process that goes beyond checking of over- or underruns of data extremes relative to established thresholds. It is important that significant over or under measurement or calibration of sensors be rectified. Many AWSN employ QC procedures that compare incoming data against relevant physical extremes (for example, insuring that relative humidity ≤ 100%); some use statistical techniques to identify extreme or anomalous values; others compare data among neighboring stations. Some networks flag questionable data while other networks replace questionable data with estimated values. Often, however, these QC procedures are rather broad or coarse, so that products of the QC procedures do not necessarily exhibit data having low measurement bias. This is a primary concern of the *ASCE-EWRI-ET* Committee.

Our sister professional society, the *ASABE*, 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. The *ASCE-EWRI-ET* Committee supports EP 505 and encourages its use in designing, establishing, locating, and operating AWS networks. The visual data screening and calibration procedures of ASCE (2005) complement EP 505 by providing operational processes for identifying and correcting biased weather data. These procedures are described in Appendix D of ASCE (2005) and are briefly noted in the following paragraphs.

Visual screening of weather data is supported and recommended by *ASCE-EWRI-ET* because it can readily involve the human brain's processing and determination of 'reasonableness' of data in the context of impacts of environmental factors and with implicit comparison to physically known ranges and constraints. In addition, plotted data are conducive to rapid scanning and input by the human.

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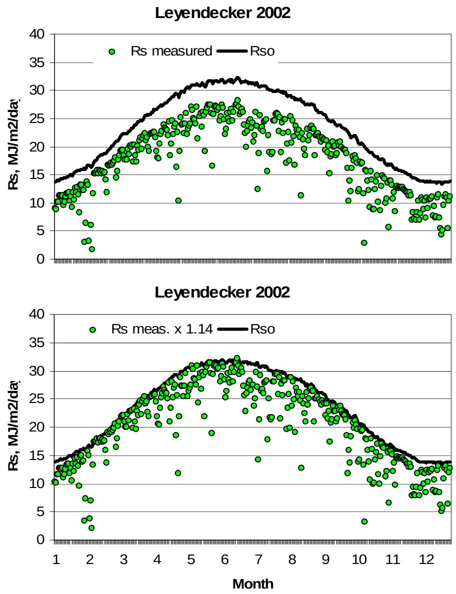
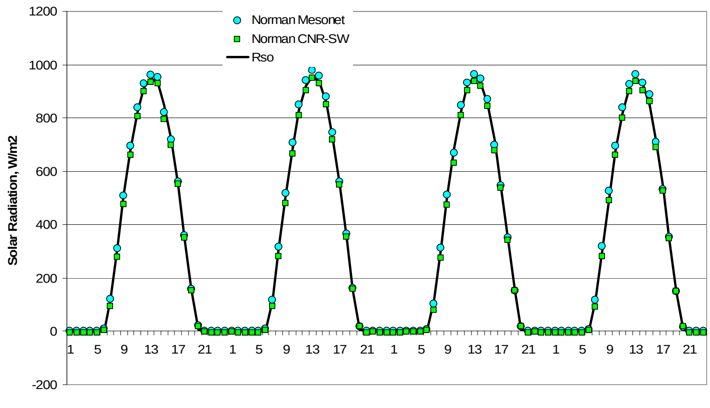
[2] An early journal paper summarizing the primary processes in the ASCE-EWRI (2005) visual QA/QC procedure is Allen, R.G. 1996. Assessing Integrity of Weather Data for use in Reference Evapotranspiration Estimation. *J. Irrigation and Drainage Engrg.*, ASCE. Vol 122 (2):97-106. A recent summary of the ASCE-EWRI method, including current calibration coefficients for clear sky solar radiation is Allen, R.G. 2008. Quality Assessment of Weather Data and Micrometeological Flux - Impacts on Evapotranspiration Calculation. *J. Agricult. Meteorology* 64(4):191-204.

Solar radiation data, R_s, can be visually screened by plotting measurements against estimates of R_s for clear sky conditions (R_{so}) for hourly or daily timesteps. R_{so} can be readily estimated from Appendix D of ASCE-EWRI (2005) using calculation procedures that include the influence of sun angle, atmospheric thickness (represented by atmospheric pressure), and water content of the atmosphere (estimated from near surface humidity data). When evaluating daily data sets, measured R_s and computed R_{so} can be plotted against the day of the year for one month or one year at a time. Hourly R_s and computed R_{so} data can be plotted against time of day for rapid scanning and assessment of R_s.[3]

A rapid visual review of the R_s -- R_{so} plots provides indication of whether measured R_s "bumps" up against the clear sky envelope of R_{so} on what appear to be cloud-free days for daily data or during cloud-free hours for hourly data. R_s will fall below the R_{so} curve on cloudy or hazy days. If these "upper" values of measured R_s lie routinely above or below the computed R_{so} curve by more than 3 to 5%, then the operator is encouraged to scrutinize the data more closely, to consider impacts of maintenance and calibration of the R_s sensor and datalogging system on the R_s data. Improper calibration, incorrect coefficient, leveling errors, the presence of contaminants on the sensor (e.g., dust, salt, or bird droppings), and electrical problems can cause R_s to deviate from R_{so} on clear days.

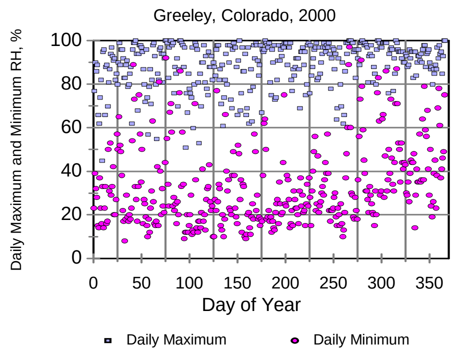


Values of R_s that are consistently above or below R_{so} on clear days can often be adjusted by dividing R_s by the average value of R_s/R_{so} for clear periods. Often, a consistent multiplier can be applied over extended periods when the cause of low or high R_s readings stems from miscalibration of the sensor. An example of visual screening of daily R_s data over one year and results of applying a 14% upward correction to the data is shown in the figure above for Leyendecker, NM. The figure to the right shows hourly solar radiation from two collocated sensors at a Norman, OK Mesonet plotted vs. the R_{so} curve on clear days, where one sensor followed the R_{so} curve relatively closely and the second sensor (CNR) averaged a few percent above the curve. Plots of R_s against the R_{so} curve also provides means to assess the accuracy of the datalogger clock, especially with older data sets.

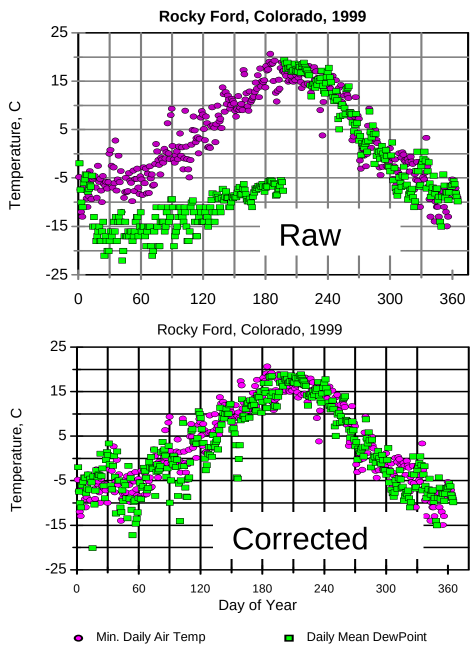


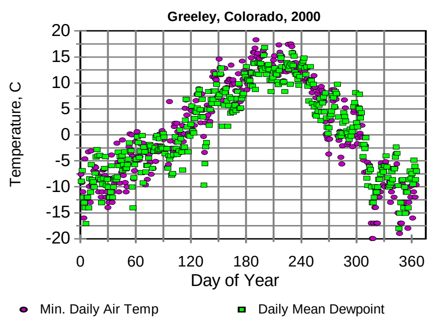
[3]The visual comparisons are often the only available means to assess historical data. For current data collection, a second, dual sensor is encouraged in the case of solar radiation, wind speed, RH and temperature, either mounted permanently or only periodically, to provide redundancy in measurements or to assist in external calibration.

Humidity and air temperature data can be screened to identify questionable or erroneous data. The screening process requires that the user has a sense of reasonable vs unreasonable values. For example, mid-afternoon relative humidity (RH) values chronically lower than 5 to 10% in arid regions and chronically lower than 30% in subhumid regions are uncommon and may indicate problems with the sensor[4]. Similarly, RH values in excess of 100% do not occur in the natural environment and generally indicate that the sensor is out of calibration. The accuracy of most modern-day electronic RH sensors is within +/- 5% RH (ASABE EP505); thus, recorded RH values in excess of 105% suggest the need for correction. Correction of RH data can generally be done using proportional adjustment of all data based on a multiplier and/or offset. The use and magnitude of the multiplier or offset can be based on visual analysis of daily maximum and minimum RH over a period of months. They may also be determined by co-comparison of data among weather stations in the same subregion.



Humidity data can be visually assessed in the form of RH or in the form of a computed dew-point temperature (T_{dew}), or both. T_{dew}, and vapor pressure, e_a, are typically calculated from RH and air temperature, T. Error and bias in RH and T will affect T_{dew} and e_a. Values for daily average and early morning T_{dew} can be compared with daily minimum air temperature (T_{min}). In humid regions, the T_{dew} measurement will typically approach T_{min} most days. Exceptions occur on days that feature a change in air mass (e.g., frontal passage). 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 °C lower than T_{min} under reference conditions, but well below T_{min} if the measurement site is subject to local dryness. 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. The example plots of daily maximum and minimum





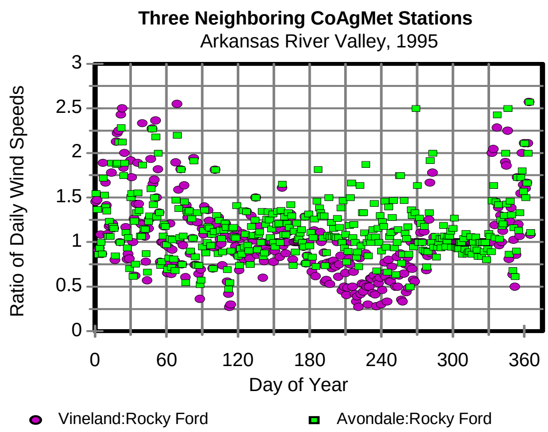
[4] The QA/QC recommendations given in ASCE-EWRI apply primarily to agricultural weather stations and other weather stations whose data are used to calculate reference evapotranspiration that is characteristic of well-watered environments. The ASCE-EWRI ET Committee recognizes that some weather station networks focus on collection of ambient weather data in natural settings. In those situations, air temperature levels may exceed and humidity levels may be lower than those expected in conditioned agricultural settings.

RH and T_{min} and T_{dew} for Greeley, Colorado, above right, show expected ranges, extremes and relationships.

In the case of the humidity data for Rocky Ford, Colorado, above left, a faulty calibration coefficient on RH caused extreme undermeasurement of RH and therefore undercalculation of e_a and T_{dew}. Data were corrected by multiplying the RH measurements over the first half of 1999 by a constant correction factor. The result of the correction on T_{dew} is shown in the bottom figure. In cases where humidity data irreparable, T_{dew} can be estimated from T_{min} using procedures suggested in Appendices D and E of ASCE-EWRI (2005).

Some precautions with scanning RH data are the tendency for some sensors to exhibit a break in calibration slope when RH > 90% (B. Nef, Campbell Sci., pers. commun., 2008).

Assessment of wind speed data generally requires comparisons between wind speed measured at two or more locations. However, a gust factor (ratio of instantaneous maximum to mean daily wind speed can serve as a useful index. Gust factors can increase as contamination increases the friction in bearings. Wind speed at nearby locations are generally related and ratios of wind speed from the two locations is expected to remain relatively constant over time. Plotting ratios over time can identify problems with anemometers or environment. Sudden and consistent changes in ratios often indicate a failed anemometer; gradual change in ratios can indicate growing contamination in bearings or effects of tall vegetation in the immediate vicinity of one of the stations (such as occurred at Vineland, Colorado in the figure above, where the 2 m anemometer was located next to field corn). When possible, the *ASCE-EWRI-ET* Committee recommends that anemometers be located at 3 m above the ground surface to reduce the impacts of surrounding vegetation on reducing wind speed. Wind speed data at the 3 m height can be adjusted to the standard 2 m height for use in standardized ET_{ref} equations using accepted adjustment procedures.



Data flagging and Reporting of Corrected Data. The *ASCE-EWRI-ET* Committee suggests that two sets of weather data (the original (or "raw") and corrected) be housed and made available to users. The nonaltered original data are valuable for assessing the nature and magnitudes of data correction. Some type of "flagging" procedure should be employed to clearly identify data that have been corrected or estimated. In addition, 'meta-data' describing the nature of corrections should be contained within the corrected data archives or be made available as readily assessable reports.

We encourage each network to produce the flagged and corrected weather data sets (as a second data set) to promote economic efficiency, where the data QA/QC and correction is done one time and by a knowledgeable, experienced and trained staff person. This consolidation and centralization of QA/QC will reduce the large number of duplicative corrections by individual data users as is often the case. The *ASCE-EWRI-ET* Committee recognizes that implementation of QA/QC processes may require additional network program funding. However, in the case of State resources, this can constitute an efficient expenditure of public monies, due to the reduction of State resources invested in multiplicative, repetitive data QA/QC by a variety data users (for studies often funded by the State), where the QA/QC is often done by users having insufficient background.

Station Siting. For purposes of calculating ET_{ref}, meteorological data should be measured over and downwind of vegetation that approximates the (well-watered) 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 defined reference surface condition. Feedback between and conditioning of the boundary layer exists above an evaporating surface, so that evaporation at the surface impacts temperature and humidity of the air layer above. Studies in southern Idaho by Burman et al. (1975)[5] illustrated how 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 an environment that conditions the boundary layer as defined by the reference surface.

Ideally, weather stations used to calculate reference ET for agricultural water management and water rights issues 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 can serve as an effective vegetation. 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 outside the periphery of a vegetated field provided the station is downwind of the conditioning field during important 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.

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, and may, in some cases, require adjustment to humidity or temperature data to make the data more representative of reference conditions (ASCE-EWRI 2005).

The ASCE Standardized Penman-Monteith Reference Evapotranspiration Equation. During the past decade, for convenience and reproducibility, the reference surface has been expressed as a hypothetical surface having specific characteristics (Smith et al., 1991; 1996[6]; ASCE, 1996[7]; FAO-56,

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[5] Burman, R.D., Wright, J.L., and Jensen, M.E. 1975. "Changes in climate and estimated evaporation across a large irrigated area in Idaho." *Trans. ASAE* 18(6):1089-1093.

[6]Smith, M., Allen, R., Monteith, J., Perrier, A., Pereira, L. and Segeren, A. 1991. Report of the expert consultation on procedures for revision of FAO guidelines for crop water requirements. UN-FAO, Rome, Italy, 54 p.
Smith, M., Allen, R.G., and Pereira, L. (1996). "Revised FAO methodology for crop water requiremens." pp. 116-123. In: C.R. Camp, E.J. Sadler, and R.E. Yoder (eds). *Evapotranspiration and Irrigation Scheduling*. Proc., Int'l. Conf., San Antonio, TX, Nov., 1184 pp.

[7]Allen, R.G., Pruitt, W.O., Businger, J.A., Fritschen, L.J., Jensen, M.E., and Quinn, F.H. (1996). Evaporation and Transpiration. Chap. 4, pp. 125-252 In: Wootton et al. (Task Com.), *ASCE Handbook of Hydrology*, 2nd ed" Am. Soc. Civ. Engrs., New York, NY., 784 pp.

1998[8]; ASCE-EWRI, 2005[1]). ASCE-EWRI (2005) defined the standardized reference evapotranspiration 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-EWRI (2005) established two standardized surfaces 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[9] was used to represent the standardized surfaces of clipped, cool-season grass (short reference) and full-cover alfalfa (tall reference).

The standardization recommended by ASCE-EWRI (2005) follows commonly used procedures for calculating vapor pressure terms, net radiation, and soil heat flux. The standardization applies the ASCE-PM equation for both reference surfaces using a single equation having fixed constants and standardized computational procedures. The computational procedures were intended to be relatively simple to apply, readily understandable, supported by existing and historical data, technically defensible, and accepted by science and engineering communities. The standardized equation has been investigated over a wide range of locations and climates across the United States. The *ASCE-EWRI-ET* Committee encourages the use of the standardized ET_{ref} equation and procedure in AWS network archives 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 ASCE standardized PM method is intended to complement, rather than to replace, other methods currently employed within AWSN for estimating ET_{ref}. The *ASCE-EWRI-ET* Committee recommends application of the standardized reference ET equation and calculation procedures to bring commonality to the calculation of reference ET among AWSN and to provide a standardized basis for determining or transferring crop coefficients for agricultural and landscape use.

The ASCE-EWRI (2005) report[1] includes all necessary calculation equations and information to apply the standardized ASCE Penman-Monteith equation for the grass and alfalfa references. The *ASCE-EWRI-ET* Committee is comprised of 30 professionals involved in ET application and research and represents more than 10 states spanning the US continent. The committee welcomes your comments, feedback and suggestions[10].

This letter is posted as a pdf file that can be downloaded from
www.kimberly.uidaho.edu/water/asceewri/index.html
Pdf copies of the main text of the ASCE-EWRI (2005) report and Appendices D and E describing visual QA/QC of weather data are also available from that site.

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[8] Allen, R.G., Pereira, L.S., Raes, D. and Smith M., (1998). *Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements*. Irrig. and Drain. Paper No. 56, United Nations Food and Agriculture Organization,. Rome, Italy, 300 pp.

[9] Jensen, M.E., Burman, R.D. and Allen, R.G. (1990). *Evapotranspiration and Irrigation Water Requirements*. ASCE Manuals and Reports on Engineering Practice, No 70, 350 pp.

[10] Current officers of the ASCE-EWRI Technical Committee on Evapotranspiration in Irrigation and Hydrology are: Michael Dukes, Univ. of Florida, Chair; Suat Irmak, Univ. Nebraska, Vice-Chair; Thomas Ley, Colorado Division of Water Resources, Secretary. Mail contact: Dr. Michael Dukes, Agricultural and Biological Engineering Dept.; 107 Frazier Rogers Hall; PO Box 110570; Gainesville, FL 32611; email: mddukes@ufl.edu; tel: (352) 392-1864 x107; fax: (352) 392-4092