Agricultural Water Management 98 (2011) 921–929

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Review

Evapotranspiration information reporting: II. Recommended documentation

Richard G. Allen[a,*], Luis S. Pereira[b], Terry A. Howell[c], Marvin E. Jensen[d]

[a] Biological and Agricultural Engineering and Civil Engineering, University of Idaho, 3793 N 3600 E, Kimberly, ID, 83341, USA
[b] Biosystems Engineering, Institute of Agronomy, Technical University of Lisbon, Tapada da Ajuda, 1349-017 Lisbon, Portugal
[c] USDA-ARS, Bushland, TX, USA
[d] Formerly USDA-ARS and Colorado State University (ret.), Ft. Collins, CO, USA

ARTICLE INFO

Article history:
Received 29 December 2010
Accepted 30 December 2010
Available online 26 January 2011

Keywords:
Evapotranspiration
Measurement
Equipment
Calibration and validation requirements
Accuracy
Descriptive documentation

ABSTRACT

Researchers and journal authors, reviewers and readers can benefit from more complete documentation of published evapotranspiration (ET) information, including description of field procedures, instrumentation, data filtering, model parameterization, and site review. This information is important for discerning the likely accuracy and representativeness of the reported data and ET parameters, including derived crop coefficients. Documentation should include a description of the vegetation, its aerodynamic fetch, water management and background soil moisture, types of equipment and calibration checks, photographs of the measured vegetation/equipment combinations, and independent assessments of measured ET using models or other means. Documentation and assessment should include a description of, or reference to, all weather recording equipment and parameters, including the vegetation and water management environment of the weather station. Suggestions are given for documentation describing the primary types of ET measuring systems including recommended independent testing.

Contents

1. Introduction

Evapotranspiration (ET) information is foundational to understanding and managing water resources systems and to assessing and quantifying production of food, feed, fiber and biofuels. ET is the primary consumer of liquid water in hydrologic systems and consumes enormous quantities of water. ET is highly variable, spatially, because of high variability in vegetation and water availability. ET is highly variable temporally because of weather and climate influences. Because of the relatively large magnitude of the ET component in hydrologic water balances, even 'small' errors in ET estimates or measurements can represent rather substantial volumes of water.

ET information is used frequently as the foundation or evidence for court determinations of injury among water users, for parameterization of important hydrologic and water resources planning and operations models, for operating weather and climate change forecasting models, and for water management and allocation in water-scarce regions. ET is typically modeled using weather data and algorithms that describe surface energy and aerodynamic characteristics of the vegetation and ET is typically measured using

* Corresponding author. Tel.: +1 208 423 6601.
E-mail addresses: rallen@kimberly.uidaho.edu (R.G. Allen), lspereira@isa.utl.pt (L.S. Pereira).

0378-3774/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.agwat.2010.12.016

systems that require the employment of relatively complex physical principles and techniques. In many agricultural systems, plant density, height, vigor and water availability are generally uniform, and the application of estimation algorithms and the measurement of ET can be relatively straightforward, although they are still not without substantial challenge. In the case of nonagricultural systems such as forest, desert and riparian systems, the heterogeneous nature of vegetation, terrain, soils and water availability make surface energy and aerodynamic processes highly variable and poorly defined. In both cases, sufficient description of the vegetation system and the data collection and/or modeling methods are essential.

ET data and ET models or model calibrations reported in the literature for even 'well-behaved' agricultural systems often may contain serious biases from flaws in experimental design, measurement equipment, vegetation management, data processing, model structure, model parameterization, and interpretation of results (Allen et al., 2011). Detection of these flaws is often hampered by insufficient or poor documentation and description accompanying the data reporting. It is essential that reporting of ET measurements and derived products such as crop coefficients or parameterized models contain sufficient description of the procedures used to measure and derive ET information to give readers the capability to discern potential flaws or shortcomings in data measurement and potentially the need to question the representativeness of ET presentations. In the same manner, even when reported ET information or derived products are of exceptional quality and integrity, the use of the data by others is often impeded by insufficient documentation and description of vegetation characteristics and relative water availability. Many land surface process models, such as the Weather Research and Forecasting Model (http://www.wrf-model.org) used to forecast near-term weather and to simulate weather under climate change, are 'hungry' for useful ET data against which to calibrate or validate. Frequently the ET information available in the literature for use in various modeling or operational processes is deficient in regard to documentation to facilitate judgment of its quality.

Because of the wide range of complexities in making ET and associated weather measurements and the abundance of opportunities for biases to enter ET and weather data sets (Allen et al., 2011), researchers and users of ET literature need sufficient information to be reported in articles on ET to assess the likelihood for opportunities of bias or error to enter reported data as well as sufficient information to utilize reported data in ET models. This article is part two of a two-part series on ET measurement requirements and accuracies (I) and ET reporting recommendations (II). The first article (Allen et al., 2011) describes common ET measuring or estimating systems including water balance, lysimeters, Bowen ratio, eddy covariance, scintillometry, sap flow and remote sensing. Common errors, biases and shortcomings of common ET measurement systems are discussed to provide support for why the supporting reporting information is needed. This second article lays out recommendations for the type and nature of useful documentation and description of information that should accompany ET findings reported in ET-related articles.

2. Recommended documentation for reported ET and associated data

A wide range of ET measurement and calculation methods exist and a wide range of errors can occur during measurement and during data reduction as reviewed by Allen et al. (2011) (Part I). Users of ET data and reviewers of publications on ET benefit from access to information describing the context of the ET measurements. This information provides the ability to transfer data to other areas and environments, and provides the means to evaluate the integrity of reported data. In addition to documentation on ET measurements and associated weather data that may be used in models, ET documentation is needed to describe the nature of the vegetation measured, including type, variety, density, age, health, water availability, timing of development and senescence, height, fraction of ground cover or leaf area index, type of irrigation, if practiced, and other features useful to users of the data or users of derived crop coefficients and other ET parameters. Sufficient description of canopy architecture is needed to assist modelers in setting model parameters and, more simply, to compare against findings from similar studies. In the case of crop coefficients, the documentation should describe whether the reported crop coefficient(s) represent potential (i.e., well-watered and nonstressed) conditions and whether they are intended to represent the basal (ET from vegetation having a mostly dry soil surface condition) or an average crop coefficient condition (Allen et al., 1998, 2005, 2007).

2.1. Comparison against models

Besides careful study and critique of the measurement method and application procedure prior to publication, authors of ET data and model results are encouraged to compare ET data or derived K_c's against ET estimates derived from more-or-less standard models and/or prior published K_c's. Dependable models, when parameterized based on description of the vegetation, weather and soil and water conditions, can be expected to reproduce general magnitudes of calibrated data within some error tolerance, for example, ±20%, and preferably even closer, on average. The model estimates should include estimation of both soil evaporation and vegetation transpiration and should consider all weather parameters impacting evaporation (air temperature, humidity, solar radiation and wind speed). Models that can be employed include single layer resistance-type models such as the Penman–Monteith (PM) model, which are useful when the vegetation nearly covers the soil. Examples of PM model application include Kustas (1990), Farahani and Baush (1995), Schaap and Bouten (1996), Daamen and McNaughton (2000), Ortega-Farias et al. (2005), Were et al. (2008), Zhang et al. (2008), Irmak and Mutiibwa (2009) and Zhao et al. (2010). Surface conductance in the PM model can be inversely determined as a fitting parameter and then compared against literature values (Garratt, 1992; Kelliher et al., 1993, 1995; Allen et al., 1996).

When vegetation cover is less than 60 to 70%, a multilayer or multi-source model may be necessary that employs separate surface and aerodynamic functions in the PM (or similar) equation to capture evaporation from soil and interaction between soil and canopy. Multi-layer models couple aerodynamic resistances in series between layers, with the layers comprising soil and one or more layers of vegetation canopy. Multi-source models often couple aerodynamic resistances from soil and canopy in parallel, rather than, or in addition to, coupling resistances in series, and may contain multiple sources of soil (shaded and sunlit, wet and dry). Common implementations of multi-layer models include Shuttleworth and Wallace (1985), Brisson et al. (1998), Choudhury and Monteith (1988), Shuttleworth and Gurney (1990), and Dolman (1993) and common implementations of multi-source models include Kustas (1990), Evett and Lascano (1993), Brenner and Incoll (1996) and Daamen and McNaughton (2000). Examples of multilayer and multi-source model applications include Brenner and Incoll (1996), Sene (1996), Daamen (1997), Iritz et al. (1999), Domingo et al. (1999), Gardiol et al. (2002), Fisher et al. (2004), Mo and Beven (2004), Villagarcía et al. (2007, 2010), and Hu et al. (2009).

Multilayer and multisource models are relatively complicated to apply and parameterize, especially in regard to within-canopy transfer mechanisms and soil evaporation parameterizations, both of which are typically empirical. However, these models can be quite useful in fully describing evaporation and transpiration processes for comparison against measured ET data.

Alternatively, if the objective is to publish K_c values or K_c curves, a simpler K_c ET_{ref} model can be used. A dual K_c model (Allen et al., 1998, 2005) is recommended to approximately separate estimated evaporation from soil from estimated transpiration for purposes of establishing a basal K_{cb} curve. That curve should then be compared against published values and differences should be described, explained and justified.

Comparisons of direct depths or rates of ET with measurements from other time periods or other regions is not an effective means for justifying or assessing ET data. ET depths are strongly influenced by weather and climate and therefore vary with time or location for that reason. Direct comparisons should be made after normalizing the ET estimate or measurement using reference ET to account for weather effects by transforming depths into a crop coefficient or expressing as a fraction of reference ET (Allen et al., 2011).

2.2. Limits on ET

Relatively simple comparisons with reference ET estimates based on available energy are recommended in part I (Allen et al., 2011) to serve as guidelines for review of data accuracy and representativeness and to indicate the potential for bias in measurement procedures. These comparisons are necessary because many of the erroneously high ET estimates reported in the literature violate the law of conservation of energy that governs the conversion of liquid water to vapor during the transpiration and evaporation processes. Expressing ET in the form of K_c's simplifies the comparison process and provides expected upper limits (Allen et al., 2011).

2.3. Recommended documentation

Tables 1 and 2 list metadata that are recommended for reporting in future studies of ET to provide both reviewers and users of data with the means to scrutinize the integrity of the data as well as with the means to judge reported results in their environmental and physiological contexts. The lists also summarize the type of information that should be asked by potential users of the data prior to the data usage.

Table 1 lists general documentation and information that should accompany any ET data set or findings based on an ET data set. Table 2 describes additional documentation (or tests) that should accompany eddy covariance, Bowen ratio, lysimeter, soil water differencing and sap flow information to improve descriptions of implementations for these systems. These systems are described in part I (Allen et al., 2011). The left hand columns of Tables 1 and 2 list what we consider to be required information to be supplied and the right hand sides list desirable, but not essential, information that can assist in data assessment for representativeness, integrity, bias, and accuracy. The lists of recommended documentation items are relatively terse, but generally self-descriptive and explanatory.

We do not intend for journals to become inundated with descriptive background information and data. In many cases, prior publications containing descriptive information can be cited, especially when measurement procedures are relatively standard. In the case of lysimeters, for example, the lysimeter system installation may have been previously described and can be cited. Cited material should be readily assessable to the public via journals or maintained web pages.

We hope that editors of journals that publish manuscripts containing findings or models based on ET data will require this type of information to be included in submitted (and accepted) manuscripts. We encourage the creation of check lists that can be published on journal web sites to assist during manuscript preparation and to even provide guidance during design and implementation of ET studies on needed information to be collected and the type of care to be exercised during these studies, as well as to assist reviewers and editors. We do not suggest that such check lists be so exacting as to cause authors to avoid submission of manuscripts to specific journals. We anticipate that the publication and use of these check lists will elevate the integrity and usefulness of all collected and reported ET information and end products. We encourage journals to permit online metadata appendices to articles where the appendices contain specific details, photographs, and supporting data as well as additional specifics on materials and methods that might be useful to readers, but that might not be appropriate in the manuscript itself.

3. Quality assessment and quality control

Quality assessment (QA) and quality control (QC) (correction) of any measured data is essential to data integrity. Rigorous procedures should be part of any measurement system. Often QA includes graphical (ASCE-EWRI, 2005; Allen, 2008) and/or statistical (Meek and Hatfield, 1994; Snyder et al., 1996; Shafer et al., 2000; You and Hubbard, 2006) analyses. Comparison of data against independent measurements or models is also strongly advised. For example, plotting measured ET against ET simulated by a model, such as the Penman–Monteith equation calibrated to the data, as previously described, can identify periods of data that do not conform to expected behavior and can give cause for closer scrutiny. In other cases, independent measurements or estimates can be compared, for example comparing ET derived by eddy covariance with ET derived by Bowen ratio or ET derived via scintillometry to evaluate consistency in measurements. ET and H from eddy covariance or Bowen ratio can also be compared against ET and H derived from aerodynamic methods using the vapor pressure gradient or temperature gradient data from the Bowen ratio system combined with a measurement of wind speed and an estimate of surface roughness (Brutsaert, 1982; Campbell and Norman, 1998), or, if combined with eddy covariance system, using friction velocity (Meyers and Baldocchi, 2005). Combined operation of Bowen ratio and eddy covariance systems is strongly encouraged due to the opportunities for independent assessments of data integrity.

3.1. Solar and net radiation data

Where net radiation (R_n) is measured, values should be compared with R_n estimated from standard equations that are based on solar radiation, R_s. For example standard calculations presented in FAO-56 (Allen et al., 1998; ASCE-EWRI, 2005) can be used as a means for integrity assessment. One should not expect measured R_n to exactly agree with estimated R_n, especially if albedo or surface temperature is substantially different than that from the well-watered reference surface. Allen et al. (2011) (Part I) demonstrated that emitted long-wave radiation and thus measured or computed R_n can differ by 100 W m^{-2} due to surface temperature differences caused by moisture availability. However, significant variation between the two data sets 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. Other measurement related factors that can shift the relationship between measured and estimated R_n include scratched or dirty radiometer domes, an unlevel sensor, condensation of moisture inside domes of the R_n sensor, nonrepresentative vegetation underneath the sensor, an obstructed view of the sky, and obstruction by the mounting tower or other sensors or solar panels. When possible, four-component net radiometers are recommended, where each component (incoming short-wave, downwelling long-wave,

Table 1
Recommended check list for required and desired information to be reported for all systems of evapotranspiration measurement and with water consumption data, crop coefficients or calibrations of resistance-based ET methods for publication.

Required	Desired
All systems	
Vegetation:	
• Vegetation variety or varieties	• LAI vs. time
• Dates of crop stages or phenological stages	• Crop yield
• Planting or green-up	• Photograph(s) of crop and of the ET measurement system (can be placed with metadata)
• Full cover or effective cover or maximum cover	• Relative adequacy of soil water in fields (or vegetation systems) surrounding the field (or vegetation system) being measured
• Flowering	• Error analysis on the measurement system
• Senescence starts	• Fitting of measured ET data to a Penman–Monteith-type equation and indication of required surface resistances for the fitting (including statistics)
• Harvest, or maturation or end season	
• Plant density	• Calibration of a model to ET data with reporting of:
• Plant spacing along row (if ag.)	• Statistical evaluation of model
• Spacing between plant rows	• Model calibration methods
• Measured or estimated vegetation height vs. time	• Method to estimate roughness height and values in model
• Measured or estimated fraction of ground cover vs. time	• Method to estimate evaporation from soil
• Size of field (or stand of trees) containing the measurement system	
• Location of measurement system relative to the field, system or expanse of vegetation measured	
• Size of general agricultural area (or other vegetation system) surrounding the measurement field	
• Mulch type, density and coverage	
If an orchard, tree crop or forest, additional information include:	
• Age of trees and year of planting (if relevant)	*If a tree crop or forest, additional information*:
• Size of trees, height and crown diameter	• Photos of (can be placed with metadata):
• Tree spacing along row and between rows	• Individual trees
• Ground covered by mulch:	• Community of trees
• Type of mulch,	• Pruning
• Density	• Description of uniformity of trees
• Coverage	• Dates for treatments that may change ground cover by the trees
• Ground covered by active substory vegetation	• Leaf out
• Understory vegetation height	• Leaf fall
• Density	
• Tillage and ground cover management	
• Soil moisture management	
Supporting meteorological data:	
• Reference ET method (if used) and procedures used for calculation (can be a citation of published work)	• Description of other weather or micrometeorological equipment
• Description of supporting meteorological data for calculating ET, including solar radiation, net radiation, soil heat flux, air temperature, surface temperature, soil temperature, vapor pressure, wind speed	• Description of local climate for a period of several years
• Summary of primary weather data relative t the experimental period	• Description of weather data source (and url if from or on a public web site)
• Location(s) of meteorological system/sensors	
Size of weather station area and vegetation type and maintenance of station	
• Soil moisture management of the weather station	
• Degree and type of QA/QC applied, including calibration adjustment and procedures for filling missing data.	
Soil and irrigation description	
• Soil type and layering or NRCS soil taxonomy (USDA, 1999)	• Soil information (by layer or NRCS soil taxonomy (USDA, 1999))
• Irrigation type (method and system)	• Textural characteristics
• Irrigation frequency and duration	• Field capacity and wilting point
• Irrigation application depth per irrigation and total	• Soil bulk density
• Irrigation treatments (if applied) with description of	• Soil permeability
• Non-stressed treatments	• Irrigation
• Stressed treatments in relation to non-stressed	• Equipment
• Relative adequacy of soil water in stressed or non-stressed treatments	• Factors affecting performance
• Whether incidental water stress occurred	• Application uniformity
• Method for measuring irrigation input (depth)	• System for delivery of water to the fields
• Fraction of surface wetted by irrigation	• Fertility
• Description of treatment of rain events (measurement of rain, inclusion of the rainy day)	• What fertilizers were applied
• Method for soil water measurement	• Rates and timing of applications
• Drainage management	• How fertilizer rates were determined
• Tillage system type	• Any pesticides or growth regulation chemicals
• Salinity levels and management (if impacting ET)	• Dates of application
	• Application method
	• Dosage rate of active ingredient

Table 1 (*Continued*)

Required	Desired
ET information	
• If K_c is reported, provide basal and/or averaged K_c's based on the standardized reference ET	• If desired, provide basal and/or averaged K_c's based on a second reference (besides the standardized reference)
• If K_c is reported, indicate whether it should represent well-watered conditions,	• Type of filtering or moving average used on the ET and/or K_c data
• Refer to reported K_c as $K_{c\ adj}$ when some type of environmental stress had reduced the reported value	
• Comparison of derived K_c to literature values with comments on:	
• If grass-reference based, the agreement or lack of agreement of K_c for nearly full cover conditions to the expected range of 1.1-1.3	
• If alfalfa-reference based, the agreement or lack of agreement of K_c for nearly full cover conditions to the expected range of 0.95–1.0	
• Specific explanations of values exceeding the above ranges, especially if K_c values are to represent agricultural field settings	
• If grass-reference based, co-reporting of midseason K_c values based on the standard FAO climate of RH_{min} = 45% and wind speed at 2 m height = 2 m s^{-1}. (See Allen et al., 1998, eq. 62; 2005, eq. 5 or Allen et al., 2007, eq. 8.59)	
• Average daily minimum relative humidity and average wind speed during the four growth stages	

reflected short-wave and emitted long-wave) can be more readily compared against independent measures or expected values of each component than can an integrated measurement of R_n. For example, solar radiation can be compared against a theoretically derived clear sky 'envelope' as shown in Fig. 1 and downwelling long-wave radiation is graphed for ten radiometers in Fig. 2. These types of comparisons are helpful in assessing whether an instrument requires recalibration and can confirm that the datalogger clock time is accurate.

3.2. Weather data

Quality assessment and control (correction) of weather/meteorological data are essential to calculation of accurate and representative reference ET and to avoid bias. Weather/meteorological data should be quality assessed and quality controlled before use in any ET equation, including standardized reference ET equations, to ensure that data are of good quality and are representative of well-watered conditions. This is especially important with electronically

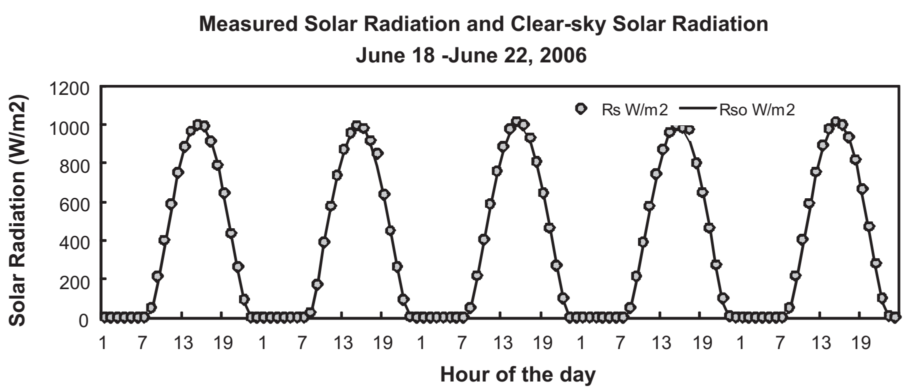

Fig. 1. Hourly average measured solar radiation, R_s, plotted with theoretical R_{so} calculated following ASCE-EWRI (2005), for five nearly clear sky days at Kimberly, Idaho, USA. R_s data courtesy of USBR-Agrimet.

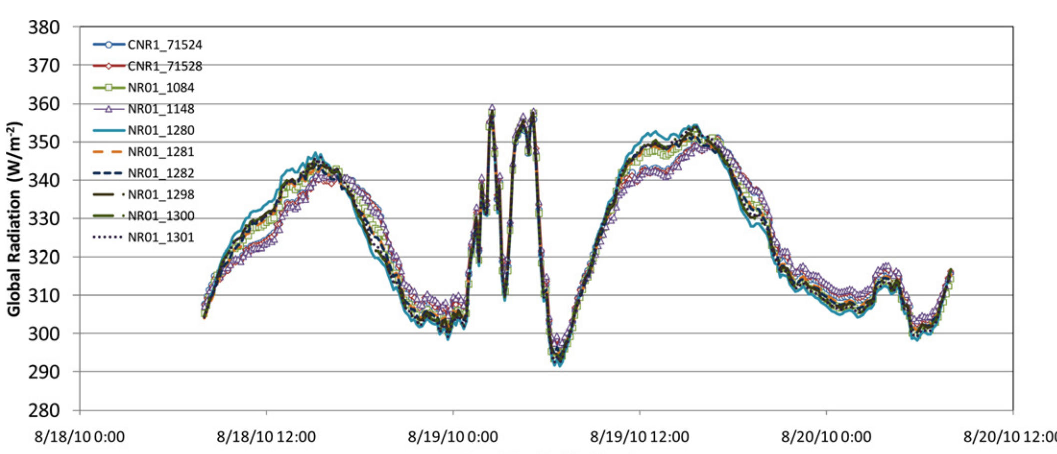

Fig. 2. Thirty-minute measured downwelling long-wave radiation over a three day period at Kimberly, ID, USA from the long-wave sensor components of ten four-component net radiometers after inter-instrument calibration. Moderate differences between model types (CNR1 vs. NR01) are noted, however, general agreement is good. (Data by Dr. Wenguang Zhao and R.G. Allen, University of Idaho).

Table 2
Recommended check list for required and desired descriptive information to be reported for specific ET measurement systems: Eddy covariance, Bowen ratio, lysimeters, soil water differencing and sap flow.

Required	Desired
Eddy covariance	
• Measurement frequency	• Description of multiple R_n and G sensors, especially when the fraction of ground cover is <0.8 or when mean vegetation height is >2 m.
• Averaging period	• Footprint analysis
• Height of sonic anemometer and hygrometer relative to (a) ground, (b) mean vegetation height, (c) maximum vegetation height (or limb)	• Indication of adequacy of soil water supply to support transpiration
• Anemometer and hygrometer instrument separation distances and orientation (a photo is desired)	• Description of soil water content monitoring in the vegetation root zone
• Types of corrections to the flux measurements and specific software used for corrections	• Soil type, field capacity, wilting point (and how these values were determined)
• Type of coordinate rotation employed	• Estimated rooting depth
• Fetch length in predominate wind directions and direction thresholds for data filtering	• Summary of QC analysis on R_n measurements using measured R_s and estimated or measured albedo and net long-wave radiation (if there is no R_s measured, use calculated R_{so} for comparing on clear days)
• Description of measurement of R_n and G for energy balance (EB) closure assessment	• Collocation with a Bowen Ratio system to confirm values for ratios of H/LE and to provide independent 'looks' at LE from EC and BR methods as well as aerodynamic estimates of H and LE based on $T_1 - T_2$ and $e_1 - e_2$.
• Description of (a) closure error amount and (b) method of closure	• Ages of all sensors and loggers and information on annual maintenance and storage
• Brands and maintenance procedures for R_n and G sensors, sonic anemometer, and hygrometer, including purchase and last rebuild dates	• Datalogger type and model
• Description on numbers of and placement of R_n and G sensors relative to vegetation and individual plants	
• Height of R_n sensor to (a) ground, (b) mean vegetation height, (c) maximum vegetation height (or limb)	
• For G, method for measuring soil water content and soil temperature	
• For vegetation, a description of:	
• distribution of height	
• fraction of ground cover by vegetation	
• LAI (measured or estimated)	
• Description of vegetation type, extent and soil water status upwind of the vegetation being monitored	
Bowen ratio	
• Brands and maintenance procedures for vapor and temperature sensors, R_n and G sensors, including purchase and last rebuild dates	• Description of multiple R_n and G sensors, especially when the fraction of ground cover is <0.8 or when mean vegetation height is >2 m.
• Description on numbers of and placement of R_n and G sensors relative to plants	• Footprint analysis
• For G, method for measuring soil water content and soil temperature	• Indication of adequacy of soil water supply to support transpiration
• Separation of the T and e sensors and placement relative to (a) ground and (b) vegetation	• Description of soil water content monitoring in the vegetation root zone
• Timing of exchange of sensors, if applicable	• Soil type, field capacity, wilting point (and how these values were determined or NRCS taxonomy (USDA, 1999))
• If sensors are not exchanged, indication of system for bias reduction between T and e measurements at the two elevations	• Estimated rooting depth
• Values of typical ΔT and Δe measured	• Summary of QC analysis on R_n measurements using measured R_s and estimated or measured albedo and net long-wave radiation (if there is no R_s measured, use calculated R_{so} for comparison on clear sky days)
• For vegetation, a description of:	• Collocation with an eddy covariance system to confirm values for ratios of H/LE and to provide independent 'looks' at LE from EC and BR methods as well as to provide wind speed or friction velocity, u^*, estimates for aerodynamic estimation of H and LE based on $T_1 - T_2$ and $e_1 - e_2$
• Distribution of height	• Datalogger type and model
• Fraction of ground cover by vegetation	
• LAI (measured or estimated)	
• Fetch length in predominate wind directions and direction thresholds	
• Description of vegetation type, extent and soil water status upwind of the vegetation being monitored	
Lysimeter[a]	
• Dimensions (width, length and depth):	• Report on two or more lysimeters with the same vegetation and water treatments with error analysis between/among them
• a. inner tank	• Salinity measurements of lysimeter drainage water
• b. outer tank	• Confirmation of adequacy of soil water supply to support transpiration
• Tank material and thickness	• Soil water content monitoring in the vegetation root zone
• Insulation of inner tank walls	• Soil type, field capacity, wilting point (and how these values were determined)
• Gap between inner and outer tank	• Estimated rooting depth

Table 2 (*Continued*)

Required	Desired
• Photos of lysimeter without vegetation	
• Photos of lysimeter with vegetation including immediate area outside lysimeter	
• Crop yields for the lysimeter and from the field	
• Photo of landscape surrounding the lysimeter	
• How the representative effective areas of the lysimeter are calculated for evaporation and transpiration determination	
• Scale type and specifications	
• No. scans of load cell(s) per reporting period	
• Calibration checks and estimated precision and accuracy	
• Method of lysimeter soil construction (monolithic vs. reconstructed)	
• Comments and notes on any differences between lysimeter vegetation and that of surrounding field or expanse including relative vegetation amount, fraction of ground cover, height, LAI, soil water availability	
• plant density of field or expanse and that inside lysimeter	
• fraction of soil visible inside and outside lysimeter	
• plant height inside and outside lysimeter	
• Drainage process for lysimeter	
• Soil layering inside and outside of the lysimeter	
• If lysimeter area is not an integer multiplier of average area per plant, including space between plant rows (if applicable), describe how evaporation from nonsampled areas is estimated	
• Description of supporting vegetation data including height (vs. time), LAI	
Soil Water Differencing	
• Soil water holding properties by layer to depths greater than the rooting depth	• Errors in observations
• Description of equipment	• Validation of pedo-transfer functions when used to characterize soil water holding capacity
• Maximum depth of measurement	• Description of the model when one is used, with particular attention to procedures for estimation of deep percolation and groundwater contribution
• No. of locations measured	• Procedures used when the crop season includes winter-time with frozen soil
• Locations of measurement sites	
• No. of depths observed and respective intervals	
• Time intervals for measurements	
• Comments on monitoring locations vs. areas wetted by irrigation, shadows cast by trees, etc.	
• Special treatment of surface layer	
• Estimation procedure for drainage and upward flow, including evidence that fluxes were small or negligible	
• Treatment of rainfall and irrigation events in the water balance	
• Sampling procedures when observations are performed for tree and vine crops	
• Procedures used when there is mulch	
• Procedures used when there is active ground cover	
• Procedures for estimation of soil evaporation	
Sap flow	
• Clear reference to the method used	• Sensor orientation
• Information about sampling, concerning the number of plants equipped with sap flow sensors and the selection criteria for different dimensions/species in a stand	• Height of sensor installation
• Description of scaling-up method to the stand level	• Description of insulation method
• Number of sensors per plant and sensor technical characteristics (ex.: probe length, number of measurement points in a probe)	
• Data treatment procedures, including corrections	
• Information about calibration procedures, if performed	

[a] Some of the details listed for lysimeter specifications can be referenced to previously published information on the specific lysimeter installation, provided the reference material is accessible via the internet or journal articles.

collected data, since human oversight and maintenance may be limited. When measurements are determined to be faulty, they can frequently be adjusted or corrected using justifiable and defensible procedures, such as simple visual (graphics-based) methods by ASCE-EWRI (2005) that can be used to screen and correct large amounts of data. The user may elect to replace perceived faulty data with estimates (ASCE-EWRI, 2005).

In the case of calculating reference ET, it is best that the weather/meteorological measurements be taken over a relatively well-watered and vegetated surface, for example, from an agricultural environment. This is encouraged because the standardized Penman and Penman–Monteith equations are calibrated to 'expect' the weather data to be from such an environment. The ET from a well-watered environment tends to condition the near surface boundary layer, reducing air temperature as much as 5 °C and increasing humidity, as compared to conditions experienced in an otherwise dry environment. Use of 'arid' weather data will tend to cause the reference ET estimate to be overstated.

The primary variables measured at standard agricultural weather stations are typically solar radiation, air temperature, wind speed and humidity. Because modern automated weather stations (AWS) are electronic and frequently are in remote locations, data are impacted by measurement biases caused by sensor malfunction, sensor aging, sensor calibration errors, sensor alignment, sensor cleanliness, datalogger programming, and sensor environment. When data are used to calculate ET, the AWS should measure air temperature, humidity and wind speed within the dynamic equilibrium boundary layer (EBL) overlying the ground surface in either the same environment as the ET measurement (if reporting ambient conditions) and/or in a 'reference weather environment'. Properties of the boundary layer characterize the energy balance at the surface and are generally implicit to assumptions and conditions used in developing the particular ET equation used, for example, the Penman–Monteith equation (ASCE-EWRI, 2005). In the case of calculating reference ET, where the reference ET represents the rate of ET from an extensive surface of well-watered vegetation having full-ground cover, the weather measurements should be made in a setting that includes enough well-watered vegetation within about 1 km in the upwind direction to condition the EBL to create congruency with the reference ET equation. Studies in southern Idaho by Burman et al. (1975) and modern blending height/profile theory models (Chen and Dudhia, 2001) have shown how the lower level of the atmosphere (i.e., EBL) 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 reference ET, that weather measurements are accurate and that the weather measurements reflect the environment that is defined by the reference surface.

Failure of a weather station site to meet the definition of a reference condition described above does not preclude the use of the data for estimating reference ET. 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. Allen et al. (1998, annexes 5 and 6), ASCE-EWRI (2005, appendices D and E), and Allen (2008) provide guidance for assessing whether temperature and humidity data from a weather station located in an arid or semiarid climate exhibit 'reference-like' characteristics.

3.3. Fetch requirements for weather stations

Allen (2006) applied results from Horst and Weil (1992) and Hsieh et al. (2000) to various fetch lengths of well-watered vegetation and dry soil to demonstrate the impact that fetch at various distances has on air temperature and humidity measurements at weather stations. The impact increases more-or-less logarithmetrically with distance upwind and then decreases after some distance even further upwind. Results indicate that the 100:1 fetch distance:measurement height rule-of-thumb appear to apply to unstable conditions (positive Bowen ratio) for measurement of temperature and humidity at weather stations, but may underestimate the fetch requirement for neutral and stable conditions.

4. Conclusions

Recommendations are provided on the types of documentation that should accompany ET data sets and associated products when published and that should be referenced in journal publications. This documentation helps to insure careful and quality data measurement and handling by the data collectors and it provides insight to readers of articles and users of data as to data representativeness, context and quality. These recommendations may be useful for consideration by editors of journals publishing ET information and during review of submitted manuscripts.

Acknowledgements

The authors express their appreciation to the Technical Committee on Evapotranspiration in Irrigation and Hydrology of the American Society of Civil Engineers – Environmental and Water Resources Institute for encouraging quality assurance and integrity in evapotranspiration and weather measurement and for functioning as a sounding board for this article; to Dr. Edward Glenn of the University of Arizona and Dr. Teresa do Paço of the Technical University of Lisbon for contribution to the section on documentation for sap flow measurement; and to Dr. Jim Oster, editor of Agricultural Water Management, for encouraging the publication of this article.

References

Allen, R.G., 2006. Footprint analysis to assess the conditioning of temperature and humidity measurements in a weather station vicinity. In: Paper presented at the 2006 World and Environmental Resources Congress of the American Society of Civil Engineers and Environmental and Water Resources Institute , Omaha, NE, May 22–25, 2006, Published on CD-ROM, ASCE, 12 p.

Allen, R.G., 2008. Quality assessment of weather data and micrometeorological flux: impacts on evapotranspiration calculation. J. Agric. Meteorol. 64 (4), 191–204.

Allen, R.G., Pruitt, W.O., Businger, J.A., Fritschen, L.J., Jensen, M.E., Quinn, F.H., 1996. Evaporation and transpiration. In: Wootton, et al. (Eds.), (Task Com.), ASCE Handbook of Hydrology, 2nd ed. Am. Soc. Civ. Engrs., New York, NY, pp. 125–252.

Allen, R.G., Pereira L.S., Raes D., Smith M., 1998. Crop Evapotranspiration. Guidelines for Computing Crop Water Requirements. United Nations FAO, Irrigation and Drainage Paper 56. FAO, Rome, Italy.

Allen, R.G., Pereira, L.S., Smith, M., Raes, D., Wright, J.L., 2005. FAO-56 Dual crop coefficient method for estimating evaporation from soil and application extensions. J. Irrig. Drain. Eng. 131 (1), 2–13.

Allen, R.G., Wright, J.L., Pruitt, W.O., Pereira, L.S., Jensen, M.E., 2007. Water requirements. In: Hoffman, G.J., Evans, R.G., Jensen, M.E., Martin, D.L., Elliot, R.L. (Eds.), Design and Operation of Farm Irrigation Systems (2nd Edition). ASABE, St. Joseph, MI, pp. 208–288.

Allen, R.G., Pereira L.S., Howell T.A., Jensen M.E. Evapotranspiration information reporting: I Requirements for accuracy in measurement. Agric. Water Manage. this issue.

ASCE-EWRI, 2005. The ASCE Standardized Reference Evapotranspiration Equation. Report 0-7844-0805-X, ASCE Task Committee on Standardization of Reference Evapotranspiration. Reston, Va., American Soc. Civil Engineers.

Brenner, A.J., Incoll, L.D., 1996. The effect of clumping and stomatal response on evaporation from sparsely vegetated shrublands. Agric. For. Meteorol. 84 (3–4), 187–205.

Brisson, N., Itier, B., L'Hotel, J.C., Lorendeau, J.Y., 1998. Parameterisation of the Shuttleworth–Wallace model to estimate daily maximum transpiration for use in crop models. Ecol. Model. 107 (2–3), 159–169.

Brutsaert, W., 1982. Evaporation into the Atmosphere. D. Reidel Publishing Co., Dordrecht, Holland, 300 pp.

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

Campbell, G.S., Norman, J.M, 1998. An Introduction to Environmental Biophysics, second edition. Springer, 286 p.

Chen, F., Dudhia, J., 2001. Coupling an advanced land surface-hydrology model with the Penn State-NCAR MM5 Modeling System. Part I: Model implementation and sensitivity. Monthly Weath. Rev. 129, 569–585.

Choudhury, B.J., Monteith, J.L., 1988. A four-layer model for the heat budget of homogenous land surfaces. Quart. J. R. Meteorol. Soc. 114, 373–398.

Daamen, C.C., 1997. Two source model of surface fluxes for millet fields in Niger. Agric. For. Meteorol. 83 (3–4), 205–230.

Daamen, C.C., McNaughton, K.G., 2000. Modeling energy fluxes from sparse canopies and understorys. Agron. J. 92, 837–847.

Dolman, A.J., 1993. A multiple-source land surface energy balance model for use in general circulation models. Agric. For. Meteorol. 65 (1–2), 21–45.

Domingo, F., Villagarcía, L., Brenner, A.J., Puigdefábregas, J., 1999. Evapotranspiration model for semi-arid shrub-lands tested against data from SE Spain. Agric. For. Meteorol. 95 (2), 67–84.

Evett, S.R., Lascano, R.J., 1993. ENWATBAL.BAS: a mechanistic evapotranspiration model written in compiled basic. Agron. J. 85 (3), 763–772.

Farahani, H.J., Baush, W.C., 1995. Performance of Evapotranspiration Models for Maize-Bare soil to closed Canopy. Trans. ASABE. 38 (4), 1049–1059.

Fisher, J.B., DeBiase, T.A., Qi, Y., Xu, M., Goldstein, A.H., 2004. Evapotranspiration models compared on a Sierra Nevada forest ecosystem. Environ. Model. Softw. 20 (6), 783–796.

Garratt, J.R., 1992. The Atmospheric Boundary Layer. Cambridge University Press, 316 p.

Gardiol, J.M., Serio, L.A., Maggiora, A.I.D., 2002. Modeling evapotranspiration of corn (Zea mays) under different plant densities. J. Hydrol. 271 (1–4), 188–196.

Horst, T.W., Weil, J.C., 1992. Footprint estimation for scalar flux measurements in the atmospheric surface-layer. Bound. Layer Meteorol. 59, 279–296.

Hsieh, C.I., Katul, G., Chi, T., 2000. An approximate analytical model for footprint estimation of scalar fluxes in thermally stratified atmospheric flows. Adv. Water Resour. 23, 765–772.

Hu, Z.M., Yu, G.R., Zhou, Y.L., Sun, X.M., Li, Y.N., Shi, P.L., Wang, Y.F., Song, X., Zheng, Z.M., Zhang, L., Li, S.G., 2009. Partitioning of evapotranspiration and its controls in four grassland ecosystems: application of a two-source model. Agric. For. Meteorol. 149 (9), 1410–1420.

Irmak, I., Mutiibwa, D., 2009. On the dynamics of evaporative losses from Penman–Monteith with fixed and variable canopy resistance during partial and complete maize canopy. Trans. ASABE 52 (4), 1139–1153.

Iritz, Z., Lindroth, A., Heikinheimo, M., Grelle, A., Kellner, E., 1999. Test of a modified Shuttleworth–Wallace estimate of boreal forest evaporation. Agric. For. Meteorol. 98-99, 605–619.

Kelliher, F.M., Leuning, R., Schulze, E.D., 1993. Evaporation and canopy characteristics of coniferous forests and grasslands. Oecologia 95, 153–163.

Kelliher, F.M., Leuning, R., Raupach, M.R., Schulze, E.-D., 1995. Maximum conductances for evaporation from global vegetation types. Agric. For. Meteorol. 73 (1–2), 1–16.

Kustas, W.P., 1990. Estimates of evapo-transpiration with a one and two layer model of heat transfer over partial canopy cover. J. Appl. Meteorol. 29 (8), 704–715.

Meek, D.W., Hatfield, J.L., 1994. Data quality checking for single station meteorological databases. Agric. For. Meteorol. 69, 85–109.

Meyers, T.P., Baldocchi, D.P., 2005. Current micrometerological flux methodologies with applications in agriculture. In: Hatfield, J.L., Baker, J.M. (Eds.), Micrometeorology in Agricultural Systems. Am. Soc. Agron. No. 47 in the Agro Series. , pp. 381–396.

Mo, X., Beven, K., 2004. Multi-objective parameter conditioning a three-source wheat canopy model. Agric. For. Meteorol. 122, 39–63.

Ortega-Farias, S.O., Olioso, A., Fuentes, S., Valdes, H., 2005. Latent heat flux over a furrow-irrigated tomato crop using Penman–Monteith equation with a variable surface canopy resistance. Agric. Water Manage. 82 (3), 421–432.

Schaap, M.G., Bouten, W., 1996. Forest floor evaporation in a dense Douglas fir stand. J. Hydrol. 193 (1–4), 97–113.

Sene, K.J., 1996. Meteorological estimates for the water balance of a sparse vine crop growing in semiarid conditions. J. Hydrol. 179, 259–280.

Shafer, M.A., Fiebrich, C.A., Arndt, D.S., 2000. Quality assurance procedures in the Oklahoma Mesonetwork. J. Atmospheric. and Oceanic. Tech. 17, 474–494.

Shuttleworth, W.J., Gurney, R.J., 1990. The theoretical relationship between foliage temperature and canopy resistance in sparse crops. Q. J. R. Meteorol. Soc. 116 (492), 497–519.

Snyder, R.L., Brown, P.W., Hubbard, K.G., Meyer, S.J., 1996. A guide to automated agricultural weather station networks in North America. In: Stanhill, G. (Ed.), Advances in Bioclimatology. Springer Verlag, New York, NY, pp. 1–61.

Shuttleworth, W.J., Wallace, J.S., 1985. Evaporation from sparse crops: an energy combination theory. Q. J. R. Meteorol. Soc. 111, 839–853.

United States Department of Agriculture, Natural Resources Conservation Service. 1999. Soil Taxonomy: A Basic System of Soil Classification for Making and Interpreting Soil Surveys. 2nd edition, p. 870.

Villagarcía, L., Were, A., Domingo, F., García, M., Alados-Arboledas, L., 2007. Estimation of soil boundary-layer resistance in sparse semiarid stands for evapotranspiration modeling. J. Hydrol. 342 (1–2), 173–183.

Villagarcía, L., Were, A., García, M., Domingo, F., 2010. Sensitivity of a clumped model of evapotranspiration to surface resistance parameterisations: application in a semi-arid environment. Agric. For. Meteorol. 150, 1065–1078.

Were, A., Villagarcía, L., Domingo, F., Moro, M.J., Dolman, A.J., 2008. Aggregating spatial heterogeneity in a bush vegetation patch in semi-arid SE Spain: a multi-layer model versus a single-layer model. J. Hydrol. 349, 156–167.

You, J., Hubbard, K., 2006. Quality control of weather data during extreme events. J. Atmos. Oceanic Technol. 23, 184–197.

Zhang, B., Kang, S., Li, F., Zhang, L., 2008. Comparison of three evapotranspiration models to Bowen ratio-energy balance method for a vineyard in an arid desert region of northwest China. Agric. For. Meteorol. 148 (10), 1629–1640.

Zhao, W.Z., Ji, X.B., Kang, E.S., Zhang, Z.H., Jin, B.W., 2010. Evaluation of Penman–Monteith model applied to a maize field in the arid area of Northwest China. Hydrol. Earth Syst. Sci. 14, 1353–1364.