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Review

Evapotranspiration information reporting: I. Factors governing measurement accuracy

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ABSTRACT

More and more evapotranspiration models, evapotranspiration crop coefficients and associated measurements of evapotranspiration (ET) are being reported in the literature and used to develop, calibrate and test important ET process models. ET data are derived from a range of measurement systems including lysimeters, eddy covariance, Bowen ratio, water balance (gravimetric, neutron meter, other soil water sensing), sap flow, scintillometry and even satellite-based remote sensing and direct modeling. All of these measurement techniques require substantial experimental care and are prone to substantial biases in reported results. Reporting of data containing measurement biases causes substantial confusion and impedance to the advancement of ET models and in the establishment of irrigation water requirements, and translates into substantial economic losses caused by misinformed water management.

Basic principles of ET measuring systems are reviewed and causes of common error and biases endemic to systems are discussed. Recommendations are given for reducing error in ET retrievals. Upper limits on ET measurements and derived crop coefficients are proposed to serve as guidelines. The descriptions of errors common to measurement systems are intended to help practitioners collect better data as well as to assist reviewers of manuscripts and users of data and derived products in assessing quality, integrity, validity and representativeness of reported information. This paper is the first part of a two-part series, where the second part describes recommendations for documentation to be associated with published ET data.

Contents

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1. Introduction

Evapotranspiration (ET) is typically modeled using weather data and algorithms that describe surface energy and aerodynamic characteristics of the vegetation. ET is typically measured using 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 non-agricultural 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. This is especially true, for example, for riparian systems such as cottonwood, tamarisk and Russian olive in semi-arid regions that can have widely varying vegetation density, tree height, stand extent and availability of water. Most information and estimates of water consumption by forest and riparian systems come from in-place measurements that have a strong empirical and local character. ET data and ET models or model calibrations reported in the literature for even 'well-behaved' agricultural systems can contain serious biases caused by flaws in experimental design, measurement equipment, vegetation management, data reduction, model parameterization, and interpretation of results. Therefore, it is essential that reporting of ET measurements and related products such as crop coefficients or parameterized models contain sufficient description of the procedures used to measure and derive ET information so that readers can be aware of potential flaws or shortcomings in data measurement and can be alerted to the need to question representativeness of ET presentations. ET information is more and more frequently used as a foundation for court determinations of injury among water users, for parameterization of important hydrologic and water resources planning and operation models, for operating weather and climate change forecasting models, and for water management and allocation in water-scarce regions, including the partitioning of water resources among states and nations. All too frequently the ET information used in these processes is deficient or uncertain, with too little descriptive information in the reporting 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, users of ET literature need sufficient information 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 examine or recreate the reported data using some type of ET model. This is currently often not the case, and many journal articles do not contain sufficient information to enable readers to gauge accuracies and representativeness of information. This article is part one of a two-part series on I: ET measurement requirements and accuracies and II: ET reporting recommendations (Allen et al., 2011a). This first article describes common ET measuring systems including water balance, lysimeters, Bowen ratio, eddy covariance, scintillometry, sap flow and remote sensing. The 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. In this first article, common errors, biases and shortcomings of common ET measuring systems are discussed to provide support for why the accompanying reporting information is needed.

Measurements of ET include a variety of methods ranging from soil water sampling to lysimeters to eddy covariance to scintillometry. Inherent to all of these methods is the reality that an improperly designed experiment or measurement can lead to highly erroneous water use estimates. 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. The environmental energy provided by solar radiation plus heat energy advected to the vegetation may be insufficient to explain the measurements. Relatively simple comparisons with reference ET estimates based on available energy are recommended to give cause for review of data and measurement procedures.

2. The case for limits on maximum values for ET and crop coefficients

Before addressing challenges and precautions with ET measurement systems, it is important to discuss what constitutes realistic limits on rates of ET. Evaporation constitutes the conversion of liquid water to vapor and as a result requires substantial amounts of energy. The availability of energy incident to vegetation places a constraint on the potential evaporation rate and forces adherence to the law of conservation of energy. ET rates that exceed available radiation energy (R_n) at the surface less the energy conducted as sensible heat to the ground (G), i.e., $R_n - G$, must essentially extract that additional energy from the atmosphere via downward (negative) sensible heat flux (H) via convective transfer through the equilibrium boundary layer of air above the surface. Because increasingly negative H creates increasingly stronger density-induced stability to the equilibrium boundary layer, it becomes increasingly more difficult to transport the required H to the surface to support the conversion to ET, especially without strong mechanical mixing brought about by high wind speed (Brutsaert, 1982; De Bruin et al., 2005). As a result there is an upper limit on ET, even under extreme advection, caused by limitations on aerodynamic transport and on equilibrium forces above a vegetation canopy. That upper limit on ET is relatively well represented by the tall (alfalfa) reference that has been defined by ASCE-EWRI (2005) using a parameterized Penman–Monteith equation (Allen et al., 1989, 2007c).

The upper limit on potential crop evapotranspiration (ET_c) is readily approximated by comparing against the widely used reference ET (ET_{ref}) through a crop coefficient (K_c). ET_{ref} may refer to two types of reference crops, clipped, cool-season grass or tall alfalfa (whose common symbols are ET_o and ET_r, respectively), thus crop coefficients may be expressed in relation to clipped, cool-season grass as more often used (Allen et al., 1998, 2007c) or to alfalfa; for which the symbol K_{cr} is adopted (ASCE-EWRI, 2005; Allen et al., 2007c). An alternative and synonymous expression for K_{cr} can be used, which is the term alfalfa reference ET fraction, ET_rF (ASCE-EWRI, 2005; Allen et al., 2007a). The terms K_c and ET_rF are simply defined as the ratio of ET for a specific surface, ET_c, to the ET of the standard reference surface, ET_{ref}. The crop coefficient was defined in 1968 (Jensen, 1968) for use with a reference crop ET_{ref} and first used in computerized irrigation scheduling by Jensen (Jensen, 1969; Jensen et al., 1970; Jensen et al., 1971). One can express ET_c