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Comparison of hourly and daily reference crop evapotranspiration equations across seasons and climate zones in Australia

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ABSTRACT

Estimates from the FAO Penman–Monteith (FAO-PM) and the standardized ASCE Penman–Monteith (ASCE-PM) hourly and daily reference evapotranspiration (ET_0) equations were compared at daily scale, based on the hourly climate data collected from forty (40) geographically and climatologically diverse Automatic Weather Stations (AWS) across the Australian continent. These locations represent 23 agricultural irrigation areas in tropical, arid and temperate climates. The aims of this paper are to: compare the effects of different methods of estimating Clear-sky-radiation—(R_{so}); compare sum-of-hourly and daily ET_0; compare the results of aggregation of hourly ET_0 over 24 h compared with daylight hours; and examine the impact of seasonality and climate type. At selected AWS locations, the hourly ET_0 was calculated using the hourly FAO-PM and the ASCE-PM equations and then summed to derive daily ET_0 (reported as $ET_{0,soh}$). This was compared against the daily ET_0 values, calculated using the corresponding daily equation (reported as $ET_{0,daily}$). Using R_{so} calculated following the "complex" approach improves the agreement between $ET_{0,soh}$ and $ET_{0,daily}$ of both hourly equations, compared with the "simple" approach. Better agreement between $ET_{0,soh}$ and $ET_{0,daily}$ estimates for the FAO-PM and ASCE-PM were found, when the hourly values are aggregated over 24 h rather than over daylight hours. The average ratio between $ET_{0,soh}$ and $ET_{0,daily}$ for the FAO-PM and ASCE-PM equations is 0.95 and 1.00, respectively. The range of the former is 0.90–0.98 and that of the latter is 0.96–1.04. There was very strong correlation between the two hourly equations at the daily time step: on average 0.997, with a range of 0.993–0.998. The results imply that the ASCE-PM hourly equation's daily ET_0 values are higher than those of FAO-PM, which can be explained by the difference in the treatment of surface resistances. Better agreements between $ET_{0,soh}$ and $ET_{0,daily}$ values for winter, spring and autumn were found for the FAO-PM version, while during summer, the ASCE-PM version showed better agreement. The best agreement between the hourly and daily results for the FAO-PM version was found in temperate climates and the ASCE-PM version showed best agreement in the tropical and arid climates.

1. Introduction

During the 20th century, the rate of fresh water consumption has increased at more than twice the rate of population growth, (UN-Water, 2006). It is anticipated that in 2025 there will be 50% and 18% growth in fresh water withdrawals in developing and developed countries, respectively (UNEP, 2007). At present, agricultural irrigation consumes 70% of the world's fresh water withdrawals. Therefore, more efficient irrigation water use is essential. Irrigation water requirement depends mainly on evapotranspiration (ET). Quantification of ET assists in carrying out tasks such as water allocation, water resource management and planning, water and energy balance estimation, yield estimation and irrigation scheduling. However, direct measurement of ET is difficult and costly, given that it is a vapour transfer process affected by dynamic factors such as weather parameters, crop characteristics and management and environmental aspects (Allen et al., 1998).

Jensen (1968) introduced a conceptual approach to estimate crop-ET using reference evapotranspiration (ET_0) and a crop coefficient (K_c), where ET_0 is crop-ET from the reference surface and K_c is the ratio between actual crop ET and ET_0. Based on this concept, the Food and Agricultural Organization's (FAO) Irrigation

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and Drainage Paper no. 24 provided guidelines to calculate ET_0 based for a reference crop of 8 to 15 cm tall green grass. They also provided a range of K_c for various crops (Doorenbos and Pruitt, 1977). They recommended four methods to calculate ET_0, namely, Blaney–Criddle, FAO-24 radiation, modified Penman, and pan evaporation, depending on data availability. The modified Penman was the preferred method of the four recommended methods, but it has frequently overestimated ET_0 (by up to 20%) in low evaporative conditions, with the over-estimation of ET_0 differing with locality (Allen et al., 1998). Subsequently, FAO Irrigation and Drainage Paper no.56 (FAO-56) was published along with hourly and daily FAO Penman–Monteith (FAO-PM) ET_0 equations. These are based on a 12 cm high hypothetical reference crop and updated K_c values are supplied (Allen et al., 1998). The daily FAO-PM equation was recommended as the sole standard method for computing daily ET_0 and numerous studies were conducted to evaluate its performance against other ET_0 equations as well as against measured ET_0 (Allen et al., 1989; Amatya et al., 1995; Chen, 2005; Chiew et al., 1995; George et al., 2002; Jensen et al., 1990). However, only a handful of studies have been conducted to evaluate the FAO-PM hourly ET_0 equation and its performance at daily and sub-daily time scales (Irmak et al., 2005; Itenfisu et al., 2003; Temesgen et al., 2005).

In 1999, the Evapotranspiration in Irrigation and Hydrology Committee of the American Society of Civil Engineers (ASCE) endeavoured to standardize ET_0 calculations, and updated the hourly and daily ET_0 equations provided in the FAO-56 (Walter et al., 2005). As an alternative to FAO-PM hourly and daily ET_0 equations, the ASCE committee proposed a standardized Penman–Monteith equation to calculate both hourly and daily ET_0. The standardized Penman–Monteith (ASCE-PM) ET_0 equation is based on two different reference surfaces, a short crop (similar to clipped grass) and a tall crop (similar to full-cover alfalfa). During the standardization process, the ASCE committee used two constants, namely the numerator—C_n (as an alternative to 900 in the FAO-PM) and the denominator—C_d (as an alternative to 0.34 in the FAO-PM). Values of C_n and C_d vary according to the reference surface and time step. The FAO-PM and ASCE-PM ET_0 equations for daily time step are identical. However, for a short crop, the ASCE-PM hourly equation C_n values use surface resistances of 50 s m^{-1} and 200 s m^{-1} during the day-time and night-time, respectively, compared with the uniform surface resistance of 70 s m^{-1} throughout 24 h period for the FAO-PM hourly equations. This is due to the fact that several studies have shown that the uniform surface resistance assumption of 70 m s^{-1} (standard height of 0.12 m) of the FAO-PM hourly version results in day-time hourly ET_0 estimates being more than the actual field observations and vice-versa for night-time conditions (Allen, 1996; Allen et al., 2006; Irmak et al., 2005; Ventura et al., 1999; Walter et al., 2005).

As part of the ASCE standardization process, (Itenfisu et al., 2003) estimates from hourly (aggregated to daily) and daily ET_0 equations for grass and alfalfa reference surfaces across 49 locations in the United State of America (USA) using ASCE-PM were compared with various other ET_0 equations including the FAO-PM. Results showed that the ratio between the sum-of-hourly and daily ET_0 values for the FAO-PM version ranged from 0.90 to 1.04 and from 0.94 to 1.07 for the ASCE-PM version. In terms of agreement between hourly and daily versions, it was found that the ASCE-PM ET_0 equations agreed better than the FAO-PM equations. The study did not examine possible causes of differences between the two versions that were found in terms of location, especially advective and non-advective environments. Irmak et al. (2005) stated that the differences were partially due to the constant daily ratio between soil heat flux density and net radiation at the crop surface. They recommended the ACSE hourly ET_0 equation, as opposed to the FAO-PM version, when hourly climate data is available; due to the fact that neither daily equation reflects diurnal changes in wind speed, air temperature, or vapour pressure deficit. Similar conclusions were drawn by Gavilán et al. (2008) for semi-arid climate conditions in Andalusia, Southern Spain. They found that hourly ET_0 calculated using the ASCE-PM version was 4% higher on average compared with the FAO-PM version. However, daily ET_0 calculated using the ASCE-PM hourly equation was higher than the ASCE daily ET_0 equation, and the differences between these two estimates were not dependent on the wind speed or the magnitude of the ET_0 values.

Studies comparing ET_0 estimates with measurements have also been conducted. Berengena and Gavilan (2005) found that hourly ET_0 calculated using the ASCE-PM and FAO-PM versions underestimated measured hourly ET_0 by 2% and 3%, respectively, in Cordoba, Spain. Contrasting conclusions were derived by Lopez Urrea and López (2006) after evaluating measured and calculated hourly ET_0 under the semiarid conditions in Albacete, Spain. They revealed that on an average calculated hourly ET_0 using the FAO-PM version was similar to the measured hourly ET_0, but on average the ASCE-PM version was 4% higher. This result was supported by Suleiman and Hoogenboom (2009) using 15 min climate data for eleven representative and well-distributed sites throughout the state of Georgia, USA. They stated that more consistent results were found between hourly and daily FAO-PM ET_0 equations in humid climates, and that the hourly ET_0 calculated using ASCE-PM were higher than those of FAO-PM during the day and vice-versa during the night, which results from the treatment of surface resistance as 50 s m^{-1} during the day and 200 s m^{-1} during the night, respectively. In contrast, Yildirim (2004) calculated daily ET_0 using 12-min interval meteorological data for the GAP project, Turkey and found that the FAO-PM hourly equation underestimated daily ET_0 by 2 mm day^{-1}. These results all suggest inconsistencies between daily ET_0 calculated using the hourly equation (ASCE-PM or FAO-PM) and the respective daily equation as well as between daily ET_0 calculated using the two hourly equations.

Previous studies conducted to evaluate the agreement between daily ET_0 calculated using hourly and daily equations in the USA and Europe have drawn conflicting conclusions. Therefore, on the global scale, we are unable to distinguish a version (ASCE-PM or FAO-PM), which provides the best agreement between the hourly and daily ET_0 equation at daily scale. The degree of agreement respect to ASCE-PM or FAO-PM equations were highly influenced by the locality and the degree of diurnal change. On the other hand, the hourly ET_0 equations have often been used to calculate daily ET_0 due to the sub-daily reporting frequency of expanded AWS networks and sub-daily temporal scales for numerical weather prediction models and irrigation scheduling tools. For these reasons, it is important to distinguish the agreement between daily ET_0 calculated using the hourly and daily equation and to understand whether the degree of agreement is geographically consistent or location dependent. Furthermore, no studies have compared hourly and daily based estimates of ET_0 by season to identify whether systematic differences between the methods are seasonally dependent.

This paper aims to quantify the estimation performance of daily ET_0 calculated using the FAO-PM and ASCE-PM hourly ET_0 equations, against the daily ET_0 calculated using the corresponding daily ET_0 equation over the Australian continent. We calculated daily ET_0 using the hourly equations for 40 locations (automatic weather stations), across 23 agricultural irrigation areas from 9 diverse climate zones and assessed the agreement with the daily ET_0 calculated using the corresponding daily equation. We also evaluated the temporal, spatial and climatological variation of agreement between the methods. Further, we investigated the possible causes of differences between the methods.