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Spatially distributing monthly reference evapotranspiration and pan evaporation considering topographic influences

Tim R. McVicar [a,*], Thomas G. Van Niel [b], LingTao Li [a], Michael F. Hutchinson [c], XingMin Mu [d], ZhiHong Liu [d]

[a] *CSIRO Land and Water and eWater Cooperative Research Centre, GPO Box 1666, Canberra, 2601 ACT, Australia*
[b] *CSIRO Land and Water and eWater Cooperative Research Centre, Private Bag No. 5, Wembley, 6913 WA, Australia*
[c] *Centre for Resource and Environmental Studies, The Australian National University, Canberra, 0200 ACT, Australia*
[d] *Institute of Soil and Water Conservation, Chinese Academy of Sciences, 26 Xinong Road, Yangling 712100, Shaanxi Province, China*

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Summary Many hydrological models engage spatially distributed measures of 'potential evapotranspiration' (ET_{pot}). The reliability and utility of the physically based Penman–Monteith approach to generate ET_{pot} has been recently advocated. Assuming land-surface conditions, spatial surfaces of reference evapotranspiration (ET_0) can be generated taking into account the topographic influence of forcing meteorological variables. This was performed in this paper by spatially interpolating maximum (T_{max}) and minimum (T_{min}) air temperatures, wind speed (u) and vapor pressure (e_a), using a spline model with a linear sub-model dependency on elevation, and modelling the radiation environment, taking topography (*i.e.*, elevation, slope and aspect) into account, prior to calculating ET_0 at each grid-cell. In accordance with previous research, resultant lapse rates showed a strong seasonal pattern; values were steeper in summer than winter and those for T_{max} were steeper than for T_{min}. Monthly mean T_{max} lapse rates varied from $-3.01\ ^{\circ}C\ km^{-1}$ in winter to $-7.69\ ^{\circ}C\ km^{-1}$ in summer, with T_{min} lapse rates ranging from $-2.79\ ^{\circ}C\ km^{-1}$ in winter, to $-6.64\ ^{\circ}C\ km^{-1}$ in summer. Monthly climatologies of the near-surface elevation-dependence (NSED) for u and e_a also showed strong seasonal values. NSED of u varied from $2.01\ ms^{-1}\ km^{-1}$ in winter reducing to $0.75\ ms^{-1}\ km^{-1}$ in summer. The NSED for e_a ranged from $-0.08\ kPa\ km^{-1}$ in winter to $-0.64\ kPa\ km^{-1}$ in summer. For a 252-month sequence from 1980 through 2000, spatial surfaces of ET_0 with a 100 m resolution for the 113,000 km^2 study site located in the Loess Plateau, China were generated using an

* Corresponding author. Tel.: +61 2 6246 5741; fax: +61 2 6246 5800.
E-mail address: Tim.McVicar@csiro.au (T.R. McVicar).

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Interpolate-then-calculate;
Calculate-then-interpolate

'interpolate-then-calculate' approach. Resultant ET_0 values varied from about 20 mm month^{-1} in winter to over 150 mm month^{-1} in summer. In order to assess the reliability of these ET_0 surfaces, pan evaporation (E_{pan}) was also spatially interpolated and from these a set of pan coefficient (K_{pan} – a unitless ratio defined as ET_0/E_{pan}) surfaces were calculated. Spatio-temporally averaged K_{pan} values for the study site varied from 0.44 in April to 0.65 in late summer. K_{pan} values were in agreement with another study using a Chinese 20 cm diameter micro-pan, and, as expected, were lower than other values documented using a Class A pan. The influence of topography, especially aspect, was seen on the resultant ET_0 and K_{pan}, but not E_{pan}, surfaces. Sensitivity analysis showed that results were particularly stable in the hydrologically active portion of the year extending from March to October, inclusive. This study demonstrated that high spatial resolution monthly surfaces of ET_0 can be spatially modelled while taking into account the influence of topography on the forcing variables.

Introduction

Many hydrological, agricultural and environmental models, including assessments of global water cycle intensification due to climate change (Huntington, 2006) and frameworks to predict impact of re-vegetation activities on regional hydrology (*e.g.*, Donohue et al., 2007; McVicar et al., in press; Zhang et al., 2001), require a spatially distributed measure of 'potential evapotranspiration' (ET_{pot}). The generally accepted broad 'definition' of ET_{pot} is that it defines an upper limit of evapotranspiration if the land-surface for a given environment (meaning both meteorological and land-surface conditions Lhomme, 1997) was brought to saturation (Granger, 1989); noting that ET_{pot} is an idealised value as no feedbacks between the evaporating land-surface and the governing meteorological variables are included (Lhomme, 1997). That is, if a regional surface were evaporating at its potential the fact that this would alter atmospheric conditions, therefore changing rates of ET_{pot}, is not considered. For ET_{pot} to be a useful index, it must be calculated from readily available data (Lhomme, 1997), and it must be physically robust taking into account the known interactions between variables controlling evaporation (*e.g.*, McKenney and Rosenberg, 1993; Monteith, 1965; Penman, 1948; Penman, 1956). For example, interactions between minimum air temperature, dew point and the corresponding vapor pressure deficit should be accounted for, especially when considering a changing climate.

Since the 1950s the concept of ET_{pot} has been increasingly used by more disciplines, for different purposes, and for vastly different climates, with the number of empirical definitions growing (*e.g.*, Allen et al., 1998; Oudin et al., 2005; Xu and Singh, 2002 and the references therein); many of these were only calibrated locally. To encourage the use of a standard ET_{pot} the concept of 'crop reference evapotranspiration' (ET_0) was developed, which was calculated using four approaches in the mid 1970s (Doorenbos and Pruitt, 1975; Doorenbos and Pruitt, 1977). Following extensive analysis of the four methods in many locations world-wide, the Penman–Monteith approach (Monteith, 1965) was unanimously accepted (Smith et al., 1991) as the sole Food and Agricultural Organisation (FAO) endorsed approach to estimate ET_0, culminating in publication of Allen et al.'s (1998) FAO-56 report.

Development of ET_0 from the Penman–Monteith equation requires simplifying assumptions via the detailed definition of reference land-surface conditions. The Allen et al. FAO-56 report (1998, pp. 23) defines the land-surface conditions as: 'A hypothetical reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 s m^{-1} and an albedo of 0.23. The reference surface closely resembles an extensive surface of green grass of uniform height, actively growing, completely shading the ground and with adequate water. The requirements that the grass surface should be extensive and uniform result from the assumption that all fluxes are one-dimensional upwards'. Using these reference land-surface conditions, and given a few other assumptions, the FAO-56 formulation of ET_0 (Allen et al., 1998) is:

$$ET_0 = \frac{0.408\Delta(\boldsymbol{R}_n - \boldsymbol{G}) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (1)$$

where ET_0 is the reference evapotranspiration (mm day^{-1}); Δ is the slope of the saturation vapor pressure curve (kPa °C^{-1}); $\boldsymbol{R}_n$ is the allwave net radiation at the surface (MJ m^{-2} day^{-1}); $\boldsymbol{G}$ is the allwave ground heat flux (MJ m^{-2} day^{-1}); γ is the psychrometric constant (kPa °C^{-1}); T is the mean daily air temperature, that is $T = (T_{max} + T_{min})/2$ (°C), where T_{max} and T_{min} respectively are the daily maximum and minimum air temperatures (°C); u_2 is the daily average wind speed at 2 m above ground level (m s^{-1}); $e_s - e_a$ is the saturation vapor pressure deficit (kPa); with e_s being the saturation vapor pressure (kPa) and e_a the actual atmospheric water vapor pressure (kPa). Starting from the one-dimensional single-source formulation of the Penman–Monteith equation (Monteith, 1965) the FAO-56 ET_0 is fully derived, including explicitly expanding the 'few other assumptions', in several sources (*e.g.*, Allen et al., 1998; McVicar et al., 2005a). If the time-step of all data are monthly then the resultant ET_0 is provided with units of mm month^{-1} (Allen et al., 1998; McVicar et al., 2005a).

To our knowledge there is only one previous case where ET_0 has been spatially distributed (Xu et al., 2006). This was performed for the entire Yangtze River basin with an approximate 25 km resolution output. Even though there is an elevation range of 6621 m, changes in meteorological conditions as a function of topography (*e.g.*, Barry, 1992;