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An R Package for Implementing Multiple Evapotranspiration Formulations

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Abstract: The use of multiple evapotranspiration (ET) models is critical for exploring the ambiguity in the representations of ET processes. Although ensemble ET models are increasingly used to address this ambiguity, practical issues include: 1) the diversity of process representations, which require different input data and constants; 2) the diversity of nomenclature, terminology and units used in the literature; and 3) the complexity of some formulations, requiring significant time for coding and leading to potential user errors. We describe an R package that estimates both actual and potential ET from 17 well-known formulations. Results are presented as summary text and plots, and the package also can be easily coupled to rainfall-runoff modelling packages such as *hydromad* to estimate the effect of changing ET on runoff response. Additional plotting tools within the package allow users to visualise the association between estimated ET and climate variables such as temperature, solar radiation, wind and relative humidity. We provide a case study using Penman, Penman-Monteith FAO56 and Priestley-Taylor potential ET estimated using historical data from Kent Town weather station in Adelaide. The estimation from Priestley-Taylor formulation can be up to 20% lower than the estimation from the other two formulations which indicates the importance of the advection process at Kent Town.

***Keywords**:* evapotranspiration (ET), evaporative demand, hydrological modelling

1 INTRODUCTION

Evapotranspiration (ET) processes are important in the hydrologic cycle. There are a range of different processes involved in ET such as open-water evaporation, actual evapotranspiration (AET), potential evapotranspiration (PET) and reference crop evapotranspiration (ET_0). PET is defined as the amount of water that can evaporate from a surface when sufficient water is available; ET_0 refers to the evapotranspiration rate from a defined crop surface in a well-irrigated area; where AET represents the actual rate of evaporation that can be less than or equal to PET depends on the soil moisture. The individual ET processes provide useful information for diverse hydrologic applications. For example, hydrologic modelling usually requires the input of PET; for the management of a reservoir information on the open-water evaporation is critical; while information on AET could provide recommendation for managing irrigation requirement.

The multiple processes involved in ET leads to the development of multiple ET models which represent different processes and estimates different ET-related quantities. However, for each individual quantity there are also multiple formulations available, which are based on different representations for the same process. According to McMahon et al. (2012), different formulations can represent a single ET process differently by (i) placing emphasis on different sub-processes, such as aerodynamic and advection processes, (ii) conditioning on different environment, including humid and arid climates, (iii) having different requirements for inputting climate data and different interpretations of the constants' values, (iv) conforming to different hierarchies for handling missing data and adjustment to specific environments and (v) being subject to varying terminology in the literature, therefore they can provide varying estimations.

In this situation where ambiguity exists in hydrologic process representation (i.e. hypothesis), it is suggested that each hypothesis should be tested against each other (Clark et al., 2011). However, ET related quantities are difficult to measure. For example, the measurement of AET requires sophisticated scaling techniques or expensive micrometeorological eddy flux instrumentation;

difficulties in obtaining the direct measurements of ET_0 have also been reported (Testi et al., 2004; Allen et al., 2005); furthermore, potential ET is a conceptual quantity which cannot be 'measured' while can only be estimated from pan evaporation (Gasca-Tucker et al., 2007; Fisher et al., 2011). Therefore, it is difficult to test the performance of different models for each ET-related process and resolve the ambiguity in process representations.

In order to address modelling ambiguity, ensemble models have been increasingly employed in applied hydrology. Ensemble models usually include a number of different models for representing the same process which enables the full discovery of the uncertainties as well as the credits and caveats in different process representations. These ensemble models have been used for simulations and predictions under current and future conditions, including studies to improve current hydrologic modelling (Duan et al., 2007; Kavetski and Fenicia, 2011) and studies to assess future climate impact (Velázquez et al., 2012). There are also software packages developed to facilitate the implementation of ensemble hydrologic models such as hydromad (Andrews et al., 2011).

Recently ensemble models have also been employed to represent the ET-related processes. However, the number of formulations investigated is generally relatively small. For example, Fisher et al. (2011) investigated the difference in the PET estimation from three PET models including the Thornthwaite (Thornthwaite, 1948), the Priestley-Taylor (Priestley and Taylor, 1972) and the Penman-Monteith (Monteith, 1965). McKenney and Rosenberg (1993) sampled eight PET formulations to investigate the sensitivity of ET to future climate conditions, and Kingston et al. (2009) studied the uncertainty range of future climate impact on ET using six ET formulations. The lack of consideration of a larger number of alternative ET formulations might, at least in part, be due to the difficulty in implementing large numbers of inherently different ET formulations in a consistent manner. Oudin et al. (2005) could be the most ambitious study so far, in which 27 PET formulations have been compared. But still, the authors have reported difficulties in comparing and evaluating the formulations due to the big number of equations and the wide range of data types needed.

To facilitate the use of ensemble models for ET processes, we have developed an R software package to estimate ET from 17 alternative formulations. Fifteen of the formulations are based on those summarised in McMahon et al. (2012), as well as the Jensen-Haise and the McGuinness-Bordne formulations, sourced from Oudin et al. (2005). The package enables the calculations required for each ET formulation to be implemented in a consistent and convenient manner, thereby enabling the ambiguity in ET modelling to be easily explored for future studies.

In this paper, the general structure of the package is described in Section 2, including details of its three main components – data pre-processing, calculation of ET and presentation of results. In Section 3, a demonstration of the package is presented using meteorological data collected from Kent Town, Adelaide, South Australia. In Section 4, the paper is concluded and the contribution of this package to future research in hydrologic modelling is highlighted.

2 THE EVAPOTRANSPIRATION PACKAGE

2.1 Evapotranspiration Formulations

The package *Evapotranspiration* (now available on CRAN at: http://cran.r-project.org/web/packages/Evapotranspiration/index.html) includes 17 formulations which perform direct calculations of different evapotranspiration-related quantities, including PET, ET_0 and AET (including evaporation) under different spatial and climate conditions. Implementation of the 17 formulations requires different input climate variables at different time steps (Table 1). The PET and ET_0 formulations interpret different ET sub-processes, including the incoming radiation, the aerodynamic process, the advection process, the heat exchange with ground and the surface resistance for vegetation, in different ways (see the references in Table 1 for further details). The five AET formulations (i.e. Brutsaert-Strickler, Granger-Gray, Szilagyi-Jozsa, Morton CRAE and Morton CRWE) estimate AET based on the Complementary Relationship between PET and AET (Morton, 1983a).

Table 1. Data requirements for different formulations. D = daily, M = monthly

Formulation name	Quantity estimated	Data required						
		T_{max}/T_{min}	T_d	R_s	n	u_z/u_2	RH_{max}/RH_{min}	E_{pan}
Penman (Penman, 1948)	Open-water evaporation/ PET	D		D		D	D	
Penman-Monteith FAO-56 (Allen et al., 1998)	ET_0 from short crop surface	D		D		D	D	
Matt-Shuttleworth (Shuttleworth and Wallace, 2009)	Well-watered ET_0 from short crop surface	D		D		D	D	
Priestley-Taylor (Priestley and Taylor, 1972)	PET from advection-free saturated surface	D		D			D	
Penpan (Rotstayn et al., 2006)	Class-A pan evaporation	D		D		D	D	
Brutsaert-Strickler (Brutsaert and Stricker, 1979)	Actual areal ET	D		D		D	D	
Granger-Grey (Granger and Gray, 1989)	Actual areal ET	D		D		D	D	
Szilagyi-Jozsa (Szilagyi, 2007)	AET	D		D		D	D	
Makkink (De Bruin, 1981)	PET			D				
Blaney-Criddle (Allen and Pruitt, 1986)	Well-watered ET_0				D	D	D	
Truc (Turc, 1961)	ET_0			D				
Hargreaves-Samani (Hargreaves and Samani, 1985)	ET_0	D						
Chapman Australian (Chapman, 2001)	ET_0 from short crop surface							D
Jensen-Haise (Oudin et al., 2005)	ET_0 in irrigated fields in arid and semiarid areas	D						
McGuiness-Bordne (Oudin et al., 2005)	ET_0 in irrigated fields in arid and semiarid areas	D						
Morton CRAE (Morton, 1983a)	PET/wet-environment areal ET/AET	M	M		M			
Morton CRWE (Morton, 1983b)	PET/shallow lake evaporation	M	M		M			

*Notations in the table: T_{max}/T_{min} = maximum/minimum temperature, T_d = dew point temperature, R_s = incoming solar radiation, n = sunshine hours, u_z/u_2 = wind speed at the height of wind instrument/at 2 m from ground, RH_{max}/RH_{min} = maximum/minimum relative humidity, E_{pan} = Class-A pan evaporation

2.2 Structure and Core Functions

The package *Evapotranspiration* is designed to achieve the following objectives:

1. To perform basic checks of each input variable for missing values, fill in missing values by linear interpolation, and generate warning messages or terminate the program where poor quality data are detected;
2. To aggregate raw data to the appropriate time step for ET calculation;
3. To check missing input variables to satisfy different data requirements for 17 different ET formulations, and perform calculations to fill in missing data entries from the available data;
4. To perform calculations using 17 ET formulations that cover open-water evaporation, pan evaporation, PET or AET;
5. To allow user commands to choose among different filling strategies for missing input variables for 17 ET formulations, among different versions of any single formulation, as well as among different adjustments of results for specific environment where the formulations are applied ;
6. To display a summary that informs the user about which ET formulation has been used, which ET quantity has been calculated and which assumptions and calculation options have been used
7. To plot the results of daily ET estimates, as well as plots of the monthly and annual aggregations and statistics calculated from the daily estimates;
8. To plot the results from different sets of ET estimates (which can be from different formulations, different versions of the same formulation or different input data) for comparison;
9. To plot the association between estimated ET and different climate variables.

The package *Evapotranspiration* contains a set of functions that work together to achieve the abovementioned objectives using the structure outlined in Figure 1.

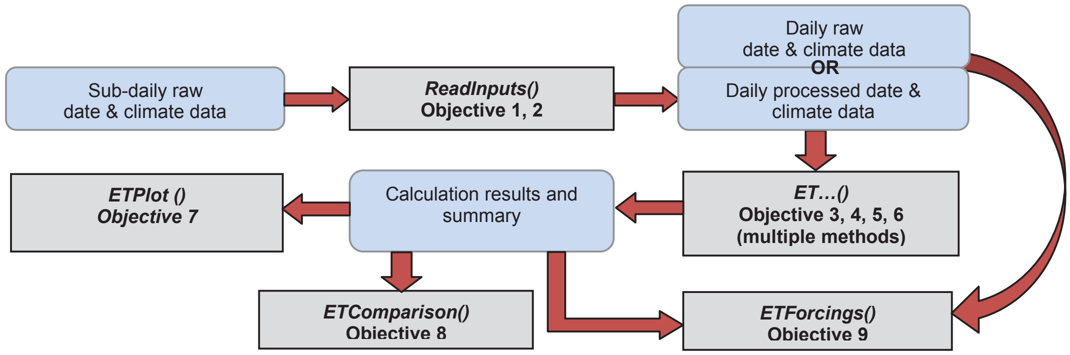

Figure 1. Schematic diagram of the functionality of package *Evapotranspiration*

In Figure 1, the blue boxes represent data or results that are produced and/or processed by the functions represented in the grey boxes. The data pre-processing function *ReadInputs()* is developed for loading and processing sub-daily raw climate data. The processed data are then ready to feed into function *ET..()*, which is a generic function for performing direct calculation of ET using user-selected formulations. If the raw climate data is daily it can be input straight into *ET..()* once the variables names are correct. The function then implements calculations for different ET formulations and generates the calculation summary. Function *ETPlot()* can then be called to plot the aggregation plots and average plots using the ET estimates. Function *ETComparison()* enables users to compare results and statistics from different sets of ET estimates produced by using different formulations and/or different input data. *ETForcing()* is for plotting the association between estimated ET and different climate variables.

2.3 Detailed Functions

ReadInputs() is designed for checking data availability, including the presence of missing entries and errors from the input sub-daily raw climate data. The availability of the date data is firstly checked since it is necessary for interpreting the time series of climate data. *ReadInputs*() also checks for the existence of climate input variables that will be required by the following ET calculation. This is a general check of data availability, which searches for the combined set of raw climate input variables that are required by all the formulations, including temperature, wind speed, solar radiation or sunshine hours, relative humidity and dew point temperature. Specific checks of data requirements for individual formulations as in Table 1 will be performed prior to implementing the calculations. In situations where data for a certain input variable are not available, *ReadInputs()* fills in the missing data from the available data using their monthly average. Next, *ReadInputs()* checks for missing entries in each of the available climate variables. The function allows two user-defined thresholds to be entered for 1) the maximum acceptable percentage of missing data; 2) the maximum acceptable duration of continuous missing data as percentage of total data duration. If the percentage of missing data is below the threshold, the missing data will be filled in by monthly average from all other available data entries; if not, the program will be terminated. The sub-daily time series for each input variable is then aggregated to daily timestep as required by most ET formulations. The last task performed by *ReadInputs()* is to check for abnormal values in the daily time series of temperature (which is defined as greater than 100ºC) and relative humidity (which is defined as greater than 100). If abnormal values exist, they are adjusted to the monthly averages of all other data entries of temperature and/or relative humidity correspondingly. For daily raw climate data no pre-processing by *ReadInputs()* is required given that the climate variables are named according to the requirements provided in the user's manual.

ET..() is a generic function which directs to different ET formulations according to user-defined class of input data. ET..() contains 17 different formulations which are used for direct calculations of different evapotranspiration-related quantities, including PET and AET (including evaporation) under different spatial and climate conditions. Each of the 17 formulations in ET..() has different data requirements (Table 1), which are checked before implementing the calculations in each formulation. The function will be terminated when there are insufficient data for performing the required calculations. Each formulation within ET..() has individual arguments to allow users to choose different versions within a single formulation, for example, within the Penman-Monteith formulation the FAO-56 version for short crop (Allen et al., 1998) and the ASCE-EWRI version for standard crop (Allen, 2005) are available. Alternative calculation options for filling missing input variables and adjustments on results for specific environment can also be specified through arguments in the function. For example, for most of the formulations the users can select if the values of incoming solar radiation will come directly from the data, or from alternative estimations using data of sunshine hours or cloud cover; in the Truc formulation, adjustment on the results for non-humid conditions (with relative humidity less than 50%) can be performed upon user's request. Based on the selected version of a particular ET formulation with specified calculation options, ET..() produces monthly and annual aggregate ET estimates, as well as a number of simple summary statistics. Lastly, a summary of the calculation results is generated by ET..(), which includes messages that show the choices of formulation and sub-formulation, the quantities calculated and the user-selected formulation versions, options for alternative calculations and assumptions. The results and calculation summary are also saved into a comprehensive data list for the user to extract for further analysis. For example, the results can be used as an input to conceptual hydrologic models, such as hydromad (Andrews et al., 2011).

ETPlot() uses the estimated daily ET data to generate aggregation plots and average plots at daily, monthly and annual time steps.

ETComparison() enables users to plot different sets of ET estimates for comparison to investigate the effect from either one or a combination of 1) different ET formulations; 2) different versions of the same ET formulation; 3) the same ET formulation with different calculation options and/or levels of input climate variables. Comparison plots can be produced for daily estimates, monthly and annual aggregates and monthly and annual averages. For each quantity, three plots, including time series plots, non-exceedance probability plots and box plots are produced.

ETForcing() generates plots of all values of ET estimates against all values of a single input climate variable which is selected by the user. It enables the user to quickly visualise how the ET estimates from different formulations are correlated with each climate forcing variable.

3 APPLICATION OF THE PACKAGE

In order to demonstrate the utility of the package, it is applied to a case study. The meteorological site selected for the case study is the Kent Town (34.92° S, 138.62° E) station in Adelaide, South Australia. Sub-daily climate data from the period 01/04/1969 to 30/03/2005 have been used for the study. *ReadInputs()* is firstly called to check and process the raw data with the maximum percentage of acceptable number and duration of missing data are defined as 10% and 1% of all the data entries. The function displays summary messages of data when checking through each input variable. Figure 2 shows an example of the message generated from checking the wind speed data.

```
warning: missing values in 'uz.subdaily'
Number of missing uz.subdaily:  3
% missing data:  0.03 %
Maximum duration of missing data as percentage of total duration:  0.02 %
Monthly averages have been calculated to fill missing data entries
```

Figure 2. Message generated from checking the wind speed data using *ReadInputs()*

ET..() is then called to perform the ET estimations. Here, the calculation for Penman PET is demonstrated. The arguments are set so that 1) the actual sunshine hours are used for calculating solar radiation; 2) the actual wind data are used; 3) the Penman 1948 wind function is used to estimate the aerodynamic component in the Penman formulation; 4) the evaporative surface is short grass. The calculated time series of Penman potential ET has been saved in a data list, while the output summary from *ET..()* confirms the choice of formulation and the selection of alternative calculation options (Figure 3).

```
Penman Potential Evaporation
Evaporative surface: user-defined, albedo = 0.26 ; roughness height = 0.02 m
Sunshine hour data have been used for calculating incoming solar radiation
Wind data have been used for calculating the Penman evaporation. Penman 1948 wind function has been used.
```

Figure 3. Calculation summary from *ET..()*

Plots of estimated daily ET (Figure 4a) and monthly averaged daily ET (Figure 4b) have been produced by *ETPlot()*. It is difficult to detect any trend from the daily plot in Figure 4a. However, there is a very strong seasonal pattern displayed in the monthly average plot in Figure 4b. The potential ET peaks during the summer months throughout a year due to higher solar radiation received.

Comparison plots of the estimates of potential ET obtained using the Penman, Penman-Monteith FAO56 and Priestley-Taylor formulations have been produced using *ETComparison()*, as shown in Figure 5. Figure 5a and 5b display the non-exceedance probabilities for daily and monthly PET from these three formulations. They show that the Penman formulation generally yields higher daily and monthly ET estimates than the other two formulations. However, the Penman-Monteith formulation sometimes produces higher peaks in daily estimates. Figure 5c shows the distribution of monthly estimates from the different formulations considered, in which the Penman and Penman-Monteith formulations produce similar ranges of ET estimates, while Priestley-Taylor formulation generates significantly lower estimates. The maximum difference occurs at the peak estimates, where the Priestley-Taylor estimate is over 50 mm lower comparing to those from the other two formulations which are around 250 mm. This significant difference indicates importance of the advection process at Kent Town – this advection process is modelled by the Penman and Penman-Monteith formulations explicitly, while the Priestley-Taylor formulation uses only a constant value to represent this process. In fact, the Priestley-Taylor formulation has already been found to underestimate PET particularly under arid and advective conditions (McKenney and Rosenberg, 1993). Figure 5d shows the seasonal patterns of estimated PET from the three formulations, which have similar shapes indicating that PET reaches its maximum during summer. This could be an indication of the importance of sensible heat transfer at Kent Town which peaks in summer with higher air temperature.

The association of daily Penman PET with daily maximum temperature is investigated by using *ETForcing()* in Figure 6, from which a clear positive association is observed.

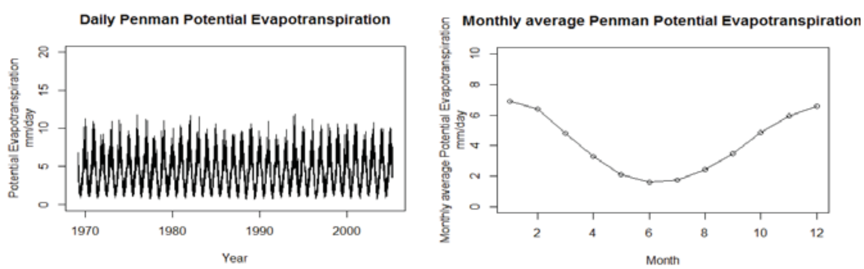

Figure 4. a. Daily estimates of Penman PET; b. Monthly averaged daily Penman PET

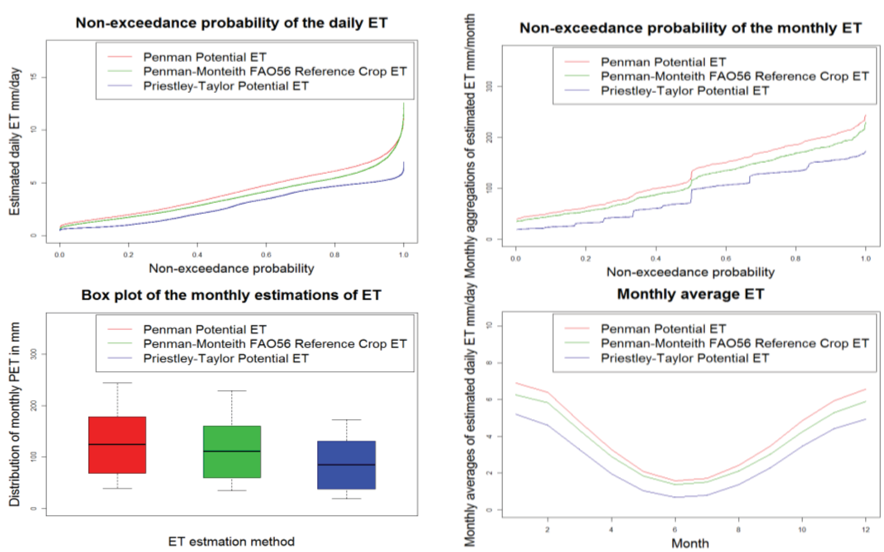

Figure 5. non-exceedance probability of a (top-left). daily ET; b (top-right). monthly ET; c (bottom-left). box plot of monthy ET; d (bottom-right). monthly average ET

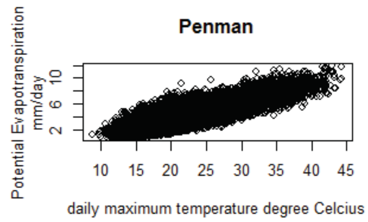

Figure 6. Correlation between Penman PET and daily maximum temperature

4 CONCLUSIONS

The application and investigation of multiple ET models is critical for investigating different hypotheses in representing various ET-related processes. This paper presents an R package for the estimation of actual and PET using 17 formulations in a consistent manner, with functions that enable pre-processing of data, which then feed into user-selected formulations. The presentation of results is in the form of summary text and plots, which is convenient for the extraction of information for further analysis, such as linking with hydrologic models. Additional plotting tools within the package allow users to quickly visualise the association between estimated ET and different climate variables, as well as comparing different sets of ET estimates.

It is worth mentioning that the 17 formulations in *ET..()* represent a range of existing methods for representing various ET processes. However, this function is limited to include only formulations that are time-independent (i.e. ET estimates for a later time do not depend on estimates from previous time steps). For example, the time-dependent Morton CRLE formulation for deep lake evaporation (Morton, 1986) has not been included. However, this is necessary for quality control to ensure that calculation accuracy is not affected by bad data quality at any point in the input time series.

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