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EVAPOTRANSPIRATION MAPS FOR AUSTRALIA

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Abstract

Evapotranspiration is a key component of the water and energy balance. Estimates of evapotranspiration are required for many applications. The Bureau of Meteorology and the Cooperative Research Centre for Catchment Hydrology released a set of Evapotranspiration Maps for Australia in July 2001 as part of the Bureau's Climatic Atlas series. The maps give average monthly and annual values of three evapotranspiration variables: point potential evapotranspiration, areal potential evapotranspiration and areal actual evapotranspiration. The evapotranspiration estimates are based on Morton's complementary relationship model and are derived using climate data from over 700 locations throughout Australia. This paper presents an overview of the evapotranspiration maps, describes how the estimates are derived, and where the various evapotranspiration variables can be used.

Key Words: **evapotranspiration, maps, Australia, potential evapotranspiration, climatic atlas**

Introduction

Evapotranspiration is a collective term for the transfer of water, as water vapour, to the atmosphere from both vegetated and unvegetated surfaces. It is affected by climate, availability of water and vegetation.

Evapotranspiration is an important component of the water balance and the energy balance. Over a long term, the sum of runoff and evapotranspiration equals precipitation. Net radiation onto the earth's surface is returned to the atmosphere as latent heat of evapotranspiration and sensible heat. Averaged over the earth's land surface, almost two thirds of precipitation is returned through evapotranspiration to the atmosphere. Over the continent of Australia, evapotranspiration is more than 90% of precipitation.

Estimates of evapotranspiration are required for many applications, ranging from estimation of water yield, evaluation of crop water requirement, determination of losses from water bodies, and as an input into hydrological models. However, despite its importance, it is difficult to measure evapotranspiration directly at a meaningful scale in space and time. In practice, evapotranspiration is usually estimated from pan evaporation measurements, or derived from climate data using established evapotranspiration models/algorithms.

There has been considerable research on evapotranspiration since Penman (1948) derived the combination equation for estimating evapotranspiration. However, there are differences between the various methods available for estimating evapotranspiration, and some confusion over the appropriate use of local data and the type of evapotranspiration variable estimated.

In July 2001, the Australian Bureau of Meteorology and the Cooperative Research Centre for Catchment Hydrology released a set of Evapotranspiration Maps for Australia (Bureau of Meteorology, 2001) as part of the Bureau's Climatic Atlas series. This paper presents an overview of the evapotranspiration maps, describes how the estimates are derived, and where the various evapotranspiration variables can be used.

Evapotranspiration Maps for Australia

The maps give average monthly and average annual values for three evapotranspiration variables,

- Areal actual evapotranspiration (AAET)
- Areal potential evapotranspiration (APET)
- Point potential evapotranspiration (PPET).

There are altogether 39 maps. Figures 1, 2 and 3 show the annual maps for the three evapotranspiration variables.

The maps are based on a 30-year climatology between 1961-1990. It should be noted that 1961-1990 is a relatively wet period over most of Australia compared with climate means over a longer period. The Evapotranspiration Maps should be used in conjunction with the Bureau's Rainfall Maps which are also based on a 30-year climatology between 1961-1990.

The Evapotranspiration Maps can be viewed at http://www.bom.gov.au/climate/averages. The printed volume of maps in A3 format is available for $33 from the Bureau of Meteorology Publications Unit (Phone: 03-96694312, Fax: 03-96694699, Email: publications@bom.gov.au). Gridded data (0.1 x 0.1 degree) for the 39 maps are also available on CD-ROM for $330 from the Bureau's National Climate Centre (Phone: 03-96694072, Email: webclim@bom.gov.au).

Definition of Evapotranspiration Variables

Potential evapotranspiration is the evapotranspiration (ET) that would occur if there is an unlimited soil water supply.

Areal potential evapotranspiration (APET) is the ET that would take place, if there is unlimited water supply, from an area large enough such that the effects of any upwind boundary transitions are negligible, and local variations are integrated to an areal average.

Point potential evapotranspiration (PPET) is the ET that would take place, if there is unlimited water supply, from an area so small that the local ET effects do not alter local air mass properties.

Areal actual evapotranspiration (AAET) is the actual ET that would take place under the prevailing soil water condition, from an area large enough such that the effects of any upwind boundary transitions are negligible, and local variations are integrated to an areal average.

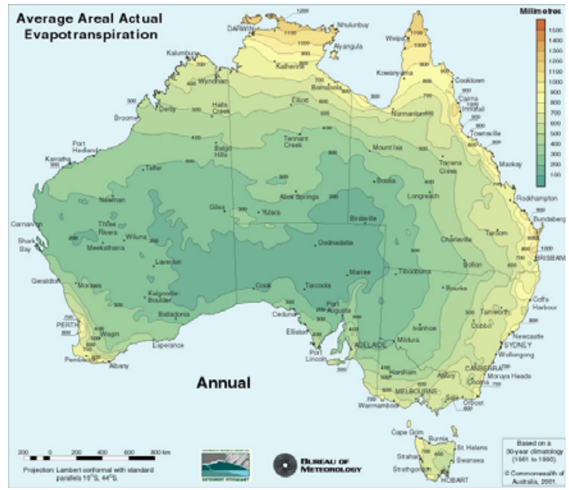

Figure 1 Map of average annual AAET

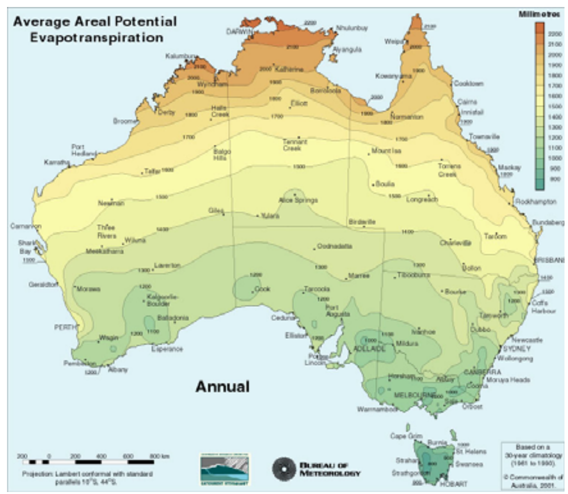

Figure 2 Map of average annual APET

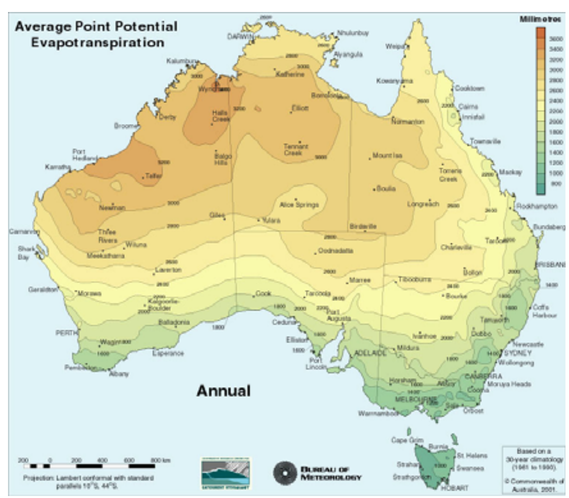

Figure 3 Map of average annual PPET

Application of Evapotranspiration Variables

The APET is conceptually the upper limit to AAET in most rainfall-runoff modelling studies. It also provides an estimate of ET from a large irrigated area with no water shortage. As a rough guide, an area greater than 1 km^2 may be regarded as 'areal'. In contrast, PPET provides an estimate of ET from a very small irrigated field surrounded by unirrigated land.

By definition, the PPET is very similar to the Penman-Monteith potential ET (Monteith, 1965). The latter, although defined for a large area, also assumes that the actual ET does not affect the overpassing air. However, the estimates of the two are not the same because they are calculated differently.

The ET maps are not intended for use in estimating open water evaporation. However, as a guide, the PPET values in the maps are similar to Class A pan evaporation values, which are commonly used to guide the estimation of open water evaporation.

Data

The ET variables are estimated using climate data from 713 meteorological stations throughout Australia (see Figure 4). Data over the World Meteorological Organisation standard period 1961-1990 are used and the stations are selected based on the criterion that there are at least five years of data.

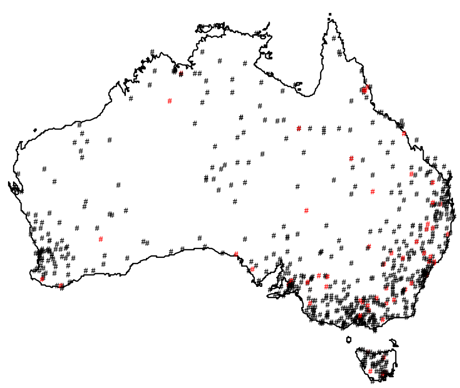

Figure 4 Locations of stations used in the evapotranspiration analyses (red dots show 60 stations where comparisons of ET variables are carried out - presented later in this paper)

The main input data used for the ET computations are solar global exposure (commonly called global radiation), temperature, saturation vapour pressure at air temperature and actual vapour pressure.

The monthly time series temperature and vapour pressure data used to estimate ET are derived from daily data (taken as the average of all the daily data). Only months with ten or more days of data are used in the computations.

The daily mean temperature is estimated as the average of the daily maximum and minimum temperatures.

The daily mean saturation vapour pressure at air temperature is estimated as

$$e_s = \frac{e_s(T_{max}) + 2e_s(T_{mean}) + e_s(T_{min})}{4} \quad (1)$$

where e_s is the daily mean saturation vapour pressure and $e_s(T_{max})$, $e_s(T_{mean})$ and $e_s(T_{min})$ are the saturation vapour pressures at daily maximum, mean and minimum temperatures respectively.

The actual vapour pressure is estimated from pairs of drybulb temperature and wetbulb temperature data. The daily mean actual vapour pressure is estimated following this priority order: (1) average of 0900 and 1500 vapour pressures; (2) either the 0900 or 1500 vapour pressure; and (3) average of all available vapour pressure data for the calendar day.

The mean monthly solar global exposure data derived by the Bureau of Meteorology by relating solar global exposure to satellite radiance observations for the period 1990-1994 (Forgan, 1997) are used for the ET computations. The satellite derived data are used because solar global exposure is very sparsely observed in Australia. Comparisons of the satellite derived data with ground measured data showed good agreement between the two with the differences generally below ten percent. The period 1990-1994 is also found to be reasonably representative of the period 1961-1990 at the mean monthly level (Weymouth, 1998). The interannual variability in the monthly solar global exposure is also relatively low and therefore does not need to be accounted for here.

Monthly rainfall data and long-term rainfall and runoff data from 77 catchments are also used to make water balance adjustment to the estimated AAET values (see later).

Method of Estimation

Complementary relationship between AAET and PPET

Morton's (1983) complementary relationship AAET model is used to estimate the ET variables.

The complementary relationship considers that changes in the availability of water for AAET respond in a complementary way to changes in the PPET (Bouchet, 1963; Morton, 1983). It states that under normal conditions, the sum of AAET and PPET is equal to twice the APET (see Figure 5).

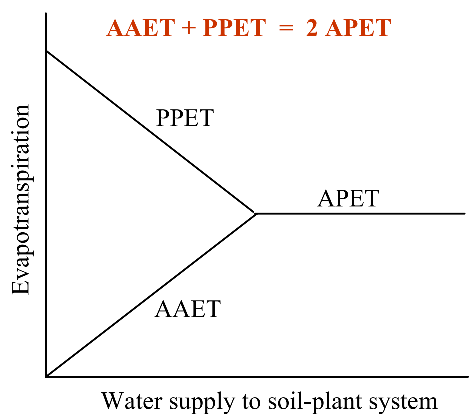

Figure 5 Complementary relationship between AAET and PPET

Under dry conditions, there is no water to evaporate, and AAET = 0 and PPET is at its maximum rate.

As water becomes available, AAET increases. This increase in AAET causes the overpassing air to become cooler and more humid (reducing the vapour pressure deficit at a point), producing an equivalent decrease in the PPET.

Finally, when the soil water has increased sufficiently, the values of AAET and PPET converge to that of the APET.

The APET therefore depends only on the meteorological conditions, while the AAET and PPET also depend on the soil water availability in the surrounding area.

Estimation of ET variables

In Morton's model, the PPET is estimated by solving simultaneously the energy (equation 2) and vapour transfer (equation 3) equations, using a constant energy transfer coefficient,

$$PPET = R_T - \lambda f_T (T_p - T) \quad (2)$$

$$PPET = f_T (e_s - e_a) \quad (3)$$

where R_T is net radiation at air temperature, T is air temperature, T_p is equilibrium temperature, e_s is saturation vapour pressure at air temperature, e_a is actual vapour pressure, λ is heat transfer coefficient and f_T is vapour transfer coefficient.

Morton's method for estimating PPET differs from the Penman-Monteith method in which the energy transfer coefficient is a function of the wind speed.

In Morton's model, APET (called wet environment evapotranspiration by Morton) is estimated using a modified Priestley-Taylor equation,

$$APET = b_1 + b_2 (1 + \gamma \, p / \Delta_p)^{-1} R_{TP} \quad (4)$$

where b_1 and b_2 are empirical coefficients, γ is psychrometric constant, p is atmospheric pressure, Δ_p is slope of saturation vapour pressure on temperature curve at equilibrium temperature and R_{TP} is net radiation at equilibrium temperature.

The Priestley-Taylor equation is

$$P\text{-}T\ ET = 1.26 (1 + \gamma \, p / \Delta_p)^{-1} R_T \quad (5)$$

For the computations here, b_1, b_2 and f_Z (a constant used in calculating f_T) are re-calibrated using data from the 713 locations and set to 13.4 W m^{-2}, 1.13 and 29.2 W m^{-2} respectively to give an overall equivalent of the commonly used 1.26 value in equation (5) instead of the 1.32 used by Morton (1983).

The complementary relationship is then used to estimate AAET,

$$AAET = 2\ APET - PPET \quad (6)$$

The ET variables are estimated for each month in the 1961-1990 data and averaged to obtain the average monthly ET estimates.

Seasonal adjustment to ET estimates

Based on the authors' experience, Morton's model appears to underestimate winter ET and overestimate summer ET. To obtain more realistic ET estimates for the maps, the three average monthly ET variables estimated using

Morton's model are adjusted by the depths shown in Table 1.

Table 1 Seasonal adjustment to average monthly ET estimates (in mm)

Jan	Feb	Mar	Apr	May	Jun
-12	-7	-2	+2	+7	+12

Jul	Aug	Sep	Oct	Nov	Dec
+12	+7	+2	-2	-7	-12

Water balance adjustment of average annual AAET estimates

The AAET can only be accurately estimated by measuring AAET directly or by water balance estimation where there are rainfall and runoff data. Although the average annual AAET estimated using Morton's model are not accurate, the model gives a good spatial trend of the AAET values. To obtain better estimates of the annual AAET, the AAET values are adjusted to remove bias and extremes, using ET values derived from the long-term water balance of 77 catchments as a guide. The AAET values are adjusted separately for nine climate zones (see Figure 6) as defined by the Koeppen classification system (Koeppen, 1931).

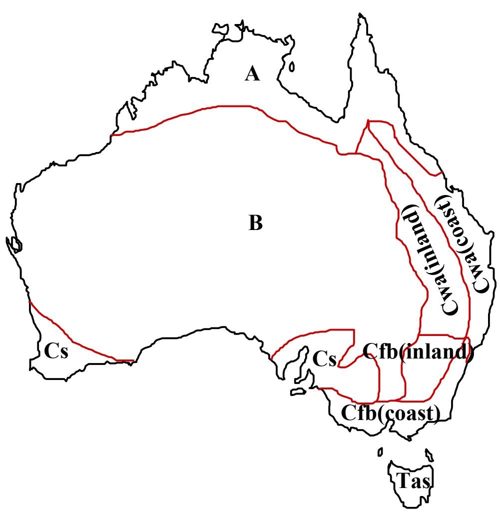

Figure 6 Climate zones used for adjustment of AAET

In the method used to adjust the average annual AAET estimates, Morton's AAET and catchment water balance AAET estimates are plotted against average annual rainfall (see Figure 7). A line of best fit for Morton's AAET is then established using a LOWESS procedure (Cleveland, 1979), and a line of best fit for the water balance AAET is fitted to a curve described by,

$$\text{AAET} = 300 + c \times \tanh \frac{\text{MAP} - 300}{c} \qquad (7)$$

where c is the fitting constant and MAP is mean annual precipitation.

Morton's average annual AAET estimates are then adjusted by the difference between the two lines in Figure 7. The method therefore adjusts the mean of Morton's AAET series at a given rainfall to the mean of the water balance AAET series at the same rainfall, whilst preserving the variance.

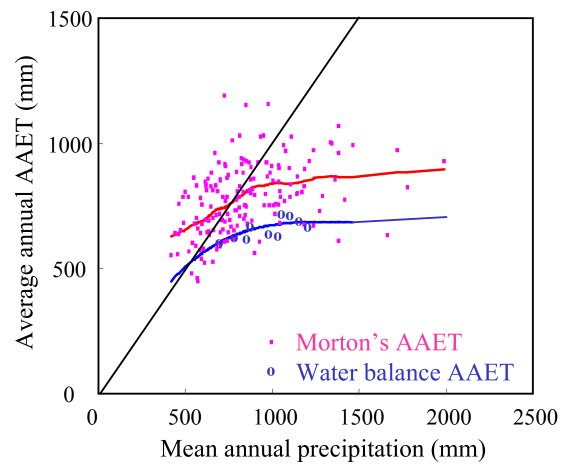

Figure 7 Illustration of method used to adjust Morton's average annual AAET to match the water balance AAET (example for climate zone Cfb(coast))

Following the above adjustment, there are still some locations where the average annual AAET exceeds the average annual rainfall or appears to be too low. Where this occurs, the average annual AAET is set to an arbitrarily defined lower or upper limit shown by the curves in Figure 8 (as described by equation (7) with constants of 300 and 1500 respectively).

Adjustment of monthly AAET

One of three methods is used to adjust Morton's estimate of average monthly AAET depending on the average annual rainfall. Where the average annual rainfall is greater than 600 mm, the monthly AAET is scaled upwards or downwards by the adjustment applied to the annual AAET. Where the average annual rainfall is less than 400 mm, the monthly AAET is set to equal the monthly rainfall. Where the average annual rainfall is between 400 and 600 mm, a weighted average (as a linear function of rainfall) of the above two methods is used,

$$\text{AAET} = \text{rain}\left(1 - \frac{\text{MAP} - 400}{200}\right) + \text{AAET}_{wba}\left(\frac{\text{MAP} - 400}{200}\right) \quad (8)$$

where rain is monthly rainfall and AAET_{wba} is the monthly AAET scaled upwards or downwards by the water balance adjustment applied to the annual AAET.

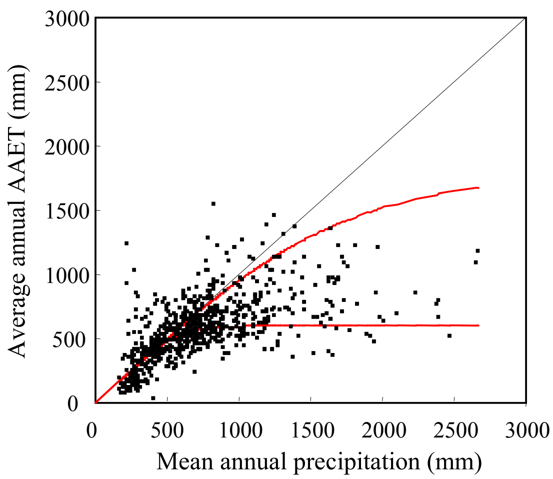

Figure 8 Lower and upper limit boundaries for AAET estimates

At locations where the average annual rainfall is less than 600 mm, a further adjustment is made to ensure that the monthly AAET is less than the APET. When the monthly AAET is greater than the APET, it is set to equal the APET, with the remainder added to the next month's AAET. The iteration is carried out over a 24-month cycle to ensure that the sum of the monthly AAETs is the same as the annual AAET.

Mapping and Gridded Data

The average monthly and annual ET variables estimated for the 713 locations are interpolated using Hutchinson's (1991, 1995) interpolation method of thin plate smoothing splines to produce gridded data at 0.1 degree resolution. The elevation, latitude and longitude are used as the explanatory variables.

The gridded ET variables are adjusted where necessary to maintain consistency (for example, AAET < APET < PPET, and average annual AAET < average annual rainfall). Only very minor adjustments are required.

The interpolated (gridded) data are smoothed using a one-pass 5x5 binomial smoother. The gridded data are then imported into the Arc/Info[TM] GIS engine and mapped using the map creation tools within the GIS software suite. A final 'polishing' of the maps is carried out to smooth jagged edges resulting from the automated contouring process and to label the contours.

Evapotranspiration Map Variables and Other Commonly Used ET Variables

The whisker plots in Figure 9 show the spread of average annual AAET, APET, PPET, Priestley-Taylor ET and two other commonly used ET variables (class A pan evaporation and reference crop ET) over 60 of the 713 stations used to establish the ET maps.

The locations of the 60 stations are shown in Figure 4 and they are stations where wind run below 3 m data are available to estimate reference crop ET.

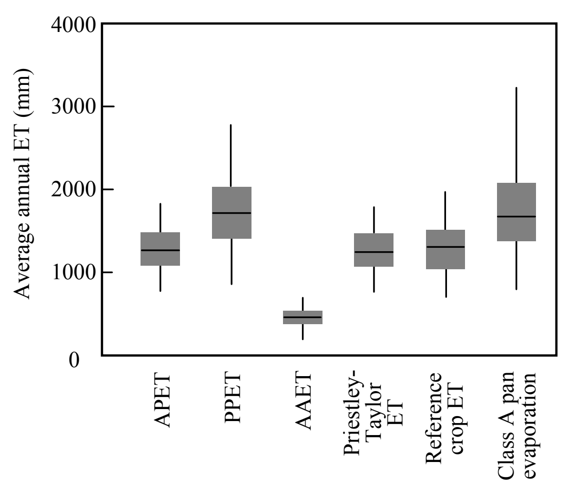

Figure 9 Spread of average annual values of various ET variables at 60 locations throughout Australia (whisker plots show median, 25th and 75th percentiles and 10th and 90th percentiles)

Local pan evaporation data and the maps of average monthly and annual pan evaporation published by the Bureau of Meteorology (1988) have been commonly used as surrogate measures to estimate ET.

The reference crop ET is a worldwide standard used in computing crop water requirements (FAO, 1998). The reference crop ET is defined as the ET from a hypothetical green reference crop of height 0.12 m growing in a large well-watered field and completely shading the ground, with a field surface resistance of 70 s m^{-1} and an albedo of 0.23. The reference crop ET is calculated using a modified FAO Penman-Monteith equation. The reference crop ET for the 60 stations are estimated using climate data from 1961-1990, using the guidelines recommended by the FAO (1998).

Figures 9 and 10 show that the average annual PPET values at the 60 stations are similar to the average annual class A pan evaporation (for high ET values, PPET is slightly lower than pan evaporation).

Figures 9, 11 and 12 show that the average annual APET values are similar to the average annual Priestley-Taylor ET and reference crop ET values.

The results here are based on a recently completed study by Christhoper Leahy and Francis Chiew at the University of Melbourne, and they will be discussed in more detail elsewhere.

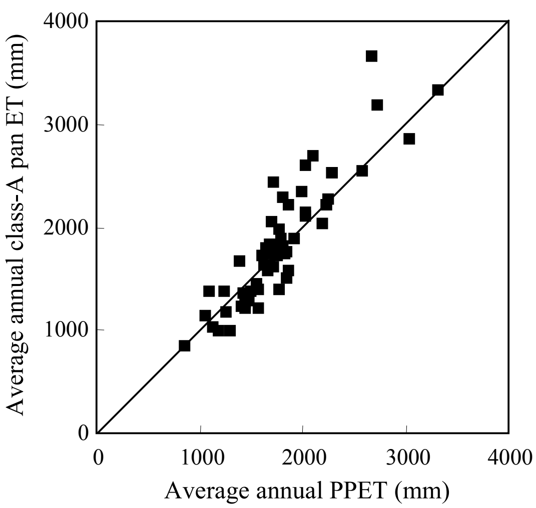

Figure 10 Comparison of average annual class A pan evaporation and PPET at 60 locations throughout Australia

Summary and Conclusions

This paper presents an overview of the ET variables in the set of Evapotranspiration Maps for Australia released by the Bureau of Meteorology as part of the Bureau's Climatic Atlas series. The paper describes how the estimates are derived, compares the ET values in the maps with other commonly used ET variables, and provides suggestions on where they can be used.

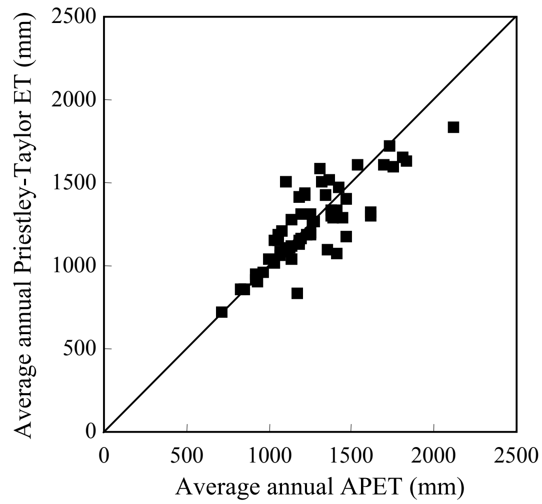

Figure 11 Comparison of average annual Priestley-Taylor ET and APET at 60 locations throughout Australia

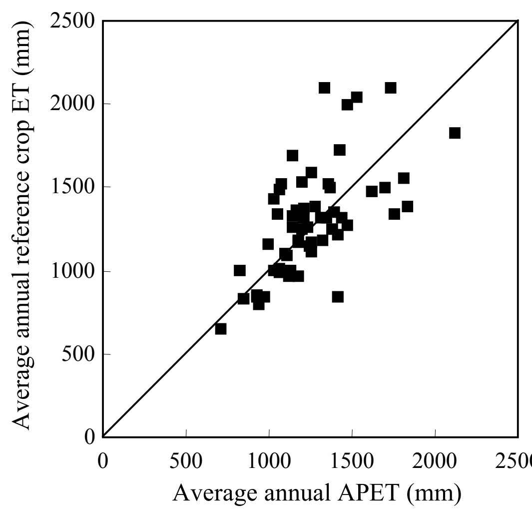

Figure 12 Comparison of average annual reference crop ET and APET at 60 locations throughout Australia

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Authors Biographies

Dr Francis Chiew has over ten years experience in hydrologic research, teaching and consulting. Francis has an engineering degree and a PhD from the University of Melbourne. He is the author of almost 200 publications and has presented in conferences and expert workshops throughout the world. Francis is currently leader of research projects in the CRC for Catchment Hydrology. His interests include hydroclimatology, hydrological modelling and water quality.

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Dr Fiona McConachy is a Senior Hydrologist at Hydro Tasmania, and works on a variety of projects both overseas and within Australia. Fiona's main areas of expertise are in statistical hydrology, hydrologic modelling, and flood hydrology. Fiona holds a BE (Agr) (Hons) from The University of Melbourne. She undertook research work with the CRC for Catchment Hydrology at Monash University, where she was awarded a PhD in flood hydrology in 1997. Fiona has worked for the Rural Water Commission of Victoria and Sinclair Knight Merz as an engineer, and The University of Melbourne as a research fellow.

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Ross James has a degree in Civil Engineering and a Master of Engineering Science from Monash University. During 25 years with the Bureau of Meteorology Hydrological Services Programme, Ross has developed expertise in hydrological modelling for flood warning systems, management of data, automated data collection systems and data collection networks.

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Dr William Wright is a Senior Meteorologist with the Bureau of Meteorology, and has been with the National Climate Centre since 1992, following three years as a weather forecaster in the Victorian Regional Office. He received his PhD from the University of Melbourne, specialising on the causes of interannual rainfall variability, an interest which he still holds. His current work includes climate analysis and mapping, research into rainfall during El Nino years, and compiling a review of Australian climate and its variations during the 20th century. His other interests include climate change, monitoring and prediction.

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Graham deHoedt has experience in a range of meteorological related areas. He has worked as a weather forecaster and has been involved in the generation and provision of climate information. More recently, Graham has worked on climatological mapping using GIS, and he is particularly interested in the visualisation of meteorological information. He is currently a Senior Meteorologist in the Climate Analysis Section of the Bureau of Meteorology's National Climate Centre in Melbourne.

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