Estimating Evaporation – Issues and Challenges

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EXTENDED ABSTRACT

Loss of water through evaporation is a major consideration in the design and management of water supply reservoirs, and water supply managers are particularly interested in the potential impacts of climate change on future yields. Trends of decreasing pan evaporation around the world, including Australia, have prompted a re-examination of the mechanisms of evaporation and renewed interest in the complementary principle which links apparent potential and actual evaporation. The linkages between evaporation and climate change are still not fully understood and an improved understanding of evaporation processes may assist in more accurately modelling evaporation in general circulation models.

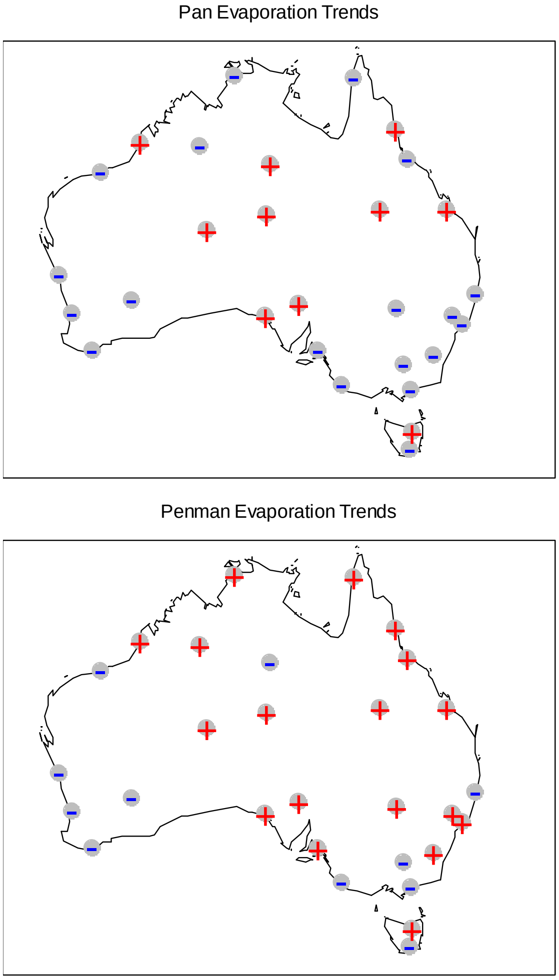
One advantage of evaporation pans is that they incorporate all possible physical effects. The problem is that we cannot attribute which effects are responsible for changes. However if we use the Penman equation to also analyse trends, then we have more control over the analysis since we can analyse the different variables that contribute to the Penman estimates of evaporation.

We compared the trends derived for open water bodies from Penman equation to those recorded by evaporation pans with a pan coefficient applied. Figure 1 presents a comparison of the direction of the pan evaporation trends and the Penman estimates at 29 stations across Australia. The pan evaporation trends are mainly negative across Australia, particularly for coastal stations. On the other hand, the Penman estimates of trends are generally positive. Trends averaged across Australia are shown in Table 1.

Table 1. Australian Average Annual Evaporation Trends with 95% Confidence Interval

Variable and Period	Average Trend
Pan Evaporation	-4.2 ± 3.6 mm/yr^{-2}
Penman Evaporation	1.4 ± 2.2 mm/yr^{-2}
Penman: Radiation	0.2 ± 0.7 mm/yr^{-2}
Penman: Advection	1.2 ± 1.9 mm/yr^{-2}

Further work is required to answer the questions raised by the differences found between Penman and pan estimates of evaporation, described in this paper. Areas for future research include examining the impacts of different climate change scenarios on the trend estimates.


Pan Evaporation Trends

Penman Evaporation Trends

Figure 1. Pan and Penman evaporation trends across Australia. Positive trends are shown as red "+", negative trends as blue "-".

1. INTRODUCTION

Loss of water through evaporation is a major consideration in the design and management of water supply reservoirs. Due to the large surface area of most water supply reservoirs, there is little that can be done to reduce evaporation losses, which makes it even more important to accurately predict evaporation losses from the system. Concerns about the impacts of climate change on the security of water supplies have led to renewed interest in evaporation processes.

Evaporation is difficult to measure directly, and therefore many theoretical and empirical approaches have been developed. Some of the commonly used techniques include the Penman equation (Penman, 1948), the Priestly-Taylor equation (Priestley and Taylor, 1972) and energy balance methods. For open water bodies, the Penman combination approach is often used, and Shuttleworth (1993) recommends it as the preferred method for "estimating the rate of evaporation from open water".

Evaporation pans are another common method of estimating evaporation, although the problems introduced by adopting a suitable pan coefficient lead to doubts about the reliability of the open water body evaporation estimates. Brutsaert (1982) suggests that use of evaporation pans, with a pan coefficient can only give a "rough estimate of lake evaporation, mostly on an annual basis".

Despite the inaccuracies in the indirect evaporation estimates, the Penman equation and evaporation pans are commonly used in research and practice to predict evaporative losses. But we wonder whether these methods will still be suitable in the future if climate change leads to variations in evaporation – can indirect estimates of evaporation predict future trends accurately?

This paper aims to analyse historic evaporation records in Australia at 29 locations, with a view to understanding how estimates of open water body may vary due to the method used. The information thus gained may be useful for improving estimates of future evaporation under conditions of climate change.

2. THE "PAN EVAPORATION PARADOX"

Many studies completed in the last ten years have shown trends of decreasing pan evaporation over large parts of the world in the last 40 to 50 years. Individual stations have reported increasing trends of pan evaporation, but regional/national averages have generally shown a decreasing trend on the whole.

In Australia, recent analyses (e.g. Jovanovic et al., in press, Kirono and Jones, in press) using high quality data sets of homogenised pan evaporation records have found pan evaporation trends are not significant when averaged over Australia, despite individual stations and some geographic regions showing decreases significant at the 95% level (Jovanovic et al., in press). These findings emphasise the importance of quality control in trend analysis and attribution studies.

Table 2 summarises some of the trends that have been found world wide by various researchers.

Table 2. Annual Pan Evaporation Trends

Location	Annual Trend - Period of Analysis (Reference)
Australia	-2.9 ± 1.7 mm/yr^{-2}: 1970 – 2002 (Roderick and Farquhar, 2004)
Australia	-2.5 ± 5.1mm/yr^{-2}: 1970 – 2005 (Jovanovic et al., in press)
Australia	-0.7 ± 1.6 mm/yr^{-2}: 1970 – 2004 (Kirono and Jones, in press)
New Zealand	-2.1 mm/ yr^{-2}: varying periods (Roderick and Farquhar, 2005)
China	-2.9 mm/ yr^{-2}: 1955 – 2000 (Liu et al., 2004)
USA	-2 to 0.7 mm/ yr^{-2}: 1948 – 1998 (Lawrimore and Peterson, 2000)
USSR	-4 to 0.1 mm/ yr^{-2}: 1950 – 1990 After Golubev et al. (2001)

These trends were initially interpreted as evidence that evaporation is decreasing, contrary to the commonly held belief of an intensifying hydrologic cycle under global warming (Huntington, 2006) and were therefore described as paradoxical. However in Brutsaert and Parlange (1998), the pan evaporation trends are explained with reference to the complementary principle of evaporation, which was first described by Bouchet (1963).

This theory argues that pan evaporation represents potential evaporation and thus the decreasing trends in pan evaporation indicate that potential evaporation has decreased. The complementary principle can be summarised by (1), which shows that the potential evaporation (E_p) and actual evaporation (E_a) sum to form twice the wet environment evaporation (E_w), which is a constant for a particular location, when the surface is brought to saturation (Granger, 1989).

$$E_P + E_A = 2E_W \qquad (1)$$

Therefore Brutsaert and Parlange (1998) maintain that decreases in E_P must be accompanied by increases in E_a, and thus there is no “paradox”.

A second theory to explain the pan evaporation trends assumes that the complementary principle is not applicable and that changes in pan evaporation reflect changes in actual evaporation occurring from the catchment. The decreases in pan evaporation (and hence in actual evaporation) are attributed to changes to decreases in solar radiation (Liepert et al., 2004) or changes in wind run (Rayner, 2007) or both (Roderick et al., 2007)

One possible explanation for solar radiation decreases is increasing cloud cover, leading to more scattering and reflection of incoming solar radiation. However, Norris and Wild (2007) found that cloud cover changes could not fully account for trends in solar radiation in the Northern Hemisphere between 1965 and 2004. Instead the authors offer as the most likely explanation that changes in the concentrations of anthropogenic aerosols led to a period of “global dimming” during the 1970s to the mid 1980s, followed by a period of “solar brightening” from the mid 1980s.

Potential reasons for changes in wind run are less clear, and may be due to large-scale climatological changes or alterations to the environment surrounding a particular evaporation pan (Rayner, 2007).

As stated by (Roderick et al., 2007) one advantage of evaporation pans is that they incorporate all the possible physical effects. The problem is that we cannot separate or attribute which particular physical effect(s) is responsible for any changes, and hence know with any certainty whether radiative changes are responsible for the pan evaporation trends, or if the trends are a manifestation of the complementary principle. However if we use the Penman equation to also analyse trends, then we have more control over the analysis since we can analyse the different variables that contribute to the Penman equation estimates of evaporation.

3. EVAPORATION ESTIMATES

The details of the data sources for the evaporation estimates are provided in the Appendix. The Penman estimates of evaporation were calculated on a daily basis using (2), assuming an open water body (Brutsaert, 1982):

$$E = \frac{\Delta}{\Delta + \gamma} Q_n + \frac{\gamma}{\Delta + \gamma} E_a \qquad (2)$$

where Q_n is the evaporation due to radiation and E_a is the evaporation due to advection. Δ is the gradient of the saturated vapour pressure function, and γ is the psychrometric constant. The above formulation ignores heat lost to the ground, and changes in heat storage, which is acceptable for daily or longer evaporation estimates (Shuttleworth, 1993).

Various formulations of the Penman equation have been developed to model evaporation pans (e.g. Thom et al., 1981, Rotstayn et al., 2006), however these require additional information on the components of net radiation not available at most of the stations analysed, and were therefore not used. To account for the increase in available energy at an evaporation pan compared to an open water body, an annual pan coefficient (k_p) was calculated for each station using the monthly pan and Penman evaporation estimates. The pan coefficient was then applied to the recorded pan evaporation data. The impact of using a monthly or seasonal pan coefficient could be investigated in the future.

For the advection component of the Penman equation, E_a, the original Penman wind function was used as recommended by Shuttleworth (1993). In calculating the radiation factor of the evaporation, Q_n, estimates of net radiation are required. Longwave radiation was estimated at all sites according to (3) (Brutsaert, 1982):

$$R_{NL} = \varepsilon_s \sigma T^4 (\varepsilon_a - 1)\left(0.2 + (1 - 0.2)\frac{n}{N}\right) \qquad (3)$$

where ε_s and ε_a are the surface and atmospheric emissivity, T is the mean daily air temperature, n is the number of daylight hours and N is the maximum daylight hours, calculated as a function of the time of year and latitude.

Net solar radiation measurements were only available for 15 of the 29 stations, and generally for relatively limited durations. Satellite derived estimates of solar exposure are also available from the Australian Bureau of Meteorology (BOM) for all stations, however these records are not yet long enough for meaningful trend investigations, and hence were not analysed. Therefore to increase the length of the time series analysed, an empirical relationship between solar radiation and sunshine duration developed by Prescott (1940), shown in

(4), was used to estimate net solar radiation at all stations:

$$R_S = R_A\left(a + b\frac{n}{N}\right) \qquad (4)$$

where R_S is the solar radiation, R_A is the radiation which would reach the earth in the absence of the atmosphere, n and N are as defined for (3) and a and b are constants dependant on location and season, and take values of 0.25 and 0.5 in the absence of local calibration data.

The excellent agreement between the monthly estimates of open water body evaporation using the evaporation pan data and the Penman equation is shown in Figure 3.

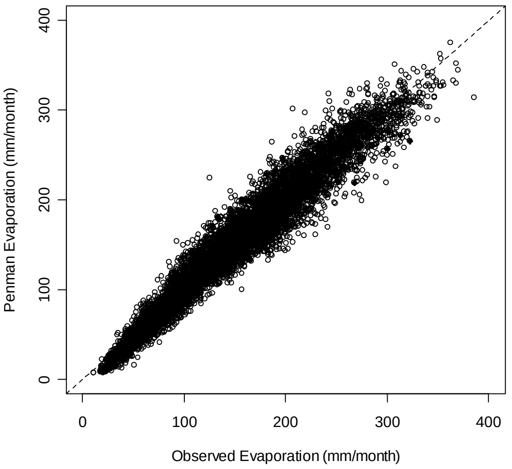
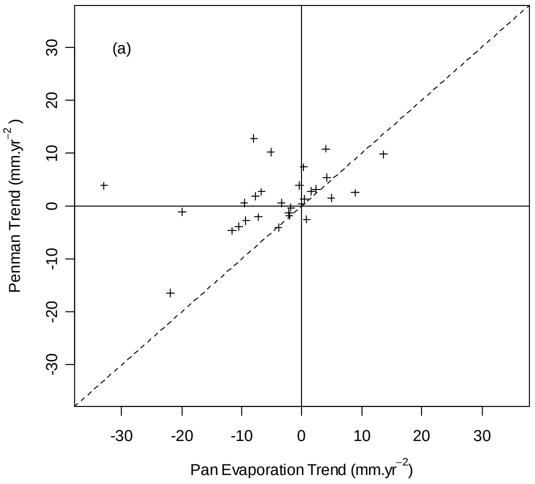


Figure 2. Estimated and observed monthly evaporation data. Correlation coefficient is 0.97.

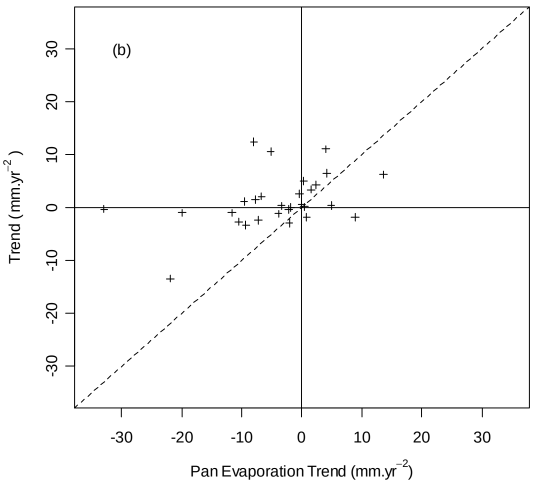
4. CONTRIBUTIONS TO EVAPORATION TRENDS

We compared the trends derived from using the Penman equation to those recorded at evaporation pans. The trends at 29 stations across Australia are presented in Table 3 along with an indication of their significance. The trends in the radiative and advective components of the Penman estimates at each station are also listed. Figure 1 presents a comparison of the direction of the pan evaporation trends and the Penman estimates across Australia, whilst Figure 3 shows scatter plots of the trends and their components at all stations.

Trends in evaporation were calculated using annual totals of evaporation. The magnitude of each the trend was assessed using ordinary least squares linear regression against time. The significance of the trends was assessed using a t-test and also using the non parametric Mann Kendall test (Salas, 1993).



Advective Component (E_a)



Radiative Component (Q_n)

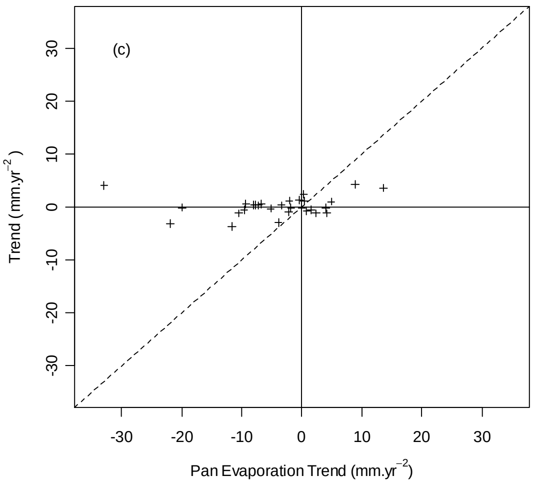


Figure 3. Comparison of evaporation trends direction and magnitude, for a) Penman vs Pan trends; b) E_a vs Pan trends and c) Q_n vs Pan trends

Table 3. Trend comparisons for all stations. Significant trends at the 5% level are marked with an asterisk.

Station Number	Record Length	Pan Trend (mm/yr^{-2})	Penman Trend (mm/yr^{-2})	Radiative Trend (mm/yr^{-2})	Advective Trend (mm/yr^{-2})
Stn002012	1970-1981	-8.0	12.8	0.4	12.4
Stn003003	1993-2006	13.6	9.7	3.6	6.2
Stn004032	1968-1991	-19.9*	-1.1	-0.1	-1.0
Stn008051	1969-1992	-3.9	-4.1	-2.9*	-1.2
Stn009021	1993-2006	-21.9*	-16.4*	-3.1	-13.4*
Stn009741	1992-2006	-2.1	-1.9	1.2	-3.0
Stn012038	1979-1991	-11.6	-4.7	-3.7	-1.0
Stn013017	1967-2006	2.4	3.1	-1.2*	4.3*
Stn014015	1968-2006	-7.7*	1.9	0.4	1.5
Stn015135	1969-2006	0.8	-2.5	-0.7	-1.8
Stn015590	1968-2006	4.1	5.3*	-1.2*	6.5*
Stn016001	1968-2006	4.0	10.8*	-0.2	11.0*
Stn018012	1969-2006	1.5	2.8*	-0.6	3.4*
Stn023090	1977-2006	-5.2*	10.2*	-0.3	10.5*
Stn026021	1968-2006	-7.2*	-2.1*	0.3	-2.4*
Stn027045	1993-2006	-32.9*	3.8	4.1	-0.3
Stn031011	1973-2006	0.3	7.3*	2.4*	5.0*
Stn032040	1981-2006	-6.7	2.7	0.6	2.1
Stn036031	1968-1991	8.9	2.5	4.3*	-1.9
Stn039083	1973-1988	4.9	1.5	1	0.4
Stn048027	1978-2006	-9.6*	0.5	-0.6	1.1
Stn059040	1972-2006	-9.3*	-2.8*	0.5	-3.3*
Stn061078	1974-2006	0.0	0.4	-0.1	0.5
Stn061089	1972-1996	-0.4	3.9	1.3	2.6
Stn070014	1978-2006	-3.4	0.5	0.3	0.3
Stn082039	1975-1997	-10.5*	-3.9*	-1.2	-2.7
Stn085072	1971-2006	-2.2	-1.3	-0.9*	-0.4
Stn091104	1972-2004	0.4	1.3	1.1*	0.1
Stn094069	1968-1994	-1.8	-0.3	-0.2	0.0

The analysis period of the trends varies for between different stations, but the analysis period is constant for a particular station for the pan and Penman estimates. The years analysed for each station are listed in Table 3.

The pan evaporation trends are mainly negative across Australia, particularly for coastal stations. On the other hand, the Penman estimates of trends are generally positive. Table 1 summarises the trends averaged across all stations; the average pan evaporation trend is significant at the 5% level, whilst the average Penman evaporation trend is not statistically significant.

We can see from Table 1 and from Figure 3c that the trends in the radiative component of the Penman estimates are generally quite small and do not correlate well with the pan evaporation trends.

It is acknowledged that the radiation component of the calculation is based on solar radiation estimated from sunshine duration, rather than actual measurements. If changes to aerosols (either anthropogenic or natural) have led to changes in radiative energy at the earth’s surface, then these changes may not be reflected in the sunshine duration measurements. However analysis of the relationship (not shown here) between the monthly averages of radiation and sunshine duration show no significant changes in the relationship over time or space, indicating that the trends derived using sunshine duration data should be representative of the solar radiation trends.

The correlation between the Penman trends and the advection component of the trends is very high (r = 0.95); this is illustrated by the similarity of Figures 3a and 3b, where both are compared to the pan evaporation trends.

There is only a weak correlation between the Penman trend estimates and the evaporation pan trend estimates (r = 0.42), which is surprising given the high correlation between the monthly evaporation estimates from the two methods. The correlation between the advection component and the pan evaporation trends is similar (r = 0.4).

Generally there is a longer record of wind data at each station than the sunshine duration data, so the length of the period of analysis at each station is mainly limited by the sunshine data. If we extend the analysis period, and only look at the advection component of the Penman estimates, then the correlation between the pan and advection component trends improves slightly (r = 0.47). Further work is required to determine what other factors could improve the correlation of the advection component trends, and hence also the Penman trends, with pan evaporation trends.

Two other recent attribution studies on pan evaporation trends in Australia support the finding in the current research that radiation changes generally do not appear to be responsible for the pan evaporation trends. Rayner (2007) found, from a linear regression approach, that solar radiation made the smallest contribution to pan evaporation trends. Roderick et al. (2007) also split the modelled evaporation estimates into a radiation and aerodynamic component, finding that changes in the aerodynamic component, and specifically the wind speed changes, were responsible for most of the trends in the pan evaporation data.

5. CONCLUSIONS

The combined analysis of pan evaporation trends, Penman estimates of evaporation trends and trends in meteorological variables has shown that there are some differences between the trends derived from two methods. The reasons for these differences are not clear.

The analysis has shown however that the trend in radiative component of the evaporation is generally quite small, and that variations in the advective component is primarily responsible for the trends in the Penman estimates of open water body evaporation. This finding corresponds with the findings of other recent attribution studies of Australian pan evaporation trends.

Questions that have been raised by the analysis that require further investigation include:

1. Can the correlation between the evaporation pan and Penman estimates of the open water body trends be improved?
2. Will trends in evaporation continue under conditions of future climate change; how will different scenarios impact the trends?

6. ACKNOWLEDGMENTS

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APPENDIX A

Pan evaporation data was sourced from the BOM high quality database of monthly pan evaporation data (Jovanovic et al., in press).

Data required for the Penman estimates of evaporation include mean temperature, relative humidity, wind speed and net radiation. Daily mean temperature data was sourced from the BOM high quality database of daily mean temperature data (Bureau of Meteorology, 2007). Forty one stations had both high quality pan evaporation and temperature data sets. These stations were therefore adopted for analysis.

In the absence of published high quality data sets for the remaining variables (relative humidity, wind speed and sunshine duration), data for the Penman estimates were sourced from the MetAccess National Weather database, which is a database of daily historical meteorological data developed by the CSIRO (Horizon Agriculture Pty Ltd, 2006).

Daily data from each of the data sources was collated and checked for inconsistencies and gaps. Gaps in the records were filled with monthly average values calculated for each station for each variable.

Stations with less than ten consecutive years of all variables required for the Penman estimates were eliminated from the analysis. The remaining 29 stations (i.e. 12 stations with less than ten years of data) were used for the trend comparisons as reported in Table 3.