Comparison of evaporation rate on open water bodies: energy balance estimate versus measured pan

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ABSTRACT

Much attention has been paid to establish accurately open water evaporation since the lake itself is the largest consumer of water. The aim of this study is to assess the discrepancy in the measured (pan evaporation) and estimated (Penman) evaporation rate, seasonally, based on the results from a 37-year energy budget analysis of Lake Burrumbeet, Australia. The detailed analysis of meteorological data showed that evaporation is fully radiation driven and that the effect of wind is minimal. Sensitivity analysis shows that evaporation estimation is more sensitive to shortwave radiation followed by relative humidity. An increase or decrease of estimated shortwave radiation by 10% could result in an increase or decrease of estimated evaporation up to 18%. The Penman combination method is relatively the least sensitive to wind speed but could bring a significant effect on the lake level fluctuation since a 10% increase of wind speed increases the estimated evaporation by 2.3%. The current analysis highlights the relative roles of radiation, temperature, humidity, and wind speed in modulating the rate of evaporation from the lake surface, by employing an inter-monthly seasonal adjustment factor to the estimated evaporation in the lake water budget analysis, with implications for the inter-monthly variability and short-term trends assessment of water resource through various meteorological parameters.

Key words | climate, evapotranspiration, lake, meteorology, water resources, wetland

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INTRODUCTION

Evapotranspiration is the amount of soil moisture lost to the atmosphere via evaporation from the ground surface and transpiration from the plant leaves. Evaporation is often the dominant control on lake water budgets, particularly in more arid regions (Allison & Barnes 1985; Jankowski & Jacobson 1989; Lhomme *et al.* 2015; Yihdego & Panda 2017), so it is important to estimate its contribution accurately (Yihdego 2017; Yihdego & Waqar 2017; Yihdego *et al.* 2017a). Evapotranspiration is a physical and a biological process whereas evaporation is a purely physical process. There are many ways of calculating evaporation from open water bodies: water balance, mass transfer, energy balance or Penman combination and measured pan evaporation. These methods have been applied in previous lake modelling studies (Swancar *et al.* 2000; Rosenberry *et al.* 2007). Commonly regarded as the most accurate is the energy-budget method (e.g. Winter 1981), but this requires more data than is available for the present study. In addition, a recent study (Bhattarai *et al.* 2012) suggests that a complex energy balance model may not perform as well under open water conditions as they do under vegetative conditions. There are sophisticated methods of calculating evaporation from open water (Allen *et al.* 2007; DeJonge *et al.* 2015; Liebert *et al.* 2015). Water balance, mass transfer, energy balance or Penman combination and pan evaporation approaches are some to mention (Szilagyi 2014; Moiwo & Tao 2015). Dingman (2002) indicates that due to its demand of usually unavailable data from most

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meteorological stations, like surface water temperature, most of the approaches are less applicable to data scarce areas.

Evaporation from open water bodies is influenced by many factors. Here, we investigate hydrological effects, including surface. Crop water requirements are commonly estimated with the FAO-56 methodology based upon a ‘two-step’ approach: first a reference evapotranspiration is calculated from weather variables with the Penman–Monteith equation; then ET_0 is multiplied by a tabulated crop-specific coefficient to determine the water requirement of a given crop under standard conditions. This method has been challenged to the benefit of a ‘one-step’ approach, where crop evapotranspiration is directly calculated from a Penman–Monteith equation, its surface resistance replacing the crop coefficient (Dalton *et al.* 2004; Lenters *et al.* 2005). Evaporation calculated by the energy budget method is generally considered to be the most accurate; with proper care, the error in annual estimate can be 10% or less, and seasonal estimates are considered to be within about 13% (Winter 1981). It implies that any other method of estimation of evaporation will have more than 13% error in its seasonal estimates (Liebert *et al.* 2015). Results show a one-step approach (for estimating evaporation) can have better spatial/temporal correlation and smaller interpolation error and therefore, the accuracy of the evaporation value is more related to the method of computing evaporation than the type of climatic data being interpolated. The importance of capturing the seasonal climatic/evaporation rate is a key step to analyze and comprehend the historic and existing open water bodies and further predict the feature in the evaporation component (Yihdego & Webb 2017).

Practical estimates of lake evaporation must rely on data that can be observed in the land environment. This requires the ability to take into account the changes in the temperature and humidity that occur when the air passes from the land to the lake environment. The complementary relationship between potential and areal evapotranspiration provides such a capability and is used herein, in combination with an approximate technique for taking into account subsurface heat storage changes, as the basis for formulating the complementary relationship lake evaporation model. Because it has a realistic basis, the energy/mass balance model can utilize routine climatological data observed in the land environment to provide estimates of lake evaporation with less need for locally calibrated coefficients (Morton 1986; Elsawwaf *et al.* 2010; Alazard *et al.* 2015).

Commonly, evaporation is measured by measuring evaporated water from open water. The sensitivity analysis in the calibrated model for Lake Burrumbeet showed that errors in the model can largely be attributed to erroneous estimates of evaporation and rainfall, and surface inflow to a lesser extent (Yihdego & Webb 2012, 2015). Therefore, reducing the uncertainties associated with the evaporation will have an implication on making predictions (Yihdego *et al.* 2016; Yihdego & Paffard 2016; Yihdego & Drury 2016). The aim of this paper is to provide a comparison on the estimation of the lake's water evaporation. This helps to enrich our understanding on historic, present and future water resources management (groundwater, water bodies, wet lands, lakes, lagoons) as evaporation plays a key role in water budgeting. The paper presents an interesting study on the estimation of the lake's water evaporation through a comparison of methods.

SITE DESCRIPTION

The study area lies south of the Great Dividing Range in southwest Victoria, ~200 km west of Melbourne, and encompasses a large part of the catchments of the Hopkins River (Figure 1) as well as much of the Victorian Volcanic Plain which was formed by volcanic eruptions in western Victoria over the past six million years (Yihdego & Webb 2007, 2008; Yihdego 2010).

Lake Burrumbeet (Figure 1) is located in central western Victoria and is the largest of four shallow lakes in the Ballarat region, with an area of ~23 km^2. The lake is the major wetland for the region, and has been utilized for recreational boating, fishing and camping. Lake Burrumbeet lies within the upper Hopkins River catchment. The lake catchment has an area of 298 km^2 (Yihdego & Webb 2016).

Climate

The study area experiences a temperate climate with dominant westerly winds, variable cloud and moderate precipitation, with wet, cool winters and dry, warm summers.

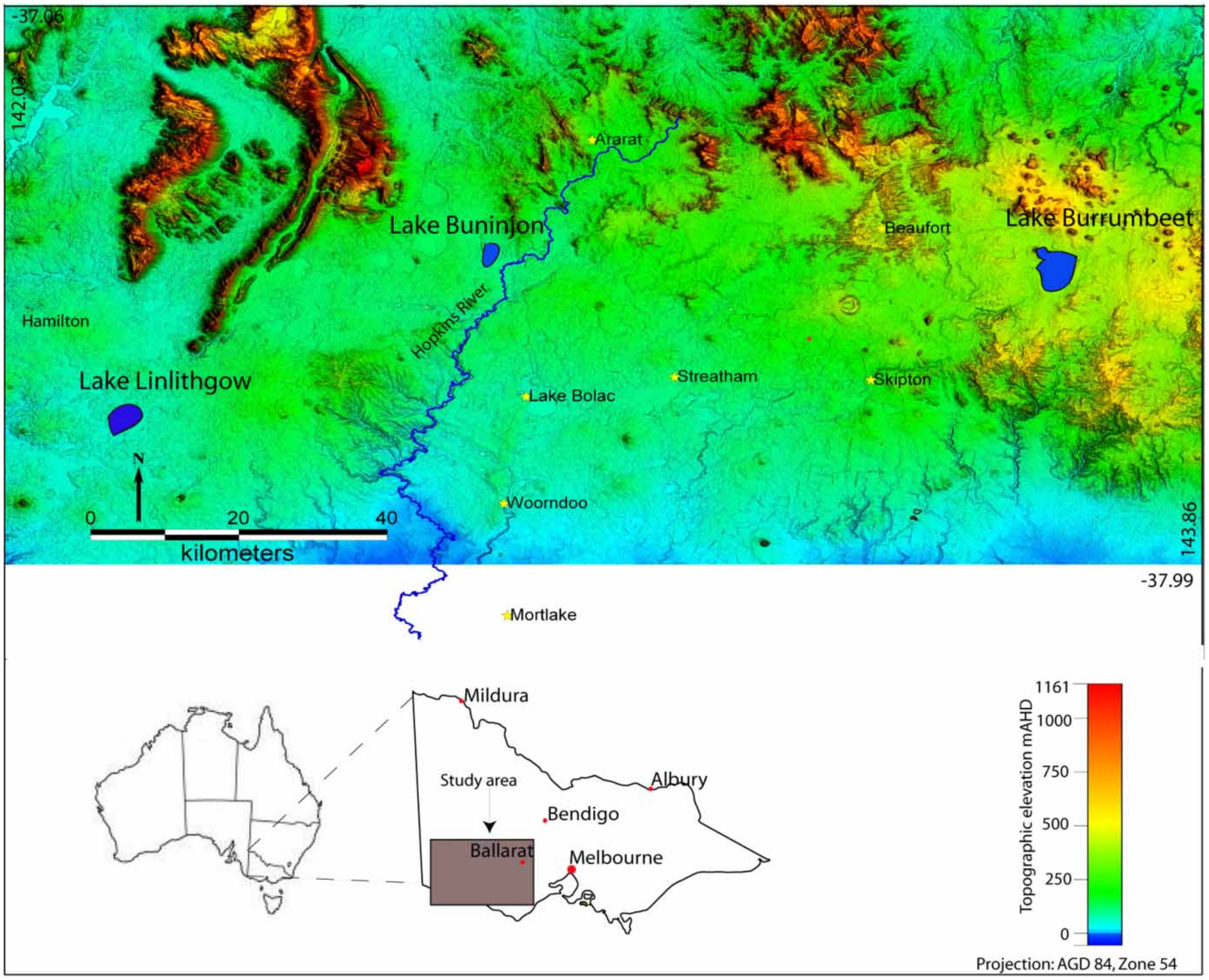

Figure 1 | Study area.

Daytime temperatures are generally mild to hot in summer, and mild to cool in winter. For example, at Hamilton, the hottest and coldest months are February and July with mean daily maximum and minimum temperatures of 26.1 and 4.1 °C respectively. Similarly, at Ballarat, the hottest and coldest months are February and July with mean daily maximum and minimum temperatures of 25 and 3.2 °C respectively (BOM 2009). Mean relative humidity at Hamilton is 40–60% in summer and 71–88% in winter (9 am and 3 pm relative humidity values respectively) (BOM 2009).

EVAPORATION

Throughout the study area, potential evaporation is highest in summer and lowest in winter (Figure 2), and the average evaporation declines from north to south and with increasing altitude. Pan evaporation is highest from October to April (Yihdego & Webb 2016). Although in southern Australia there is usually a surplus of rainfall over evaporation during winter, it is only in high-altitude, high-rainfall zones (generally where annual rainfall exceeds 850 mm) where there is an annual surplus. Class A pan evaporation as measured at Hamilton Research station from January 1969 to June 2000 averages 1,350 mm evaporation annually. Annual class A pan evaporation varies from <1,000 mm north-west of Ballarat to over 1,350 mm around Hamilton, and over most of the volcanic plains it is 1,150–1,200 mm. Areal actual evapotranspiration (calculated using FAO 56) supplied by the Bureau of Meteorology is estimated at 500–600 mm per annum for most of the Victorian volcanic

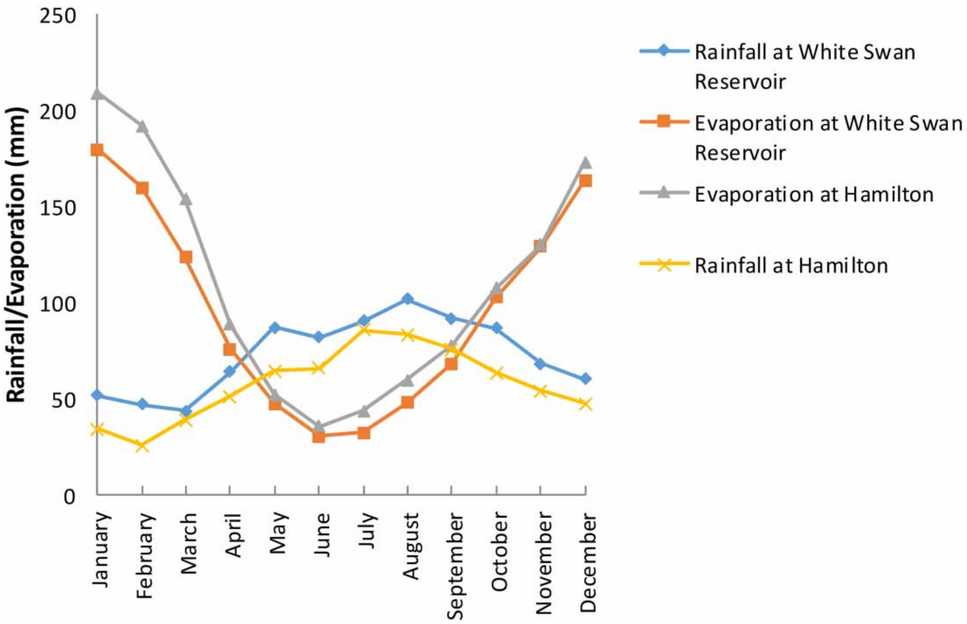

Figure 2 | Average monthly rainfall and pan evaporation for Hamilton and White Swan Reservoir (BOM 2009).

plains. Maximum rainfall is received over winter and exceeds or equals evaporation (Figure 3).

METHODOLOGY

The actual evaporation from a fresh water lake, E_{fresh} (Equation (1)), can also be estimated by the relationship between E_{pan} (measured class A pan evaporation) and α (pan coefficient). This is the method most frequently applied in lake modelling studies in western Victoria (e.g. Coram 1996; Bennetts 2005; Raiber 2008; Tweed *et al.* 2009).

$$E_{fresh} = E_{pan} \times \alpha \tag{1}$$

A pan coefficient must be applied to convert measured pan evaporation to lake evaporation, because in contrast

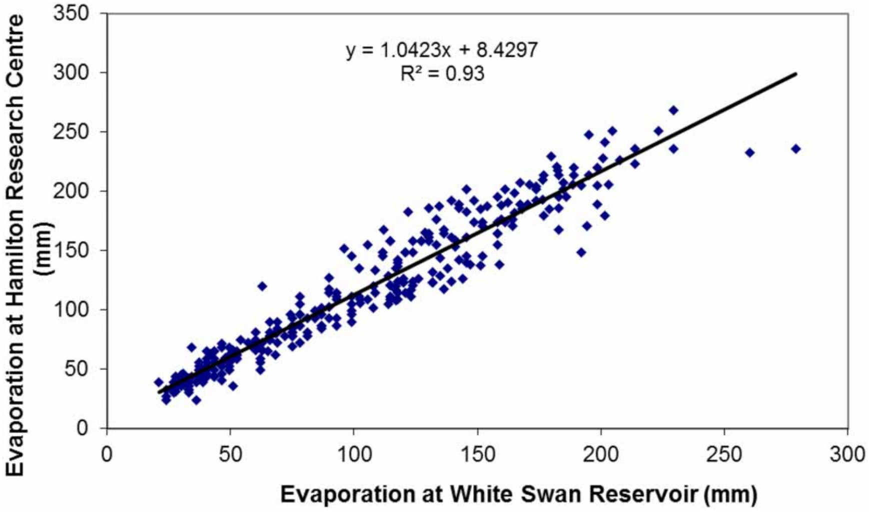

Figure 3 | Correlation of class A pan evaporation from Hamilton Research Centre station and White Swan Reservoir.

to a lake, a pan receives large quantities of energy through its base and sides, because it is exposed to air and sun. As a result, pan evaporation measurements generally overestimate evaporation from open water bodies, because the US standard class A pan gets much hotter than a lake (Lee & Swancar 1977). Moreover, the differences between a pan and a lake will vary through the year because of seasonal differences in radiation, air temperature, wind and heat storage within the larger body of water. Various factors such as the pan structure and site conditions can also influence the pan coefficient (e.g. Chiew & McMahon 1992; Fu *et al.* 2004). The monthly pan coefficients (α) can differ from the commonly used value of 0.7 by more than 100% (Winter 1981; Taghvaeian *et al.* 2015). Therefore, a pan coefficient that varies through the year must be applied to the measurement of pan evaporation in order to estimate water loss from a lake (Dune & Leopold 1978; Elsawwaf *et al.* 2010; Alazard *et al.* 2015). Evaporation from the pan will be larger than from a lake under the same meteorological conditions.

A comparison of different methods of calculating evaporation in the United States showed that using pan evaporation produces errors between −8 and +12%, but averaging <1% (Swancar *et al.* 2000; Usman *et al.* 2015).

The measured pan evaporation rates are normally 30% higher than lake evaporation; therefore 0.7 is a commonly used pan coefficient value in lake studies (e.g. Dingman 2002; Linacre 2004). Research undertaken in Australia on free-water evaporation has shown that the measured and modelled annually-averaged pan coefficients are comparable, e.g. 0.87 (Garrett & Hoy 1978) and 0.9 (Vardavas 1987) respectively, from Manton Dam in the Northern Territory. Pan correction factors applied in recent water budget studies in western Victoria are 0.8 (Hagerty 2006) for the Tullaroop Reservoir, 0.81 for Lake Bolac (Raiber 2008), 0.5–0.9 for Lakes Corangamite and Colac (Tweed *et al.* 2009) and 0.9 for Lake Wallace (Fawcett 2005).

In this study, pan evaporation and calculated evapotranspiration data were used. The monthly pan evaporation data was obtained from the Bureau of Meteorology (BOM 2009). The reference evapotranspiration values were daily gridded data obtained from the SILO website (www.nrm.qld.gov.au/silo/), and represent evapotranspiration by short grass that has no shortage of water supply (calculated by FAO 56; Allen *et al.* 1998).

ANALYSIS AND RESULTS

In the present study, the evaporative water losses from Lakes Burrumbeet have been calculated using US class A pan evaporation data, measured at Hamilton Research Centre (1965–2000) and White Swan Reservoir (1971–2008) (Figure 3). White Swan Reservoir is located to the north-east of Ballarat. There is a strong positive correlation between pan evaporation at the two sites (r^2 value 0.94; Figure 3), although pan evaporation at Hamilton is consistently higher than at White Swan Reservoir, reflecting the higher annual average temperatures at Hamilton.

Evaporation from a fresh water lake (E_{fresh}) is reduced as lake salinity increases, due to the lower vapor pressure of saline waters (Calder & Neal 1984; Kokya & Kokya 2008). Hence pan evaporation rates should be converted for lake salinity (Equation (2)):

$$E(t) = \frac{E_{fresh}}{(1 + (C(t-1) \times 10^{-6})} \tag{2}$$

where $C(t-1)$ is the total dissolved solids (TDS) concentration of the lake water measured in the previous month in mg/L. Lake Burrumbeet is usually moderately saline (median 3.74 mS/cm) and varies seasonally. A noticeable rise in salinity level has occurred since 2002 (up to 21,950 EC) as the lake level decreased due to abnormally dry conditions and lake levels of less than 0.4 m (Yihdego & Webb 2015). However, the calculations for the present study show that the influence of lake salinity on evaporation is very small, and this correction was not applied to the lake modeled (Yihdego & Webb 2012).

In the present study, different pan coefficients (α) were used for each month, based on the mean monthly relative humidity and wind speed at White Swan Reservoir/Hamilton Research Centre.

Pan coefficients (kp) for class A pan for different pan siting, environment and different levels of mean relative humidity and wind speed have been presented in FAO Irrigation and Drainage Paper No. 56 as in Table 1 (FAO

Table 1 | Pan coefficients for class A pan for different pan siting and environment and different levels of mean relative humidity and wind speed (FAO Irrigation and Drainage Paper No. 56; Allen *et al.* 1998)

Class A pan	Case A: Pan placed in short green cropped			
Relative humidity (%)				
Wind speed (m/s)	Windward side distance of green crop (m)	Low (<40)	Medium (40–70)	High (>70)
Light <2	1	0.55	0.65	0.75
	10	0.65	0.75	0.85
	100	0.7	0.8	0.85
	1,000	0.75	0.85	0.85
Moderate 2–5	1	0.5	0.6	0.65
	10	0.6	0.7	0.75
	100	0.65	0.75	0.8
	1,000	0.7	0.8	0.8
Strong 5–8	1	0.45	0.5	0.6
	10	0.55	0.6	0.65
	100	0.6	0.65	0.7
	1,000	0.65	0.7	0.75
Very strong >8	1	0.4	0.45	0.6
	10	0.45	0.55	0.6
	100	0.5	0.6	0.65
	1,000	0.55	0.6	0.65

Irrigation and Drainage Paper No. 56; Allen *et al.* 1998). Since the lake itself is the largest consumer of water (evaporation), much attention has been paid to establish accurately the open water evaporation. In the present study, different coefficients were used based on values given in Table 1.

The overall estimation of evaporation was improved by multiplying the adjusted pan evaporation data by a local calibration coefficient ranging from 0.7 to 1.3, to obtain the best fit between the calculated and measured lake volumes (Yihdego & Webb 2012, 2015; Yihdego *et al.* 2014, 2015, 2017b); this coefficient takes into consideration the differences in position, elevation and meteorological variables between the sites where pan evaporation was recorded (White Swan Reservoir/Hamilton Research Centre) and the modelled lakes.

Penman (combination approach) is an approach which does not require surface water temperature and is recommended for estimating free water evaporation (Maidment 1993; Hassan-Esfahani *et al.* 2015). This is referred to as a combination approach because it combines energy and mass transfer aspects. The Penman equation reads (Equation (3)):

$$Ep = \frac{1}{\lambda}\left[\left(\frac{\Delta}{\Delta + \Upsilon}\right)Rn + \left(\frac{\Upsilon}{\Delta + \Upsilon}\right)f(u) \times (es - ea)\right] \tag{3}$$

where Ep is the potential evaporation from the lake (mm day^{-1}); λ is the latent heat of vaporization of water (MJ kg^{-1}); Δ is the slope of the saturation vapour pressure curve at air temperature (kPa °C^{-1}); Y is the psychromatic constant (kPa °C^{-1}); Rn is the net radiation (MJ m^{-2} day^{-1}); $f(u)$ is the wind function (MJ m^{-2} kPa^{-1} day^{-1}); es is the mean daily saturation vapour pressure (kPa); ea is the actual mean daily vapour pressure (kPa).

The wind velocity is measured at 2 m above ground. The calculated pan evaporation data, adjusted using the monthly pan coefficients, are very strongly correlated with potential evaporation calculated using the Penman combination approach (Figure 4). In this study, the adjusted pan evaporation was used. The missing pan evaporation at Hamilton for 2000–2008 was calculated from the White Swan Reservoir data for this time period, using the correlationship in Figure 4 between the data sets.

Mean annual estimate of the pan evaporation and Penman (combination) method is 1,163 and 724 mm respectively.

Pan evaporation data and Penman (combination) evaporation values follow a similar pattern throughout the year (mainly during the wet season), the Penman value being lower than the Pan evaporation value (Figure 5).

In this study solar radiation was estimated using the available data set. A good match between the estimated and measured global solar radiation validates the estimation of evaporation using the Penman combination method (see Figure 6).

The process of vapour removal depends to a large extent on wind and air turbulence which transfers large quantities of air over the evaporating surface. When water vaporizes, the air above the evaporating surface becomes gradually saturated with water vapour. If this air is not continuously replaced with drier air, the driving force for water vapour removal and evapotranspiration rate decreases (Allen *et al.* 1998; Moorhead *et al.* 2015; Wu *et al.* 2015).

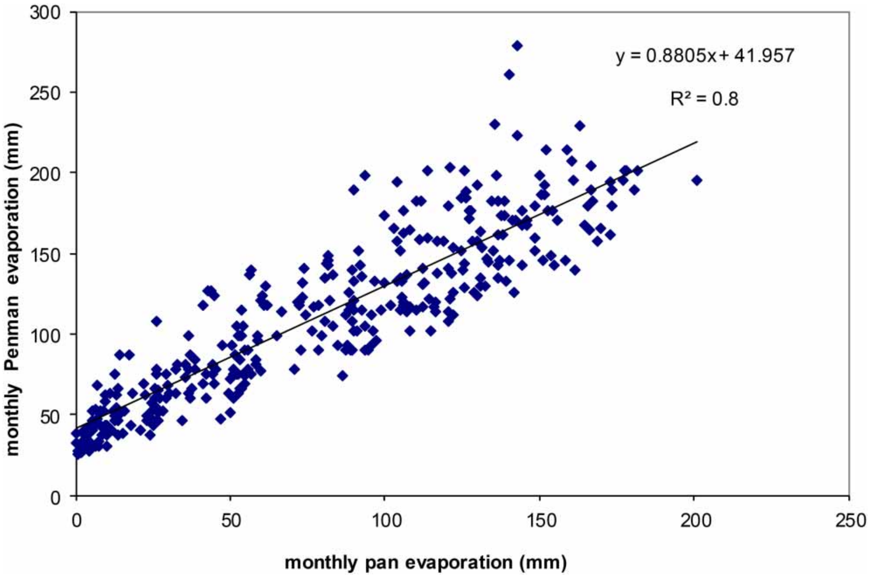

Figure 4 | Correlation between measured pan evaporation at White Swan Reservoir and calculated evaporation value using the Penman method at nearby Ballarat Aerodrome.

Sensitivity analysis of Penman (combination) evaporation method

The Penman combination approach of evaporation estimation can be seen in Figure 7, it is more sensitive to shortwave radiation followed by relative humidity. An increase or decrease of estimated shortwave radiation by 10% could result in an increase or decrease of estimated evaporation up to 18%. The cloudiness factor (i.e. 1-net incoming/incident solar radiation), could affect variation in monthly evaporation. This method is relatively least sensitive to wind speed but it could bring a significant effect on the lake level fluctuation since a 10% increase of wind speed increases the estimated evaporation by 2.3%

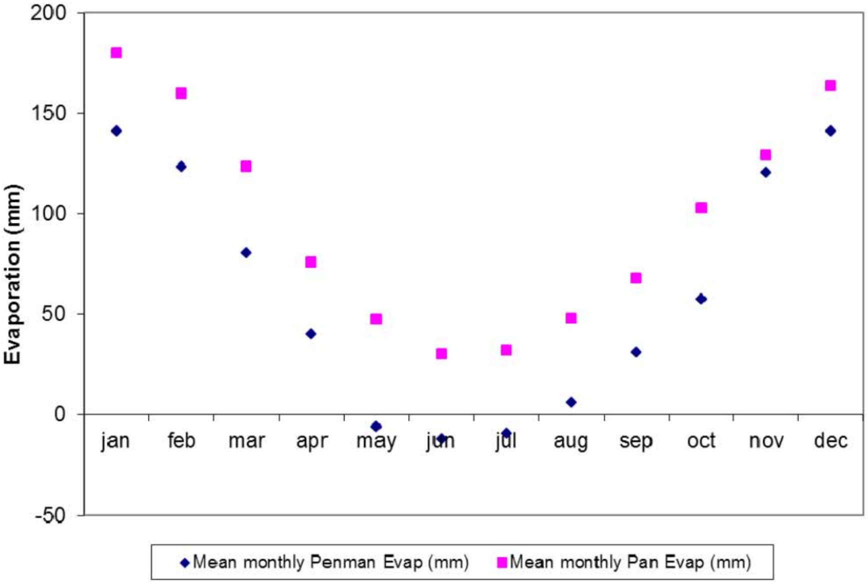

Figure 5 | Long term mean monthly evaporation (Penman/pan).

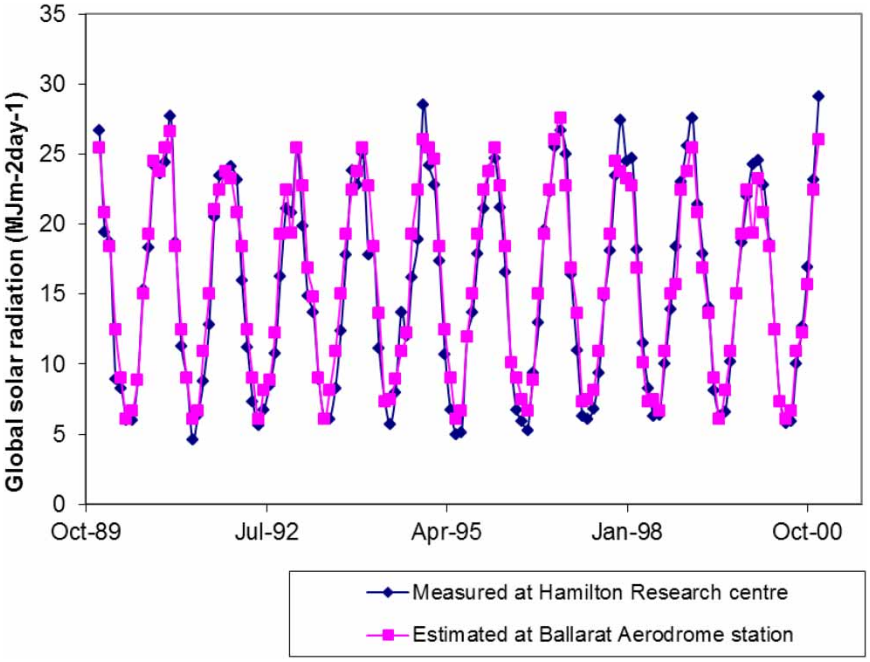

Figure 6 | Comparison of actual and estimated global solar radiation at Ballarat Aerodrome station.

(Table 2). Evaporation is one of the most sensitive variables in the lake water balance model where a 5% increase in evaporation could lead to a 3.7% (14 cm) decrease in lake level (Yihdego 2010). Temperature and wind direction were assumed inclusive as wind direction could affect local advection.

SUMMARY AND CONCLUSIONS

Evaporation is an essential variable in agro hydrological systems and its estimation on a regional scale is limited to its spatial variability. Therefore, reducing the uncertainties associated with the evaporation will have an implication

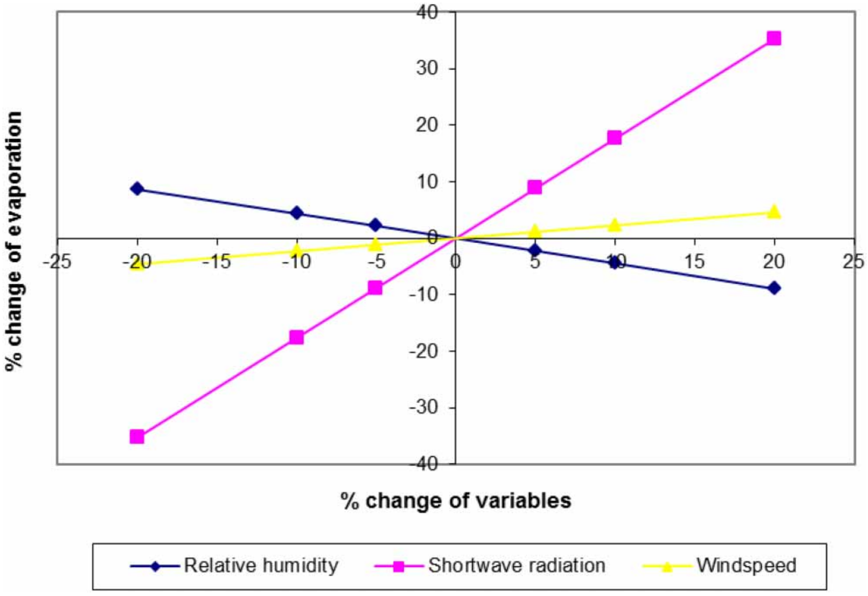

Figure 7 | Sensitive analysis of evaporation to different variables.

Table 2 | Sensitive analysis of Penman (combination) method

	Change in evaporation in % upon change of variables (relative humidity, short wave radiation and wind speed)		
Change of variables (%)	**Relative humidity**	**Shortwave radiation**	**Wind speed**
−20	8.6	−35.3	−4.6
−10	4.4	−17.7	−2.3
−5	2.2	−8.8	−1.2
5	−2.2	8.8	1.2
10	−4.4	17.7	2.3
20	−8.6	35.3	4.6

on making predictions. This paper describes the analysis of evaporation data, comparing the long-term Penman methodology with measurements from pans. The calculated/estimated evaporation was then applied to a lake using the standard coefficient methodology. It is believed that the methodology used is appropriate for the objective of the study. A result from an updated 37-year (1971–2008) energy budget analysis of Lake Burrumbeet in Western Victoria (Australia) is presented. To account for the differences in meteorological conditions of each month, different coefficients were used.

Results from this analysis showed that the estimated solar radiation matches with the measured solar radiation. Evaporation calculated from the energy budgets appears to be more accurate. The detailed analysis of the meteorological data showed that the evaporation is fully radiation driven. Also it has shown that lake evaporation varies significantly, on a wide variety of timescales, and that the climatic drivers of evaporation depend strongly on the timescale of interest, implying a cross-check of estimated evaporation data is vital before applying into further catchment/water budget analysis. Variations in lake evaporation have a significant impact on the energy and water budgets of lakes.

The current analysis highlights the relative roles of radiation, temperature, humidity, and wind speed in modulating the rate of evaporation from the lake surface, by employing a seasonal/monthly adjustment factor to the estimated evaporation in the lake water budget analysis. Seasonal variations in lake evaporation have a significant impact on the energy and water budgets of lakes. The sensitivity analysis showed that evaporation estimation is more sensitive to shortwave radiation followed by relative humidity. An increase or decrease of estimated shortwave radiation by 10% could result in an increase or decrease of estimated evaporation up to 18%. The Penman combination method is relatively least sensitive to wind speed but it could bring a significant effect on the lake level fluctuation since a 10% increase of wind speed increases the estimated evaporation by 2.3%. Previous study showed that evaporation is one of the most sensitive variables in the Lake Burrumbeet water balance model (i.e. a 5% increase in evaporation could lead to a 14 cm decrease in lake level; Yihdego 2010).

The study demonstrates the importance of seasonal (inter-monthly) evaporation variability assessment and reducing the uncertainties associated with short-term trends to arise as well as the implications for surface water resources through various meteorological parameters desired by biophysical scientists, hydrologists and irrigators, being accurate monitoring of evaporation from water bodies are rare and requires significant investment of time and resources to support energy budget and/or eddy covariance instrumentation, maintenance, and data processing studies.

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