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Water Balance and Evaporation for Two Intermittent Estuarine Lakes

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Abstract

The management of small intermittently open or closed estuaries (ICOLLs) requires the prediction of lake water levels and the probability of breaching of the entrance barrier in real time, seasonally, and long term. The water balance is a key tool that in turn requires prediction of the open water evaporation. The drivers of the water balance of two ICOLLs on the south-east coast of Australia were studied: The two ICOLLs, Durras Lake and Lake Wollumboola, have very different morphologies: Durras Lake is a drowned stream valley with a largely steep, forested catchment, while Lake Wollumboola is a back-dune lagoon ICOLL with a wider, shallow water body. For these small estuaries, hydrologic and geomorphic data are generally limited or unavailable; hence, methods were developed to use data routinely available, primarily from government agencies, without using regionally averaged or “text book” parameter values. For both lakes, evaporation was shown to be on average larger than either of the inflows from the catchment or from the direct rainfall on the lakes; thus, evaporation must be reliably predicted for use in the water balance. The calculated evaporation agreed with widely used but data-intensive formulas. For each ICOLL a robust linear correlation of lake evaporation with the incident solar radiation accounted for 94% of the variance in the evaporation. The seasonal variation of evaporation fitted a cosine curve, again accounting for 94% of the variance of the evaporation. Validation of the water balances using the evaporation-solar correlation and a derived runoff coefficient provided a close match with the historical record. On most days, the water loss from the lakes by evaporation was larger than the sum of the inflows from catchment runoff and direct rainfall on the lakes. Storms of duration 1–3 days rapidly increased the water storages and the lake levels, potentially leading to breaching of the entrance barrier. This fluctuating balance drives the intermittent behaviour of these ICOLLs and emphasises the importance of accurately assessing the lake evaporation.

Keywords Evaporation · Water balance · Estuary · Lake · Solar radiation · Durras Lake · Lake Wollumboola

Introduction

There are numerous small tidal estuaries on most temperate coasts, and many of them are intermittently closed or open to the sea (McSweeney et al., 2017; Roper et al., 2011). These lakes are commonly known as intermittently open or closed lakes/lagoons (ICOLLs) in Australia and

temporary open/closed estuaries (TOCEs) in South Africa, where they comprise around 70% of estuaries (Whitfield et al., 2012). Similar estuaries occur in New Zealand, California, and along parts of the South American coastlines. A comprehensive review of the science of this type of estuary and suitable adaptive management strategies is contained in Stein et al. (2021). Specific management actions will depend partly on government policies, especially where limited interference with the natural regime is desired. This is the case in the Australian context and specifically in the state of New South Wales. Their entrance management is currently sometimes based on water quality but usually on a trigger level for water in the ICOLL that threatens legacy infrastructure through flooding. Further knowledge would be beneficial to improve the prediction of lake water levels in real time for management of local flooding and long term for planning and design of works. The principal indicator for management is the probability

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of critical estuary water levels being reached, where natural breach may be expected or protection of assets or amenity requires an assisted breach. In addition, the water balance, aided by mass balance plots, reveals the relative magnitudes of the principal contributors to the water balance, namely the evaporation from the lake, the catchment inflow and the direct rainfall on the lake surface.

Modelling or statistical analysis of these small systems is difficult because catchment flows are rarely available and rainfall and estuary water level records are usually limited in duration and location. Specific information on wind speed and direction, and evaporation is quite rare and usually only available from major climate stations, which may be a large distance from the estuary being studied. This paper applies the limited available information to compute the water balance in Durras Lake and Lake Wollumboola, both ICOLLs in south-eastern Australia. A necessary step is the calculation of the open water evaporation from the small estuarine lakes. Both this calculation and the water balance required the development of novel approaches and provides quantitative relationships that may be used in other estuaries in similar environments.

Modelling of water level changes in an ICOLL with a closed entrance to the sea is based on the water balance equation. ICOLLs with an open entrance experience tidal flows requiring the use of dynamic equations for the entrance channel flows and are not considered here. The procedure follows that outlined in Hinwood and McLean (2022), who used a 20-year record of water levels in Durras Lake to identify the different entrance regimes and accurately determine periods when the entrance channel was fully closed for their application of the water balance.

In the next section, the two ICOLLs are described; then, the water balance equation and evaluation of the terms in it are presented, including a discussion of the methods of estimation of lake evaporation. Section 3 summarises the results of the water balances and presents and compares the results for the evaporation for the two ICOLLs. The use of

mass curves based on these results as an aid to management is shown.

Methodology

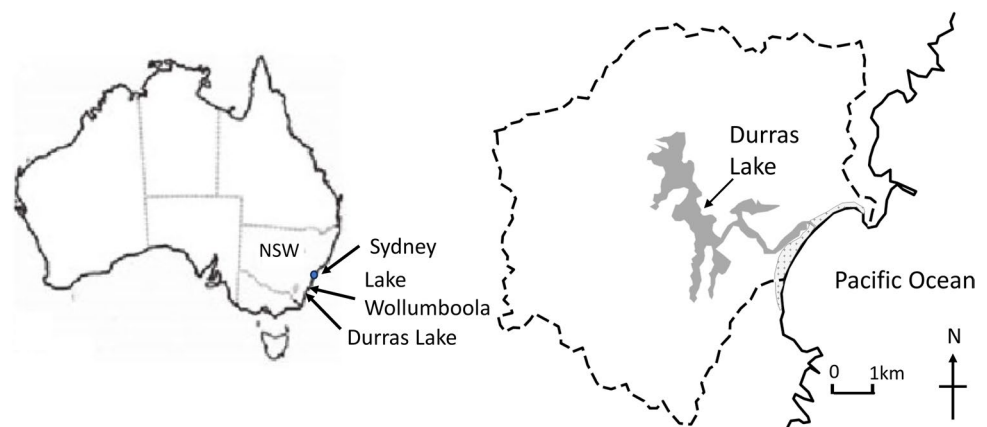
Lakes Durras and Wollumboola

Lakes Durras and Wollumboola have been selected as case studies. Both ICOLLs are located on the South Coast of NSW, exposed to the waves, tides and weather from the Tasman Sea, with entrance channels formed in wide bay openings, largely infilled with marine sands forming a shore-parallel coastal dune and entrance berm. Offshore, the continental shelf is narrow increasing the exposure to wave action. The lakes differ in form, with Durras Lake occupying a partially filled drowned valley and Lake Wollumboola filling an extensive, shallow back-berm swale.

The South Coast of NSW experiences a warm temperate coastal climate, which is mildly seasonal with most rain occurring in the warmer parts of the year, and drier conditions usually during the short winter period. No single pressure pattern dominates storm occurrence or severity (BoM-CSIRO, 2022; Mortlock & Goodwin, 2015). Low-pressure systems, bringing heavy rainfalls, can be experienced throughout the year, and distinct wet and dry seasons are not usually apparent, although decadal variations also affect storm frequency.

Durras Lake (35.639°S, 150.305°E) is located 190 km south of Sydney (Fig. 1a). It has a catchment area of 81 km², mostly located on the narrow coastal lowlands with the upper section extending up into the coast-parallel range (Fig. 1b). The tidal lake, with a water area of 3.94 km² at Mean High Water, comprises several winding channels of maximum width ~800 m, but typically ~180 m, and has an average depth of 1.4 m. The maximum typical entrance width is constricted to about 30 m when open. Flows through the entrance have not been gauged; hence, this study required

Fig. 1 **a** Location map. **b** Durras Lake and catchment boundary (beach and barrier sands stippled)



data from periods when there were no entrance flows. During 2000–2020, the entrance was closed 36% of the time for periods of 23–1038 days, with a mean of 324 days (Hinwood & McLean, 2022).

Lake Wollumboola (34.94°S, 150.78°E) is an ICOLL located approximately 172 km south of Sydney. The lake is one of an uncommon type of ICOLLS named “back dune lagoons” (Scanes et al., 2014, 2020) and is characterised by a large lake area (6.3 km²) to catchment area (34.1 km²) ratio. The inlet length is relatively short compared to other ICOLLS, with very limited flood tidal deposits. The lake is shallow with an average depth of 0.8 m. Macrophytes are a feature of the vegetation growth in the lake body (Scanes et al., 2014), and satellite images show dark green with occasionally vivid patches, indicative of algae. Scanes et al. (2014) described turbid plumes entering Lake Wollumboola, and small plumes are visible in some Landsat and other satellite images. Limited measurements (DPIE, 2020) did not show altered turbidity or salinity, so the impact of these small plumes on the water balance is small. The catchment is forested and is relatively undisturbed.

Calculating the Water Balance

The following subsections present the water balance equation and then describe the calculation procedure for each term in the water balance. Determination of the evaporation from the surface of these small lakes required special consideration and development of new procedures; it is treated in more detail following the other terms.

The Water Balance Equation for an Estuary

The water balance for an estuarine lake may be written as

$$\frac{dV}{dt} = -Q_e - Q_t + Q_c + Q_d + Q_g \quad (1)$$

where t is time, Q_e is evaporation (water loss), Q_t is net tidal outflow, Q_c is catchment inflow, Q_d is direct rainfall on the lake, Q_g is net groundwater inflow, and V is water volume in the estuary, a unique function of the water level, y .

Change in Lake Volume

For Durras Lake, a 20-year record (March 2001–November 2021) of lake water level was available. The record had many gaps of a few hours to a few days in the early years and two longer gaps. The short gaps were filled using a quadratic spline, while the longer gaps were left as blanks. The record of water levels for Lake Wollumboola over the same period was used, and its more numerous gaps were treated in the same manner.

The water levels during this period of record range from well below tidal low water in drought to well above tidal high water following heavy rain and prior to breaching the entrance barrier. Determination of the lake volume over this range requires both hydrographic and terrestrial surveys. To determine the water volume in Durras Lake, the available bathymetry, a section of the state-wide DEM and local LiDAR data sets were combined to develop the plan area of the water surface at 0.5-m height intervals. This combined topographic dataset was entered into ArcGIS and a barrier simulated across the estuary entrance area. The 0.5-m slices were then entered using the volume tool function in ArcGIS to create data on lake surface area and a volume-vs-depth plot. For simplicity in calculation, an analytical expression for the volume as a function of depth was sought. The points obtained were very well approximated by a quadratic regression with the depth ($R^2 = 0.99$): $V = 3.421 + 4.192y + 1.128y^2$. A cubic regression gave negligible improvement, and expressions of the form $V = a + y^n$ gave good fit but only over limited ranges. For Wollumboola, a quadratic regression curve was found to be a good fit to the points from the GIS. The same data yielded a similar equation for the variation of lake area, A_b , with depth.

Net Entrance Inflow/Outflow

The term Q_t is the sum of all outflows less all inflows to the lake via the entrance channel. The principal components are tidal inflow and outflow plus net freshwater discharges to the lake. Records of tidal flows over more than a few days are non-existent in Australia and extremely rare elsewhere. For this reason, and to avoid the measurement errors that they would introduce, the analyses here are restricted to periods when the entrance to the sea was closed, and thus, $Q_t = 0$ using the entrance regime results of Hinwood and McLean (2022).

Groundwater Inflow/Outflow

The shore of Durras Lake is predominantly nearly horizontally bedded dense sandstone, except in the unconsolidated sands very near the entrance to the sea. Seepage from the sandstone cliffs near the sea occasionally flows onto the beach berm following heavy catchment rainfalls. The authors' attempts to measure it yielded very approximate values of 0.5–1.1 min⁻¹. The authors have measured the transmission of water through the half kilometre of mineralogically and granometrically similar beach barrier and dune at the mouth of the Snowy River estuary, to the south, and found tidal penetration fully attenuated within 12 m. Air-photo and high-resolution Sentinel 2A/B satellite imagery were carefully examined for evidence of water discoloration

or atypical seagrass or algal growth (as is evident in a nearby estuarine area) but no signs of either were found.

As a final check, salinity surveys carried out over 2009 were used to calculate volumetric changes in the lake. Salinity surveys of Durras Lake were available for 10 dates covering the period 01 December 2008 to 10 January 2010 (DPIE, 2020). For the whole of this time, the entrance was effectively closed to exchange of water with the ocean. During this period, rainfall and evaporation continued, causing the volume stored in the lake to vary, with a net increase in the lake volume of approximately 50%. Figure 2 shows the lake volume calculated from the salinity change, against the lake volume calculated from the measured water level and lake survey, each normalised as fraction of their final volume. The salinity-based value is a close match to the survey-based value except for the single point with the lowest stored volume. This agreement confirms that there are no unaccounted inflows or outflows in the water balance, such as ground water or anthropogenic flows.

Hence, it may be concluded that any groundwater inflows or outflows from or to the ocean or catchment are negligible in the case of Durras Lake and similar ICOLLs but that is not as certain for Lake Wollumboola with its different geology and geomorphology.

Direct Rainfall

The inflow of rainwater to the estuary comprises direct rainfall on the estuary lake surface, Q_d , and catchment inflows via creeks and rivers, Q_c . The first step in computing these inflows is to determine the time series of representative rainfalls. In south-eastern Australia, the density of rainfall stations is such that frequently there are no rain gauges in these small catchments, or at best only one or two. Thus, standard geometric methods of allocating catchment area to each gauge, such as Thiessen polygons or inverse radius, are potentially unreliable. Instead, we considered all rain gauges

within 12 km of the catchment and sought gauges in areas with similar elevations, exposure, and land use to the Durras Lake catchment. We then discarded those with significant data gaps and retained two representing the higher parts of the catchment and two representing the lower parts. The two gauges within each pair were found to have high correlation, so only the gauge from each pair with fewest data gaps was retained. Remaining data gaps were filled using the other gauge from each pair with an established correlation function. The data from each gauge were weighted proportionately to the type of area they represented. For Durras Lake, trial calculations then showed that mass curves were insensitive to the use of two or all four gauges.

For Lake Wollumboola, separate representative rainfalls were required to determine Q_c and Q_d and were obtained from four rain gauges, all a few kilometres outside the catchment, two at the same distance from the coast as the lake, and two representative of the inland portion of the catchment.

Considering data obtained over a time interval T (days) and denoting the total rainfall over a lake in the interval by R (mm), the average daily rainfall is R/T , in mm/day. Hence, the input from direct rainfall is given by

$$Q_d = RA_b/T \quad (2)$$

where Q_d is in mL/day and A_b is the lake plan area in km².

Catchment Inflow

No runoff data were available for either catchment, which is typical for these small estuaries. To determine the inflow, Q_c , from an ungauged catchment, several methods are available. Use of data from a gauged catchment nearby, with similar patterns of rainfall, geology, soil, geomorphology, and land use, would be ideal, but a suitable gauged catchment was not available. Alternatively, a rainfall–runoff model that uses runoff parameters appropriate to each sub-catchment as functions of soil type, vegetation, slope, elevation, etc., should be more accurate, but only if comprehensively calibrated. The rainfall–runoff model of Boughton (1968), with regional parameter values from Pilgrim (1987) and areal potential evapotranspiration from Wang et al. (2001), was adapted to apply to the Durras Lake catchment. The calculated time history of the catchment runoff was of the correct form but the magnitude of the runoff compared with that computed for the water balance was consistently too large, which is attributed to the use of regional parameters primarily from much larger catchments. 2CSalt is another such model, and hindcast storage levels up to 2007 were made available by DPIE (Littleboy et al., 2009), but calibration data were limited. They were compared with the present results by Hinwood and McLean (2022) who showed that

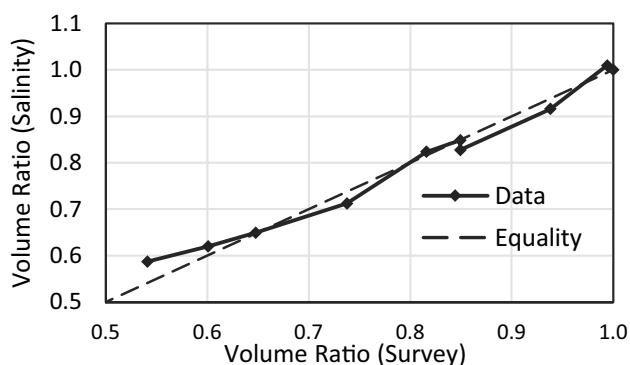


Fig. 2 Comparison of lake volume changes from salinity and survey, Durras Lake 2009

they were broadly comparable but frequently inaccurate for rapid changes. For all such models, in the absence of specific calibration data, generic parameter values must be used, and are likely to introduce significant errors.

This lack of data meant that the most appropriate choice was a one- or two-parameter method based only on the water level and rainfall data for Durras and Wollumboola Lakes. For these small catchments, the simplest method, using a catchment-wide runoff coefficient, r , has been adopted as set out in Eq. (3), where A_c denotes the catchment area. This one-parameter relation is the most robust and most easily tested parameterisation; trials including an initial infiltration or a base flow did not improve the correlation and limited field studies by the authors found negligible base flow.

$$Q_c = rRA_c/T \quad (3)$$

To calculate r , a set of time intervals from the data records was selected, each chosen to have significant rainfall in at least two events. To ensure that the uncertainties introduced into the calculated runoff by possible errors in the evaporation, the selected intervals were required to satisfy the criterion derived in Eq. (S3) and given in Eq. (4):

$$Ab * T/Ac * R < 0.06 \quad (4)$$

Evaporation

Available Methods of Estimating Open Water Evaporation

The benchmark method to determine the evaporation from a lake would appear to be a simple matter of measuring the fall in lake water level over one or more days. In practice, this is complicated by other water losses and gains, including rainfall incident on the water surface and catchment inflows, thus necessitating a water balance determination. Problems include the fact that catchment inflows are very rarely measured and, as Richardson pointed out as early as 1930, “there is a regrettable scarcity of reliable data for evaporation studies.” This scarcity has only marginally improved since that time as elaborated by Todorovic et al. (2013). In addition, the attainable accuracy of measuring small changes in the water level may impact the calculation. These problems lead to the requirements for longer-term water level records plus catchment flow modelling or to other methods as discussed in the next subsections.

One of the widely used methods is to measure the evaporative loss from an open pan, which is then scaled to the open water value using an empirical “pan factor.” In Australia, the Bureau of Meteorology (BoM) records Class A Pan evaporation at selected sites and publishes daily evaporation values (Jovanovic et al., 2008); similar data are available in other countries. While this method has proved

to be adequate for regional and climatic applications, it has not been adequate for the daily or weekly prediction of small areas that is required for estuary management, as the conversion of pan evaporation to apply to a lake is affected by a host of site conditions (Budyko, 1956; Cummings & Richardson, 1927; Penman, 1948), and very few of these small catchments have a pan measurement station.

Alternatively, the evaporation may be estimated by modelling aspects of the physics of the evaporation process, as comprehensively catalogued and grouped by McMahon et al. (2016) into three broad classes. In the mass transfer methods, also called Dalton’s law models (Helfrich et al., 1982), a semi-empirical equation is used to relate the rate of evaporation to the lake surface temperature and the up-wind air temperature, vapour pressure deficit, and wind speed. Data are required throughout the day, but such comprehensive data are only rarely available and never for long periods of record. Semi-empirical constants must be applied but the authors have found regional values to be unreliable for these small catchments, and Helfrich et al. (1982), in a review of cooling pond evaporation studies, found that the semi-empirical constants required local calibration.

The thermodynamically based methods use a heat balance for the lake that equates net radiation on the lake surface to the change in energy content of the air due to temperature change and the latent heat of vaporisation of the increased moisture content of the air plus heat convected or conducted to the environment. The factors involved and the resultant formulas for evaporation over a saturated surface, such as a lake, have been given by Ångström (1920), Cummings and Richardson (1927), Penman (1948), Budyko (1956), and Monteith (1965). Richardson (1930), in a paper that has been largely neglected, used available field data collected by US government and state agencies to calibrate and test his analytical energy balance model, including the convected heat loss, via the Bowen ratio, then used order of magnitude values to simplify it to Eq. (5) from which evaporation may be calculated with practical accuracy:

$$E_h = (S - B_r) \quad (5)$$

where E_h is the heat energy used in evaporation and S is solar radiation at the water surface, obtained from radiometric measurement and empirically corrected to remove non-solar radiation. The back radiation of solar energy, B_r , is calculated from thermodynamic principles assuming that the water and air temperatures are known, but Richardson (1930) showed that regional data are adequate for water resource studies. The relative magnitudes of the energy terms he has calculated from actual data are of great value as are those of Ångström (1920) and Cummings and Richardson (1927).

Doubts about use of spatially averaged values have been raised in the discussion of Richardson (1930) and by Priestley and Taylor (1972).

Penman simplified his heat balance formula by dropping the terms for radiative heat transfers between the water body and the surroundings, but it still contained the Bowen ratio, which requires data for air and near surface temperature and humidity. He developed this into a more practical form by introducing E_a , the evaporation that would be predicted if the vapour pressure in the air was the same as that of the evaporating surface. Priestley and Taylor (1972) revisited this result using calculated values of the Bowen ratio to justify including the effect of the transport term in the radiation term, to obtain one of the simplest and most often used formulas for potential evaporation; i.e., the evaporation that would occur from a saturated surface, such as a lake, if the air was not saturated:

$$E_p * L = \alpha \frac{\Delta}{\Delta + \gamma} (H - G) \quad (6)$$

where E_p is the potential evaporation; L is the latent heat of water; Δ is the slope of the saturation vapor pressure–temperature curve at the mean air temperature; γ is the psychrometric constant; H is the net radiation; G is the heat loss to the substrate, i.e., the lower layers of water; and $\alpha = E/E_p$ which they found to be 1.26 using data from a wide variety of water bodies. Although developed about 50 years ago, the Priestley–Taylor formula continues to be one of the standard methods of calculating evaporation, as evidenced by the important recent studies of Milly et al. (2020) and Zhou et al. (2023) that were based on that formula.

Hobbins et al. (2001) and McMahon et al. (2013) critically reviewed the publications that reported values of the P–T constant, α , and showed it depended on the nature of the evaporating surface and on the duration of the correlation—Priestley and Taylor used 1 day and their evaporating surface was water or saturated soil or vegetation. The value of 1.26 for evaporation from a clear water surface was confirmed by two theoretical studies reported by McMahon et al. (2013) and field-based shallow lake studies (Stewart & Rouse, 1976), although others have found 1.35 or somewhat larger values and most studies of evapotranspiration from crops or natural vegetation found higher values.

To obtain the net radiation energy input, required by both Richardson and Priestley–Taylor methods, short and long wave radiation are relevant, the short wave being dominated by incident solar radiation while the long wave comprises back radiation from the water and incident radiation from the surroundings. The long wave back radiation from the water surface may be calculated from the water surface temperature, but that is rarely measured; direct measurement of the back radiation is difficult and very few meteorological

stations make this measurement. Satellite data are available for some regions; otherwise, it may be estimated. Radiation from the environment is generally neglected or occasionally included by use of typical values. Anda et al. (2016), in a useful study of back radiation performed tests in a Class A pan with clear water, and with water with submerged macrophytes or a sediment bed. They found that the latter two cases had higher evaporation, which they determined was caused by the decreased albedo of the shallow water: the albedo of clear water (standard Class A pan test) averaged 0.12, with a sediment bottom 0.113, and with submerged vegetation 0.096. A similar effect was shown in some studies reviewed by Hobbins et al. (2001).

More rigorously, used by itself, the heat balance method predicts a potential evaporation from a saturated surface, which differs from the actual evaporation, mainly due to approximations required to cope with data deficiencies. A combined method using both mass and heat balances can provide a more accurate estimate but the data requirements are greater. Approximations justified in the sources cited above include transfers of energy to the water mass, which are generally neglected for shallow lakes and the assumption that the lake is sufficiently wide that transition zone from overland to over water has a negligible effect on the evaporation of the area (McMahon et al., 2013; Morton, 1983).

Another simplification was made by Makkink (1957) in analysing a set of long records of pan and vegetation plot data. He applied a more realistic upper atmosphere boundary condition to obtain a slightly improved formula for back radiation for his heat balance but used Penman's evaporation equation and showed that it accurately predicted his data. He then dropped the heat loss to the substrate and the back radiation to obtain Eq. (7) for potential evaporation from a water surface in terms of incident radiation, S_m , which fitted his data almost as well as Eq. (5) using net radiation.

$$E_p = 0.61 \frac{\Delta}{\Delta + \gamma} S_m - 0.12 \quad (7)$$

in which E_p and S_m are expressed in mm/24 h and presumably values < 0 are not permitted. The Makkink equation is widely used, for example recent applications in Saudi Arabia (Ghumman et al., 2020), Europe (Weiss, et al., 2021), and China (Dai et al., 2022). Dai et al. tested 14 formulas for evapotranspiration and found the Priestley–Taylor and Makkink equations were among the best of their respective types.

In summary, of the methods available to estimate the evaporation from the lake, pan evaporation, mass transfer methods, and the more advanced thermodynamic balance may all be rejected due to lack of data for small estuaries such as those studied here. This leaves the water balance or a simple thermodynamic balance for consideration. The water balance has been chosen as the primary method as it

utilises available but highly site-specific data. Development of a simple thermodynamic balance method has been chosen for confirmation and has the advantage that it does not require a water level record. This facilitates the possibility of applying this method to other estuaries in the region.

Evaporation Using the Water Balance

The water balance, chosen as the primary method and described in this subsection, was only possible because of the availability of long water level records for each lake. The thermodynamic balance method, chosen as a check and to enable the results to be applied to other ICOLLs, is described in the next subsection. Each of these methods includes some novel features as described in the relevant subsections.

The evaporation was calculated using the water balance equation (Eq. (1)), with the terms Q_d and Q_c replaced by the expressions in Eqs. (2) and (3), and the terms Q_i and Q_g omitted as discussed in Sects. 2.2.3 and 2.2.4, respectively. The resulting equation, after rearranging to solve for E , is Eq. (8), in which all quantities on the right side may be evaluated from the data, except for r which is explained below.

$$E = \frac{\{\delta V + R(A_b + A_c * r)\}}{(T * A_b)} \quad (8)$$

where the change in volume over the time of record replaces the derivative: $\frac{\delta V}{T} = \frac{dV}{dt}$.

The estimation of E is sensitive to the catchment inflow, and, as is shown in Eq. (S2), this may be characterised by the parameter $A_c * R/A_b * T$, where a large value indicates sensitivity. With the screening test of Eq. (S2) adopted in Eq. (9), the selected intervals were all acceptable.

$$A_c * R/A_b * T < 10 \quad (9)$$

Equation (8) contains the two unknowns E and r . As may be seen by comparing Eqs. (4) and (9), evaluation of these two unknowns requires selection of intervals of record with different characteristics, which prevents a simultaneous solution for E and r , but leads to the use of an iterative procedure to evaluate the two unknowns, in which an approximate first trial value of r for the entire record was obtained by solving Eq. (1) for r for each interval, and neglecting E . This first trial value was then used to calculate the first trial values of E using Eq. (1). Using this value of E , r was recalculated and then E recalculated, rapidly achieving convergence. Iterative methods to evaluate evaporation have been described by Budyko (1956) but were only used to find the temperature at the evaporating surface, rather than as used here in the evaluation of both runoff coefficient and evaporation.

The principal outputs from this stage are the set of E values for the intervals, the average seasonal variation of lake

evaporation, the average value of r , and hindcast time series of daily evaporation, runoff, and water level, supported by edited time series of water level, solar radiation, and rain gauge data.

Check of Evaporation Using Thermodynamic Balance

Solar irradiation is now routinely available from satellite observations (BoM, 2023). Most of the evaporation formulas based on solar radiation require water surface temperature and back radiation. Such data are rarely available but the conduction and back radiation terms in the thermodynamic heat balance are loosely correlated with the incident solar radiation. These factors led to the choice of a simple correlation of evaporation and incident solar radiation. A record of solar radiation for the 20 years was available for the nearby coastal station of Batemans Bay (12 km south) and the more distant Ulladulla (37 km north). The two records were highly correlated. Until late 2001, the limited satellite data resulted in frequently missed daily records, but thereafter, gaps were fewer. The Batemans Bay record was used, with gaps filled from the Ulladulla record using seasonal correlation coefficients. The evaporation calculated from the water balance was plotted against the daily total incident solar radiation, averaged over each of the calculation intervals, to yield the solar radiation-evaporation formula for each ICOLL.

Results

Water Balance

Water Level Hindcasts

The computed evaporation and catchment inflow were used to hindcast the volume of water in Durras Lake for each closure period of the 20 years of record. The average value of the runoff coefficient, r , was found to be 0.10 (Hinwood & McLean, 2022). The volumes have been calculated from the measured volume at the start of each closed period. The hindcast and measured lake volumes are compared in Fig. 3a.

Although there are differences, the overall hindcasts are satisfactory for management. To better assess the reliability of the hindcasts, a closer look is required and is given for two periods of closure in Fig. 4. The high accuracy of the daily evaporation hindcasts is shown by the parallel slopes of the “measured” and “this study” lines for the periods between rainfalls, when evaporation was the only significant process causing volume change. Both the complete record and the expanded plots show that the hindcast volume changes for rainfalls were accurate overall but frequently

Fig. 3 **a** Measured and hindcast water volume in Durras Lake. **b** Daily volume inflow to Durras Lake from direct rainfall

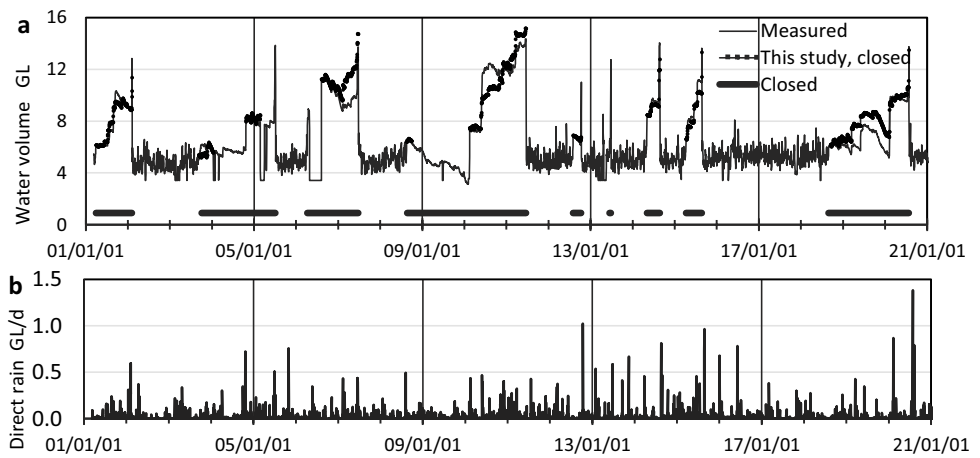
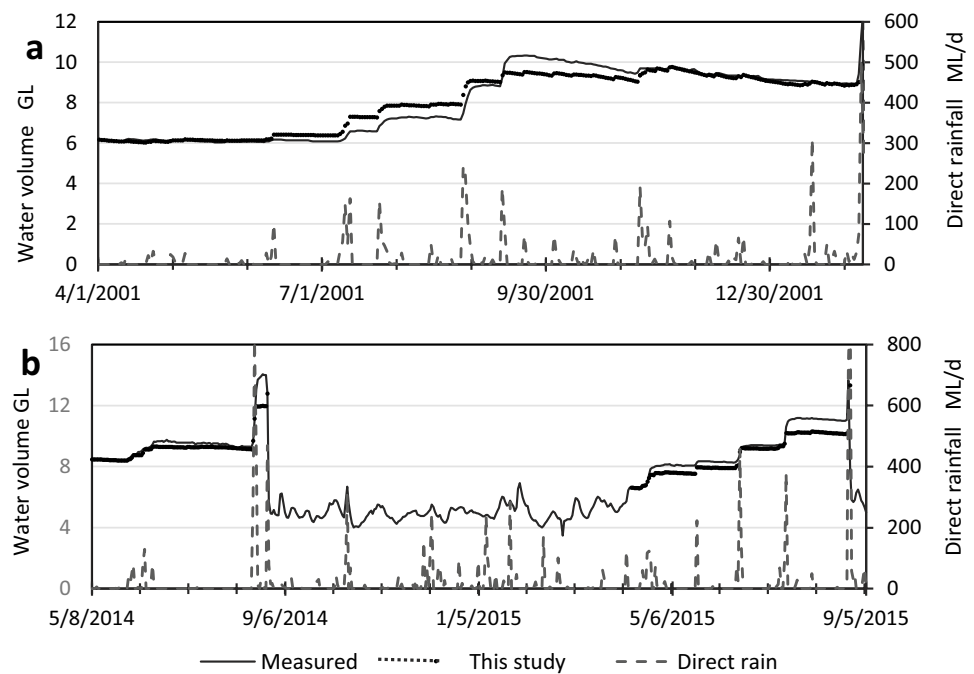


Fig. 4 **a, b** Comparisons of measured and hindcast volumes in Durras Lake. Note the slopes of the short line segments between rainfalls (US date format)



over or under-predicted the volume changes for a moderate to large rainfall event.

Comparable accuracy was attained for Lake Wollumboola although comparisons were more restricted by small data gaps. The entrance to Lake Wollumboola was normally closed—approximately 86% of the time over the 20 years, with a further 6% nearly closed and in the spilling/overtopping regime. The entrance berm was breached six times, compared with 12 for Durras Lake, and the subsequent tidal regime was very attenuated and lasted only a few months.

Mass Balances

The use of cumulative or mass balances is well established as an aid in applying water balances and managing lake

water level impacts. The mass inflows evaluated here are direct rainfall, catchment runoff, and evaporation, the last being treated as a negative inflow. Mass balances for these three inflows for the two longest closure intervals of Durras Lake are shown in Fig. 5a, b. The fourth curve, the sum of direct rainfall and catchment inflow, may be compared with the evaporation to see the net inflow to the lake. Each record is terminated by a high rainfall event that caused a berm breach. By coincidence, each of the two intervals had a high rainfall event near mid-record that failed to cause a breach. The importance of infrequent very high rainfall events is evident; other trends and effects are detailed in the “Discussion.” The Lake Wollumboola record (Fig. 5c) also contains a high rainfall event on 4–6 Aug 2007, which was both preceded and followed by moderately high rainfalls

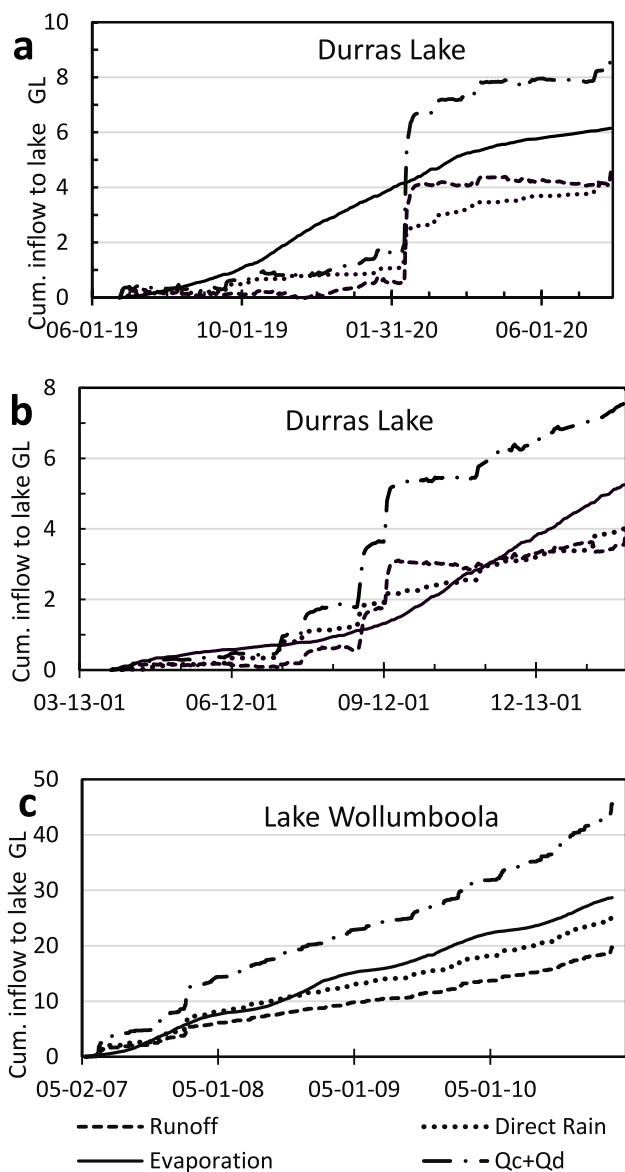


Fig. 5 Mass curves of cumulative inflows to lake (evaporation is a negative inflow) in the longest closure intervals in the respective water level records. **a, b** Durras Lake. **c** Lake Wollumboola. Net inflow to the lake occurs if $Q_c + Q_d > Q_e$

within a few days. These combined events caused relatively little change in inflows and lake storage volume, but note the different scale of Fig. 5c.

Evaporation

Seasonal Evaporation From Water Balance

These intervals selected for the determination of evaporation were of duration at least 15 days, and preferably 25–45, with low rainfall. The criterion of Eq. (9) ensured that the uncertainty in the runoff coefficient did not introduce errors as

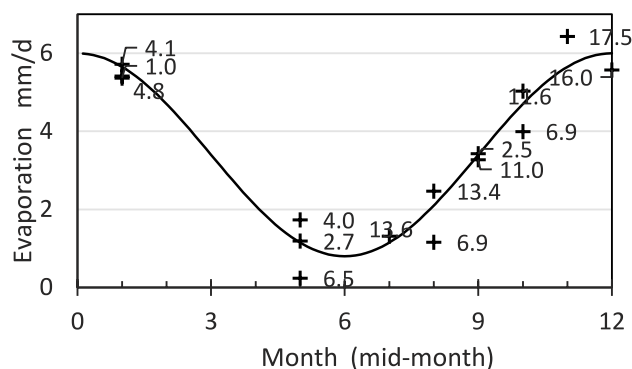


Fig. 6 Durras Lake, evaporation from the water balance (+), fitted by Eq. (10); labels show prior 5-day rain has no correlation

large as the uncertainties arising from possible errors in the data. The intermittent opening and closure of the entrance to the lakes broke up the periods of closure and limited the number of intervals suitable for the determination of the evaporation. The selected intervals include several from each season and cover the expected range of values of the evaporation and solar radiation. The seasons apply to the southern hemisphere with winter months occurring mid-year. The strong seasonal variation in Durras Lake is shown in Fig. 6, fitted by Eq. (10). The abscissa is the calendar month of the mid-point of each record interval, on average the 15th of the month; use of Julian day slightly reduced the scatter but we have retained the monthly representation as being more familiar; note that the best fit had zero phase shift.

$$E = 3.4 + 2.6\cos(2\pi m/12) \tag{10}$$

where m is the date in months for which the evaporation is required, and the relationship has the excellent statistics $t=3.49$, $p=0.00326$, and 95% confidence interval = 0.264.

Equation (10) accounts for 94% of the variance of E . To account for the remaining variation in E , as there were insufficient data points for a multi-variate regression or other large-data techniques, labels were added to the points as shown in Fig. 6. Seven such plots were used to test:

- prior 5-day rain
- prior 10-day rain
- total rain during the measurement interval
- localised rain, recorded at one station rather than the weighted value
- length of interval
- presence/absence of strong wind in interval
- fraction of no-rain days in the interval

Figure 6, which is an example plot for one of the seven independent variables, examines the possibility that prior

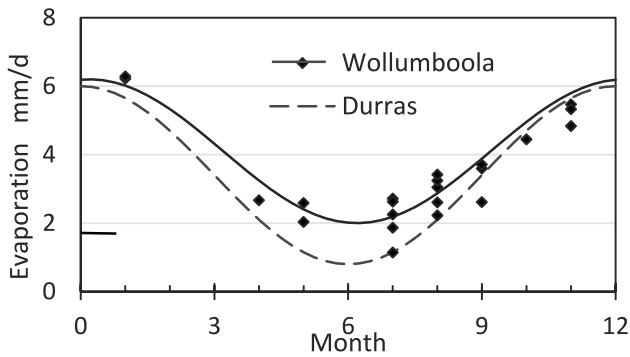


Fig. 7 Evaporation from Lake Wollumboola, from the water balance, fitted by Eq. (11)

rainfall was correlated with the residuals but shows that it was not. None of the seven was correlated.

The same method was applied to Lake Wollumboola, yielding the seasonal evaporation curve plotted in Fig. 7 and fitted by Eq. (11). The intervals of the water level record that were suitable for analysis were spread over the year but with fewer in summer than the other seasons. The curve is similar to that for Durras Lake although scatter is somewhat larger than for Durras and shows higher values of evaporation throughout most of the year; these differences are discussed in Sect. 4. Again, no phase adjustment was required for best fit.

$$E = 3.8 + 2.0\cos(2\pi m/12) \tag{11}$$

For Lake Wollumboola, the water level changes were small and the water level was subject to significant fluctuations, presumably due to the effect of variable winds acting on the large shallow water body, potentially causing an error in r and subsequently in E . The potential error in E may be found using Eq. (S4). It will be largest for a short data analysis interval. Using the shortest interval, 27 days, and taking the random error in water level as $dy=5$ mm, the worst case error in E from this cause is a negligible 0.2 mm/day. A persistent strong wind acting on the lake surface could create a larger water level change at the sole recorder, leading to a larger error.

Evaporation-Solar Correlations

The correlation between evaporation and incident solar radiation is shown in Fig. 8a and was fitted by Eq. (12). The linear trend line accounts for 94% of the variance in the calculated evaporation. The linear relationship has the convincing statistics $t=3.51$, $p=0.0032$, and 95% confidence interval=0.253.

$$E = -1.774 + 0.289S \tag{12}$$

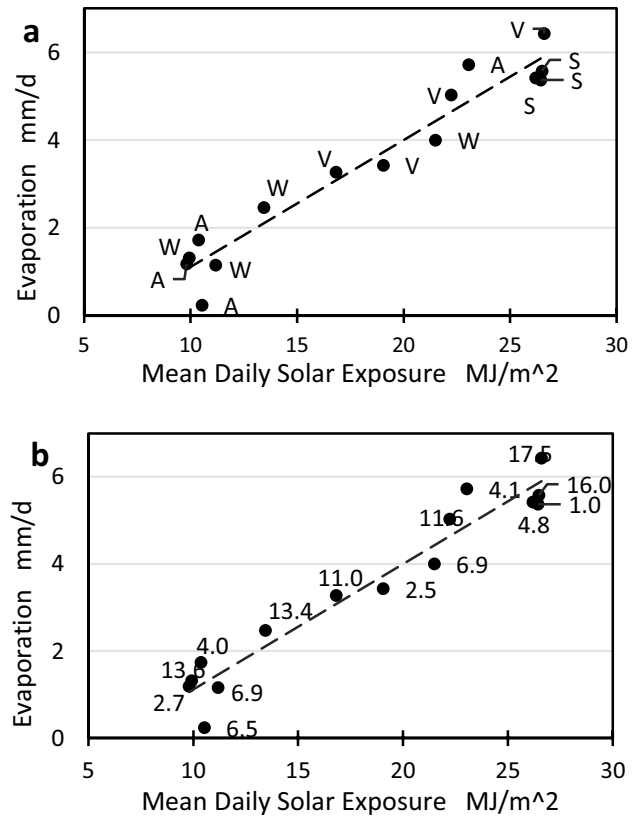


Fig. 8 Evaporation v incident solar radiation for Durras Lake. **a** Labels are season: A: autumn, W: winter, V: spring, S: summer, showing scatter is not seasonal. **b** Labels are prior 5-day rain (mm), showing that scatter is not due to prior rain

The seasonal variation shown in Figs. 6 and 7 suggested that some of the scatter might be seasonal, but as Fig. 8a shows, that was not the case. As was done with the seasonal plots, a wide range of possible influences leading to the scatter was examined, without any showing correlation, Fig. 8b being typical.

The dependence of the evaporation on the incident solar radiation for Lake Wollumboola is shown in Fig. 9: Eq. (13) is the equation for the linear trend line, with an $R^2=0.90$. It has virtually the same slope as the trend line for Durras Lake but a significantly larger intercept:

$$E = -0.816 + 0.275S \tag{13}$$

For this very different ICOLL, the method outlined has yielded a reliable averaged plot of seasonal evaporation (Fig. 7) and a practical correlation of the daily evaporation with incident solar radiation (Fig. 9).

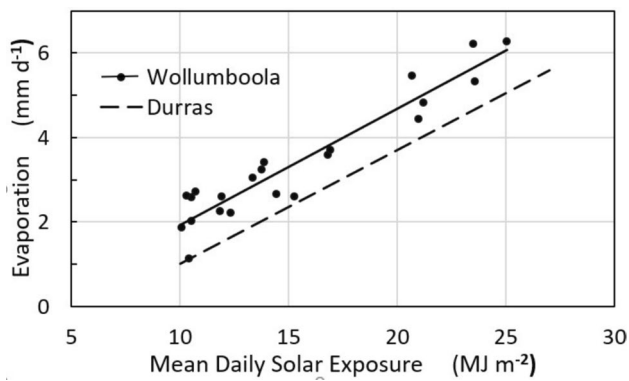


Fig. 9 Correlation of evaporation from the water balance and incident solar radiation for Lake Wollumboola, fitted by Eq. (13), and comparison with Durras Lake (Eq. (11))

Discussion

Water Balance

Appraisal of Method and Results

The calculated water balances provided hindcasts of the lake water volumes and levels in general agreement with the measured levels. In particular, the higher water levels, of importance for local flooding and berm breaching, were accurately predicted. The water balance comparisons with measured water levels show that the methods are suitable for management purposes. Response to some rainfall events was not accurately modelled but no correlation with available physical factors was found.

The mass balance, or cumulative inflow plots, proved a convenient and effective way of visualising the relative importance of the different inputs and the events that affected these inputs. A notable feature of the Durras Lake record is the major impact of high rainfall storms lasting 1–3 days, seen near the midpoint of Figs. 4a, b. These storms may occur at any time of the year at intervals of a few months to a couple of years. The impact of these rainfall events was less in Lake Wollumboola with catchment flow consistently smaller than either direct rainfall or evaporation, due to the relatively small catchment area to lake area ratio. In the absence of storms, the evaporation from the lake was shown to be generally slightly larger than either the catchment inflow or the direct rainfall, which shows the importance of accurately determining evaporation. As the evaporation was usually, but not always, less than the sum of catchment flow and direct rainfall, it may be deduced that both lakes tend to have falling water storage levels, but during and soon after a brief high rainfall event, the storage levels will rise and entrance breaching is likely. The data show, as expected, that attaining a breaching level depends

on the antecedent storage level in addition to the magnitude of the rainfall and also show that a long rainy season may not attain a breaching level due to the longer period available for evaporation in such a season.

Evaporation

Seasonal Evaporation

A well-defined seasonal cycle of evaporation was found in both lakes. The seasonal curves are of value to the estuary manager in assessing water budget. The evaporation cycles correlated in magnitude and phase with the seasonal cycle of solar radiation. The best fit curves for evaporation did not show a phase lag with respect to the solar cycle, whereas the long-term average air temperatures from Batemans Bay show an approximately 2-month lag, as is typical in this region. These facts provide strong independent support for the use of the simple correlation of evaporation and solar irradiation used here.

Comparison of Lake Wollumboola and Durras Lake Results

The evaporation and solar radiation correlations for Durras Lake and Lake Wollumboola (Fig. 5) have small scatter and almost the same slope, but Lake Wollumboola has uniformly higher evaporation. The seasonal curve of evaporation in Lake Wollumboola was similar to that of Durras Lake (Fig. 7), but evaporation was higher in winter although most meteorological data are similar for the two sites. These differences are believed to be due to the high productivity of submarine vegetation and occasional turbid plumes in Lake Wollumboola (see “Lakes Durras and Wollumboola”). These factors have been shown to reduce the albedo, thus increasing the solar energy available for evaporation. None of these conditions has been observed in Durras Lake.

It is also possible that these differences could result from an error in the data or analyses. The lake volume change depends on the water level, but the test developed in the Online Resource has shown that the likely effect is very small. Other tests have shown that the effect of possible errors in the runoff coefficient have little effect on the catchment inflows, mainly due to careful selection of the time intervals used in the calculations. An error related to the magnitude of a variable would show up as a dependence of the evaporation on the erroneous variable, so additional checks were made, as detailed in “Water Balance,” but no correlations were detected. Thus, errors in the data and analyses are most unlikely to be the cause.

Finally, considering the possibility that the difference resulted from omission of some factors in the analysis, groundwater flows were omitted, and the differences could be explained either by groundwater outflows from Lake

Wollumboola or inflows to Durras Lake. Groundwater outflows for Lake Wollumboola have not been reported; on the contrary, Scanes et al. (2014) have reported small inflows. Groundwater inflows to Durras Lake have been observed by the authors at the base of cliffs fronting the beach berm following rainfall, but the magnitudes were far too small to have a detectable effect. Therefore, it seems probable that Lake Wollumboola does experience higher evaporation as observed in the results, caused by conditions leading to a lowered albedo, and hence increased solar energy available for evaporation.

Limited data on water level were available for two other ICOLLs in the study area: Lakes Brou and Mummaga. The authors had deployed portable pressure recorders near the bed of both lakes for the period March 2018 to March 2019. Lake Mummaga was in closed regimes for the final 5 months, while Lake Brou was closed for the whole period, except for a brief period midway through the record. The records from both lakes were very noisy due to wave action and possibly vibration of the recorder mountings, which resulted in only two useable intervals from Lake Mummaga and five from Lake Brou. All of the Lake Brou points lay within the spread of the Lake Wollumboola data, and above the Durras Lake seasonal curve. The two Lake Mummaga points straddled the Durras Lake seasonal curve but with more spread. Hypsometric curves were not available for either lake so the values of A_b were held constant at the value from OzEstuaries (2010). In view of these limitations, the datasets for Lakes Brou and Mummaga may be said to give results consistent with those for Lakes Durras and Wollumboola but indicate that longer water level records and surveyed hypsometry are required to establish the empirical constants in the formulas for runoff and evaporation.

Comparison with Published Formulas

The evaporation and solar radiation results for both lakes are compared with the equations of Makkink (1957) and Priestley and Taylor (1972) in Fig. 10. The results agree with the Makkink formula at moderate to high values of solar radiation but appear to show that Makkink overpredicts at low values. The Priestley–Taylor formula (Eq. (6)) predicts much larger evaporation. It uses net solar radiation, which has been evaluated here as $0.744S$, based on data in Tables 7 and 11 in Richardson (1930). A very close match to the Makkink relationship, and a closer fit to this study, is given by changing the factor to 0.475 or equivalently to changing the Priestley–Taylor α from 1.26 to 0.804. This discrepancy may be due to uncertainty in the value of the back radiation; the neglect of the heat loss, G in Eq. (6), is unlikely to account for a change of this size but could contribute at low values of irradiation.

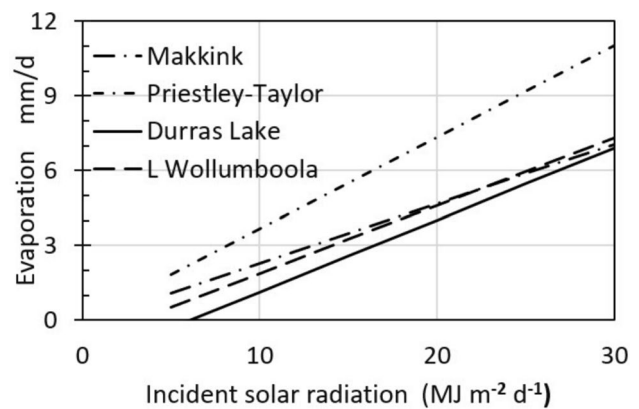


Fig. 10 Comparison of calculated evaporation with the Makkink and Priestley–Taylor formulas

The relationships between evaporation and solar radiation shown in Figs. 7 and 8 do not take account of air temperature since the primary dependence of evaporation from shallow water bodies on the incident solar radiation is well established, particularly for long term averages, and the effect of the incoming humidity is local (Cummings, 1921; Cummings & Richardson, 1927; Richardson, 1930; Budyko, 1956; McMahon et al., 2013). Richardson (1931), Makkink (1957), and Priestley and Taylor (1972) found the same for small lakes and pans as discussed in “Available Methods of Estimating Open Water Evaporation.” They retained the term $\Delta/(\Delta + \gamma)$, which takes the values 0.83/0.91/0.97 for lake surface temperatures of 5/10/35 °C (Gad & El-Gayar, 2010). Near-surface temperature data are scarce for the Australian ICOLLs, but 1 year of records from Lake Wollumboola and nearby Lakes Brou and Mummaga had temperature ranges of 10–32 °C (occasional lower temperatures are likely), limiting the scatter from neglect of this term to less than 5%.

The very low evaporation under low solar radiation ($< 5 \text{ MJ/m}^2/\text{day}$) may indicate that one or more of the following assumptions is in error:

- ground water inflow is negligible;
- heat loss to the lake water and ultimately to the lake bed is negligible;
- heat loss to the atmosphere is proportional to the incident solar radiation.

These assumptions have been discussed above and appear reasonable; however, the direct measurements required for a conclusive proof are not available. This issue does not invalidate the method or the specific results obtained here.

Conclusions

For these very small estuaries, routinely available data are very limited, in particular nothing on catchment flows, unrepresentative regional averages for evaporation, and frequently no rain gauges actually in the catchment. Novel procedures were developed to overcome these data deficiencies, as follows:

- Rainfalls from catchment and nearby rain gauges were analysed for correlations and representative lake and catchment rainfall data series obtained.
- Trial catchment flows were obtained using correlations with rainfalls to deduce simple rainfall–runoff relations.
- Lake evaporation was calculated using the water balance.
- The coefficients in the rainfall–runoff relation and hence in the evaporation were then optimised by iteration.
- The consistency of the calculated evaporation was then independently checked by correlating it with the solar radiation; this furnished an independent predictor of the evaporation.

For both Durras Lake and Lake Wollumboola, water balances have been performed using only publicly available data. For both ICOLLS, mass balance plots obtained from the water balances have shown that direct evaporation from the lake water surface is comparable or slightly greater than either of the two principal inflows: direct rainfall on the lake surface and net catchment runoff. The evaporation is less than the sum of the inflows, and these relative magnitudes are drivers of the intermittency of each ICOLL.

For each ICOLL, a robust linear correlation of lake evaporation with the incident solar radiation accounted for 94% of the variance in the evaporation. Validation of the water balances using the evaporation–solar correlation and a derived runoff coefficient is provided by the close match with the historical record. The calculated evaporation was compared with the predictions of the formulas of Priestley and Taylor (1972) (P–T) and Makkink (1957). The formula of Makkink lay within the spread of data for Lake Wollumboola, and slightly above the data for Durras Lake. The P–T formula lay well above the data, very likely due to inaccurate estimation of the back radiation, which P–T requires but is not available. The P–T formula achieved a close match to the data if the empirical constant, α , was given the unusually low value of 0.475.

The seasonal variation of evaporation fitted a cosine curve, again accounting for 94% of the variance of the evaporation. The seasonal curve of evaporation of Lake Wollumboola was similar to that of Durras Lake, but evaporation was higher in winter. The evaporation was higher for all values of incident solar radiation, believed to be caused by vegetation and turbidity in the more extensive shallows of

Lake Wollumboola trapping more radiation. The seasonal curve is essential for the management of ICOLLS where local flooding and water quality issues must be controlled, and where entrance bar breaching is anticipated or assisted.

Application of the method to other ICOLLS with only short water level records gave evaporation values consistent with those of lakes Durras and Wollumboola, but insufficient data points to establish specific correlations, suggesting that about 3 years of water level data with a closed entrance are required. It is likely that a denser network using recording rain gauges would be required to reduce scatter of results. For both correlations, the scatter of results was comparable with other published studies and could not be accounted for using any combinations of the available physical data.

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Author Contribution The project was conceived by the first two authors. The third author brought significant additional expertise and contributed to the aims and scope being modified. The first draft was prepared by the first author with all authors contributing to checking, revisions, amendments, and additions.

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Data Availability As stated in this paper, the data used are publicly available at the discretion of the owners of the data.

Declarations

Conflict of Interest The authors declare no competing interests.

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