CHAPTER
8

THERMAL BALANCE

8.0 INTRODUCTION

In this chapter thermal balance concepts are introduced and thermal balance data for Perry Lake East is presented. A technique for determining the difficult to measure sediment term *Qse* is developed and its importance in estimating evaporation by thermal balance discussed. This is expanded in Chapter 9.

A thermal balance relies on the measurement of all sources of incoming and outgoing thermal energy plus changes in energy storage. It is considered to be one of the most accurate methods for estimating evaporation from a water body when integrated over long periods of time (Harbeck *et al* 1958, Winter 1981). In such studies all thermal terms are measured except evaporation. The residual in the balance is then considered to be the heat used to evaporate water. In many studies however, heat advected in the difficult to measure ground water components (discharge into the lake and recharge from the lake back to the aquifer) are either ignored or poorly estimated. Sturrock *et al* (1992) noted that 'the importance to the heat budget of groundwater flux to and from lakes has not been evaluated at all'. Likewise heat conducted from the lake into the sediments and from the sediments back into the water column has been generally ignored. Heat flux from sediments can comprise a significant source of heat to the water (Geiger 1965). Hughes (1967) noted that the importance to a lake energy budget of heat flux to and from the sediments had been addressed in only a few studies.

At East Lake evaporation was measured directly by floating pan. Likewise groundwater components were independently measured and their temperature throughout the year well documented (Chapter 9). Therefore heat used for evaporation and heat transported via groundwater were known. The thermal contribution of the lake sediments could then be estimated as the balance residual.

In most studies where it has been addressed, the sediment term has represented a very small component of the energy balance. At Pretty Lake (Indiana) Ficke (1972) concluded that bed conduction was seasonally important but did not include it in the final balance. In extensive studies at Perch Lake (Ontario) Robertson & Barry (1985) considered bed conduction to be insignificant. At Williams Lake (Minnesota) Sturrock *et al* (1992) found that bed conduction varied seasonally and reduced calculated evaporation by 2-7%. All of the lakes in these surveys are located in glacial clay till aquifers and all appear to function as flow through lakes. Also these lakes were much deeper than Perry Lakes with well defined temperature stratification. Their temperature at depth changed very slowly and the sediments did not receive direct solar radiation. Perry Lakes are the exact opposite. They are very shallow and always well mixed. In very shallow water bodies much of the daytime radiation absorbed by the water is conducted to the underlying sediments and at night both the water and sediments may release sufficient heat energy not only to offset the net long-wave radiative loss at the surface but also to support continued evaporation throughout the night (Oke 1987, p103). Ficke (1972) found that 50% of thermal energy transfer was occurring in the top metre of sediment, but effects were still measurable below 5.3m. We believed that the excessive short term area/volume changes experienced in East Lake would render the sediment thermal effects extremely difficult to quantify directly, further substantiating the case for a thermal balance.

Jacobs *et al* (1998) applied simple models to study thermal regimes within a standard Class A evaporation pan. The principal characteristics of such pans are similar to a small very shallow lake where the water generally remains well mixed. During the day incoming short wave radiation is the driving force. This is absorbed at the surface, within the water column, and on the upper sediments. At the water surface long wave radiation (incoming and outgoing) and sensible and latent heat exchange processes take place. Wind mixing in very shallow water largely precludes stratification. At night under calm conditions, long wave radiative cooling at the water surface becomes the driving force. As the surface layer cools, its density increases. Over the night this mixing layer descends and continues to decrease in temperature retaining a generally well mixed water column. Pilot investigations confirmed that the sediments have large diurnal temperature cycles and may be either warmer or cooler than the water column. This was first noticed while wading barefoot in sediments that were noticeably warmer than the water column. This led directly to the hypothesis that in very shallow lakes sediments may act diurnally as both heat sinks and heat sources. The net daily sediment heat flux could be positive (net heat flux into the water column), or negative (net heat flux into the sediments). Taking into account the seasonal changes in flow regime, the hypothesis was expanded to include net seasonal changes in flux direction.

Measurement of the sediment term is potentially very difficult and can be achieved at varying levels of accuracy. Chapter 9 includes an expanded discussion on methodology and the significance of sediment heat regimes in the study of wetland flow regimes. As the sediment term was to be determined as the balance residual it was crucial that all other components of the thermal balance were determined as accurately as possible.

8.1 THEORY AND METHOD

The thermal balance or heat budget method is described by Anderson (1954 a&b), Harbeck *et al* (1958), Harbeck *et al* (1959), Hughes (1967), Ficke (1972), Sturrock *et al* (1992). These describe large government funded studies on reservoirs and lakes in the United States. In Australia thermal balance studies have also been completed on a number of large lakes and reservoirs including Mundaring near Perth (Hoy & Stephens 1979).

A thermal balance relates net energy transfer into and out of a water body to changes in stored energy and takes the general form:

Sensible and latent heat lost from the lake surface = Net incoming radiation + Net heat transport through other surfaces - Change in stored heat

At Perry Lakes this was expanded, taking the form:

$$E = \frac{(Q_s - Q_{sr} + Q_a - Q_{ar} - Q_{bs}) + (Q_{rn} + Q_{sd} + Q_{tu}) + (Q_{dc} - Q_{rc} + Q_{se}) - Q_x}{\rho[L(1 + R) + c(T_e - T_b)]} \qquad (8.1)$$

where

Q_s	incoming short wave radiation
Q_{sr}	reflected short wave radiation
Q_a	incoming long wave radiation
Q_{ar}	reflected long wave radiation
Q_{bs}	long wave radiation emitted from the water
Q_{rn}	heat in rain falling directly on the lake
Q_{sd}	heat in storm drain flows
Q_{tu}	heat in summer top up water
Q_{dc}	heat in groundwater discharged to the lake
Q_{rc}	heat in lake water recharged to the aquifer
Q_{se}	heat conducted into and out of the lake sediments
Q_x	change in heat energy stored in the lake
ρ	density of evaporated water at surface water temperature T_o
L	latent heat of evaporation of water
R	Bowen ratio, dimensionless (sensible heat flux Q_h / latent heat flux Q_e)
c	specific heat of water at surface water temperature T_o
T_e	temperature of the evaporated water, taken as equal to surface water temperature
T_o	see below
T_b	arbitrary base temperature set to 0°C, therefore (T_e-T_b = T_o)

The denominator derives from a compositing of the non-radiative surface heat loss terms which cannot be measured directly:

Q_e	energy used for evaporation = ρEL	(8.2)
Q_h	energy conducted from the water as sensible heat = RQ_e	(8.3)
Q_w	energy advected from the water body via evaporated water = $\rho cE(T_e - T_b)$	(8.4)

Computational Notes:

The brackets in (8.1) group (solar radiation), (surface flows), (groundwater flows) and (storage) terms. It is standard practice to express heat budget terms in watts m^{-2} *(*$W\ m^{-2}$*).*
For computational purposes all terms in the numerator of (8.1) were expressed as Megajoules $day^{-1}\ m^{-2}$ *and the denominator in Megajoules* $day^{-1}\ m^{-3}$ *yielding evaporation E in metres. Refer Appendix 8.1.*

8.2 DETERMINATION OF THERMAL BUDGET TERMS

8.2.1 Incoming short and long wave radiation Q_s & Q_a

Incoming short wave radiation Q_s and long wave radiation Q_a were measured at the Swanbourne automatic weather station (AWS) site using a Middleton model CN9 short wave pyranometer and Eppley model PIR long wave pyrgeometer. Both instruments were calibrated in the Bureau of Meteorology laboratories prior to installation. Outputs were amplified 100x and 200x respectively using calibrated Carter-Scott amplifiers (refer Appendix 8.2 for instrument specifications). Instrumentation was installed and monitored specifically for this study by the Department of the Environment (DEP). The data sampling rate for both instruments was 1 second, stored in a data logger as 10 minute averages. Swanbourne AWS is 3km southwest of Perry Lakes. Experiments by Rosenberry *et al* (1993) indicate that solar radiation measured up to 100km distant from a study lake may only present a 2-3% change in annual calculated evaporation. Siting the solar instrumentation at Swanbourne was considered to introduce negligible error.

No long wave data was recorded over the period 15:00 hr August 8 to 12:00 hr August 13 1997 due to instrument malfunction. Data for the week preceding instrument failure was also suspect. Long wave radiation over this period was estimated using the Brunt (1944) equation where the atmosphere is treated as a grey body and using Stefan's law, the only variable becomes air temperature:

$$\frac{Q_a}{\sigma T_a^4} = c + d\sqrt{e_a} \qquad (8.5)$$

where

Q_a	incoming long wave radiation
σ	Stefan Boltzmann constant
T_a	air temperature °K
c & d	constants
e_a	vapour pressure of the air

Equation (8.5) was applied as modified by Koberg (1964) where *c* (cloud factor) is determined from a family of curves defining the ratio of measured Q_s to theoretical Q_s adjusted for day, latitude and air temperature and *d* is taken as 0.0263 (as determined by Anderson 1954a).

8.2.2 Reflected short and long wave radiation Q_{sr} & Q_{ar}

Reflected short wave radiation Q_{sr} was calculated using the method of Anderson (1954a) as modified by Koberg (1964). Koberg presented a family of curves defining the relationship (in cal cm^{-2} day^{-1}) between incoming and reflected radiation for clear sky (<20% cloud) and cloudy sky (>20% cloud). Polynomial expressions were developed describing these relationships in watts m^{-2} allowing clear sky and cloudy sky Q_{sr} to be calculated directly from daily averaged Q_s. Final value used was the average of expressions developed for clear and cloudy sky (<20% cloud and >80% cloud). Details in Figure 8.2c.

Reflected long wave radiation Q_{ar} was calculated as 3% of incoming long wave radiation as determined by Gier & Dunkle cited Anderson (1954a).

8.2.3 Emitted long wave radiation Q_{bs}

Long wave radiation emitted from the water surface Q_{bs} follows the Stephan-Boltzman fourth power law (Monteith & Unsworth 1990 p25):

$$Q_{bs} = \varepsilon \sigma T_o^4 \qquad (8.6)$$

where

ε emissivity of the surface, taken as 0.97, dimensionless (Sturrock *et al* 1992)

σ Stefan-Boltzman constant 5.67×10^{-8} W m^{-2} $°K^{-4}$ s^{-1}

T_o water surface temperature in degrees Kelvin

8.2.4 Change in stored heat energy Q_x

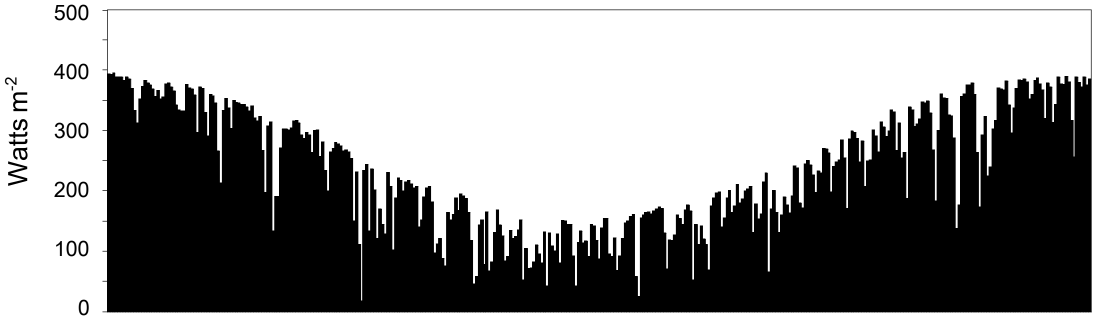
Thermal balance studies of large lakes and reservoirs typically measure the change in stored energy by extensive periodic manual surveys (Table 8.1). East Lake is extremely small. At a mean annual stage (1997) of 3.18m it has an average surface area of only 38600m^2 (3.86ha) and a volume of 7975m^3. Mean annual depth is 0.2m and maximum depth over the survey period was always <1m. Lake size is a principal determinant of acceptable balance period. In large lakes Q_x, the change in thermal energy stored in the water body (as indicated by water temperature) may be small compared to measurement error. Therefore minimum balance periods of 2-3 weeks are recommended (AWRC 1970). In smaller lakes such as East Lake, short term changes in Q_x may be quite large in

Thermal Balance Components

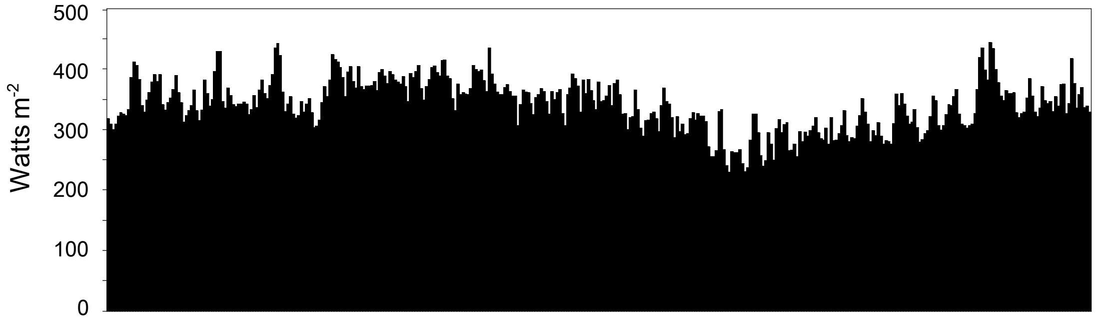
Dec 22 1996 - Jan 3 1998

Figure 8.1

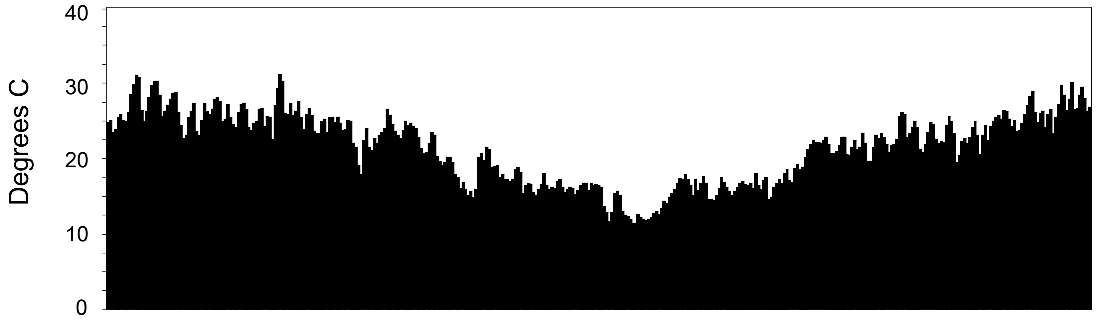
A Incoming Short Wave Radiation Qs 08:00 hr - 08:00 hr
Sampled every second, daily average of 86,400 readings



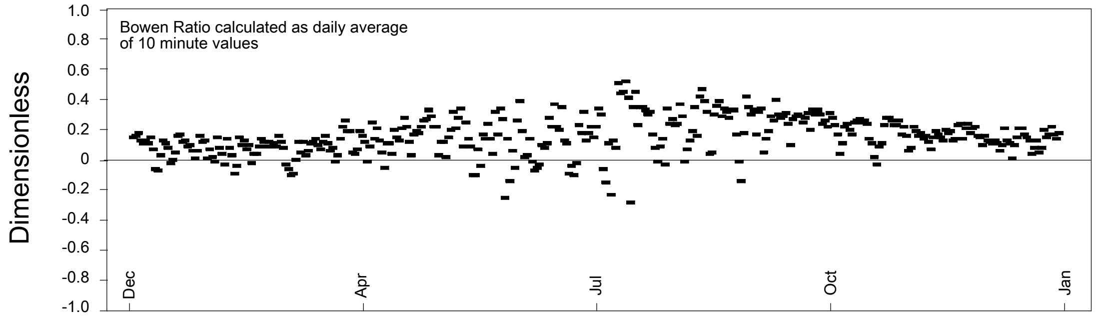
B Incoming Long Wave Radiation Qa 08:00 hr - 08:00 hr
Sampled every second, daily average of 86,400 readings



C Daily Average Lake Surface Temperature 08:00 hr - 08:00 hr
Average of 10 minute data



D Daily Average Bowen Ratio 08:00 hr - 08:00 hr



comparison to measurement error and shorter balance periods are feasible. At East Lake daily thermal balances were achieved.

Table 8.1 Determination of *Qx*

Study	Ref	Area (ha)	Av D (m)	Determination of *Qx*	Frequency
Salton Sea (California)	1	89000	8.3	35 profiles, 0.6 & 1.2m layers	10-29 days
Lake Mead (Nevada)	2	63900	55.8	30 profiles, 5m layers	30 days
Lake Hefner (Oklahoma)	3	1050	9.6	16 profiles, no layer data	10 days
Rifle Creek Reservoir (Qld)	4	190	5.0	5 profiles, 0.9m layers	30 days
Lake Wyangan (NSW)	4	98	2.0	5 profiles, 0.3m layers	30 days
Pretty Lake (Indiana)	5	74	7.8	24 profiles, 0.76m layers	7-56 days
Williams Lake (Minnesota)	6	36	5.2	16 profiles, no layer data	14 days
Blue Lagoon (Victoria)	4	13	3.5	5 profiles, 0.9 layers	21-112 days
Perry Lake East		3.8	<1	mid level temperature at 1 site	10 min, av daily

1: Hughes (1967), 2: Harbeck *et al* (1958), 3: Anderson (1954a), 4: Hoy & Stephens (1979), 5: Ficke (1972), 6: Sturrock *et al* (1992)

Surface, mid and bottom level temperature records (Chapter 9) confirm that the lake is almost always well mixed. The single mid level temperature recorded every 10 minutes was taken to be mean lake temperature at any given time. Even in a much larger (36ha) and deeper (mean 5.2m) lake, Rosenberry *et al* (1993) found that the use of one central temperature profile resulted in less than a 1% change in daily evaporation compared to profiles at 16 stations. The change in stored heat was calculated for each daily balance period using average mid level temperature at average volume and area minus the equivalent calculation for the previous day.

It is evident from Table 8.1 that Perry East is extremely small compared to other thermal balance sites. Harbeck (1954) provides criteria, summarised in Table 8.2 for judging the suitability of a lake for energy balance studies.

Table 8.2 Criteria for Energy Balance Studies

Mass Balance Components	Lake Form	Physiography
accuracy extremely importance	ideally circular	low surrounding relief
no bank storage	min 5x8km if not circular	small catchment
small transpirative losses	area>25km^2 & <125km^2	arid climate
accurate area:capacity curve	depth 80%>3m	long periods of low rainfall
advected components<<lake volume		unfrozen in winter

In addition Harbeck recommended that the error in the monthly difference between total surface and sub surface inflow and outflow including changes in storage should be less than 5% of the mean monthly evaporative loss. Overall it was considered that accurate evaporation figures could only be obtained from lakes where highly accurate mass balances could be guaranteed *i.e.* lakes with small or nil groundwater components and surface flows which were small compared to the lake volume and which could be accurately measured. Deep lakes were considered preferable because they implied a large volume relative to the surface flows and small changes in stored energy relative to the total. Early oceanic thermal balances (for example Sverdrup 1940) relied on yearly balance periods or water bodies within which the net advected energy was either negligible or constant.

Perry East satisfies none of these criteria. Surface flows and groundwater fluxes can comprise a large proportion of total volume. It is extremely shallow with a mean annual depth of only 0.2m. Hence diurnal heating and cooling produce large diurnal changes in stored heat energy. Despite this, by constructing highly accurate area capacity curves, accurately measuring all fluxes, and providing evaporation calibration data from daily floating pan measurements, useable thermal balances were compiled.

8.2.5 Heat advected in surface water *Qrn, Qsd & Qtu*

These terms include rain falling directly on the lake surface, storm water in drains and pumped summer level maintenance. A polynomial expression was developed to allow thermal capacity to be easily calculated for any given temperature (Figure 8.2a). Advected heat energy (in Mj m^{-3}) was calculated for all three terms and divided by the lake area at 08:00hr at the finish of each daily balance period. Compatibility with the solar energy terms required final conversion to Watts m^{-2} (Mj m^{-2} day^{-1} x 11.574).

Rainfall Qrn

Various methods have been used to estimate rain water temperature. These include mean daily dry bulb temperature (UNESCO 1984), wet bulb temperature (Harbeck *et al* 1958, Sturrock *et al* 1992) and flat plate radiometer temperature (Anderson 1954a). Raindrops fall at terminal velocities varying from about 3.3 to 9.8 m sec^{-1} for drop diameters of 0.8-4.0mm (Maidment 1993). Evaporation from the surface of the drop should cause its temperature to approach that of a wet bulb thermometer. Examination of wet and dry bulb screen temperatures and corresponding storm water temperatures suggested that the wet bulb temperature probably provides the best approximation of precipitation temperature. In Figure 8.2d (panels 1-3), wet and dry bulb temperatures are plotted with storm water temperatures for major late summer, mid winter and spring rain events. In late summer storm water is 2°-5° warmer than the wet bulb temperature. Here dry bulb temperature tracks the storm water temperature more closely (within 1°-2°) but always with the storm water warmer suggesting heating of the run-off on pavements and within the storm drain system. In winter (panel 2), the dry bulb temperature is variously warmer and cooler than the storm water. Wet bulb temperature however is consistently 1°-2° cooler than the storm water which reflects pipe and pavement heating. In spring, significant pavement heating is apparent with both wet and dry bulb temperatures 1°-5° cooler than the storm water.

Rainfall was read daily in standard funnel gauges. Therefore it was not directly evident when rain fell over the period. This was estimated by pro rating total 24 hour rainfall against hourly storm drain flow volumes. Rainfall thermal energy was calculated using corresponding average hourly wet bulb temperatures.

Storm water Qsd

Stormwater temperature was measured directly using continuously operating LM35 temperature sensors and data loggers in the East Main and Basketball drain sediment traps (Figure 5 1a). Up to April 15 1997, the East Main (EM) drain only was instrumented. Over this period temperatures measured in the EM drain were applied to all four drains. The Basketball (BB) drain temperatures were measured from April 16 onwards. Over this period BB temperatures were applied to the remaining unmonitored drains. There was typically a 1°-2° difference in the temperature of water flowing in the EM and BB drains (Figure 8.2d panels 1-3) but with no consistent pattern of one warmer than the other. This probably reflects different local storm intensity and pavement heating of run-off. Storm water thermal content was calculated by applying thermal capacity and temperature to the corresponding flow volume in each drain, integrated over two minutes.

Lake level maintenance Qtu

Groundwater extracted from bores screened close to the base of the superficial aquifer within Perry Lakes Reserve is consistently 20.5°-21.0°C. Variations as measured manually by laboratory thermometers at the north and south outlets reflect heating or cooling within the extensive shallow irrigation ring main system. Measurements were made opportunistically and varied from 19.9° to 21.5° (Figure 8.2b). Where temperature data was absent, average values of 20.8° (north outlet) and 20.7° (south outlet) were used.

8.2.6 Heat advected in groundwater discharge *Qdc*

Groundwater discharge into East Lake could only be calculated every four days using the integrated mass-solute-isotopic balance data (Chapter 6). The four day total was pro rated against daily apparent groundwater flux (Appendix 6.2) to estimate daily discharge. The temperature of discharged water was estimated from monthly temperature profiles in piezometer N3c (Figure 9.8b). The average of 1m measurements between the water table and 22m varied by less than 1°C over a year (19.35° to 20.25°).

8.2.7 Heat advected in lake water recharge *Qrc*

Lake water recharged to the aquifer was also calculated every four days from the integrated mass-solute-isotopic balances. Again the four day total was pro rated against daily apparent groundwater flux (Appendix 6.2) to estimate daily recharge. Recharge water temperature was taken to be the daily average (10 minute samples) mid level temperature from station HT5 in the centre of the South Basin (Figure 5.1a).

8.2 8 Heat conducted to and from the lake sediments *Qse*

Lake evaporation was measured independently using a floating Class A pan (Chapters 5 & 10). Heat conducted to and from the lake sediments (*Qse*) is the residual in the thermal balance where all other components have been measured independently, including evaporation. In equation (8.1), *E* was set equal to floating pan evaporation, yielding *Qse*.

8.3 BOWEN RATIO

The Bowen Ratio is the ratio of energy conducted to the air (as sensible heat) to the energy lost through evaporation and is given by Bowen (1926) as:

$$R = \frac{cP(T_o - T_a)}{1000(e_o - e_a)} \tag{8.7}$$

where

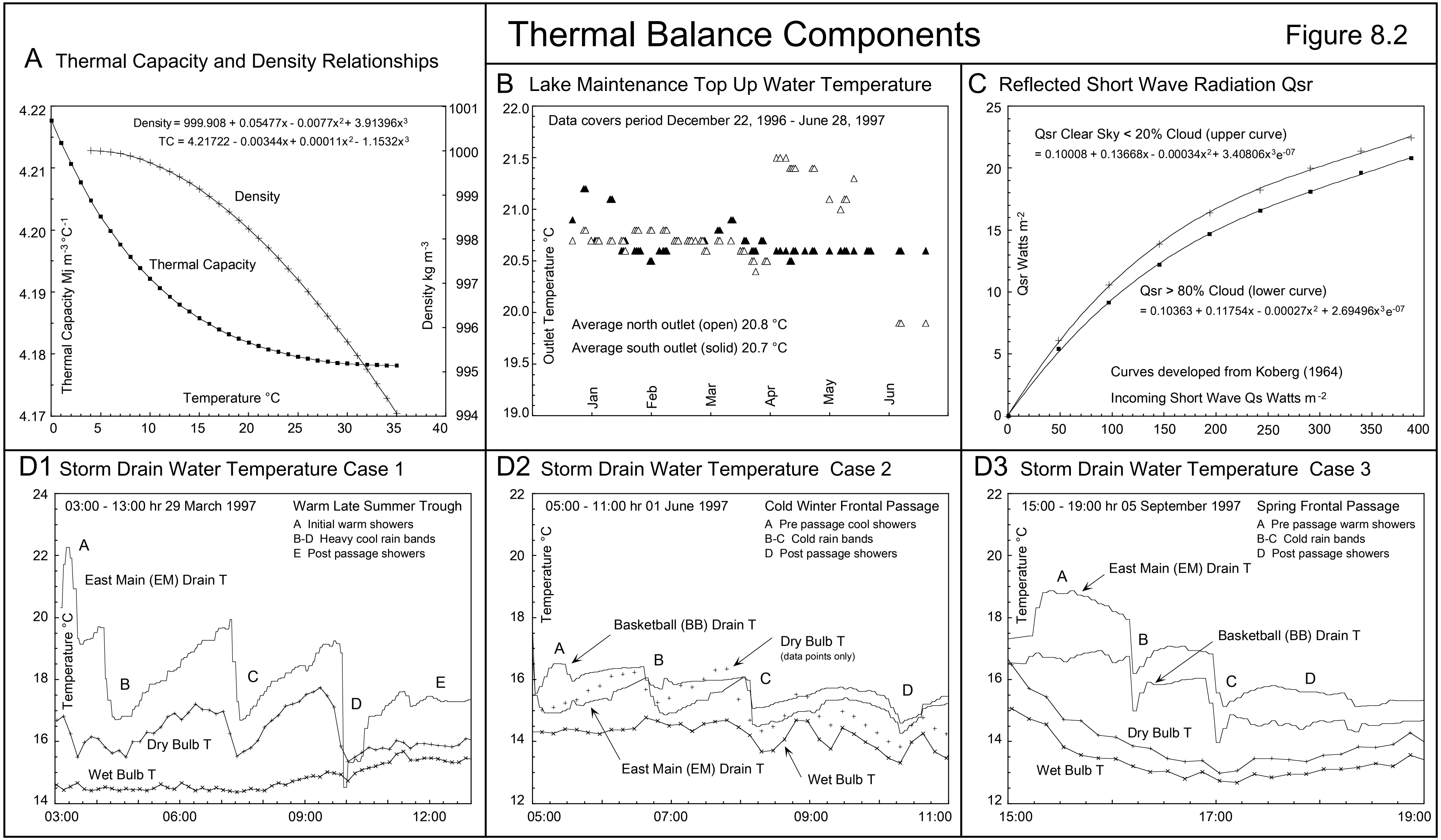
c	constant, generally taken to be 0.61
P	air pressure in mb
T_o	lake surface temperature
T_a	dry bulb air temperature
eo	saturated vapour pressure at the temperature of the water surface
e_a	vapour pressure of the air

Perry East Bowen Ratios were calculated every 10 minutes based on instantaneous T_o T_a e_o and e_a (measured at East Lake) and air pressure *P* measured by the Bureau of Meteorology at Mount Lawley and adjusted to mean sea level (Perry Lakes is only ± 3m ASL). Vapour pressure e_a was calculated from the relative humidity:

$$r = \frac{m}{m^*} \cong \frac{e}{e^*} \tag{8.8}$$

where

r	relative humidity
m, m^*	actual mixing ratio and mixing ratio in water vapour saturated air
e, e^*	actual vapour pressure and saturation vapour pressure at air temperature T



Thermal Balance Components Figure 8.2

Saturation vapour pressure was calculated using the expression of Richards (1971), cited Brutsaert (1982 eqn 3.24a):

$$e^* = 1013.25\,exp(13.3185t_R - 1.9760t_R^2 - 0.6445t_R^3 - 0.1299t_R^4 \tag{8.9}$$

where $t_R = 1 - (373.15 / T)$ in which T is the temperature in °K. The thermal balance used daily average R, calculated from the daily average of 10 minute ratios.

There is considerable discussion in the literature regarding the validity of the Bowen Ratio generally (Anderson 1954a, Ficke 1972, Angus & Watts 1984) and the value of the constant c, which has limits of 0.58 and 0.66 and is generally taken to be 0.61. For R<<1, small errors in R in equation 8.1 have little effect on evaporation. At values of R approaching unity however errors in the determination of R can have an increasingly large influence on computed evaporation. Average daily Bowen Ratios are plotted in Figure 8 1. The maximum was 0.52; minimum, -0.28. This indicates that on a daily basis evaporation always exceeded sensible heat as a means of dissipating energy from the water-air interface. Negative values indicate that the two fluxes have different signs. At Perry Lakes the summer and winter 10 minute data typically exhibit negative morning values when the sun is warming the surface water (negative sensible heat flux). The daily average however is usually positive as the sensible heat flux becomes positive during the afternoon and over night. Summer negative daily Bowen Ratios occurred when very hot days were followed by cloud cover at night and very high minimum over night temperatures. In winter large negative daily values can occur in the 24 hours preceding a major frontal passage characterised by warm, cloudy conditions and easterly winds preceded by a clear cold night.

The Bowen Ratios calculated for Perry East lie well within the range of $-1.0 < R < 1.0$ which is considered typical (Bowen 1926, Crago & Brutsaert 1996). Where ten minute data was outside these limits, data was clipped at -5.0 and 5.0. The daily average Bowen Ratio used in the thermal balance calculations is the average of ten minute calculations based on instantaneous values of T_a, T_o, e_a and eo. Alternative calculations using daily averaged values of these parameters to calculate a daily average R were found to be very similar but not identical. The difference in the final thermal balance using either method is probably insignificant.

All parameters in a thermal balance will include some measurement error. Harbeck *et al* (1958) estimated that the greatest error lay in the Bowen Ratio (up to 20%) followed by reflected solar radiation (<10%) and reflected long wave radiation (<10%). Overall Harbeck *et al* estimated total annual error to be less than 10%. Given the small size of East Lake annual error is also probably less than 10%.

Table 8.3

East Lake

Thermal Balance Summary

Bal	Start Date	Days	Med Area	Med Vol	Qa	Qar	Qbs	Qs	Qsr	Qrn	Qsd	Qtu	Qdc	Qrc	Qse	Qx	Qe	Qh	Qw	Total E_{Tb}	Daily E_{Tb}	Total E_p	Daily E_p	E_{Tb} - E_p	E_{Tb} : E_p
1996																									
20	December 22	12	44775	11672	4077.4	122.3	5302.8	4522.8	257.3	0	0	134.7	0	240.3	-175.4	-3.7	2325.6	206.1	104.7	88.2	7.4	82.7	6.9	0.5	6.7
1997																									
21	January 03	12	40989	9336	4321.6	129.6	5419.8	4418.0	254.1	0	0	329.1	0	376.8	-353.3	-70.6	2269.8	214.0	108.6	91.8	7.7	80.8	6.7	0.9	13.6
22	January 15	12	38921	8175	4134.7	124.0	5265.2	4224.6	248.7	0.3	0	350.9	0	374.9	-244.2	-63.2	2260.7	159.7	99.9	88.1	7.3	80.3	6.7	0.6	9.7
23	January 27	12	28627	4978	4426.7	132.8	5321.7	3860.9	238.0	0	0	382.2	0	403.9	-508.9	-84.9	1957.2	107.2	88.4	86.0	7.2	69.6	5.8	1.4	23.6
24	February 08	12	25887	3702	4153.0	124.6	5259.0	3971.0	241.5	0.3	0	498.8	0	494.2	-411.2	59.7	1797.1	156.6	78.8	76.7	6.4	63.8	5.3	1.1	20.2
25	February 20	12	38300	8093	4492.0	134.8	5343.3	3133.4	213.9	1.1	1.6	718.6	0	571.4	-581.7	82.0	1376.9	60.5	63.3	65.6	5.5	49.0	4.1	1.4	34.0
26	March 04	12	26336	5826	3982.5	119.5	5232.9	3436.7	226.4	0.2	0	68.7	0	506.3	331.6	-212.8	1714.8	150.5	74.2	50.5	4.2	60.9	5.1	-0.9	-17.0
27	March 16	12	17723	2028	4682.0	140.5	5165.7	3002.5	211.7	4.9	13.9	539.7	0	570.7	-484.0	54.0	1383.7	181.5	57.4	63.7	5.3	49.1	4.1	1.2	29.9
28	March 28	12	31420	5034	4562.2	136.9	5033.9	1975.1	162.1	59.3	156.0	230.0	0	389.0	9.8	96.4	1026.6	116.3	39.6	36.0	3.0	36.3	3.0	0.0	-0.9
29	April 09	12	36197	6666	4613.3	138.4	5153.0	2335.6	185.7	12.7	25.6	381.9	0	445.2	-339.6	-28.7	924.6	169.5	37.9	42.6	3.6	32.8	2.7	0.8	30.0
30	April 21	12	31634	5120	4666.0	140.0	4934.3	1748.9	153.9	11.0	27.0	150.7	0	282.0	-253.2	-77.4	754.4	129.6	26.9	34.0	2.8	26.6	2.2	0.6	27.6
31	May 03	12	27173	3555	4464.6	133.9	4693.8	1775.5	154.3	2.4	11.3	242.7	0	239.9	-364.2	5.6	784.4	103.2	23.1	39.0	3.3	27.6	2.3	1.0	41.4
32	May 15	12	26389	3385	4488.7	134.7	4786.4	1395.0	132.7	22.4	59.0	228.7	0	292.2	-177.6	-26.2	619.2	61.7	19.5	27.4	2.3	21.8	1.8	0.5	25.7
33	May 27	20	35832	7906	6952.8	208.6	7758.1	2110.2	206.0	99.4	221.6	237.9	19.7	338.1	44.0	105.4	902.6	146.0	25.7	30.4	1.5	31.7	1.6	-0.1	-4.1
34	June 16	12	41610	9841	4376.3	131.3	4629.6	1398.4	133.5	5.4	6.0	2.5	5.9	116.7	-282.7	-52.6	496.5	37.0	13.7	26.3	2.2	17.4	1.5	0.7	50.9
35	June 28	12	38650	8037	4210.5	126.3	4488.5	1423.0	135.2	27.7	71.0	0	7.3	72.1	-244.8	-14.8	604.9	81.7	14.2	28.6	2.4	21.2	1.8	0.6	35.0
36	July 10	12	39593	8566	3833.5	115.0	4374.5	1719.6	151.1	13.9	29.4	0	4.2	45.5	-216.0	-9.8	544.8	172.5	11.2	25.0	2.1	19.0	1.6	0.5	31.3
37	July 22	12	38661	8014	3837.1	115.1	4610.8	1707.8	153.5	16.8	31.0	0	7.6	46.9	161.4	35.6	675.8	128.1	18.2	19.0	1.6	23.7	2.0	-0.4	-19.9
38	August 03	16	43803	11248	4644.5	139.3	6152.8	2356.3	206.4	54.3	117.4	1.7	32.3	88.2	659.2	57.9	989.5	227.1	27.1	16.3	1.0	34.8	2.2	-1.2	-53.1
39	August 19	12	48688	14266	3231.2	96.9	4652.2	2204.3	180.8	9.0	17.9	0	28.7	44.7	507.6	20.6	821.6	176.0	23.1	14.6	1.2	28.9	2.4	-1.2	-49.4
40	August 31	12	54920	20856	3410.7	102.3	4673.3	2085.7	172.5	69.5	119.7	0	24.4	70.7	555.6	169.0	842.8	219.4	24.6	14.3	1.2	29.6	2.5	-1.3	-51.7
41	September 12	12	60060	25909	3508.2	105.2	4955.1	2754.8	203.5	0.6	0.4	0	12.3	40.0	420.6	49.9	1038.4	266.9	37.7	25.2	2.1	36.7	3.1	-1.0	-31.3
42	September 24	12	57074	22255	3543.0	106.3	4975.5	3082.2	214.5	2.0	2.2	0	25.0	52.0	288.0	-77.6	1314.1	312.3	48.3	38.5	3.2	46.4	3.9	-0.7	-17.1
43	October 06	12	55180	19962	3621.9	108.7	5002.1	3307.9	222.2	20.5	35.4	0	28.9	69.1	234.0	-17.3	1486.1	318.9	55.4	45.9	3.8	52.5	4.4	-0.6	-12.6
44	October 18	12	51547	16734	3849.2	115.5	5127.0	3561.0	229.2	1.1	1.4	0	21.7	89.2	148.8	-64.9	1732.1	287.4	70.0	57.0	4.8	61.4	5.1	-0.4	-7.1
45	October 30	12	44418	11548	3820.8	114.6	5100.9	3842.6	237.1	0	0	0	1.5	56.7	-23.4	-23.3	1802.4	276.2	72.0	64.5	5.4	63.8	5.3	0.1	1.1
46	November 11	12	37620	7557	4129.7	123.9	5038.8	3538.6	225.3	4.7	13.0	0	7.1	55.5	-306.6	-81.8	1685.4	265.9	65.7	68.7	5.7	59.6	5.0	0.8	15.2
47	November 23	12	29286	4441	4586.3	137.6	5217.9	3870.8	238.4	1.2	1.1	0	0	58.9	-636.0	-47.6	1808.7	325.0	77.9	82.7	6.9	64.2	5.4	1.5	28.8
48	December 05	12	16476	1754	4105.2	123.2	5278.8	4452.0	255.1	0	0.4	0	0	96.0	-1.8	-73.1	2481.3	273.7	109.5	88.2	7.4	88.1	7.3	0.0	0.1
49	December 17	8	10419	812	2792.5	83.8	3560.9	2941.2	169.4	0	0	145.6	0	116.6	-122.0	27.1	1516.1	200.6	69.9	57.6	7.2	53.9	6.7	0.5	6.8
1998																									
50	December 25	9	10593	831	3206.9	96.2	4066.2	3243.4	188.6	0	0	136.5	0	184.3	-275.6	-19.8	1496.6	214.0	71.5	61.5	6.8	53.3	5.9	0.9	15.4

Notes

Lake area in m^2, volumes m^3

All balance periods commence and end at 08:00 hr on date shown

All Q terms expressed in watts per square metre ($W\ m^{-2}$)

Evaporation (E) expressed in millimetres

Total E_{Tb}	Total evaporation calculated by thermal balance ignoring the sediment thermal term (Qse set to zero)
Daily E_{Tb}	Daily evaporation calculated by thermal balance
Total E_p	Total evaporation calculated by floating Class A pan
Daily E_p	Daily evaporation calculated by floating Class A pan
E_{Tb} - E_p	Average daily error (mm) induced by ignoring the sediment heat flux
E_{Tb} : E_p	Error (%) per balance period between thermal balance and pan evaporation

8.4 RESULTS

Thermal balance results by balance period from 08:00 December 22, 1996 to 08:00 January 3, 1998 are summarised in Table 8.3. Appendix 8.1 is the individual daily calculations from which Table 8.3 was derived. The appended data show evaporation (as derived from equation 8.1) with the sediment term *Qse* set to zero. Included is the daily average value for the sediment term required to make thermal balance evaporation and floating pan evaporation equal. This figure multiplied by the number of days in the balance period appears as the *Qse* figure in Table 8.3. Also in Table 8.3 total and daily evaporation are shown both ignoring and including the sediment heat flux term. The final columns are the daily average error in evaporation if the sediment term is ignored, expressed as daily error (mm) and as a percentage of independently measured floating pan evaporation.

For the year 1997, total East Lake evaporation was 1378.8mm. Ignoring the sediment term, the thermal balance estimate of evaporation was 1468.4mm, an over estimate of 6.5%. Over a year, much of the error is cancelled because the thermal balance both over and under estimates evaporation however within individual balance periods the error was much greater (final column Table 8.3). Greatest error was 50.9% over estimate (Balance 34) and -53.1% under estimate (Balance 38). Expressed as daily evaporation, the average daily error over 1997 was 0.24mm however within individual balance periods this rose as high as 1.54mm in Balance 47 (refer column E_{Tb}-E_P in Table 8.3). These errors are significantly greater than those reported by Rosenberry *et al* (1993) who determined that the effect of heat advected to the sediment was generally <3mm d^{-1}. Data is displayed graphically in Figure 8.3.

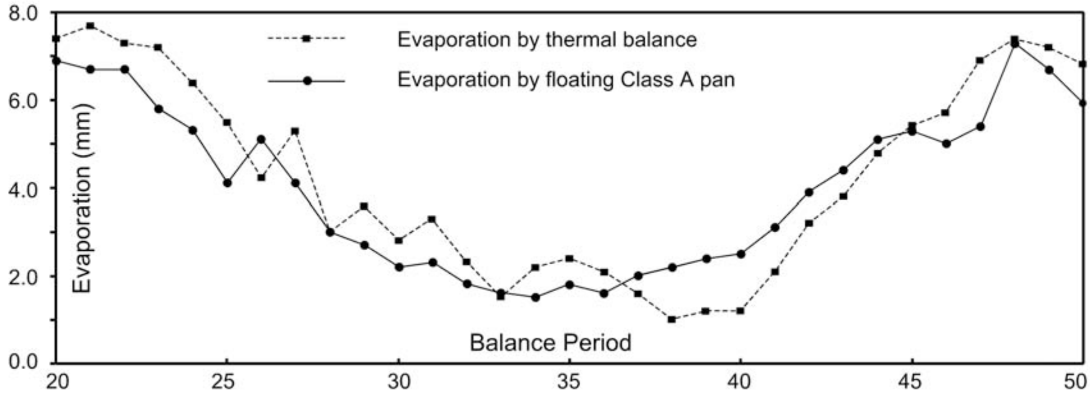


Figure 8.3 Comparison of evaporation by floating Class A pan and thermal balance ignoring *Qse*. The difference is the sediment heat flux expressed as equivalent mm of evaporation

The problem of measuring evaporation by thermal balance, while at the same time attempting to quantify the heat flux to and from sediments in shallow wetlands presents a continuing challenge to wetland research. Parkhurst *et al* (1998) is a recent example with similar problems and implications. Perry Lakes is no doubt an extreme example because of its very shallow water and highly variable surface area. The results confirm quite clearly that the sediment heat flux term is an important component in the thermal balance of such wetlands. Thermal balance estimates of evaporation must include the sediment term, particularly for balance periods of less than one year. The results also confirm the hypothesis that the polarity of the sediment flux varies seasonally. This and other aspects of the sediment thermal regime are examined in Chapter 9.