CHAPTER
10

EVAPORATION STUDIES

10.1 INTRODUCTION

In hydrology, evaporation (E) is the phenomenon by which water is converted from the liquid into vapour. Transpiration (T) is a special case where vaporisation occurs through the stomata of living plants. Frequently these two phenomena are combined in the term evapotranspiration (ET) since direct evaporation from the soil and small water bodies and transpiration from vegetation are difficult to separate (Brutsaert 1982). Under arid conditions evaporation is often reported as potential evaporation (PE), a concept introduced by Thornthwaite (1948) in relation to climate classification. It is now generally understood to define the maximum rate of ET that could occur over an area of soil and actively growing vegetation supplied with adequate water at all times (Granger 1989). A more agriculturally specific definition defines it simply as the 'maximum rate of ET from a large area covered completely and uniformly by an actively growing vegetation with adequate moisture at all times' (Brutsaert 1982 p214). This reflects the widespread use of the concept in agriculture where transpiration dominates over soil evaporation as the principal mechanism of transferring water to the atmosphere. Where used here, PE is the maximum transfer of water to the atmosphere that could occur over a given area under given micro-climatic conditions through evaporation from open water and soil, and through transpiration. Actual evapotranspiration is the amount of evapotranspiration actually occurring. This should never exceed PE if they have been correctly calculated. Where plants or soils cannot meet the atmospheric demand on their evaporating surfaces, actual evaporation may be much less than PE (Fleming 1997).

Evapotranspiration and precipitation are the two principal phases of the hydrological cycle. Some indication of their magnitude and importance can be gained from global and regional water balance estimates (Table 10.1). On the Swan Coastal Plain open water evaporation is the largest single factor contributing to wetland water loss and may exceed precipitation by three times in drought years.

The general water balance (equation 6.1) expresses the conservation of mass in anything from a small wetland to a large lake. Regardless of scale, many of these components are seemingly easier to estimate or accurately measure than evaporation. Despite its importance, evaporation is therefore frequently estimated as the residual in the balance despite the potentially large cumulative errors and uncertainties (Chapter 4). Frequently this is the only avenue available to researchers when budgets, available data or instrumentation are limited.

Table 10.1 Estimates of world water balance (m y^{-1})

Land (1.49×10^8 km^2)		Oceans (3.61×10^8 km^2)		Global	Reference*
P	Et	P	Et	P = Et	
0.73	0.42	1.14	1.26	1.02	Budyko (1970, 1974)
0.73	0.47	1.14	1.24	1.02	Lvovitch (1970)
0.83	0.54				Lvovitch (1973)
0.75	0.48	1.07	1.18	0.97	Baumgartner & Reichel (1975)
0.80	0.49	1.27	1.40	1.13	Korzun *et al* (1978)

*Table adapted from Brutsaert (1982) and references therein, P (precipitation), Et (evapotranspiration)

Evaporation is an important component of lake hydrology. At Perry Lakes it can comprise up to 40% of the water budget (Chapter 6). Viewed at a regional scale, all components of the hydrological cycle present formidable problems in both estimation and sampling (Brutsaert 1982). Often when the scale is reduced to something like a small wetland, many of these problems are likewise reduced. A simple rain gauge for example provides a reasonable event by event estimate of rainfall. Evaporation however, remains notoriously difficult to determine either at a point location or regionally. This difficulty frequently results in gross inaccuracies in water balance estimates (Winter 1981).

It is generally accepted that a thermal balance represents the most accurate method of estimating evaporation (Anderson 1954a, Harbeck *et al* 1958, Rosenberry *et al* 1993). However any thermal balance is extremely complex, time consuming, logistically difficult and expensive. These drawbacks have therefore generally precluded such studies being sustained for more than several years at any one site. The five year study by Sturrock *et al* (1992) being an admirable exception. Such difficulties have also resulted in many attempts to design much easier to implement empirical field methods. These frequently claim ease of implementation and high accuracy (for example Webb 1966, Keijman 1974, de Bruin 1978, Stewart & Rouse 1976). Based largely on Northern Hemisphere studies their unquestioned adoption under Australian conditions is fraught with uncertainty.

The general approach adopted in many large studies therefore has been to complete short term thermal balance estimates (often for one full year) concurrent with a variety of empirical techniques and evaporation pan studies. The thermal balance data is taken as 'true' and used to calibrate the empirical techniques which generally rely on much easier to measure meteorological and other parameters and can usually be run over much longer periods. In the end the choice of a method for measuring or calculating evaporation depends on the problem under consideration and is governed by the available data, instrumentation and, all too often, financial resources.

On the Swan Coastal Plain research is frequently centred on urban wetlands either because they are conveniently located in relation to universities or other research institutions or because increasingly such wetlands are being recognised as valuable assets within urban environments and their proper management is of increasing concern to wetland managers. The Perry Lakes thermal balance therefore represented an opportunity to calibrate both evaporation pans and a number of empirical techniques under local conditions. Those presented in this chapter can now be applied to nearby wetlands with much greater confidence than would otherwise be the case.

10.2 EVAPORATION PANS AS SIMPLE PHYSICAL MODELS

Evaporation pans are probably the simplest physical model for evaporation from a lake. As Brutsaert (1982) notes, their intuitive appeal is easy to understand because they model evaporation from a free water surface in a visible way. Depending on their construction and whether they are situated above or below ground, evaporation from a pan and a nearby wetland can differ significantly. These differences result from the basic factors affecting evaporation from water bodies such as surface water temperature, heat storage, wind, turbulence, wave action, soluble salts and nature and shape of the evaporating surface (WMO 1966). Wind effects and heat advection not typical of the natural environment (Winter 1981) and air turbulence created by the pan rim are their principal source of error. Jacobs *et al* (1998) showed that the physical analogy between a pan and reference evaporation is predominantly dependent on the weather and that a unique constant pan co-efficient cannot exist. As the predominating character of the weather changes seasonally, so too does the average pan co-efficient. Generally pans tend to over estimate evaporation from lakes. These errors can be decreased by sinking the pan below ground level and increasing its thermal mass (*i.e.* increasing both diameter and depth) thereby more closely approximating a small natural water body.

Pan coefficients, defined as the ratio of lake evaporation to pan evaporation represent the simplest method of relating pan evaporation to lake evaporation. In practice this coefficient varies seasonally and is highly site specific. In southern coastal areas of Australia the coefficient may approach 1.0 while in the arid interior it may be as low as 0.6 (AWRC 1970). Pan coefficients can be reasonably accurate for some areas when applied over long time frames (Hoy & Stevens 1979, Knapp 1985) however they cannot be used with any accuracy over the short term. The seasonal range in coefficients may be as low as 0.2 in the tropics to 0.5 in southern Australia (AWRC 1970). In general however coefficient values for Class A pans vary from about 0.5 to 0.9 with 0.7 being a generally assumed global average for an unguarded pan (WMO 1966). This figure appears to derive originally from the Lake Hefner (Oklahoma) studies (Kohler 1954) where a mean annual figure of 0.69 was determined for 1950-51.

Pan data is most valuable where evaporation has been determined independently for a lake and a nearby evaporation pan. Pan data can then be used to make further estimates of lake evaporation. Data for fourteen Australian lakes is compiled as Table 10.2.

Table 10.2 Measured Class A pan and sunken pan coefficients for Australian lakes

Lake	Location	Pan 1	Pan 2	Sunken
Lake Menindee	SE Broken Hill - Darling River area NSW	0.71	0.76	0.79
Lake Pamamaroo	SE Broken Hill - Darling River area NSW	0.66	0.71	0.73
Lake Cawndilla	SE Broken Hill - Darling River area NSW	0.71	0.76	0.79
Stephens Creek Reservoir	Broken Hill NSW	0.69	0.74	0.77
Lake Albacutya	Western NSW	0.79	0.85	0.88
Lake Hindmarsh	Western NSW	0.74	0.79	0.82
Lake Eucumbene	Snowy Mountains, NSW	0.81	0.87	
Cataract Reservoir	West of Sydney NSW	0.92	0.98	
Manton Reservoir	South of Darwin NT	0.87	0.93	
Mundaring Reservoir	East of Perth, WA	0.93	1.00	
Blue Lagoon	Gippsland, eastern Victoria	0.88	0.94	
Lake Wyangan South	Griffith, central NSW	0.77	0.82	
Rifle Creek Reservoir	Mount Isa, Queensland	0.64	0.68	
Lake Albert	SE South Australia	0.81	0.87	
MEAN		0.78	0.83	

Class A data is for unguarded pans (1) and pans equipped with standard bird guard (2), sunken pan coefficients for standard Australian sunken pan. Data from Hoy & Stephens (1979) and Australian Water Resources Council (AWRC 1970). Lake evaporation measured by thermal balance.

The data demonstrate the potential for error in applying an average coefficient to a specific location. Lakes have large heat storage capacity and mean temperatures which vary little on a diurnal basis. In comparison, evaporation pans contain very small quantities of water, hence their heat storage capacity is small and mean temperatures show wide diurnal variation. Therefore pan evaporation depends predominantly on present weather while lake evaporation is more strongly influenced by antecedent weather (Edgeloe *et al* 1987). For this reason even a well calibrated above ground pan cannot be used with any confidence to measure lake evaporation over short periods. Monthly coefficients are the shortest period routinely reported (for example WMO 1966, Kohler 1954).

Class A pans are mounted above ground. This configuration accentuates the effects of radiation from the pan walls and heat transfer from the air. Sunken pans eliminate many of these problems with aerodynamic and radiation properties which approximate those of a lake. They have therefore been widely used to estimate open water evaporation (Kohler 1954, WMO 1966, AWRC 1970, Brutsaert 1982) and evapotranspiration

(Rijtema 1965). There are numerous sunken pan configurations with little standardisation country to country (WMO 1966). The Australian sunken tank was designed to reduce soil to tank conduction and was widely used before Class A pans became the Bureau of Meteorology standard. It comprised an inner circular metal tank three feet in diameter and three feet deep within an outer tank, the annulus width being six inches. The entire assembly was sunk in the ground approximately flush with the soil surface. Sunken pan to lake coefficients are included in Table 10.2.

Russian sunken pans of 5m diameter (surface area 20m^2) and 2m depth have pan to lake coefficients which exceed unity when operated under Australian conditions. These pans have no annular water jacket, the tank walls being in direct contact with the soil. Coefficients for Lake Wyangan for a pan operated at Griffith NSW varied from 1.11 to 1.16 (Hoy & Stephens 1979). They found that this tank estimated lake evaporation with similar accuracy to a neighbouring Class A pan. Comparative Russian studies (Gangopadhyaya *et al* in WMO 1966) showed that evaporation from a sunken 20m^2 tank was 11% to 29% less than a Class A pan over an 11 year monitoring period.

Floating pans represent the ultimate physical model of wetland evaporation. They float within the lake under study. Therefore they are subject to identical average conditions of wind and water temperature. Their obvious disadvantages are difficulty of use and potential error from wave slop. Neuwirth (1973 cited Winter 1981) showed that a floating pan maintained at a similar thermal regime to a lake evaporated 22% less water (over 0.5 yr) than a Class A pan operated under similar (mid lake) meteorological conditions. Published studies of floating pans typically describe large triangular rafts whose orientation changes with the wind and which employ elaborate wave damping construction (WMO 1966). In large (>3-4km^2) lakes WMO (1966) recommended that floating pans be located greater than 200m from any shore. There appears to be little literature on the use of these pans in small lakes. Clearly a central position is best, but empirical methods employing wind run can provide excellent estimates of evaporation for small lakes using shore based instruments (Winter *et al* 1995). This suggests that over longer integration periods, the position of a floating pan within a small lake may not be critical.

The floating pan described in Chapter 5 was designed to be as aerodynamically simple as possible. Due to the large water fowl population the pan had to be operated with a bird guard however this was of custom design with large (100 by 100 mm) mesh. For the purposes of the water balance in East Lake, the floating pan coefficient was assumed to be unity, the assumption being that any over estimate from pan heating would be balanced by the effect of the bird guard. If anything the floating Class A pan probably slightly under estimates East Lake evaporation; however, these errors were assumed to be small given that the lake is small, irregularly shaped, with large sections frequently in shade or protected from the wind. Certainly floating pans are most likely to nearly approximate lake evaporation (McKay & Stichling 1961). In Finland where floating GGI-3000 pans were operated in four lakes, floating pan evaporation was taken as the standard (Järvinen 1978).

All Bureau of Meteorology pans operated in Australia have standard bird screens. A 'Bureau Standard' screen was fitted to the pan operated at the UWA Field Station. Under various Australian conditions these screens have been found to reduce monthly evaporation by about 4 to 8%, mean 6.6% (van Dijk 1985). The standard screen consists of a 300mm high cylindrical frame covered with chicken wire with a mesh aperture of about 18mm. The floating pan used in East Lake had a conical guard with a mesh aperture of 100mm (Figure 5.2). Compared to a standard guard, this was assumed to have minimal attenuation of evaporation. The total error introduced by setting the floating pan to lake coefficient as unity is probably a few percent. This is of similar magnitude to the accepted error in other mass components measured directly such as rain gauge catch and artificial maintenance flow meter data.

In addition to bird guards, other nearby obstructions and even small physical barriers can strongly influence evaporation from any pan flush with a land or water surface. The resulting small changes in surface roughness can have a large influence on the flow of air over a small pan. With sunken pans Bonython (1950) cited Rijtema (1965) reported that a drop of 50mm water height in the pan reduced measured evaporation by 15%. Raft mounted Class A pans were used at three locations on Lake Mead (forming the Nevada - Arizona border) over the period 1937 to 1953. The rafts were large structures with extensive anti wave and splash baffles. These baffles can be an additional source of error in that they impede circulation resulting in warmer water between the baffle and the pan (Winter 1981). Mean annual floating pan to lake coefficients calculated from data reported by Harbeck *et al* (1958) vary from 0.79 to 0.98 over the period 1941-1953. In Saskatchewan McKay & Stichling (1961) computed an average summer coefficient of 0.93 over four months using a 'two chamber' floating pan, mounted on a large raft similar to those used at Lake Mead. In both these cases the influence of large rafts and associated structures resulted in coefficients less than unity.

10.3 PAN to LAKE VARIATION ON THE SWAN COASTAL PLAIN

As part of this study, a Class A pan was operated close to Perry Lakes at the UWA Agricultural Field Station. This pan was calibrated against the floating Class A pan in

East Lake. Monthly pan coefficients were calculated for Perry Lakes using both the Field Station pan and the Bureau of Meteorology pan at Perth Airport. Water temperature and wind run were also measured at both locations. Table 10.3 shows the differences in mean monthly maximum and minimum temperatures for Perry Lake East and a nearby Class A pan. Maximum day time temperatures in the field station pan are very similar to those in the lake suggesting that pan temperature may be attenuated by the proportionately greater cooling effect of evaporation itself. At night evaporation plays a diminished role. The data show that night time radiative cooling has a much greater effect on the pan than the lake.

Table 10.3 Mean monthly maximum and minimum temperatures 1997

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Ag pan min	18.8	19.5	16.3	16.7	12.7	11.9	7.6	9.6	12.0	13.4	15.1	17.4
Floating pan min	20.7	21.1	18.2	18.4	14.5	13.7	10.6	13.0	15.8	17.9	18.5	19.3
Ag pan max	32.8	31.6	28.0	25.8	20.1	18.6	16.6	19.2	22.7	26.2	27.7	30.1
Floating pan max	32.2	31.4	28.6	25.4	20.7	18.1	16.4	18.7	22.3	25.8	28.5	32.5

Data from 'Sixes' max-min thermometers in Ag Station Class-A pan and Perry Lakes floating pan

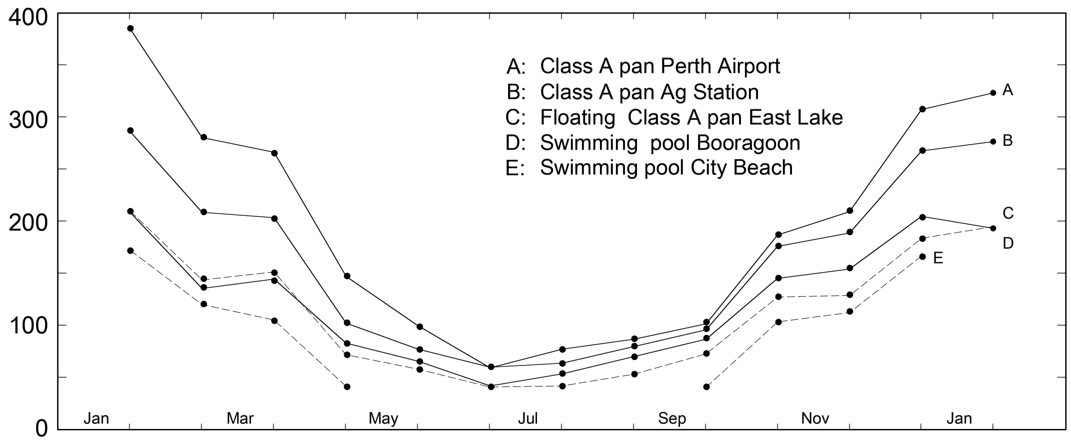
Small wetlands like East Lake tend to be somewhat sheltered, occurring within topographic depressions and usually surrounded by trees. Class A pans on the other hand are recommended to be operated in open areas with no nearby obstructions. The UWA Agricultural Field Station site is less sheltered than Perry Lakes where the floating pan was operated in East Lake. The pan site at Perth airport is completely open with fetches of several kilometres. Table 10.4 shows monthly mean daily wind run for these three pan sites plus the Swanbourne automatic weather station (AWS) located on the coast 2km southwest of Perry Lakes.

Table 10.4 Mean daily wind run (km) at 2m 1997

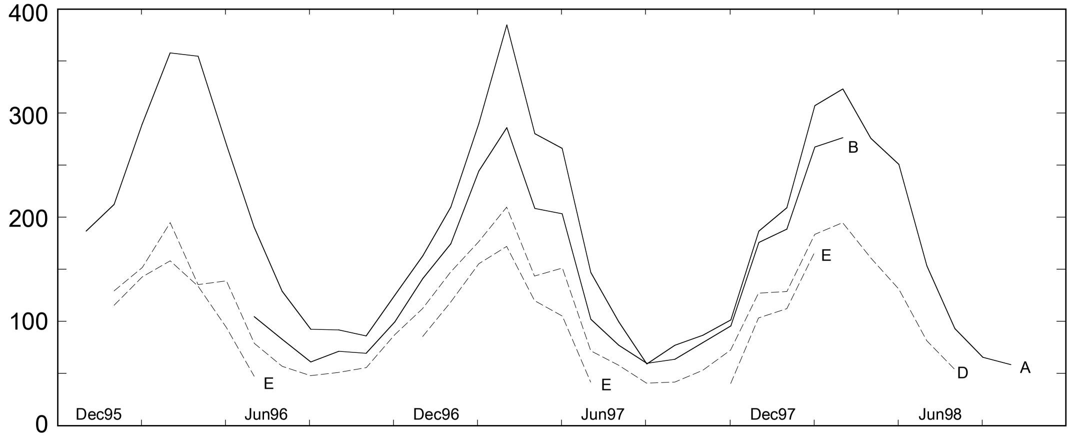
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
East Lake	141	136	136	92	105	94	86	109	101	143	139	146
Field Station	170	159	157	85	94	76	72	91	86	135	132	168
Airport	333	316	323	218	233	154	172	198	185	268	205	249
Swanbourne	471	457	458	345	401	397	359	405	350	441	433	466

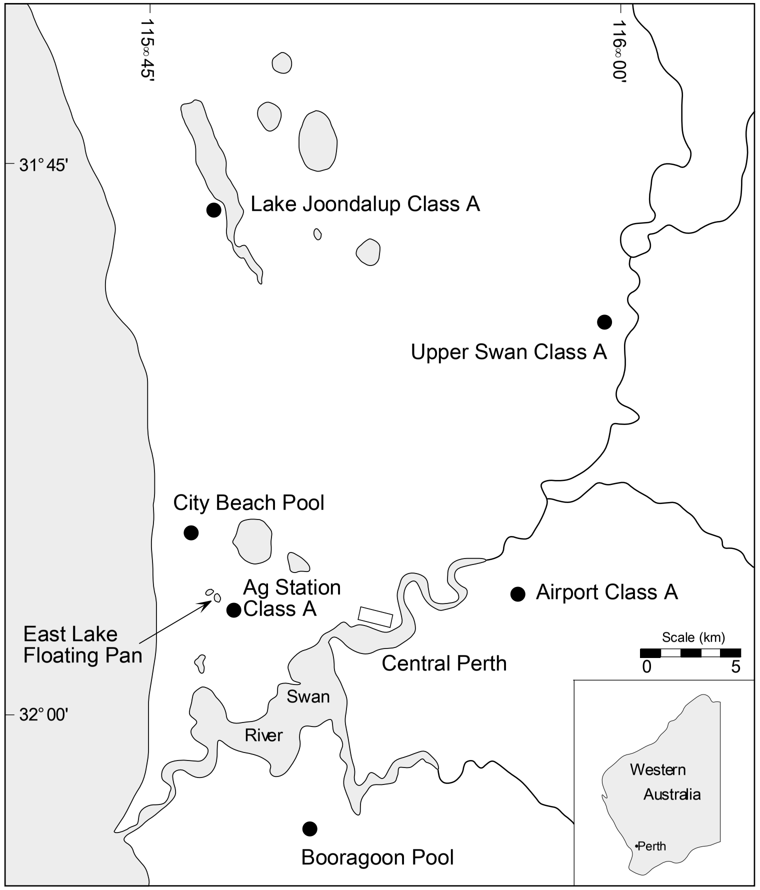
During winter when the predominant wind is from frontal systems approaching from the west, the fetch on East Lake is such that average daily wind run exceeds that at the agricultural station. In summer when east winds predominate, the situation is reversed. The Swanbourne AWS is located atop coastal dunes and receives significantly greater wind run than the other sites. It is obvious from wind data alone that pans operated in different nearby locations will have significantly differing annual evaporation.

Pan & Pool Data 1997



Pool and Pan Data 1995-1998





Evaporation Pans & Pools

Figure 10.1

10.4 SWIMMING POOLS AS SIMPLE MODELS OF SMALL WETLANDS

Evaporation pans are often difficult to operate in urban areas due to vandalism and other problems. In cities like Perth however there are abundant below ground domestic swimming pools which mimic sunken evaporation pans. Given that the typical 'back yard' pool suffers from varying degrees of shading and wind obstruction it still seemed possible that if properly calibrated, such pools could function as long term secure analogues of small wetlands.

Two back yard pools were monitored in City Beach and Booragoon (Figure 10.1). Both were of a generally northerly aspect such that the pools were as far as possible not in house shade. In both cases there was a certain amount of shading from vegetation which varied seasonally. The wind flow in a typical suburban back yard is attenuated by buildings, fences and vegetation. No meaningful wind run data was collected from either site[1]. A standard 4 inch (100mm) funnel rain gauge was mounted at 0.5m height immediately adjacent to each pool.

Evaporation was calculated using two methods. At both pools a calibrated flow meter installed in a dedicated garden hose recorded all water used to top up the pool levels to a reference depth. Evaporation was also measured directly on a daily basis. Stilling wells were mounted on both swimming pool steps. Depth was measured with a mm rule. The Booragoon pool had a 450mm concrete surround. Rain falling on the surround was included in the calculations. The City Beach pool was not useable in winter due to run off from an adjacent patio during high rain events. In both cases the pools were rarely used for swimming. Data gaps on swimming days were estimated using coefficients developed for the Ag Station and Perth Airport pans.

The data (Table 10.5) suggests that swimming pools do work as surrogates for large sunken evaporation pans. In both cases the pools had a maximum depth of about 1.8m and surface to volume ratios much smaller than East Lake. As with many sunken pans and tanks, the correlation coefficient with natural wetlands (in this case East Lake) approach or exceed unity. Given the limitations imposed by disrupted aerodynamics and measurement difficulties, we were surprised at how well the pools worked. Certainly a pool in a large open yard with minimal shading and wind flow disruption could be calibrated to act as a long term secure measuring device for a nearby urban wetland. A Class A pan located close to the wetland of interest however is much easier to use and if well calibrated will probably provide equally accurate estimates of open water evaporation for periods of a month or longer.

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[1] An anemometer left at the Booragoon site to collect annual wind run became the victim of an over enthusiastic creeping vine

Class A Pan & Pool Statistics

Table 10.5

Month	East Lake Floating Class A		Ag Station Class A		Perth Airport Class A		Booragoon Pool		City Beach Pool			Pan:Lake Coefficients		
1997	Total (mm)	Daily (mm)	Total (mm)	Daily (mm)	Total (mm)	Daily (mm)	Total (mm)	Daily (mm)	Total (mm)	Daily (mm)	Ag Station	Airport	Booragoon	City Beach
January	208.5	6.7	286.2	9.2	385.0	12.4	209.6	6.8	171.8	5.5	0.73	0.54	0.99	1.21
February	135.1	4.8	208.4	7.4	280.6	10.0	143.2	5.1	119.8	4.3	0.65	0.48	0.94	1.13
March	144.2	4.7	203.1	6.6	266.2	8.6	150.9	4.9	104.8	3.4	0.71	0.54	0.96	1.38
April	82.4	2.7	101.6	3.4	147.0	4.9	71.5	2.4	41.1	1.4	0.81	0.56	1.15	2.00
May	65.2	2.1	76.7	2.5	99.2	3.2	57.5	1.9			0.85	0.66	1.13	
June	41.5	1.4	59.3	2.0	58.8	2.0	40.4	1.3			0.70	0.71	1.03	
July	53.3	1.7	63.5	2.0	77.0	2.5	41.4	1.3			0.84	0.69	1.29	
August	69.6	2.2	79.7	2.6	86.4	2.8	52.6	1.7			0.87	0.81	1.32	
September	86.9	2.9	95.8	3.2	101.2	3.4	72.1	2.4	39.8	1.3	0.91	0.86	1.21	2.18
October	144.9	4.7	175.8	5.7	186.4	6.0	127.0	4.1	102.9	3.3	0.82	0.78	1.14	1.41
November	154.1	5.1	188.4	6.3	209.2	7.0	128.4	4.3	112.0	3.7	0.82	0.74	1.20	1.38
December	204.5	6.6	267.8	8.6	307.4	9.9	183.2	5.9	166.5	5.4	0.76	0.67	1.12	1.23
Total	1390.2		1806.3		2204.4		1277.8		Annual Mean Coefficient		0.79	0.67	1.12	1.49
1998														
January	192.9	6.2	276.7	8.9	323.4	10.4	194.7	6.3						

Notes

All land based pans fitted with standard Bureau of Meteorology bird guards

Floating pan fitted with wide aperture custom guard (refer text)

10.5 EVAPORATION ON THE SWAN COASTAL PLAIN

Evaporation records for Perth are limited. Unfortunately due to differing measurement locations and methods, data sets over extended time frames are impossible. Evaporation was measured adjacent to Kings Park from 1953 to 1966 using a below ground tank evaporimeter. In 1967 observations were shifted to Perth Airport and instrumentation changed to a World Meteorological Organisation standard above ground Class A pan. As noted above, heat transfer from soil to sunken pans and air to Class A pans results in vastly different mean and seasonal correlation coefficients with evaporation from nearby open water.

McFarlane (1984) compared evaporation data over twelve months during 1981-1982 between Class A pans operated in central Perth, Upper Swan and Perth Airport (refer map Figure 10.1). On an annual basis evaporation at Perth Airport was 18% greater than in central Perth. In late summer this difference rose to about 30%. Annual data from the Upper Swan Research Station for 1974, 1975 and 1978 indicated that evaporation there was about 12.5% greater than in central Perth. Congdon (1985) obtained weekly Class A measurements over the period August 1979 to December 1980 from central Perth and a site in Edgewater on the west side of Lake Joondalup. Annual data for 1980 showed no statistical difference between the two sites with 1705mm of evaporation recorded at Edgewater and 1702mm at Perth. McFarlane (1984) examined the climatic factors influencing evaporation in the Perth area. He found that there were significant differences in temperature, relative humidity and wind run. Evaporation in coastal areas including Perry Lakes have a strong maritime influence in the form of strong summer afternoon sea breezes. Often these are restricted to within a few kilometres of the coast and frequently do not penetrate as far inland as the airport.

Evaporation data from the current study collected over three years is displayed graphically in Figure 10.1. Data for 1997-1998 (the period in which the floating pan operated) is tabulated as Table 10.5. It corroborates the earlier data. For 1997, evaporation from the Perth Airport pan (2204.4mm) exceeded the Field Station pan evaporation (1806.3mm) by 22.0% and East Lake (1390.2mm) by 58.6%.

The data also shows clearly why annual average wetland evaporation calculated from 'rule of thumb' pan coefficients are prone to error. The annual mean coefficient for East Lake varies by 12% between the Field Station and Airport pans. Calculated coefficients for individual pans also exhibit even larger seasonal variations . Applying an annual coefficient on a monthly basis incurs potential errors of up to about 15%. Such errors are implicit in a number of earlier water balance studies of Swan Coastal Plain wetlands

(Table 10.6). Lake evaporation in these studies would have been highly prone to error. The Perry Lakes data show that evaporation from coastal plain wetlands can vary significantly from that at Perth airport.

Table 10.6 Pan coefficients in Swan Coastal Plain water balances

Lake	Determination of Lake E	Reference
Lake Mariginiup	Annual E taken as 0.8 Perth Class A pan	Hall (1985)
Lake Jandabup	Annual E taken as 0.8 Perth Class A pan	Allen (1979)
North & Bibra Lakes	Annual E based on Perth Class A pan & coefficient from Mundaring Reservoir	Congdon (1985)
Mason Gardens & Shenton Park Lake	Annual E based on Perth Class A pan & coefficient from Mundaring Reservoir	McFarlane (1984)

Perth Class A pan refers to the Perth airport pan

Mundaring Reservoir is a deep fresh water body on the Darling Plateau with a climate significantly different to that on the Swan Coastal Plain. Peel Inlet is a large coastal estuary subject to further error as evaporation from saline waters is approximately 8% less than for fresh water (Walker 1973). Both would have vastly greater heat storage abilities compared to small shallow coastal lakes. They also have widely differing rainfall. Congdon (1985) found a strong inverse relationship between rainfall and evaporation on the Swan Coastal Plain. At the time however these represented the only published pan to water body coefficients for the Perth area (Table 10.7).

Table 10.7 Published lake to pan factors prior to Perry Lakes

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mundaring	1.02	1.06	1.12	1.18	1.15	1.18	1.01	0.91	0.81	0.78	0.79	0.94	1.00
Peel Inlet	0.6	0.6	0.7	0.8	0.9	1.0	1.0	1.0	0.8	0.8	0.7	0.7	0.8

Mundaring Reservoir data: Hoy & Stevens (1979)
Peel Inlet data: Black & Rosher (1980) cited Congdon (1985)

Attempting to apply these to a balance at Lake Joondalup, Congdon (1985) estimated that annual groundwater flux (calculated as a net input residual) might be anywhere from 8% to 16% of the total annual flux.

The Perry Lakes data presented here represents one year for one wetland. Truly useful data can only be obtained from many years of consistent monitoring. Despite this, they are the only accurate lake-pan coefficients ever developed for Swan Coastal Plain wetlands. Due to their shallow depth, coastal wetlands have a low heat storage. Therefore the lake to pan phase lag should be much less pronounced than with deep water bodies and the errors from applying pan coefficients on a monthly basis should be reduced. This study represents the first attempt to accurately measure evaporation from a Swan Coastal wetland and provide accurate coefficients tied to the Bureau of Meteorology pan at Perth Airport.

10.6 REVIEW OF EMPIRICAL METHODS FOR MEASURING EVAPORATION

Despite the general difficulty in measuring evaporation, there are more (and varied) methods of estimating evaporation than any other component in the hydrologic cycle. This is largely because evaporation is directly controlled by many more easily measured parameters, almost always working in combination. Empirical methods are derived from experience and experiment. As such they are site specific. Many were derived for northern hemisphere sites. Many include empirically derived constants which may be modified for use at other sites. Empirical methods are attractive primarily because measuring evaporation or evapotranspiration directly is extremely difficult. Empirical methods allow E or ET or PE to be estimated by utilising other, more easily measured parameters. In many cases these parameters can be measured in the general vicinity and where they are routinely measured by meteorological stations, permit historical estimates to be constructed. These parameters include air and water temperature, humidity, wind, turbulence and solar radiation.

Turbulent Diffusion

Best known is the direct or eddy correlation method. Turbulent fluxes of water vapour, momentum and sensible heat are determined from co-variances. In practice at any given time or location the velocity field and vapour content cannot be quantified. Instead dependent variables are decomposed into mean and turbulent components.

Under steady conditions over a uniform surface the Reynolds or eddy flux is:

$$E = \overline{\rho w' q'} \qquad \text{(Brutsaert 1982, eqn 3.74)} \qquad (10.1)$$

where

E evaporation flux at the surface (kg m^{-2} sec^{-1})
ρ density, comprising density of water vapour plus density of air (kg m^{-3})
w' turbulent component of the vertical velocity (m sec^{-1})
q' turbulent component of the specific humidity (kg water per kg air)

In practice, methods based on turbulent fluxes have very stringent instrumentation requirements (Brutsaert 1982 p191), which until recently, precluded their use in routine field studies. In practice such studies have relied instead on empirical or mean profile methods (W. Scott pers com). Now robust krypton hygrometers and sonic anemometers facilitate direct measurement of evaporation using eddy covariance (D. Rosenberry pers com).

Mean Profiles Methods

These relate the exchange of water vapour between a water surface and the atmosphere using measurements of related parameters. The best known implementation is the mass transfer method. Extensive theoretical treatments are contained in Brutsaert (1982). Marciano & Harbeck (1954) and Harbeck *et al* (1958) provide the theoretical basis for the derivation of the basic formula used in the Lake Hefner and many subsequent studies, which can be applied using simple instrumentation. Mean profile methods are all based on boundary layer theory. A boundary layer is a general term for the layer of air adjacent to a surface (Oke 1987 p400). Where a fluid is moving close to a solid the boundary layer is a region of concentrated velocity and shear stress close to the solid (Middleton 1965 cited Gary *et al* 1974). It is both time and scale dependent (Oke 1987 p6), therefore in real world situations the extent of a boundary layer is determined by the extent to which the properties of the main flow are affected by the surface or object. A boundary layer can be divided into a roughness or turbulent layer extending above the tops of the surface roughness features and a laminar layer which is in direct contact with the surface (Oke 1987 p6).

During flow over a lake surface and while transfers are occurring, momentum, heat and moisture change with different boundary layers. Evaporation itself is a boundary layer phenomenon. The turbulent transport of momentum and water vapour are identical and are considered to have similar coefficients of eddy transport (Marciano & Harbeck 1954).

On this basis a workable field equation was derived from Sverdrup (1937)

$$E = \frac{0.623\rho k_0 u_f \left(e_0 - e_z\right)}{P\left[\ln\left(\frac{z + z_0}{\delta_l + z_0}\right) + \frac{k_0 \delta_l u_f}{D}\right]} \tag{10.2}$$

where

D	molecular vapour diffusivity (m^2 sec^{-1})
E	evaporative flux (kg m^{-2} sec^{-1})
P	atmospheric pressure (pascals)
e_0	vapour pressure of air at the temperature of the water surface (pascals)
e_z	vapour pressure of air at height z (pascals)
k_0	Von Kármán's constant (dimensionless, relates the mixing scale to height)
u_f	friction velocity (m sec^{-1})
z, z_0	height above water surface, roughness parameter (m)
δ_l	thickness of the laminar film (m)
ρ	density of the air (kg m^{-3})

Marciano & Harbeck (1954) reduced this to a simple form which continues to be used as a basic mass transfer equation of general form

$$E = Nu_z\left(e_0 - e_z\right) \tag{10.3}$$

where

N	empirically derived coefficient of proportionality (dimensionless)
u_z	average wind speed at height z (m sec^{-1})
e_o	saturation vapour pressure, usually at temperature of the water surface (mb)
e_a	vapour pressure of the air (mb)

Equation 10.3 relates evaporation to easily measured parameters which reflect the movement of air over a water surface and the capacity of the air to take up moisture from that surface. The coefficient N represents the combined effect of all other factors influencing evaporation (Hughes 1967). It is site specific and empirically derived.

Empirical Methods

Empirical methods rely on easily measured meteorological parameters to estimate potential evaporation (PE) or potential evapotranspiration (PET). Brutsaert (1982) defines potential evapotranspiration as the 'maximum rate of evapotranspiration from a large area covered completely and uniformly by an actively growing vegetation with adequate moisture at all times'. As Brutsaert points out however this botanically biased concept is difficult to apply because of numerous biological effects such as stomatal impedance and stage in the growth cycle. The concept is further complicated by meteorological effects. After rain or heavy dew fall, air over a vegetated area will be completely saturated, leading to Brutsaert's suggestion that potential evaporation is a preferable term. Clearly there is little difference between thoroughly wetted soil and vegetation and an open body of water. It is on this basis that many equations originally developed for measuring potential evapotranspiration can be adapted directly for measuring open water evaporation.

10.7 FIELD COMPARISON OF MEAN PROFILE & EMPIRICAL EQUATIONS

Monthly evaporation was computed for 1997 using ten mean profile and empirical equations (Table 10.8). The methods chosen were identical to those evaluated by Winter *et al* (1995) for Williams Lake, Minnesota. The results allow a direct comparison with this Northern Hemisphere study, and more importantly provide a basis for evaluating their applicability to Swan Coastal Plain wetlands. This study and the Williams Lake study follow in the tradition of pioneering American work in the 1950's at Lake Hefner and Lake Mead (Harbeck 1954, Harbeck *et al* 1958) where empirical techniques were tested against free water evaporation determined by thermal balance. More recent similar studies such as Warnaka & Pochop (1988) are compromised by using only pan coefficients to estimate wetland evaporation.

Many empirical equations have been developed over many years. Those tested here are representative of the principal approaches taken but are by no means a complete suite. New approaches or modifications of older techniques appear regularly in the literature. For example equations recently presented by de Bruin & Lablans (1998) and Xu & Singh (2000) may prove of interest to Swan Coastal Plain researchers.

Putting aside for one moment the inherent inaccuracies in empirical techniques, a principal practical problem has always been the cost and logistics of gathering information requiring somewhat sophisticated instrumentation. This includes such parameters as air temperature, wind run, vapour pressure or relative humidity and solar radiation. Ideally these should be measured in the central portion of the lake using rafts or other installations. Commonly however, data is collected from a land station adjacent to the lake, or (more frequently) from a government weather station many kilometres from the study lake. Winter *et al* (1995) showed that substitute data from adjacent and distant stations can in some cases be used to provide acceptable evaporation estimates. Clearly the substitute data and techniques will to a certain extent be site specific.

At Perry East wind and lake surface temperature were collected in the centre of the lake, wet and dry bulb temperatures were collected at the isotope experiment site adjacent to the lake, and solar data was collected at the Swanbourne AWS site 3km to the southwest. Normally wet and dry bulb data are collected over the water surface at typically 1-2m height (Winter *et al* 1995). Shore based data was collected here due to the requirement for daily maintenance of the wet-wick wet bulb thermistor. Equations requiring air temperature (T_a) or parameters adjusted to mean daily air temperature saturated vapour pressure (e_o) and saturated vapour density (SVD), were calculated using the shore based dry bulb data and the lake surface temperature (T_o), taken to represent air temperature just above the water surface.

Empirical methods can be assessed on their ability to accurately estimate evaporation over an extended period , say annually or their ability to estimate evaporation over shorter periods (seasonally, monthly, daily). Apart from the mass transfer method, empirical equations are generally applied without calibration against other techniques. At Perry East equations were ranked on the basis of best 'annual' estimate over 377 days (December 22 1996-January 3 1998, being balance periods 20-50) and best estimate over the individual balance periods (average period 12 days) after equations were calibrated against the floating pan evaporation for the same period.

Table 10.8 Equations Tested for Estimating Potential Evapotranspiration (PET) and Evaporation, Perry Lake East

Method	Equation	Application	Ref
Makkink	$PET = 10[(0.61(s/(s+\gamma))(Q_s/L)) - 0.012]$	Monthly PET (Netherlands)	1
Stephens-Stewart	$PET = 10[(((0.0082T_a) - 0.19)(Q_s/1500))2.54]$	Monthly PET (Florida)	1
Jensen-Haise	$PET = 10[((((0.014T_a) - 0.50)(Q_s))0.000673)2.54]$	PET (Nebraska) >5 days	1
Hamon	$PET = 10[(0.55(D/12)^2(SVD/100))2.54]$	Daily PET	2
DeBruin	$PET = 10[((\alpha/\alpha - 1))1.141(\gamma/(s+\gamma))((3.6 + 2.5(U_3))(e_0 - e_a)))/L]$	PET 10+ days	3
Mass Transfer	$E = 10[NU_2(e_0 - e_a)]$	Evaporation	4
Penman	$PET = 10[[(s/s+\gamma))(Q_n - Q_x) + (\gamma/(s+\gamma))((15.36(0.5 + 0.01U_2))(e_0 - e_a))]/L]$	PET 10+ days	5
DeBruin-Keijman	$PET = 10[((s/(0.95s + 0.63\gamma))(Q_n - Q_x))/L]$	Daily PET	6
Priestley-Taylor	$PET = 10\alpha(s/(s+\gamma))[(Q_n - Q_x)/L]$	PET 10+ days	7
Brutsaert-Stricker	$PET = 10[(2\alpha - 1)(s/(s+\gamma))(Q_n - Q_x) - (\gamma/(s+\gamma))[0.26(1 + 0.86U_2)(e_0 - e_a)]]/L$	Daily PET	8

Where: $s + (s + \gamma)$ and $\gamma / (s + \gamma)$ are parameters derived from s (slope of the saturated vapour-pressure curve) and γ (the psychrometric contant); α is the Priestley-Taylor constant (dimensionless); Q_n is net radiation (cal cm^{-2} d^{-1}); Q_s is solar radiation (cal cm^{-2} d^{-1}); Q_x is change in stored heat within the lake (cal cm^{-2} d^{-1}); U_x wind speed (m sec^{-1}) at height x(m) above the water surface; e_0 is saturated vapour pressure (mb); e_a is vapour pressure at temperature and relative humidity of the air (mb); SVD is saturated vapour density at mean air temperature (g m^{-3}); T_a is air temperature °C (except for Jensen-Haise & Stephens-Stewart equations which require degrees Fahrenheit); L is latent heat of evaporation (cal g^{-1}); N is the mass transfer coefficient (dimensionless); D is hours of daylight at latitude of the lake.

Notes

General format modified from Table 1 of Winter *et al* (1995).
Equations listed from best to worst fit (refer Table 10.10), All equations return E as mm/day
DeBruin, Penman, DeBruin-Keijman and Brutsaert-Stricker in their original form return calories mm^{-2} d^{-1}, division by L returns mm d^{-1}

References: (1) McGuinness & Bordne 1972; (2) Hamon 1961; (3) DeBruin 1978; (4) Harbeck *et al* 1958; (5) Jensen *et al* 1974; (6) DeBruin & Keijman 1979; (7) Stewart & Rouse 1976; Brutsaert & Stricker 1979

Table 10.9 shows evaporation over 377 days using uncalibrated equations. Exact form of each equation is that which produced the best calibrated fit (shown with an asterisk in Table 10.10 and plotted in Figure 10.2). On this long term basis, the Penman and DeBruin-Keijman methods were within 1.1% of the floating pan total with the Penman under estimating by only 1.1mm.

Table 10.9 Annual Evaporation Estimates Using Uncalibrated Equations

Method	Makkink	Stephens-Stewart	Jensen-Haise	Hamon	DeBruin
Total E (mm)	1267.1	1288.8	1667.5	1121.7	613.1
Floating Pan	86.3%	87.8%	113.6%	76.4%	41.8%

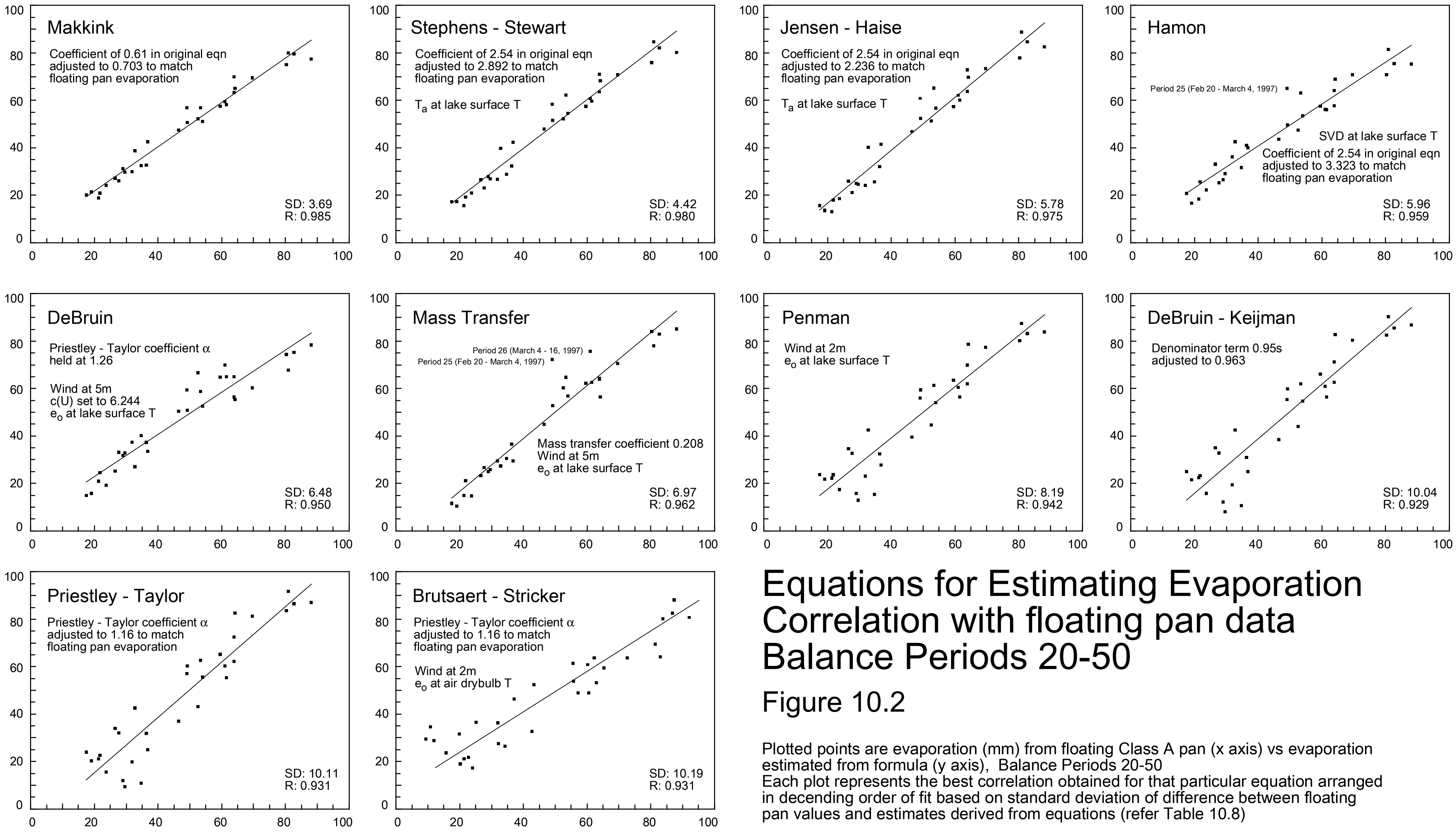
Method	Mass Transfer*	Penman	DeBruin-Keijman	Priestley-Taylor	Brutsaert-Stricker
Total E (mm)	1467.6	1466.5	1483.2	1590.4	1908.1
Floating Pan	100.0%	99.9%	101.1%	108.4%	130.0%

Total evaporation December 22 1996-January 3 1998 (Balance Periods 20-50) compared to floating pan total for this period of 1467.6mm. * Mass Transfer method cannot be compared because it requires calibration of the Mass Transfer coefficient N against an independent calculation of evaporation. The Mass Transfer method thus calibrated can only be compared on a balance period basis.

Comparing methods on a balance period basis essentially shows how well the method copes with seasonal variations. All equations are essentially linear in form and can be adjusted against evaporation measured independently either by adjusting an existing coefficient or introducing a local coefficient of proportionality. Each equation was adjusted to produce a total evaporation of 1467.6mm. Balance period totals were plotted against the corresponding floating pan data (Figure 10.2).

Seasonal fit was measured in two ways. For each method, the difference between the floating pan total and the equation total was computed for each balance period. Methods are ranked in Table 10.10 on the basis of the standard deviation of these differences, the lower the standard deviation, the better the fit. Equations can also be ranked on the basis of the linear regression coefficient of determination which produces a similar (but not identical) ranking. It is evident from Table 10.10 that much better estimates were obtained where T_a or e_o were adjusted to lake surface temperature. Within individual equations the height at which wind data was recorded however was of little practical consequence. Figure 10.2 is a graphical representation of the best fit for each of the ten equations tested.

The extent to which seasonal or other variations contribute to overall correlation was examined by calibrating equations against corresponding floating pan data on a monthly basis (Figure 10.3). It is evident from the graphs and the standard deviations of the monthly coefficients that those equations which displayed the best correlation on a balance period basis also display the smallest seasonal variations. The Mass Transfer method



Equations for Estimating Evaporation
Correlation with floating pan data
Balance Periods 20-50

Figure 10.2

Plotted points are evaporation (mm) from floating Class A pan (x axis) vs evaporation estimated from formula (y axis), Balance Periods 20-50
Each plot represents the best correlation obtained for that particular equation arranged in decending order of fit based on standard deviation of difference between floating pan values and estimates derived from equations (refer Table 10.8)

(Table 10.8) displays diminished correlation during June and July, while the Penman, Debruin-Keijman, Priestley-Taylor and Brutsaert-Stricker all display diminished correlation during July and August where they grossly under estimate evaporation. These last four equations have an underlying common form (Table 10.8) based on net radiation and changes in stored heat (Q_n-Q_x) which at Perry East, provide poor estimates of evaporation during late winter.

Table 10.10 Analysis of Empirical Equations for Estimating Evaporation

Method	Modification	Wind	PT Coeff	N	Coeff 1	Coeff 2	SD	R
Makkink*	none				0.610	0.703	3.69	0.985
Stephens-Stewart*	Ta at lake surface T				2.540	2.892	4.42	0.980
Stephens-Stewart	Ta at air dry bulb T				2.540	3.249	5.19	0.976
Jensen-Haise*	Ta at lake surface T				2.540	2.236	5.78	0.975
Hamon*	SVD at lake surface T				2.540	3.323	5.96	0.959
DeBruin*	eo at lake surface T	5m	1.260		2.5(U)	6.244(U)	6.48	0.950
DeBruin	eo at lake surface T	2m	1.260		2.5(U)	6.971(U)	6.60	0.949
DeBruin	eo at lake surface T	5m	1.094		2.5(U)		6.75	0.948
DeBruin	eo at lake surface T	2m	1.084		2.5(U)		6.96	0.946
Mass Transfer*	eo at lake surface T	2m		0.208			6.97	0.962
Mass Transfer	eo at lake surface T	1m		0.221			6.98	0.962
Mass Transfer	eo at lake surface T	5m		0.018			7.07	0.963
Hamon	SVD at air dry bulb T				2.540	3.851	7.32	0.936
Jensen-Haise	Ta at air dry bulb T				2.540	2.618	7.60	0.965
Penman*	eo at lake surface T	2m				unity	8.19	0.942
Penman	eo at air dry bulb T	2m				1.047	8.99	0.936
DeBruin	eo at air dry bulb T	5m	1.066		2.5(U)		9.44	0.892
DeBruin	eo at air dry bulb T	2m	1.060		2.5(U)		9.50	0.890
DeBruin-Keijman*	none				0.95s	0.963s	10.04	0.929
Priestley-Taylor*	none		1.160				10.11	0.931
Brutsaert-Stricker*	eo at air dry bulb T	2m	1.0855				10.19	0.931
Brutsaert-Stricker	eo at lake surface T	2m	1.0873				10.25	0.931
Mass Transfer	eo at air dry bulb T	2m		0.289			12.13	0.897
Mass Transfer	eo at air dry bulb T	5m		0.258			12.21	0.897
Mass Transfer	eo at air dry bulb T	1m		0.307			12.55	0.889

Notes: PT is the Priestley-Taylor coefficient, N is the Mass Transfer coefficient, Coefficient 1 is original coefficient of proportionality (refer Table 10.8), coefficient 2 is modified form to achieve calibration against floating pan evaporation. SD is standard deviation (difference against floating pan evaporation), R is the linear regression correlation coefficient, U is wind speed. DeBruin-Keijman coefficient requires *s* (slope of the saturated vapour-pressure curve). Equations marked * are plotted in Figure 10.2

Lake top up pumping appears to detract from equation accuracy. The poor mass transfer correlation for balance periods 25 and 26 and Hamon correlation for period 25 (Figure 10.2) are interpreted to be the result of excessive lake top up pumping and measurement of e_a from shore based instruments. Analysis of day to day evaporation showed that mass-transfer values of approximately twice the floating pan values occurred on days when top up pumping occurred. Pumped water is uniformly about 20.7°C. Where pumping occurred over night, average daily lake surface temperatures were elevated, increasing the value of the term $(e_o - e_a)$. This error is further augmented by measuring e_a from the shore where night time values would be less than if measured over the lake. The correlation between pan and mass-transfer data always showed a slope of the regression line >1 indicating that the mass-transfer method on average tended to over

Equations for Estimating Evaporation Seasonal Variations in Correlation

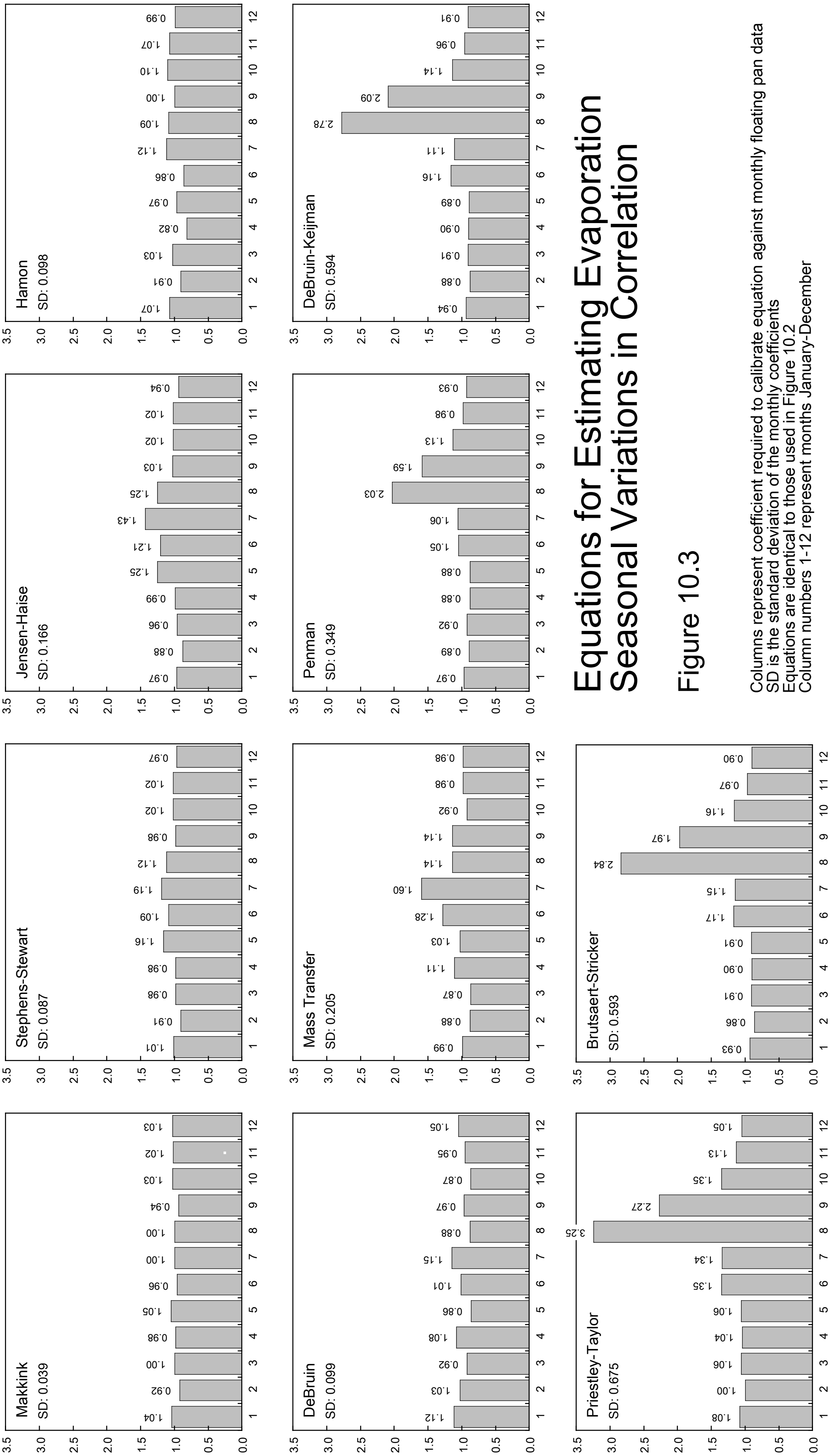


Figure 10.3

Columns represent coefficient required to calibrate equation against monthly floating pan data
SD is the standard deviation of the monthly coefficients
Equations are identical to those used in Figure 10.2
Column numbers 1-12 represent months January-December

estimate evaporation. This may reflect the use of shore based e_a data which on a daily averaged basis is less than the equivalent data collected over the water.

Clearly where wetlands on the Swan Coastal Plain can be instrumented and independently calibrated, empirical methods such as presented by Makkink (McGuinness & Bordne 1972) which display minimal seasonal variation, can provide reasonable evaporation estimates over extended periods.

10.8 NOTES ON IMPLEMENTATION OF EMPIRICAL EQUATIONS

Hamon

A relatively simple method based on solar radiation (estimated from the theoretical maximum hours of daylight) and humidity expressed as saturated vapour density (*SVD*).

$$PET = [0.55\left(D/12\right)^{2}\left(SVD/100\right)]2.54 \tag{10.4}$$

where

D maximum possible hours daylight is $(24/\pi)\omega s$ (10.5)

ωs sunset hour angle in radians, arcos(-tan (site latitude)tan δ) (10.6)

δ solar declination (radians), $0.4093\sin((2\pi/365)J-1.405)$ (10.7)

J is Julian day number

Site latitude is negative in the southern hemisphere. Saturated vapour density (*SVD*) at mean air or water surface temperature (g m^{-3}) was calculated using equation (6.5) of Fritschen & Gay (1979). Daylight hours were calculated from equations (4.4.1)-(4.4.3) of Maidment (1993). *SVD* was calculated from both mean daily air temperature and mean daily water surface temperature which for balance periods 20-50 returned:

SVD @ T_o	1121.7mm	Setting coefficient at 3.32 yields total pan evaporation
SVD @ T_a	968.1mm	Setting coefficient at 3.85 yields total pan evaporation
Floating pan	1467.6mm	

As with the Brutsaert-Stricker method, better results were obtained where air temperature is assumed to be water surface temperature. The Hamon coefficient of 2.54 was adjusted to match total pan evaporation, and yielded good correlation using both methods of calculating *SVD*. The exception again was Balance Period 25 where using *SVD* calculated from shore based air measurements during periods of excessive overnight top up pumping resulted in excessively high evaporation estimates. The Hamon method is extremely simple and when calibrated for a specific wetland appears to provide good estimates with a minimum of instrumentation.

DeBruin

Initial trials using the Priestley-Taylor constant set at 1.26 and wind at any height (1, 2 or 5m) resulted in total yearly values of 30-40% of pan values. This was the poorest correlation using an uncalibrated version of any equation for all methods tested. The original formula uses wind speed at 3m. No attempt was made to interpolate a value for U_3 as the wind profile above Perry East frequently deviates from the theoretical logarithmic wind profile equation (Monteith & Unsworth 1990) because of trees and other obstructions around its perimeter. This was most common in light breezes (wind speed less than about 0.4m sec^{-1}). Under these conditions hourly wind run at 1m and 2m was up to 40% greater than at 5m. The approach taken using the DeBruin equation was to adjust the wind speed coefficient since Perry Lakes is effectively a 'hole' in the tree canopy. Therefore the coefficient 2.5(U_3) in the original equation was felt to be too low. Taking e_o at lake surface T, values of 6.244(U5) and 6.971(U2) were required to achieve calibration (Table 10.10). Almost identical results were obtained adjusting the Priestley-Taylor coefficient α from 1.26 to 1.084 (U_2) and 1.094 (U_5).

The DeBruin plots produce better fits when modelled using polynomial expressions. Evaporation calculated by the DeBruin method during summer are low suggesting that over summer α is also too low. Certainly α does vary both on a daily basis (Katul & Parlange 1992, Parlange & Stricker 1996) and seasonally (DeBruin & Keijman 1979) who found that in Holland α varied from 1.20 to 1.50, with lowest values in mid summer and highest values in spring and autumn. This may contribute to the extreme under estimation of evaporation during August and September in methods such as the Priestley-Taylor and Brutsaert-Stricker.

Mass-Transfer

Detailed analysis of mass-transfer theory are contained in Marciano & Harbeck (1954), Harbeck *et al* (1958). Mass transfer equations relate easily measured meteorological parameters to the exchange of water vapour between a water surface and the atmosphere. The most common form relates evaporation to wind speed and vapour pressure difference. The equation tested at Perry East takes the general form of that developed for Lake Hefner (equation 10.3).

The mass-transfer coefficient N represents numerous difficult to quantify variables including wind variation with height, lake size, water surface roughness, atmospheric stability, barometric pressure and density and kinematic viscosity of the air (Harbeck 1962). The principal practical difficulty with the mass-transfer method is that N tends to be unique to each lake. Calibration requires evaporation to be determined over at least one year by an independent means (typically a thermal balance), *N* being obtained by dividing the independently determined value of evaporation by the product $u_x(e_o - e_a)$. At Perry East *N* was determined using the annual floating pan evaporation over the period December 22 1997-January 3 1998.

Winter *et al* (1995) experimented calculating e_o at air temperature and using air temperature and humidity collected from the centre of the lake and the shore. In that particular study (Williams Lake, Minnesota, area 36 ha) best results were obtained using e_o at lake surface temperature and air and humidity data collected from the centre of the lake. At Perry Lakes air temperature and humidity were collected only from the shore however Perry East is typically <0.1 the area of Williams Lake which suggested that the difference between raft and shore based data was likely to be minimal. Results for the Mass Transfer and other equations however show significantly improved correlation when e_o or T_a are calculated from lake surface temperature, more closely approximating the air temperature over the lake (Table 10.11).

Table 10.11 Comparative Mass-Transfer Results

	U_1, e_o Lake	U_1, e_o Air	U_2, e_o Lake	U_2, e_o Air	U_5, e_o Lake	U_5, e_o Air
Slope m	1.111	1.140	1.117	1.145	1.126	1.150
Pearson's R	0.962	0.889	0.963	0.897	0.963	0.897
M-T coeff N	0.22139	0.30685	0.20813	0.28873	0.18626	0.25784

Where wind is in m sec^{-1} and saturation and partial pressures in mb, these values of *N* provide evaporation in mm. Dividing *N* by 1000 yields evaporation in metres.

Mass transfer appears to be a simple method for long term evaporation measurement from Swan Coastal Plain wetlands, however the small size of these wetlands means that their local climatic influence is limited. Measurements must therefore be taken preferably from the centre of the open water and require independent measurement of evaporation for a minimum of one year (preferably more) to establish the correct mass-transfer coefficient.

Brutsaert-Stricker

This was the only method tested using the term (e_o-e_a) where calculating e_o from lake surface temperature had minimal effect. Using the standard equation with the Priestley-Taylor coefficient (α) set to 1.26, total evaporation (balance periods 20-50) is

$e_o@T_o$	1903.6mm
$e_o@T_a$	1908.1mm
Floating pan	1467.6mm

Total evaporation equals that of the floating pan when the Priestley-Taylor coefficient is set in the range 1.0855-1.0873. The Priestley-Taylor coefficient is generally interpreted as the ratio between the actual evaporation rate and the equilibrium evaporation rate. Field experiments confirm the applicability of the 1.26 value for evaporation from either wet (water bodies) or well watered surfaces (Eichinger *et al* 1996 and references therein). They note that this coefficient will approach unity where saturated air overlies water, a situation common during calm nights at Perry Lakes particularly in spring. It is likely that for small Swan Coastal Plain wetlands, α varies with time of day and season and that the generally accepted value of 1.26 is inappropriate. The method returns negative daily evaporation on some winter days when relative humidity is very high and/or rainfall relatively constant.

10.9 PICHE EVAPORIMETERS

Piche evaporimeters represent a simple, easy to use instrument for estimating evaporation. They consist of a glass tube 30cm in length with 0.1mm graduations, 1cm in diameter and closed at the top. Water within the tube evaporates via a circular disk of blotting paper, typically 8-13cm^2 in area held against the open bottom of the tube. The instrument is installed in a standard Stevenson screen and read daily. Brutsaert (1982) points out that the Piche evaporation rate is difficult to relate to natural evaporation. Being sheltered from solar radiation it responds primarily to humidity deficit and to a lesser extent, wind.

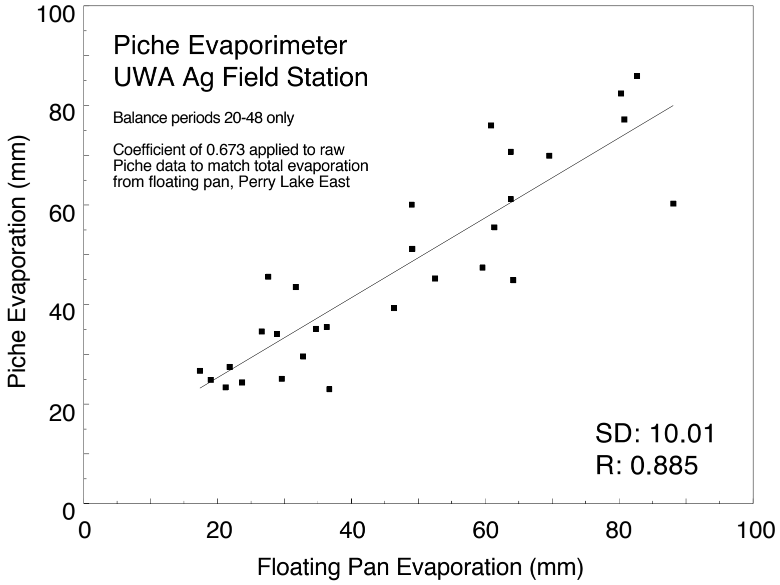


Figure 10.4 Piche evaporimeter vs floating pan evaporation, balance periods 20-48. SD is standard deviation of differences between Piche and pan period totals (compare to equivalent statistics for evaporation using empirical techniques Table 10.10).

Data from a Piche evaporimeter operated at the UWA Agricultural Field Station was compared to floating pan data for 1997, balance periods 20-48 (Figure 10.4). Total Piche evaporation was adjusted using a coefficient of 0.673 to match equivalent pan evaporation. The data indicates that the Piche provides a poor model of lake evaporation, and was inferior to any of the empirical methods tested.

10.10 THERMAL EXPANSION EFFECTS

The thermal expansion of water and measurement reference structures such as concrete dams can be significant in some water balance situations (Harbeck & Kennon 1954). The thermal expansion of water in a lake also works against observing evaporation and evapotranspiration effects. As the day proceeds evapotranspiration draws the level down while thermal expansion has the opposing effect. This is particularly the case in very shallow lakes where the entire body of water is well mixed and heats up more or less uniformly. Table 10.12 shows computed stage change from thermal expansion in East Lake.

Table 10.12 East Lake thermal expansion effects

Stage (m) at 15°C	Volume (m^3) at 15°C	Volume (m^3) at 35°C	Stage Increase (mm) at 35°C
2.800	179.6	180.5	0.24
2.900	913.5	918.2	0.42
3.000	2404.0	2416.3	0.58
3.100	5117.0	5143.1	0.79
3.200	8760.0	8804.7	1.12

The data suggests that in this case thermal expansion is insignificant and probably lies within the reading error of manual stage measurement.