CHAPTER
# 11

# TRANSPIRATION

## 11.0 INTRODUCTION

In this chapter transpiration theory is reviewed along with available data from the Swan Coastal Plain. Results of experimental determination of transpiration from emergent vegetation at Perry Lakes is presented.

Greenwood (1979) noted the difficulties hydrologists have in coming to grips with transpiration. It is silent, invisible and not easily measured by any simple recording instrument. Like evaporation, its driving force is ultimately solar energy. Therefore transpiration varies diurnally and seasonally. Transpiration is ultimately the evaporation of soil water taken up by plant roots and vaporised within the leaf stomata. In wetland water balances it can represent a significant balance component (Winter 1981). Despite its both elusive and illusive nature, transpiration can be determined directly and indirectly using a wide array of techniques (Table 11.1).

Table 11.1 Transpiration measurement techniques classified by time and space

| | Minute | Hour | Day | Month | Year | Decade |
|---|---|---|---|---|---|---|
| Region | | | Micro meteorological techniques | | | |
| | | | Mass / solute and isotopic water balances | | | |
| Catchment | | | | Precipitation / stream discharge | | |
| | | Eddy correlation | | Hydrograph separation | | |
| | | | Mass/solute and isotopic water balances | | | |
| Uniform area | | | Diurnal water table fluctuations | | | |
| | | | Energy Budget | | | |
| | | | | Hydrograph separation | | |
| Group of plants | | | Neutron soil water depletion | | | |
| | | | Weighing & drainage lysimeter | | | |
| | | Ventillated chamber | | | | |
| | γ ray | | | | | |
| Plant | | Dendrometer | | | | |
| | | Cut tree | | | | |
| | | Sap flow (heat pulse, isotope methods 32P, tritium) | | | | |
| Shoot | Bending branch | | | | | |
| | Cut shoot | | | | | |
| | | Cuvette & Humidity chamber | | | | |
| Leaf | Porimeter | | | | | |
| | Leaf weight | | | | | |

Modified from Stewart 1984

## 11.1 SWAN COASTAL PLAIN DATA

Recharge to the unconfined aquifer is derived primarily from rainfall (Davidson 1995). However most rainfall never reaches the aquifer as recharge but is returned to the atmosphere as transpiration from perennial vegetation and evaporation from soil (Allen 1981). Regional estimates of total rainfall lost to evapotranspiration are summarised in Table 11.2. At a local scale however these regional estimates cannot be applied. Sharma & Pionke (1984) cited Davidson (1995) noted that while average recharge over the Gnangara Mound was about 12%, nil recharge was occurring beneath mature pine plantations, while near the crest of the Gnangara Mound Thorpe (1989) estimated 21% recharge using tritium as a recharge indicator. In the same area Farrington & Bartle (1988) using water and chloride balances of *Banksia* woodland estimated 20-22% recharge. In native bushland within King's Park, McFarlane (1984) using a neutron probe found nil recharge at three sites during 1982.

Table 11.2 Recharge and Evapotranspiration Estimates, Swan Coastal Plain

| Area & GW Mound | Method | Recharge[1] | ET[2] | Reference |
|---|---|---|---|---|
| Mirrabooka, (Gnangara) | Pump test, water balance | 7.3 | 806 | Bestow 1970 a&b |
| Western Gnangara | Water balance | 8.5 | 804 | Allen 1975 |
| Gnangara Mound | Cl balance | 11.5 | 769 | Allen 1981 |
| Jandakot Mound | Flow net analysis | 11.9 | 766 | Davidson 1984 |
| Jandakot Mound | Water balance | 5.5 | 821 | Allen 1975 |
| Lexia (Gnangara) | Flow net analysis | 13.0 | 756 | Davidson 1987 |

1: as percentage of annual rainfall, 2: assuming average rainfall of 869mm

It is evident that over much of the Gnangara Mound most rainfall never reaches the unconfined aquifer. It is lost either as direct evaporation from leaf capture, as evaporation from the soil or is transpired by plants from the vadose zone. Regionally these annual losses approach annual rainfall.

## 11.2 WETLANDS

Evaporation and transpiration contribute considerably to the difficulties in determining water budgets for wetlands. Typically such wetlands show wide seasonal variations in presence or absence of surface water or saturated soils and over periods of decades or less, large changes in the distribution of wetland vegetation. Shallow wetlands frequently include large zones of marshy emergent vegetation where water losses to the atmosphere include evaporation from the water surface and transpiration, both of which occur at different rates and both of which are difficult to quantify (Shih 1980). Hence they are typically dealt with in combination, the quantity known as evapotranspiration (Rijtema 1965). Evapotranspiration from wetlands may vary according to species, cover density, climate and phenology (Carter 1986).

Swan Coastal Plain damplands and sumplands represent special cases where the water table is at or close to the surface. Here vegetation tends to be exclusively phreatophytic, drawing water directly from the unconfined aquifer. Within the littoral zone of wetlands macrophytes are seasonally flooded. During winter inundation transpired water is drawn directly from the water column and from the underlying sediments and evaporation occurs directly from the inter plant water surface. In summer losses are directly from the aquifer as transpiration and surface evaporation via soil suction.

At Perry Lakes the two dominant emergent macrophytes are bulrush (*Typha orientalis*) and jointed twig-rush (*Baumea articulata*). These occur as virtual monocultures in large stands in both East and West Lake (Figures 3.1 & 3.2). In East Lake *Typha* mixed with scattered flooded gum (*Eucalyptus rudis*) form a near monoculture within sumpland forming the northeast quadrant of the lake basin. In West Lake vigorous stands of *Baumea* have colonised the eastern quadrant of the lake basin since 1995 in response to an altered hydrological regime (Chapter 3). The East Lake *Typha* meadows lie outside the flooded perimeter of the lake except during the most intense late winter storms. The West Lake *Baumea* meadows are similarly isolated over summer. These areas were therefore considered suitable for estimates of evapotranspiration using simple hydrograph techniques.

## 11.3 ESTIMATES OF *TYPHA* EVAPOTRANSPIRATION

The literature contains widely divergent conclusions on the question of total water loss (*i.e.* evapotranspiration) from wetlands containing helophyte meadows compared to simple open water evaporation. Kuznecov (1949) and Kiendl (1954), both cited Bernatowicz *et al* (1976), suggested ratios of 1.5-3.0 for northern hemisphere wetlands, concluding that transpiration by helophytes is much greater than evaporation from an identical area of open water. Other reviews such as Carter *et al* (1979) cited Carter (1986) indicate a range from 0.5 to 5.3 times pan evaporation for different wetland vegetation at various times during the growing season. Experimental error is believed to account for many of the more extreme results, in particular those obtained using lysimeters operated on dry ground where the 'oasis' effect artificially accelerates transpiration rates Koch & Rawlik (1993) and references therein.

Evidence from large temperate and tropical wetlands suggests that in general, vegetation decreases evaporation from open water surfaces (Idso 1981; Koch & Rawlik 1993). In North Dakota, Eisenlohr (1966) found that for small 'prairie potholes' with mixed emergent species including *Typha augustifolia, T. glauca* and *T. latifolia* evaporation rates were 0.7 to 0.8 that of open water over two seasons. In Australia,

Linacre *et al* (1970) demonstrated that within a large *Typha orientalis T. domingensis* swamp in the Murrumbidgee, vegetated areas lost water at rates significantly lower than nearby open water. This trend was reversed only immediately after rain. Kadlec (1993) similarly reported dense emergents reduced water loss compared to open water in ten small marshes in Canada.

Such studies are difficult to compare. They are dominantly from the northern hemisphere encompassing widely varying climatic conditions and *Typha* species. Many measure only the transpirative component while others combine transpiration and open water losses. Brief studies typically employ tissue water content or vapour chamber methods which physically isolate plants or plant parts (possibly under unrealistic micro-climatic conditions). Longer studies use lysimeters, evaporation pans and micro meteorological methods. They fall into two principal categories:

- those where measurements occur within natural meadows of the macrophyte under study and include measurements of evaporation from adjacent open water
- those where measurements occur on dry land or under laboratory conditions and where 'open water' tended to be a pan evaporated under 'similar conditions' to the study area

Table 11.3 summarises these studies. Those of the first type typically involved micro meteorological methods but included pans and lysimeters operated within natural plant meadows ('Plants in situ' designation in Table 11.3). Studies of the latter type typically employed pans or lysimeters operating under what were clearly non wetland meteorological conditions. As a general rule studies operated under natural conditions typically display Novikova Indices <1 indicating that evapotranspiration in macrophyte meadows under flooded conditions is less than evaporation from open water under equivalent conditions. Conversely in experiments carried out on land the Novikova Index is typically >1. Anderson & Idso (1987) concluded that the large differences in Novikova Indices between natural sites and tanks is partially explained by canopy surface geometry. In very small tanks the peripheral surface comprises a significant percentage of the total vegetated surface area. As tank diameter increases, the Novikova Index decreases (refer footnote, Table 11.3). They note that the same principle applies to very small natural wetlands.

Studies of a few days duration are difficult to compare with continuous studies spanning months or years. Generally those carried out under 'in situ' conditions also tended to be of longer duration and are therefore considered more reliable. Finally, all studies assumed *Typha* to be growing under flooded conditions despite the fact that it can thrive for extended periods of up to many years under non flooded conditions (Froend *et al* 1993).

Transpiration and Evapotranspiration studies on *Typha* sp

Table 11.3

| Location | *Typha* species | Methodology | Plants In situ | T flood (mm) | ET flood (mm) | e (mm) | ET dry (mm) | Open Water E (mm) | Novikova Index | Period | Reference | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Kazakhstan | *augustifolia* | unknown | Yes | 247 | | | | 581 | 0.71-0.73 | 2 seasons | Novikova 1963 cited Bernatowicz *et al* 1976 | Original in Russian |
| Poland | *latifolia* | phytometer | No | 470 | 626 | 156 | | 430 | 1.45 | 1972 | Bernatowicz *et al* 1976 | 0.3m$^2$ phytometers submerged within natural |
| | | | No | 460 | 712 | 252 | | 430 | 1.65 | 1973 | | *Typha* meadow |
| Poland | *augustifolia* | phytometer | No | 395 | 551 | 156 | | 430 | 1.28 | 1972 | | Considered not to be in situ due to restricted size |
| | | | No | 608 | 860 | 252 | | 430 | 2.00 | 1973 | | |
| Poland | *latifolia* | phytometer | No | | | | 1305 | 430 | 3.03 | 1972 | Bernatowicz *et al* 1976 | 0.3m$^2$ phytometers on land in open area |
| | | | No | | | | 1028 | 430 | 2.39 | 1973 | | Considered not to be in situ due to restriced size |
| Poland | *augustifolia* | phytometer | No | | | | 1182 | 430 | 2.75 | 1972 | | and location in clear ground |
| | | | No | | | | 822 | 430 | 1.91 | 1973 | | |
| Florida | *domingensis* | lysimeter | Yes | | 1423 | | | 1270 | 1.12 | 303 days | Abtew & Obeysekera 1995 | 9.8m$^2$ lysimeter installed within *Typha* marsh |
| N. Dakota | *augustifolia, glauca & latifolia* | mass transfer | Yes | 213 | 548 | 335 | | 792 | 0.69 | 1963 | Eisenlohr 1966 | Pothole #8 Data covers period May-October |
| | | | Yes | 152 | 548 | 396 | | 701 | 0.78 | 1964 | | Pothole #8 |
| | | | Yes | 335 | 609 | 274 | | 701 | 0.87 | 1964 | | Pothole #5A |
| NSW | *orientalis & domingensis* | micro meteorology | Yes | | 15.8* | | | 24.5* | 0.65 | 4 days | Linacre *et al* 1970 | * E expressed as heat flux (mW cm$^2$) |
| India | *augustifolia* | evaporation tanks | No | 24 | 113 | 89 | | Not reported | | 15 days | Brezny *et al* 1973 | Open water evaporation not measured |
| | | | No | 315 | 781 | 466 | | Not reported | | 35 days | | 0.36m$^2$ concrete tanks on land |
| | | | No | 332 | 864 | 532 | | Not reported | | 27 days | | Comparison of ET/e suggests typical oasis effect |
| Alabama | *latifolia* | evaporation tanks | No | Not reported | | | | | 1.62 | 6 months | Snyder & Boyd 1987 | Open water evaporation not measured<br>5.8m$^2$ tanks on land, probable oasis effect<br>T+e/E varied from 1.41 to 1.84 (average 1.62) depending on fertilizer treatment |
| Arizona | *latifolia* | evaporation tanks | No | Not reported | | | | | 2.8-3.5 | 4 years | Anderson & Idso 1987 | Open water evaporation not measured<br>4.15m$^2$ tanks on land, oasis effect operative |

Novikova Index: (T+e)/E
where T is transpiration, e is evaporation from water surface among plants, E is evaporation from open water
(T+e) = ET

## 11.4 ET ESTIMATES FROM SUMPLANDS AT PERRY LAKES

### 11.4.1 Theory

Groundwater levels below phreatophytes typically fluctuate diurnally in a harmonic form. These fluctuations can provide estimates of daily water uptake by plants (White 1932, Troxell 1936, Todd 1959, Meyboom 1967, Farrington *et al* 1990). The method assumes constant lateral groundwater flow, in which inflow (as groundwater) and outflow (as evapotranspiration) is integrated, represented by the diurnal cycle. At sunrise evapotranspiration commences and the water table begins to fall (Figure 11.1b) as water loss exceeds inflow. The rate of fall peaks in early afternoon, then diminishes towards sunset as inflow eventually equals and then exceeds losses. Between sunset and dawn, inflow continues and the water table rises. Over night transpiration is essentially nil the only losses being minor evaporation from the soil surface. The rate of rise peaks, generally between midnight and about 04:00 hours. White (1932) assumed that during the period of maximum rise evapotranspiration can be considered nil. Taking this rate as the average for the day, then an approximation of total groundwater discharge becomes

$$Q_{ET} = S_y(24h \pm s) \qquad (11.1)$$

where

$S_y$ specific yield within the zone of water table fluctuation
$24h$ maximum overnight rate of water table rise applied over 24 hours
$s$ net fall or rise of the water table over 24 hours

Meyboom (1967) suggested that the $S_y$ value should reflect 'readily available' specific yield, this being the yield available over the first 24 hours. The 'readily available' yield of 0.0069 used for the clay lining at Perry Lakes represents only 28% of true specific yield (measured over 59 days) of 0.024 (Chapter 3).

Figure 11.1b illustrates the relationship between diurnal fluctuation and water volume transpired. Dolan *et al* (1984) and Rushton (1996) utilised modified forms of this method to measure wetland evapotranspiration in Florida. Farrington *et al* (1990) working on the Swan Coastal Plain found that evapotranspiration calculated by water table fluctuations correlated well with data from ventilated chambers for six days between November and March (r = 0.90). The *Typha* and *Baumea* meadows at Perry Lakes are 'uniform areas' (Table 11.1) which were considered ideal for the application of diurnal water table techniques. The water table is consistently within about 0.8m of the surface, and the equipment required is simple and capable of continuous monitoring.

### 11.4.2 Field Set Up and Method

In East Lake three wells were constructed within non inundated *Typha orientalis* meadow. Wells were spaced approximately 1.2m apart and constructed by sludge pump from fully slotted 50mm PVC (Figure 11.1a). Here palaeolake silts and clays about 2.5m thick overly sands. Wells W26 and W26b were terminated within the lining sediments at 1.8m. W26a penetrated the lining sediments and was terminated at 3.0m depth within the sands.

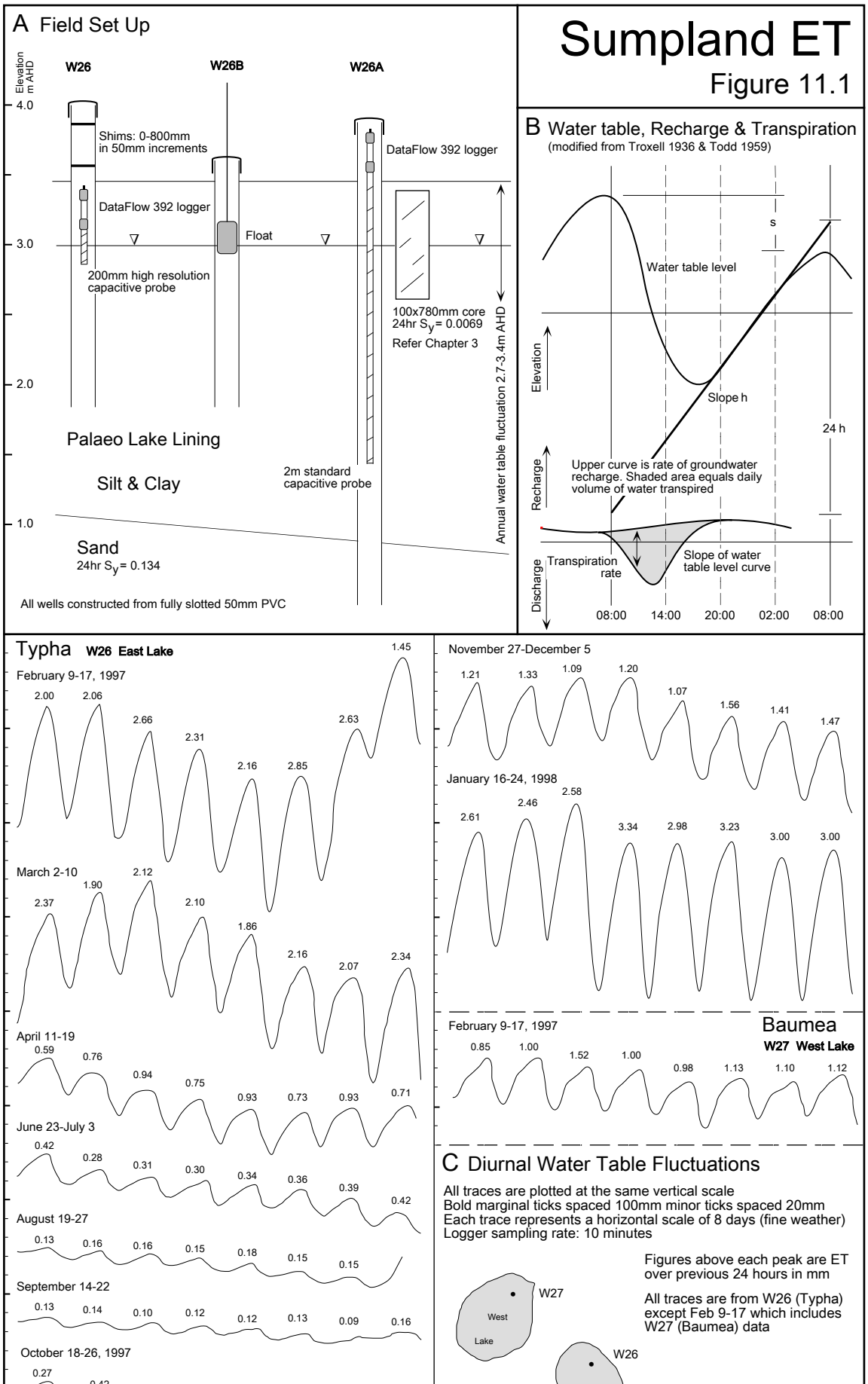
Over a year the water table fluctuated approximately 800mm within the upper portion of the lining sediments. W26 was fitted with a high resolution capacitive water level probe originally designed for detailed measurements in evaporation pans. This probe had an element length of 20cm and resolution of ±0.2mm. A set of 20 PVC shims cut in 50mm increments were inserted as needed to maintain diurnal variations in water level within the central portion of the probe. W26b was fitted with a float gauge which could be read daily to determine when W26 required shim adjustment. W26a was fitted with a standard 2m capacitive probe as part of the regional water table monitoring network.

Initial tests indicated that while similar ET estimates could be obtained from W26 and W26A, the deeper well was strongly affected by irrigation bore draw downs. The silt-clay lining appeared to buffer these fluctuations rendering hydrographs from W26 which were much easier to interpret. Data was collected from mid November 1996 to February 1998. The clays have a 'readily available' specific yield which is about 5.1% that of the adjacent aquifer sands (0.0069 vs 0.134). This low specific yield has the advantage of exaggerating the amplitude of the diurnal fluctuations facilitating easier interpretation. A vertical in situ core of sediment 780mm in length was extracted for specific yield measurements (Figure 11.1a). The core length was equivalent to the amplitude of annual water table fluctuation. Refer to Chapter 3 for details of the specific yield measurements.

In West Lake W27 was constructed within a dense, vigorous *Baumea articulata* meadow (*Baumea* height approximately 3.0-3.5m). This area is inundated over winter and damp over summer. Data was collected over February and March 1997. W27 was fitted with a high resolution probe and shims identical to W26. The geological section comprised 0.7m of silt-clay lake lining over sands. W27 was sludged to 2.2m, and terminated within the sands. This site was sufficiently distant from irrigation bores to preclude significant draw down effects.

# Sumpland ET

Figure 11.1



### 11.4.3 Hydrograph Interpretation

Hydrographs were plotted at a vertical scale of 1:1. In summer daily harmonic amplitude is typically 100-120mm within the clays. In late winter this is attenuated by an order of magnitude to 10-12mm. During and after rain no data was collected due to air entrapment effects from the downward moving wetting front (Wilson & Luthin 1963, Bianchi & Haskell 1966). The parameters *24h* and *s* were scaled off manually. Figure 11.1c shows the seasonal variation in typical hydrograph traces including comparison of *Typha* and *Baumea* meadows. Results are summarised in Table 11.4.

These figures for *Typha* were all carried out under non flooded conditions and are less than other studies where natural meadows were studied over a full growing season under flooded conditions such as Eisenlohr (1966) 548-609mm (North Dakota). The Perry Lakes data is not dissimilar to Swan Coastal Plain dampland data from Lake Pinjar (Farrington *et al* 1990) collected by ventilated chamber over mixed shrub species (Table 11.4). Wronski (1986) obtained similar results from dampland *Banksia* woodland in the same area (daily average 1.4mm) using capillary fringe solute balances over 108 days in summer.

Table 11.4 Open water E and macrophyte ET, Perry Lakes & Lake Pinjar

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Floating Pan | 192.9 | 135.1 | 139.4 | 82.4 | 65.2 | 41.5 | 53.3 | 69.6 | 86.9 | 144.9 | 154.1 | 204.5 |
| Daily average | 6.2 | 4.8 | 4.5 | 2.8 | 2.1 | 1.4 | 1.7 | 2.3 | 2.9 | 4.7 | 5.1 | 6.6 |
| *Typha* total | 89.6 | 55.2 | 57.0 | 25.8 | 19.2 | 10.8 | 9.9 | 5.6 | 3.9 | 10.6 | 33.0 | 62.0 |
| Daily average | 2.9 | 2.0 | 1.8 | 0.9 | 0.6 | 0.4 | 0.3 | 0.2 | 0.1 | 0.3 | 1.1 | 2.0 |
| *Baumea* total | | 28.3 | 25.1 | | | | | | | | | |
| Daily average | | 1.0 | 0.8 | | | | | | | | | |
| Lake Pinjar | 60.4 | 40.3 | 30.4 | 33.0 | 31.0 | 40.2 | 40.9 | 38.7 | 65.7 | 76.6 | 139.2 | 92.1 |
| Daily average | 2.0 | 1.4 | 1.0 | 1.1 | 1.0 | 1.3 | 1.3 | 1.3 | 2.2 | 2.5 | 4.6 | 3.0 |

All values in mm, all data 1997 except January which is 1998. *Typha*: 262 days of data, *Baumea*: 53 days
Lake Pinjar data modified from Farrington *et al* 1990, data collected 1987-1988.

| | | |
|---|---|---|
| Annual ET from *Typha* sumpland, Perry East: | 383mm | |
| Annual open water evaporation, Perry East: | 1385mm | |
| Annual ET from Lake Pinjar dampland: | 688mm | |
| Summer (Dec-Feb) ET East Lake *Typha* | 207mm | (data 1997-1998) |
| Summer (Dec-Feb) ET Lake Pinjar dampland | 193mm | (data 1987-1988) |

### 11.4.4 *Typha* and *Baumea* Annual Cycle

On the Swan Coastal Plain *Typha orientalis* dies back over autumn and re-shoots in spring. Plants flower December-January, with green seeds set in February and shed as plants die back during March-June (Froend *et al* 1993, Chambers *et al* 1995). In the

Perry East meadows, new shoots were evident in early August, seed heads fully formed in early January, initial senescence (leaves browning) was evident by early February, and approximately 50% of leaves were dead by mid April with seed shedding under way. This pronounced annual cycle is evident in the data (Table 11.4 & Figure 11.1c) with minimum measured evapotranspiration during September being only 4.5% of that in January. In comparison Lake Pinjar native broadleaved perennials displayed much greater winter evapotranspiration. The summer data when *Typha* is growing most vigorously is very similar to that obtained for the Lake Pinjar damplands.

*Baumea articulata* remains green all year, flowering between September and November, green seeds are set December-January and seeds shed February-March (Froend *et al* 1993). The *Baumea* evapotranspiration rates determined here for February and March are considered less than the maximum which probably occurs during December and January.

## 11.5 CONCLUSIONS

All of the Perry Lakes transpiration estimates were from plants growing under non flooded conditions. While both *Typha* and *Baumea* spend considerable periods of each year under flooded and non flooded conditions it is naive to assume that transpiration under both regimes is the same. Experimental evidence (Table 11.4) clearly indicates that:

- for *Typha* spp (and most probably other dense tall macrophytes such as *Baumea*), total evaporative loss (ET) under flooded conditions is less than open water under similar conditions
- for the same plant species under non flooded conditions ET is most likely further attenuated due to reduced wind, shading and water availability

This is consistent with Woo & Rowsell (1993) who continuously monitored ET from non inundated wetland vegetation (bulrush *Scirpus acutus* & *S. paludosus*) fringing open water within Saskatchewan prairie sloughs. Over five months the non inundated ET was consistently less than that of the open water. Our measurements for both *Typha* and *Baumea* were under non inundated conditions. It is expected that the same meadows under flooded conditions would return somewhat greater ET values but these would still be less than open water evaporation as measured by the floating pan. Therefore the evaporation values used in the water balances are probably slight over-estimates.

The area of inundated *Baumea* within East Lake was approximately 10,000m$^2$ at 3.4m stage (Figure 3.1). Table 11.5 shows the change in water loss at typical open water (floating pan) evaporation rates at theoretical rates of evapotranspiration from inundated *Baumea* meadow.

Table 11.5 Theoretical effect of *Baumea* ET on East Lake water balances

| E(mm) | Ratio ET:E 0.5 | 0.6 | 0.7 | 0.8 | 0.9 | Unity |
|---|---|---|---|---|---|---|
| 2.0 | 96.9 | 98.9 | 100.9 | 102.9 | 104.9 | 106.9 |
| 4.0 | 193.8 | 197.8 | 201.8 | 205.8 | 209.8 | 213.8 |
| 6.0 | 290.6 | 296.6 | 302.6 | 308.6 | 314.6 | 320.6 |
| 8.0 | 387.5 | 395.5 | 403.5 | 411.5 | 419.5 | 427.5 |
| 10.0 | 484.4 | 494.4 | 504.4 | 514.4 | 524.4 | 534.4 |

All ratio data (columns 2-7) are volumes ($m^3$)

In Table 11.5 volumes are evapotranspiration within a 10,000$m^2$ meadow of *Baumea* plus evaporation from the remaining 43,440$m^2$ of open water at different ratios of ET:E within the *Baumea*. Where ET=E (right hand column), volume is equivalent to open water evaporation from the entire lake surface. At 3.4m stage, lake volume is approximately 18140$m^3$. Where ET:E is 0.5, the *Baumea* reduces evaporated water volume by 9.3% representing 0.055% to 0.27% of total lake volume at open water evaporation rates of 2.0-10.0mm $d^{-1}$. Transpiration from native emergent vegetation is therefore an inconsequential component and has not been incorporated in the East Lake mass balances. It is possible however that greater (unmeasured) losses occur from European poplars and willows drawing directly from the lake.