LOSS OF STORAGE WATER DUE TO EVAPORATION

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Contents

1 INTRODUCTION

1.1 Water loss due to evaporation

With increasing environmental concern and concentration upon irrigation water use efficiency, there is now considerable pressure upon us all to optimize as far as possible the use of our most precious resource - water. The rate of evaporation is in excess of 2m per year over most of Australia's landmass and mean rainfall in Australia is less than 500mm per year and falling. On such a hot dry continent, it has been estimated that up to 95% of the rain which falls in Australia is re-evaporated and does not contribute to runoff.

Water when harvested is commonly stored in small storages and dams, but it is estimated that up to half of this may be lost due to evaporation. This represents a huge waste of our resource. The price and value of water increasing dramatically and the scarcity of water is the main limiting factor working against agricultural production in Australia.

Australia has approximately 500 large dams with a combined capacity of 80 000 GL, roughly equivalent to four times the annual amount of surface water diverted (NLWRA, 2001b). Australia has several million farm dams which account for an estimated 9% of the total water stored, or approximately 7000 GL (Environment Australia, 2000). Assuming that these small dams on average contain water only 50% of the time, and assuming that 40% of this is lost due to evaporation, it can therefore be roughly argued that the total agricultural water lost to evaporation is probably around 1400 GL. There is great uncertainty in this figure however, as the last two quantities are largely unknown. A scoping style research study is urgently required to obtain more accurate and quantitative data in this area.

The amount of water lost due to storage evaporation depends upon many factors including atmospheric evaporative demand, the size of the water storage and storage method. There have been many attempts to reduce evaporation losses by altering how the water is stored. Water loss from storage dams can firstly be managed by increasing their depth and secondly by installing a good quality liner to prevent seepage. Destratification (ref) ie. circulation of cold bottom water has been used successfully in deep storages (>20m) but is inappropriate in most agricultural storages which are generally less than 7m deep. Windbreaks can also be used in certain circumstances, but their overall effect in reducing evaporation is likely to be small, as solar radiation rather than wind is the key driver of evaporation.

With increasing price of water, a realistic management option is to invest in a cover over the dam to reduce evaporation. The National Centre for Engineering in Agriculture (NCEA), University of Southern Queensland (USQ) has been recently involved in a DNR (RWUEI) funded project to assess the relative effectiveness and economic viability of different types of cover for storage evaporation control. The control methods investigated include chemical monolayers, floating covers and shade structures (Craig et al 2004). To evaluate the relative strengths and weaknesses of each evaporation reduction method, accurate methods for measuring actual evaporation loss were developed as part of the project. A brief description of the method is also included in this review.

1.2 Definitions of evaporation

The definitions below are based on those given by Morton (1983) - taken from Bureau of Meteorology website :-

Areal actual ET
This is the ET that actually takes place, under the condition of ***existing water supply***, from an area so large that the effects of any upwind boundary transitions are negligible and local variations are integrated to an areal average.

Areal potential ET
This is the ET that would take place, under the condition of ***unlimited water supply***, from an area so large that the effects of any upwind boundary transitions are negligible and local variations are integrated to an areal average.

Point potential ET
This is the ET that would take place, under the condition of unlimited water supply, from an area so small that the ***local ET effects do not alter local airmass properties***. It is assumed that latent and sensible heat transfers within the height of measurement are through convection only.

Point potential ET by definition is the ET from a 'point' with unlimited water supply. An example is a very small irrigated field surrounded by unirrigated land. By definition, point potential ET is very similar to the Penman-Monteith potential ET. The latter, although defined for a large area, also assumes that the actual ET does not affect the overpassing air. However, the estimates of the two are not quite the same because they are calculated differently.

ET maps provided by the Bureau of Meteorology are not intended for use in estimating open-water evaporation. Analysis techniques recommended in well-known hydrological texts dealing with open-water bodies should be used. However, ***point potential ET may be taken as a rough preliminary estimate of evaporation from small water bodies such as farm dams and shallow water storages***.

1.3 Evaporative loss of water in the context Australian agricultural production

Over the last few years, Australian consumption of water has varied between dry and wet years from about 14000 and 24000 GL/yr – the figure depends on water availability which can be highly variable from year to year. Approximately 65-75% of total water consumption is used for irrigated agriculture (Figure 1). These percentages vary significantly from year to year but have declined significantly over the past decade. This is thought to be due to a global climate change driven trend to towards reduced rainfall into the future.

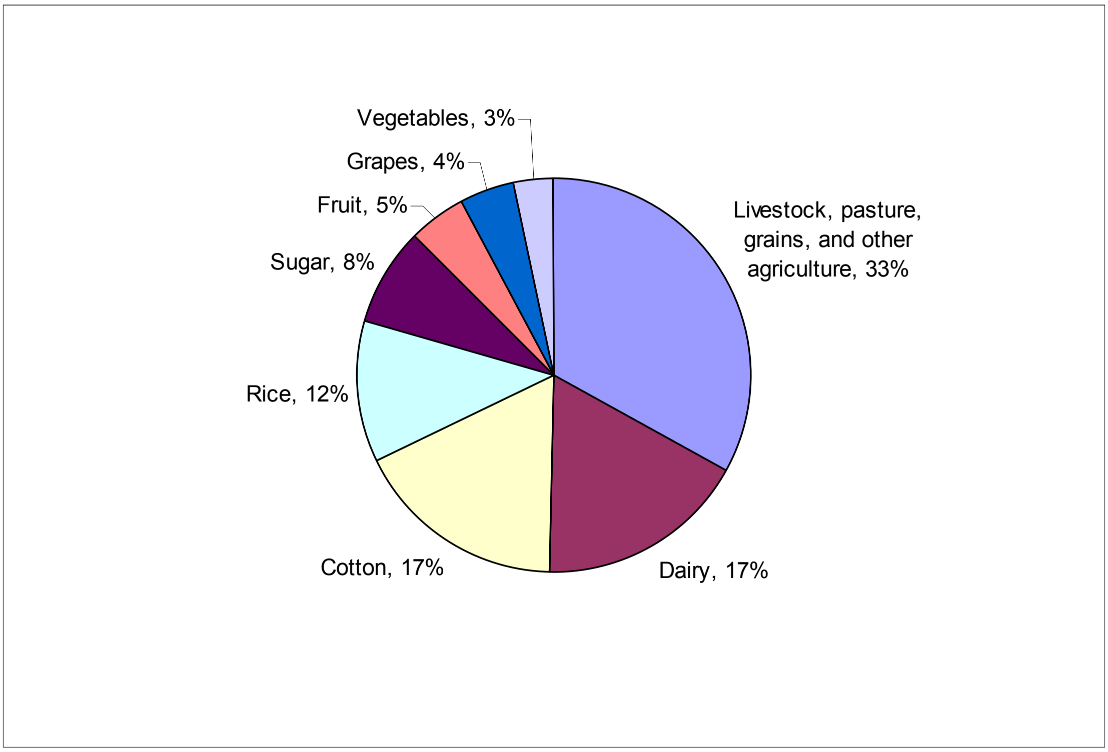

Figure 1 Approximate mean use of agricultural water in Australia (derived from ABS Water Account, Australia, 2000-01 and ABS Water Use on Australian Farms, 2003-04)

2 DIFFERENT TYPES OF COVER

2.1 Continuous plastic sheet

Floating covers in general act as an impermeable barrier that floats on the water surface to reduce evaporation. Many different materials have been trialled in the past including wax, foam and polystyrene, but polyethylene plastic has proved to be the most satisfactory and durable material for covers of this type.

Figure 2 Plastic cover (E-VapCap®) newly installed at Moons Farm, St. George

The above photograph (Figure 2) was taken from the air and shows the newly installed Evaporation Control Systems E-VapCaps® product covering Moons dam near St. George. The plastic material onsists of a unique, multi-layered, polyethylene membrane 540 micons in thickness. The material contains buoyancy cells, similar to bubblewrap or existing swimming pool cover products, but is made from much tougher material to resist degradation from sunlight. The multi-layering enables it to reflect some of the sun's heat as the top of the material is white, while the under layers are black, completely eliminating the transmission of light to the water underneath. The material is environmentally safe – the polyethylene used is commonly used in food packaging and storing and can be recycled at the end of itsusefulness as a cover, whenever that may be. Tests have demonstrated that when well managed it is over 95% effective in reducing evaporation from open storages. There are now a number of covers that have been installed on water storages in SW Queensland, using specialised equipment designed and built for the installation of covers on water. Existing test sites include, Meandarra, Stanthorpe, Barossa and NorthStar feedlot.

2.2 Suspended covers

Shade structures in general are suspended above the water surface using cables. The photograph below (Figure 3) shows Netpro black monofilament shadecloth supported by steel cables tensioned to 1500kg and attached to cement blocks set 2 metres into bank. The cloth is available in a range of % UV reduction ratings. The cable structure has a design life in excess of 30 years, and the shadecloth may or may not have to be replaced once during this period, depending upon the extent of storm damage over the period. Hail shoots or valves can be installed into the cloth to reduce damage potential.

Figure 3 Shadecloth cover installed at Andreatta's Farm, Stanthorpe

Shade structures reduce solar radiation, wind speed and trap humid air between the structure and the water surface, which are all factors that effect evaporation. Shadecloth can handle water being emptied from the dam, as the cover is not in contact with the water. In general, shade structures are not quite as effective in reducing evaporation as well managed plastic covers, but they are likely to suffer fewer problems. As the cloth is suspended it dries out quickly after rainfall. This means that wind blown soil does not collect on the surface (it either blows off or falls through) and the growth of weeds or algae on the cover surface is therefore very unlikely.

Shade structures are economically feasible for small storages less than 10 hectares in size, although rising price of agricultural water may allow installation over larger agricultural storages. The main disadvantage of this product is the relatively high capital outlay (mainly labour cost for construction) but this has now been offset with a new shadecloth knitting machine located in Malaysia which will produces a much wider roll and would therefore involve the installation of fewer cables. More research also needs to be carried out into the aerodynamics of suspended structures in high windspeeds. A limiting factor may be the ability to satisfactorily anchor the cables in poor quality soils.

2.3 Modular covers

Modular covers are similar to continuous plastic covers except that they comprise multiple individual units which are not restrained and are free to move across the water surface. Installation is therefore in theory less expensive than for continuous cover types. The evaporation reduction performance from modular covers will depend on how tightly the modules pack together, and therefore may be in general slightly lower than for continuous plastic floating cover types. Existing prototypes include a circular design (AquaCaps), a (Water Innovations), and a rectangular design (Raftex, Integrated Packaging)

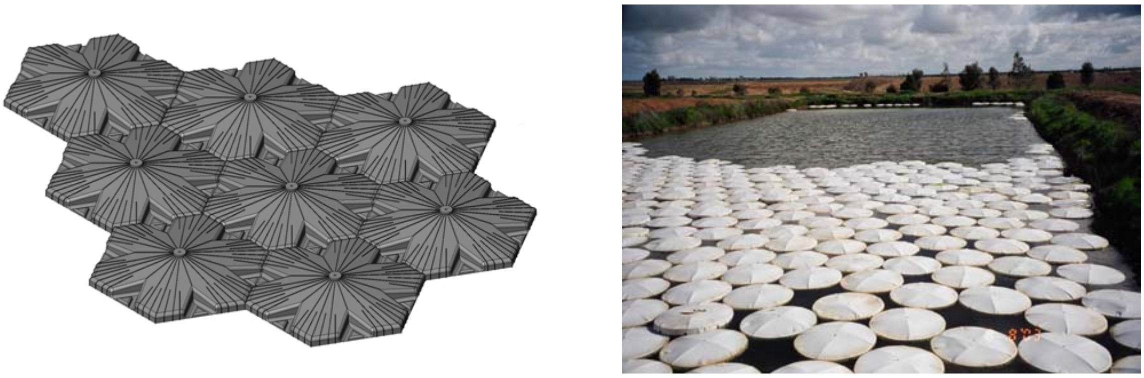

Figure 4 Two types of modular cover, a hexagonal design (AquaGuard®, left) and a circular design (AquaCaps®, right)

As each module is small in size, thousands of modules are required to cover the storage. At present the AquaCaps module is being evaluated for the protection of water used in the mining industry and the Water Innovations module is being evaluated for the protection of urban water.

As modules do not cover 100% of the surface, their evaporation saving performance will be correspondingly less than 100%. However, as they are free floating they will travel with the wind to the downwind margins of the dam and this is often where the warmest water is and where the highest evaporation occurs.

2.4 Chemical covers

Chemical monolayer is a long chain cetyl alcohol (C16-C18) which forms a thin one molecule thick oily layer on the water surface. As these layers are degradable, there is a need to reapply the chemical every two to four days. With small storages the product can be applied by hand from the bank as the chemical has some self-spreading ability. With larger storages however, some sort of mechanised delivery system is required (Figure 5). In tests, chemical methods have generally proved to be not as effective as physical methods in reducing evaporation. The performance in tests was thought to be possibly affected by wind, UV radiation, algae and bacteria. Despite only a low evaporation saving likely, the main advantage of monolayers is the low initial setup cost. Additionally, the product only need be applied when it is required, for example when the dam is full and during periods of high evaporation.

Figure 5 Application of chemical monolayer at the 120 hectare storage at Cubbie Station, Dirranbandi

With the current price of water, monolayers provide the only economically viable option for large agricultural water storages above ten hectares in size. They are particularly suited as a low risk investment option for owners of agricultural storages that do not have water in them all year and every year.

3 THE NRM&W EVAPORATION CONTROL PROJECT

3.1 Project overview

A research project took place from 2003-2005 to investigate the performance of various different types of cover (Fig 1). Outcomes from Queensland Natural Resources, Mines and Water (QNRM&W) Rural Water Use Efficiency Initiative (RWUIE) commissioned project included important new knowledge regarding the field performance of various different types of cover, technology to accurately assess evaporation and seepage losses and increased public awareness of the potential for evaporation reduction on water storages. Significant interest has been shown by landholders, agencies and consultancy companies in developing these technologies further.

3.2 Participating companies

Table 1 List of manufacturers that participated in the NRMW study

1) Nylex Water Solutions – WaterSavr monolayer Contact :- Brendon Mason (Business Development Manager) Nylex Water Solutions 29 Nepean Way, Mentone Vic 3194 Phone 03 9581 0211 0419 315 407 Email : brendon.mason@nylex.com.au Website : www.nylexwater.com.au
2) Evaporation Control Systems – E-VapCap Contact :- Warwick Hill (Managing Director) Evaporation Control Systems Darling Downs Tarpaulins Phone 07 4665 6144 Website http://www.evaporationcontrol.com.au/Evap.Cap.htm
3) Netpro shadecloth Contact :- Graham Minifie (Managing Director)

Lot 1 Sullivan Drive Stanthorpe Industrial Estate PO Box 337, Qld 4380 Email graham_minifie@netprocanopies.com Website *www.netprocanopies.com*
4) Water Innovations – AquaGuard (hexagonal module) Contact :- Ross Woodfield (Director), George Design (Engineer) PO BOX 347 Nathan Qld 4111 Phone 07 3423 7127 Email *Website www.waterinnovations.com.au* 5) RMIT/ RioTinto – AquaCap Contact :- Ian Burston (Research Engineer) Department of Mechanical and Manufacturing Engineering Royal Melbourne Institute of Technology Phone 03 9872 3272 Email : ianb@alphalink.com.au
6) Integrated Packaging – Raftex Contact :- Peter Johnstone (Managing Director) 35 Robins Avenue, Humevale Vic 3757 Phone 03 9474 4286 0413 949 007 Email : pjohnstone@ipstretch.com Website : *http://www.ipstretch.com/*
7) Ciba Speciality Chemicals – PAM Contact :- Andrew McHugh CIBA Specialty Chemicals, Wyong, NSW Phone : 1800 687 897 03 9282 0600 0417 017 703 Email : andrew.mchugh@cibasc.com Website : http://www.cibasc.com/ind-agr.htm

3.3 Project methodology

Novel experimental methods were developed as part of the project to measure evaporation and seepage by recording water depth to an accuracy of ±1mm using highly accurate Pressure Sensitive Transducers (Figure 6). PST units were placed at a constant 30cm height above the dam floor by a float-weight mechanism (Figure 7) and connected to solar powered dataloggers (Figure 8).

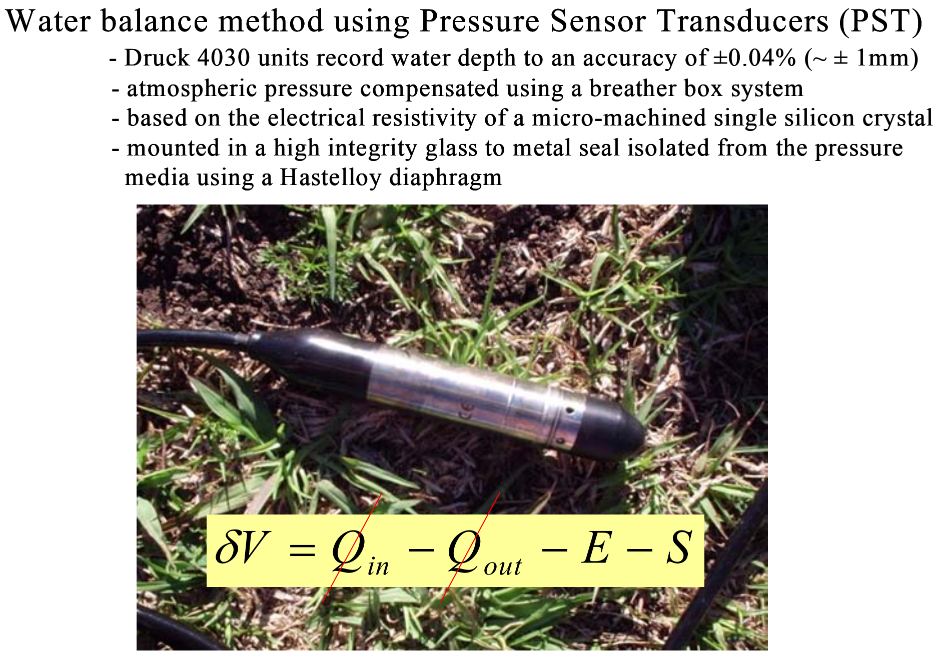

Figure 6 The Pressure Sensitive Transducer (PST) unit

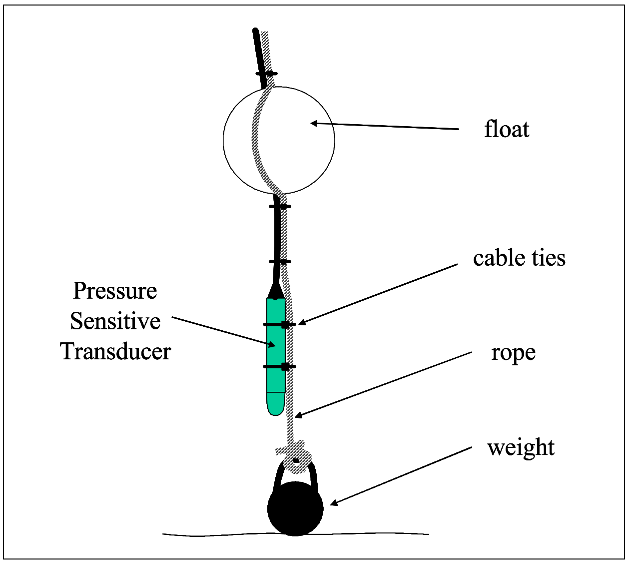

Figure 7 PST installation under the water

Figure 8 Datalogger, solar panel, battery, power management system and PST air breather system

3.4 Project results

The PST data was compared to weather station derived Penman-Monteith based estimates of evaporation (Figure 9). This enabled evaporation losses to be separated from seepage, also a very significant loss of Australian farm water.

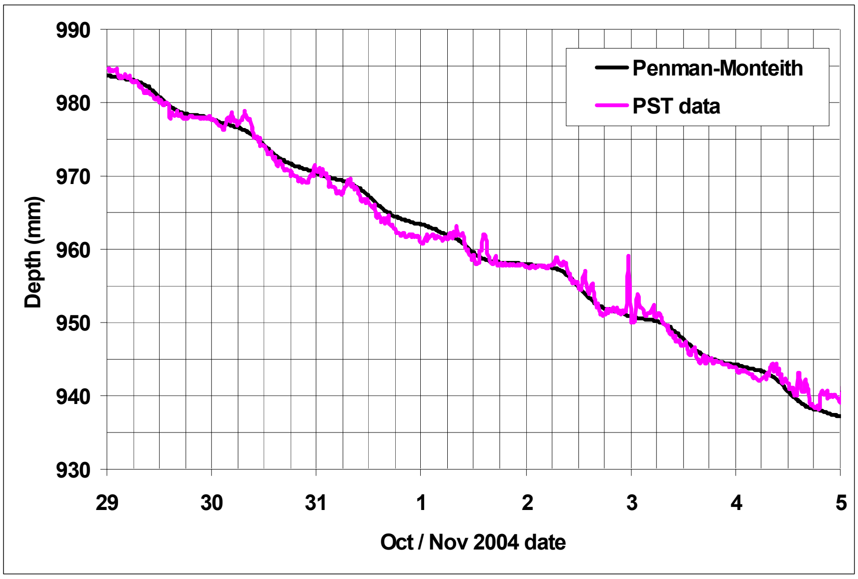

Figure 9 Some typical PST water depth data matched against Penman-Monteith prediction of evaporation

The PST methodology confirmed that evaporation losses in small farm dams in Queensland was typically 4 -7mm/day in summer rising to 10mm/day when air temperatures exceeded 40° C. The analysis also revealed that summer night-time evaporation due to heat advection effects could be as much as 10-20% of the total daily evaporation.

The PST analysis technique applied to covered dams revealed evaporation reduction performance figures of approximately 60 to 80% for shadecloth covered dams, approximately 85 to 95% for dams covered with a properly functioning floating cover, and varied from approximately 5 to 30% for dams covered with the cetyl alcohol based chemical monolayer.

The study has revealed that high evaporation savings are possible if physical covers are used on small farm dams less than 10ha in size. Physical covers can still be used on agricultural water storages larger than 10ha in size, but may be prove economically impractical due to the high amounts of capital investment required. In the future, however, increasing cost of agricultural water may allow increasingly large sizes of farm dam to be covered. Modular covers eg. Water Innovations, Aquacap, Raftex are presently being evaluated for high value water used in mining or for urban/domestic purposes.

3.5 Future research

Economic analyses have suggested that chemical covers may represent the best option for evaporation control on large agricultural water storages. Future research is planned commencing in June 2006 with the support of the CRC for Irrigation Futures. The research will focus upon developing computer based monitoring technology which will rely upon real time computerised infrared visualisation of the chemical coverage on the water surface. This will lead to the development of computerised delivery systems to optimise application across large storages (Figure 10).

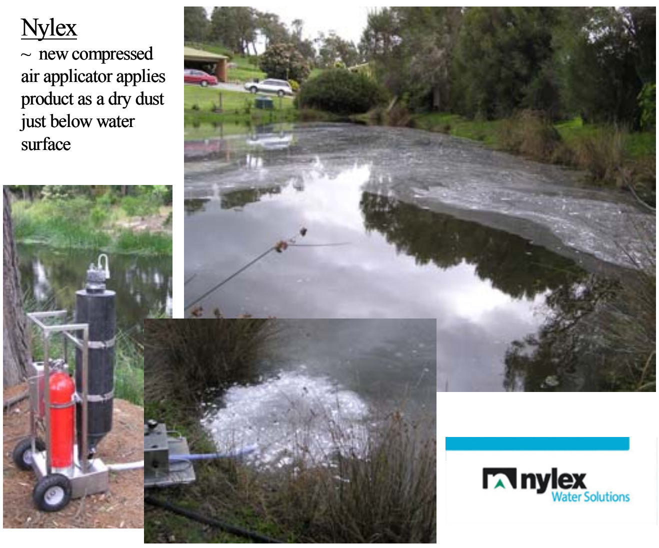

Figure 10 Future research is planned to optimise performance of chemical monolayers for agricultural water protection

Fundamental research is planned on the performance of chemical monolayers in terms of their spread and resistance to breakup, microbial and UV degradation. Preliminary investigations have indicated that the performance of cetyl alcohol based monolayers may be significantly enhanced with the addition of other chemicals, for example, poly vinyl stearate. PVS is a polymer with a comb-like structure which may enhance the resistance of the monolayer to wind stress (Barnes, pers. comm.).

4 EVAPORATION ASSESSMENT METHODS

4.1 Dalton Formula

At any water / air interface which is above absolute zero, some water molecules leave the water and move into the air. Similarly, some of the water molecules in the air reenter the water. If the rates of each process are equal, then there is no net movement of water molecules across the interface and therefore no evaporation. If however some water molecules are allowed to disperse upwards ie. they are effectively removed from the air close to the water surface, then a net transfer of water molecules from water to air takes place and evaporation occurs.

Evaporation of a free water surface is therefore defined as net movement of water molecules from water to air. The rate of evaporation is E, (mm/hr) depends upon the rate at which the water molecules are dispersed away from the surface. This is a function of windspeed $f(u)$ and the water vapour deficit or WVD. WVD is a function of the temperature and humidity of the air (**Error! Reference source not found.**).

Partial pressure, e, (Pa) is a convenient way to express the water vapour content or humidity of air. The humidity of air can contain is a function of temperature and is defined by saturated vapour pressure (e_{sat} or e_s) curve presented in **Error! Reference source not found.**. The gradient of the e_s curve ($\delta e/\delta T$) at any temperature T is defined as Δ_T.

Consider a parcel of air with temperature T and an actual water vapour partial pressure e_a. If the parcel of air is cooled adiabatically (ie. no transfer of heat), T and e change along a line which has a negative gradient equal to the psychrometric constant, λ. Once the e_s curve is reached ie. the air is fully saturated. The temperature at which this occurs is known as the wet bulb temperature (T_w). λ has an approximate value of 67 Pa C^{-1}. λ is not strictly a constant as it is a weak function of both temperature and air pressure.

Relative Humidity (RH) is simply e/e_s expressed as a percentage. Absolute humidity is the concentration of water vapour in air, expressed in ppm or in $\mu g/m^3$. Keeping temperature constant (isothermal), the amount by which water vapour pressure, e (Pa) would have to increase so that the e_s curve was reached (ie. the air becomes completely saturated) is known as the Vapour Pressure Deficit or VPD. VPD is commonly expressed in formulas as ($e_s - e_a$).

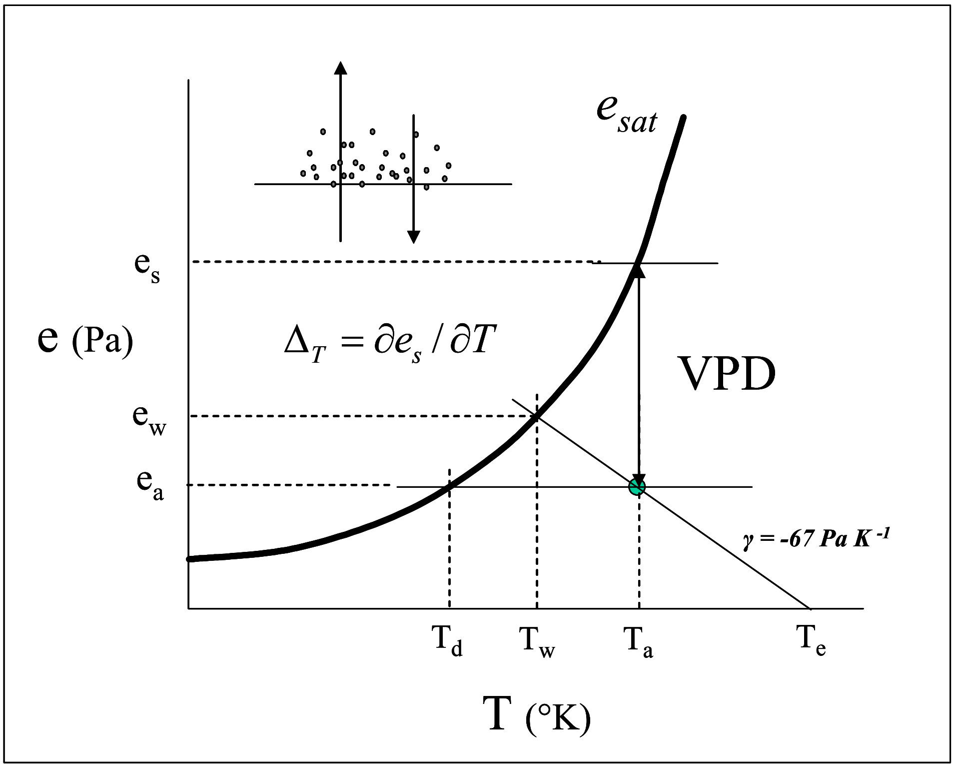

Figure 11 **Principle of evaporation**

Where f(u) is a windspeed function, Daltons formula (alternatively referred to as the "bulk aerodynamic formula") for potential evaporation, or the aerodynamic drying power of the air, E_a, is expressed as follows :

$$E_a = f(u)(e_s - e_a) \qquad 1.$$

Use of the Dalton formula represents the most basic method for estimating evaporation and is useful if meteorological data is poor or limited. If a reliable function for windspeed can be found. Dingham (1994) applied a simple constant to the wind velocity equal to 1.26 x 10-4 (s/mb/day). This is the basis of the SEBAL (Surface Energy Balance Model) Bastiaansen and Bandara 2001.

Variations upon the Dalton Formula, also referred to as the Vapour Pressure Deficit method (Howell and Dusek, 1995) or the Bulk Aerodynamic method (Lakshman, 1972, Stewart and Rouse 1976, DeBruin 1978) have been used in a number of evaporation studies, including the Snowy River Mountain scheme (AWRC, 1971 and Hoy and Stevens 1977). Estimation of the evaporation from the lake of Aswan High Dam (Lake Nasser, Egypt) using the bulk aerodynamic method was undertaken by Omar and ElBakry, 1980.

4.2 Penman-Monteith Method

Combination methods were first introduced by Penman (1948) and account for the energy required to sustain evaporation and the mechanism required to remove the vapour. Penman showed that the rate of evaporation from an open water surface (mm/day) could be expressed as

$$E_o = (\Delta Q + \gamma E_a)/(\Delta + \gamma) \quad 2.$$

where Q is the evaporation equivalent of the net flux of radiant energy to the surface, where the corresponding aerodynamic or ventilation term is

$$E_a = 0.26(e_s - e_a)(1 + U/100) \quad 3.$$

where e_s and e_a are the actual and saturated values of vapour pressure at 2m above the surface and U is the corresponding wind run, in miles per day. γ is the thermodynamic value of the pschrometric constant, equal to 0.66mb K^{-1} and Δ is the slope of the saturation-vapour pressure versus temperature curve for water at air temperature in mb/°C (Thom and Oliver, 1977).

The more commonly used "general form" of the equation (Kashyap and Panda 2001) is as follows :

$$ET_o = \frac{1}{\lambda}\left[\left(\frac{\Delta}{\Delta+\gamma}\right)(R_n - G) + \left(\frac{\gamma}{\Delta+\gamma}\right)f(u)(e_s - e_a)\right] \quad 4.$$

where ET_o is the evaporative flux (mm/day)

λ is latent heat of vapourisation (MJ kg^{-1}) = *2.501-0.002361T (°C) ≈ 2.45*

R_n is net radiation (MJm^{-2} day^{-1})

G is the soil or water heat flux (MJm^{-2} day^{-1})

Δ is the slope of the svp-t curve ($kPaC^{-1}$) = $0.2\{0.00738T + 0.8072\}^7 - 0.00016$

γ is the psychrometric constant ($kPaC^{-1}$) = $c_pP/0.622\lambda \approx 0.067$

$f(u)$ is a function of windspeed = $6.43(1+0.0536u_2)$

e_s is the saturated vapour pressure (kPa)

e_a is the actual vapour pressure (kPa)

Originally, Penman (1948), originally proposed the following equation for the windspeed function

$$f(u) = 0.26(1 + 0.54u_2) \quad 5.$$

where u_2 is windspeed in ms^{-1} at 2m above the surface (the constants assume E in mm/day and vapour pressure in mbar). The constant 1 was later altered by Penman (1956) to 0.5, although Thom and Oliver (1977) regarded 1 as preferable. Based on lysimeter measurements, Doorenbos and Pruitt (1975) suggested that 0.54 be altered to 0.86. This highlights the requirement for a single standardized method ie. FAO56 !

Alternatively, the Penman (1948) equation is expressed as follows

$$\lambda E = \frac{\Delta(R_n - G) + \Delta\rho_a c_p (e_s - e)/r_a}{\Delta + \gamma} \qquad 6.$$

$$\text{or } E = (1/\lambda)\frac{\Delta(R_n - G) + \Delta\rho_a c_p (e_s - e)/r_a}{\Delta + \gamma}$$

where r_a is a windspeed dependant aerodynamic resistance term. In 1965, Monteith presented a modified version of the Penman equation incorporating a crop surface resistance term and this forms the basis of the Penman-Monteith method and is

$$\lambda E = \frac{\Delta(R_n - G) + \Delta\rho_a c_p (e_s - e)/r_a}{\Delta + \gamma *} \qquad 7.$$

where ρ_a is the mean air density at constant pressure
c_p is the specific heat of air
$\gamma*$ is a modified psychrometer constant as follows

$$\gamma* = \gamma(1 + r_s / r_a) \qquad 8.$$

where r_s is the surface (or canopy, leaf, stomatal) resistance (s/m) term controlling release of water vapour to the surface
r_a is the aerodynamic (or ventilative) resistance (s/m) term controlling the removal of water vapour away from the surface

The aerodynamic resistance, r_a, which is now the windspeed function term, is defined according to FAO 56 as

$$r_a = \frac{\ln\left[\frac{z_m - d}{z_{om}}\right]\ln\left[\frac{z_h - d}{z_{oh}}\right]}{k^2 u_2} \qquad 9.$$

where z_m is the height of wind measurements (m)
z_h is the height of humidity measurements (m)
d is the zero plane displacement height (m)
z_{om} is the roughness length governing momentum transfer (m)
z_{oh} is the roughness length governing transfer of heat and vapour (m)
k is the von Karmon constant = 0.41
u_2 is the windspeed at height 2m (ms^{-1})

The (bulk) surface resistance, r_s, is defined as

$$r_s = r_{stom} / LAI_{active} \qquad 10.$$

According to FAO 56, the method has been developed from the Penman-Monteith Equation by Allen et al 1998. A reference crop is used consisting of watered mown grass 0.12m high. r_a is assigned a value of $208/u_2$ s/m and r_s is assigned as value of 70 s/m. Assuming an albedo of 0.23 then leads to the FAO 56 formula for reference transpiration ET_0 (mm/day). The evapotranspiration of a particular crop ET_c is then related to ET_0
as follows

$$ET_c = K_c ET_o \qquad 11.$$

The present study deals with evaporation from a free water surface. A value of 0 for r_s can therefore be assumed with the result that the FAO 56 equation can revert back to the original Penman (1948) equation for a free water surface.

<u>FAO 56 Calculations</u>

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \qquad 12.$$

$$\Delta = \frac{4098\left[0.6108\exp\left(\frac{17.27T}{T+237.3}\right)\right]}{(T+237.3)^2} \qquad 13.$$

$$\gamma = \frac{c_p P}{\varepsilon\lambda} = 0.067 \qquad 14.$$

$$P = 101.3\left(\frac{293 - 0.0065z}{293}\right)^{5.26} \qquad 15.$$

$$e_s = 0.6108\exp\left[\frac{17.27T}{T+237.3}\right] \qquad 16.$$

$$e_a = \frac{\overline{RH}.e_s}{100} \qquad 17.$$

$$R_n = (1-\alpha)R_s - R_l \qquad 18.$$

$$R_s = \{a + b(n/N)\}R_a \qquad 19.$$

$$R_l = \sigma\overline{T^4}(0.34 - 0.14\sqrt{e_a})(1.35R_s / R_{so} - 0.35) \qquad 20.$$

ET_0 reference transpiration (mm/day)

Δ slope of the saturated vapour pressure temperature curve where T is air temperature (°C)

R_n net radiation (MJ/m^2/day)

G soil heat flux (MJ/m^2/day)

γ	psychrometric constant 0.067 (kPa°C^{-1})
u_2	windspeed at 2m height (m/s)
c_p	specific heat at constant pressure 1.013 x 10-3 (MJ kg^{-1} °C^{-1})
P	atmospheric pressure 101.3 (kPa) where z is elevation above sea level (m)
ε	ratio of the molecular weight of water vapour / dry air 0.622
λ	latent heat of vapourisation, 2.45 (MJ kg^{-1}) (1/2.45 = 0.408)
e_s	saturated vapour pressure (kPa)
e_a	actual vapour pressure (kPa) where RH is the relative humidity (from AWS)
α	surface albedo (assumed 0.23)
R_s	total radiation from AWS, or calculated from eqn 19, where a= 0.25, b= 0.5, n is actual duration of sunshine hours, N is maximum possible duration of sunshine hours (for clear skies n=N and R_s = R_{so}) and R_a is the average daily extraterrestrial solar radiation (from tables)
R_l	long wave radiation (MJ/m^2/day) where σ is Stefan-Boltzmann constant = 4.903 MJ/m^2/K^4/day

There have been several recent studies (Ventura et al 1999, Hussein (1999), Al-Ghobari 2000, Kashyap and Panda 2001, George et al 2002) that have confirmed that the FAO 56 Penman-Monteith (PM) equation generally out performs other equations eg Blaney-Criddle (1945), Turc (1961), , Jensen-Haise (1963), Priestly-Taylor (1972), Doorenbos-Pruitt (1975), Hargreaves (1985), Shuttleworth-Wallace (1985), Watts-Hancock (1985) etc. The general consensus is therefore that the PM method is superior to all the other ET methods. Kashyap and Panda (2001) have clearly indicated this in their study comparing 10 ET methods to grassed weighing lysimeter data obtained in India (Table 2).

Table 2 Ranking of ETo estimation methods based upon root mean square error (after Kashyap and Panda, 2001)

Rank	*Estimation method*	*Mean deviation from measured values (%)*	*Coefficient of determination (R^2)*	*RMSE (mm per day)*
1	Penman-Monteith	-1.36	0.91	0.080
2	Kimberly-Penman	-1.51	0.74	0.211
3	FAO-Penman	-3.60	0.76	0.234
4	Turc-Radiation	+2.72	0.70	0.260
5	Blaney-Criddle	+3.16	0.72	0.289
6	Preistley-Taylor	-6.28	0.77	0.316
7	Penman	+11.87	0.78	0.317
8	Hargreaves	+8.34	0.70	0.358
9	FAO-Radiation	+17.89	0.75	0.540
10	Corrected Penman	+22.32	0.81	0.756

(1) Blainey-Criddle based on mean air temperature only
(2) Priestly-Taylor based on net radiation and temperature
(3) Jensen-Haise based on air temperature and daily integrated solar radiation

The PM method has two distinct advantages over other the other methods. Firstly, it is has a physical basis implying the equation can be used on a global basis without the need for empirically derived constants relevant to specific regions. Secondly, the equation has received the most through experimental validation against other methods, mainly weighing lysimeters and soil moisture measurements. A disadvantage of the PM method however is the relatively high data requirement including air temperature, windspeed, relative humidity and solar radiation, although Allen (1998) pointed out alternative ways of estimating solar radiation and humidity using simpler or fewer measurements.

Parameter	*Variation required*
Radiation	± 25%
Windspeed	± 25%
Temperature	± 5% (~±1°C)
Humidity	± 25%

Table 3 Error analysis of the PM equation – variation required in input parameter required to produce ±2σ (95% confidence interval) variation in the PM ETo prediction (after Droogers and Allen, 2002)

4.3 Water Balance

The mass flow balance of a dam or water storage over a specified time interval may be expressed as

$$\mathbf{Q_{in} + P + \delta D = Q_{out} + S + E} \qquad 21.$$

where Q_{in} is the inflow, P is precipitation, δD is the change in level, Q_{out} is the outflow, S is seepage and E is the evaporation rate, all in mm day^{-1}.

Water balance studies more commonly calculate evaporation so that seepage can be deduced. A recent study has been carried out at Lake Powell, Glen Canyon dam, Arizona (Myers et al 1999). Evaporation of effluent ponds has been reviewed by Louden and Reece (1983) and more recently addressed by Ham, J.M. and DeSutter (1999) and Glanville et al (1999).

The change in the water level of the dam can either be measured using pressure transducer based depth sensors, or siphon weighing systems (Glanville et al 1997). Inflow and outflow to the storage in addition to seepage have to be determined very accurately in order to obtain a meaningful evaporation estimation. The aim of this type of experimental approach may be summarized in Figure 12.

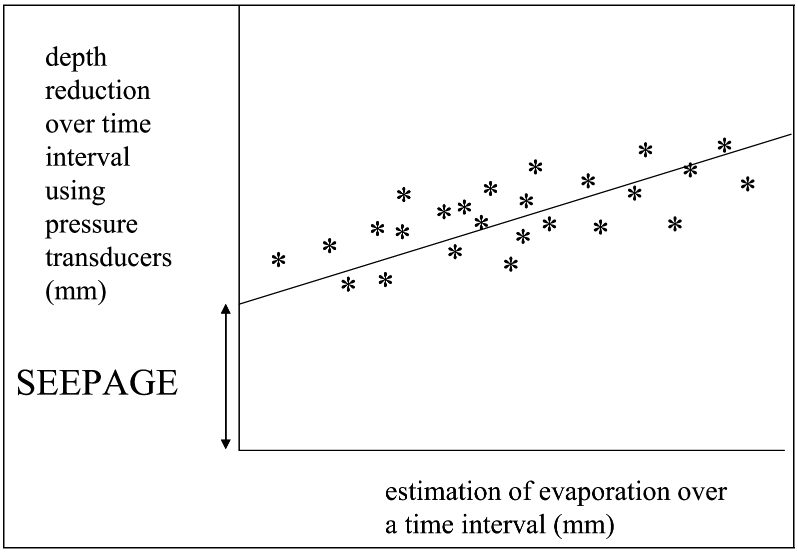

Figure 12 Principle of physical measurement of evaporation of a water storage using flow mass balance method

The main challenge is to determine seepage accurately. As part of the NRMW study, which was to evaluate the effect of various covers in reducing evaporation, three lined tanks were installed with nil seepage. With other water storages, depending upon the quality of the liner, there is usually some loss due to seepage. The best method to determine the seepage rate is to accurately measure the change in water level over night when there should be minimal evaporative loss. This necessitates the use of very accurate transducers (accurate to ± 1mm day^{-1} or better). Waste level recorders description were rigorously tested by Ham and DeSutter (1999) and found to be extremely accurate and stable (eg. ± 0.16mm)

Windspeed effects can be a cause of evaporation rate data variability (Glanville et al 1997). For example wind induced waves superimpose a signal noise on depth measurements which has to be carefully removed. More seriously, wind can effectively pile up water along the downwind shoreline of a water body. Sample calculations using the approach of White and Denmead (1989) indicated that depth errors caused by wind drag would be less than 1mm. There is also the tidal effect which may be a few mm for large water bodies.

4.4 Evaporation Pans

Evaporation pans have been and still are used extensively throughout the world to estimate reference evapotranspiration for crop surface, or evaporation from a bare soil or water surface (Kadel and Abbe, 1916). Evaporation pans (Class A pan, USDA or U.S. Weather Bureau) consist of a circular pan, generally four feet in diameter and 10 inches deep. They should be mounted on a slatted timber base on level short mown grass and equipped with a bird guard (ref).

Figure 13 Typical evaporation pan with weeds growing and no bird guard. The pan is also not filled to the top so there will be significant errors associated with the aerodynamics of the lip

A floating evaporation pan setup has been described by Ham (1999). Differences between water body and pan conditions that can affect pan data include (Burman and Pochop, 1994)

1. differing water temperature variations with depth
2. storage of heat within the pan
3. differences in wind exposure
4. differences in the turbulence, temperature and humidity of air above the water surface
5. heat transfer through the sides and bottom of the pan

Since pan evaporation (E_{pan}) normally exceeds evaporative losses from larger water bodies (E_{ws}), researchers commonly adjust the pan data as follows :

$$E_{ws} = E_{pan}.K_{pan} \quad 22.$$

where K_{pan} is a pan coefficient which generally varies from about 0.6 to 0.9 (Brutsaert, 1982) or 0.6-1.2 (Clewitt, 1980) depending on the pan and the surrounding environment. Calculation of pan coefficients for pans across Queensland was carried out by Weeks (1983) who concluded 0.7 to 1.0 was typical.

Brutseart in his famous book “Evaporation Into The Atmosphere” describes evaporation pans in terms of “uncertain and often dubious applicability as a measure of evaporation in nature”. Watts and Hancock (1985) reaffirm Brutsaert’s statement and assert that all evaporation pan data should be regarded as “untrustworthy”. The authors list the problems associated with operating pans as follows :

(i) dirt on the metal pan
(ii) contamination of the water
(iii) other inputs (rain, slash-in)
(iv) other outputs (bird and animal drinking, splash-out)
(v) ventilation changes below pan (change of grass length)
(vi) thermal property variations

(vii) presence of birdguard (reduction of both radiation input and ventilation)
(viii) possible shade at low sun angles (eg. surrounding trees)
(ix) wave action and overtopping in windy conditions
(x) surface tension problems when refilling to needle point

Even with properly maintained pans the energy exchange, heat storage and airflow characteristics for the shallow water in the pan is likely to be very different to that of open water or a crop. However, a number of studies (Doorenbos and Pruitt 1975) have demonstrated that pans can work well when properly maintained. Pans may work well if evaporative conditions are not too severe. An evaluation of Class A Pan coefficients in humid locations has been carried out by Irmak et al 2002. The problem of heat conduction in evaporation pans has been addressed by Oroud 1998.

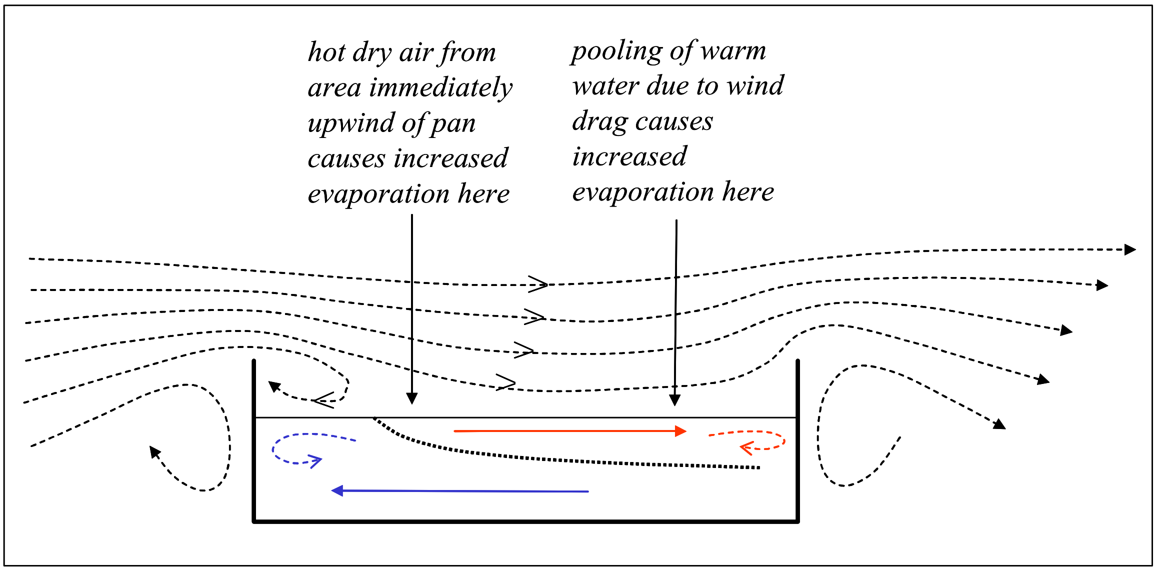

Figure 14 Aerodynamic lip / advective effects associated with evaporation pans

Many problems associated with small pans can be eliminated if the size of the pan is increased. At University of Southern Queensland (USQ), trials with very large pans or tanks are taking place. With these pans, the height of the lip is small compared to the overall width of the pan, so lip errors are significantly reduced. However, these pans still suffer from the problem of fouling by wildlife. At USQ, fouling by ducks were initially quite a problem and bird scarers had to be installed at the facility.

Figure 15 **Evaporation Research Facility based at NCEA, USQ. The experimental trial consists of three lined 10m x 0.8m deep tanks which are being used to accurately assess the effectiveness of different evaporation control methods.**

4.5 Bowen Ratio Energy Balance

Net radiation (R_n) is either absorbed as ground heat flux (G) or transferred to the air above in the form of sensible heat flux (H) and latent heat flux (λH). The latter is defined as the energy expended in converting liquid water into water vapour. Thus, the heat energy balance may be expressed as follows :

$$R_n - G - H - \lambda E = 0 \qquad 23.$$

This may be rearranged as follows :

$$\lambda E = \frac{R_n - G}{1 + \beta} \qquad 24.$$

where β is the Bowen Ratio ie. the ratio of sensible to latent heat flux (Bowen,1926). Bowen used this ratio to estimate evaporation. Equation 5 is most accurate when β is small (Brutseart, 1982). β is measured experimentally using Bowen Ratio apparatus which determines the temperature and humidity gradients over a height interval δz.

$$\beta = \frac{H}{\lambda E} = \lambda \left(\frac{\partial T}{\partial e} \right) = \gamma \frac{K_h}{K_e} \left(\frac{\partial T / \partial z}{\partial e / \partial z} \right) \qquad 25.$$

Bowen Ratio apparatus is required to accurately measure small differences in temperature and humidity over a small height interval above the evaporating surface. Traditionally, the equipment features a net radiometer and a pair of rotating precision aspirating psychrometers (Hancock, pers comm.).

The net radiometer eg. Funk type (Funk, 1959, 1962) consists of a thermopile (series of thermocouple junctions) between an upper and lower blackened surface. The temperature difference between the two surfaces is a function of the net radiation (ie.

the difference between incoming and ground reflected radiation). The unit is enclosed within a polythene dome fed with a slight positive pressure of dry nitrogen to ensure no ingress of moisture.

The two rotating psychrometers (each consisting of wet and dry bulb thermometers located inside white cylindrical radiation shields) mounted on a motor driven interchange system so that their heights are automatically alternated after each pair of measurements. This provides both the temperature and humidity gradient information with successive readings being averaged to cancel out any small calibration differences between the two psychrometers.

An even more accurate approach to measuring Bowen Ratio is to use a cooled mirror hygrometer (CMH). Usually, there is only one CMH unit and air is ducted from the high and low sample positions alternatively. The air sample is passed over a mirror which is cooled using a liquid nitrogen supply. The temperature at which dew first starts to form on the mirror (detected using an infra red beam) is then a function of the original humidity of the air sample.

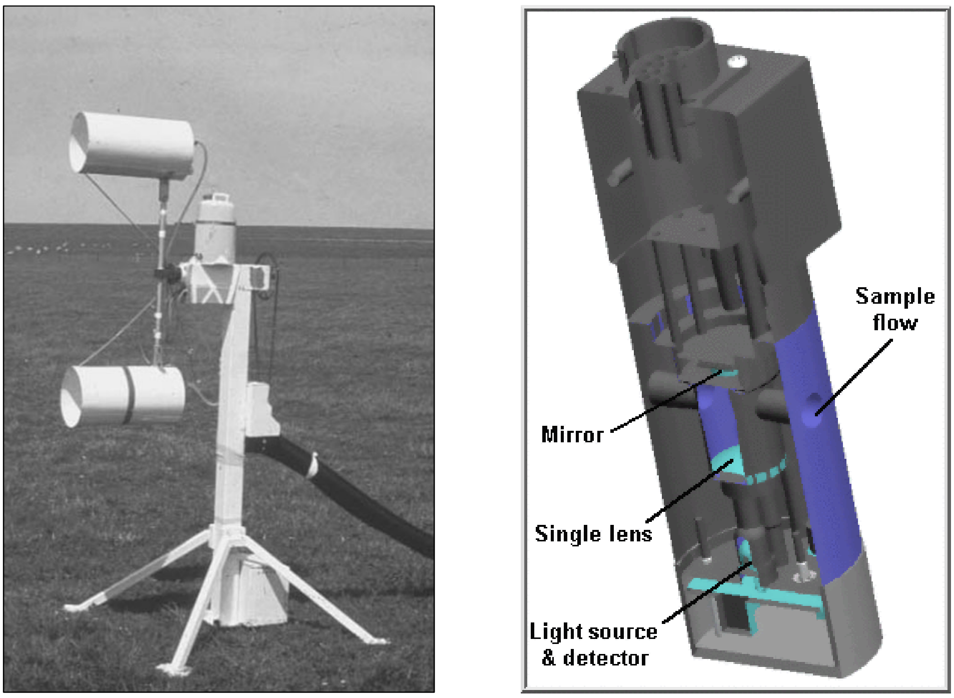

Figure 16 Rotating Arm (paired aspirating psychrometers) and Alternate Flow (cooled mirror hygrometer) units used in accurate Bowen Ratio measurements

Due to the expense and difficulty of maintaining these systems, later Bowen Ratio systems have moved to solid state temperature and humidity measurement systems consisting of usually ceramic Al/Si oxide porous material or polymer film or carbon coated plate alternatives. Temperature and relative humidity (RH) is calculated directly from changes in the electrical properties of the material (ie. capacitance, resistance, impedance). These systems are cheap, robust and reliable, but struggle to be accurate enough for precise Bowen Ratio work. Their use is mainly intended for the main market which comprises of standard meteorological stations. Reviews of the various humidity measurement techniques have been conducted by Scott 1996 and Wielderhold 1997

Bowen ratio methods have been extensively used to measure biosphere-atmosphere exchange methods as part of the OASIS program (Leuning et al 1995, Raupach et al 2003) and as part of the FLUXNET program (Wilson et al 2002). An evaluation of the Bowen Ratio method for Australian conditions was carried out by Angus and Watts, 1984. Other Australian studies include McIlroy, 1972 and McLeod et al (1998).

Some of the problems associated with the BREB method (ie in obtaining balance or "closure") have been investigated by Brotzge and Crawford (2003). A full error analysis of the Bowen Ratio method has been performed by Watts (1983).
This highlighted that there are quite large errors in very dry conditions (ie. large B). For a freely evaporating surface ($-0.2 < B < +0.2$) there can be errors of up to 30% in B which lead to errors in LE of less than 5%.

4.6 Eddy Correlation

The measurement of vertical transfer of heat and water vapour by eddies was first described by Swinbank (1951). Since then, micrometeorologists have long held that eddy correlation techniques offer the most promise for providing accurate measurements of evaporative flux with a sound theoretical basis (Kaimal and Gaynor, 1991). The method is offering an attractive alternative to other more cumbersome methods such as weighing lysimeters and Bowen Ratio. A comprehensive manual invaluable to the experimental practitioner of the method is provided by Dijk 2003.

The major challenge associated with the eddy correlation method is the response time limitations of the sensor instrumentation. Developments in electronics in recent years have resulted in new sensors with the required speed and accuracy.

Sensor	**Parameter**	**Example**
3 axis sonic anenometer	windspeed ($u\pm u'$, $v\pm v'$,$w\pm w'$)	CSAT3§
IR/UV absorption hygrometer	specific humidity ($q\pm q'$)	LiCor§, Krypton§ KH20
Fine wire thermocouple	temperature ($t\pm t'$)	13 micron

§ available from Campbell Scientific Pty Ltd

Table 4 Components of a typical eddy correlation system

Eddy correlation theory describes the turbulent transport of properties such as momentum flux, sensible heat flux and latent heat flux. The method relies on accurately measuring the fluctuations in airspeed, temperature and humidity.

Considering motion in the vertical direction, w, latent heat flux is defined by

$$\lambda E = \rho \lambda w q \qquad 26.$$

where is the instantaneous latent heat flux (W/m^{-2})
ρ is the instantaneous air density
λ is the instantaneous latent heat of vapourisation of water (J/g)
q is the instantaneous specific humidity (g/g)

λE can be converted to water vapour flux by dividing by λ, and then to a conventional evaporation rate by dividing by the density of water.

Each component in the equation can be partitioned into a mean value plus an instantaneous deviation from the mean. The instantaneous deviations of air density and latent heat of vapourisation can be assumed to be zero. The long-term mean vertical wind velocity over a flat uniform surface can be assumed to have a value of zero (Dyer, 1961). Applying these assumptions and the rules of statistical averaging, the mean vertical flux for an averaging period longer than a few seconds becomes

$$\overline{\lambda E} = \rho \lambda \overline{w'q'} \qquad 27.$$

where $\overline{w'q'}$ is defined as the covariance of vertical windspeed and specific humidity. Thus, over a level, uniform surface, the latent heat is entirely due to eddy transport, with no contribution from mean vertical flow.

A similar analysis can be applied to the sensible heat flux, yielding

$$\overline{H} = \rho C_p \overline{w'T'} \qquad 14$$

where $\overline{H}$ is the mean sensible heat flux (W/m^2)
C_p is the specific heat of air ($J/kg^{-1}K^{-1}$)
$\overline{w'T'}$ is the covariance of vertical airspeed and temperature (Kms^{-1})

Fine wire thermocouples are usually used for the fast response temperature measurement.

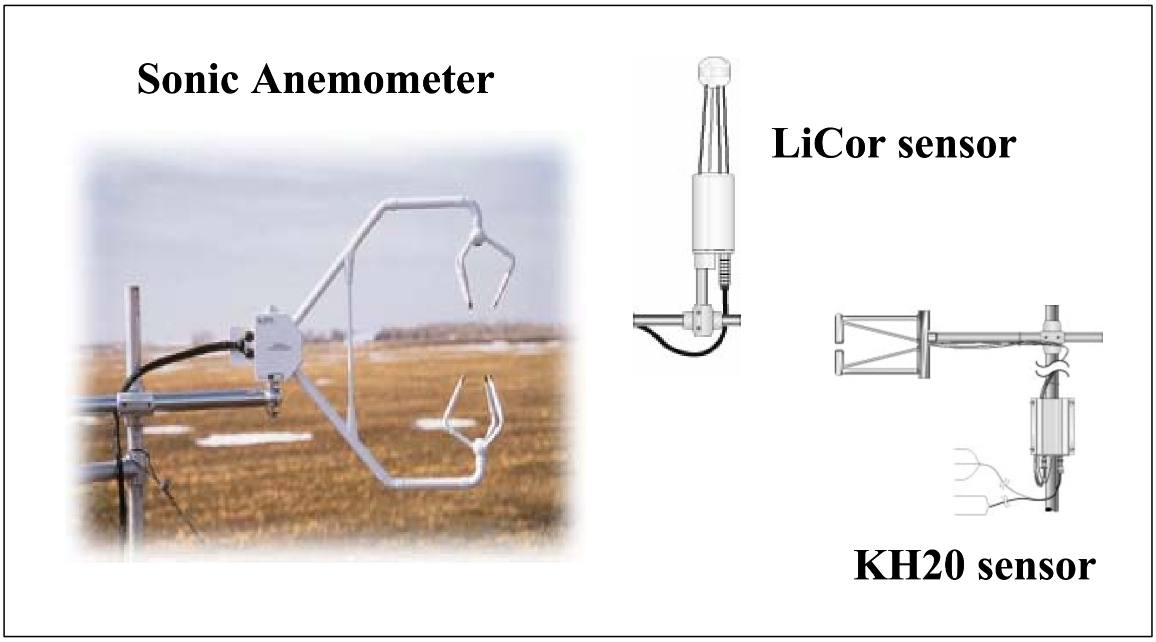

Figure 17 **Typical eddy correlation equipment including 3 axis sonic anemometer and LiCor (IR) or KH20 (UV) based fast response humidity sensors (pictures are courtesy of Campbell Scientific Australia)**

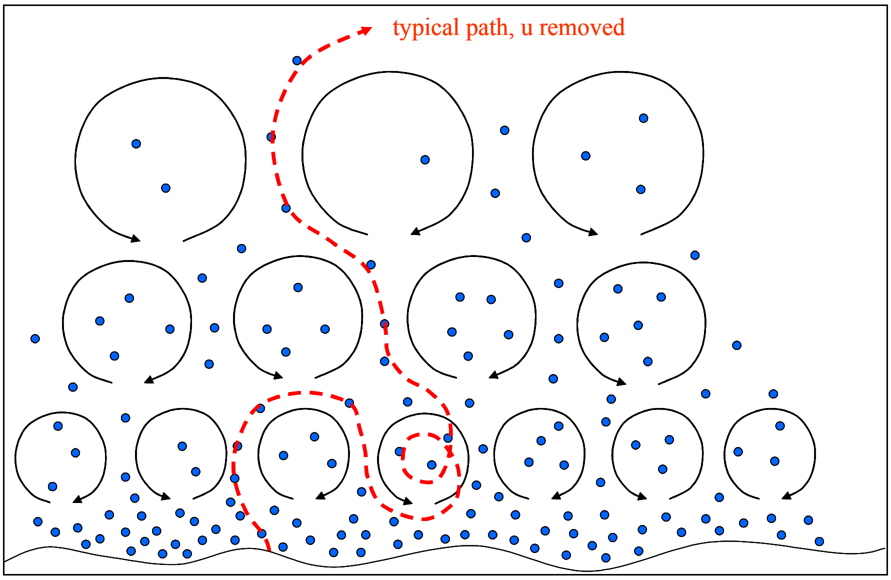

Figure 18 **Principle of operation of eddy correlation system. The humidity (concentration of water molecules) of upward verses downward moving air is compared to give the humidity flux**

Absorption hygrometers utilizing either infrared radiation (Staats et al 1965), Lyman-alpha radiation (Randall et al 1965, Miyake and McBean 1970, Buck 1976, Redford et al 1980) or the krypton UV radiation method (Campbell and Tanner 1985). An Infra Red fluctuation hygrometry method was described by Raupach in 1978.

The LiCor open path unit features an IR beam which is chopped using a grating rotating at 9000 RPM. Detection of water vapour is via absorbance at 2.59µm using a Pb-Se detector. Advantages reported for the krypton hygrometer are a more stable calibration and longer radiation tube life.

4.7 Area based methods

Other methods of investigating evaporation of water bodies include the following :-

1. Satellite Remote Sensing. This uses information in the Infra Red sensitive to ground moisture content has been used extensively for catchment evaporation evaluations (Bastiaanssen and Bandara, 2001). The recession of the shores of Lake Eyre drying up after a flood has been carefully mapped out with time using satellite data (Prata, A.J.), but seepage, rainfall, in/out flows were neglected.
2. Low Level Airborne Survey. This took place over Lake Alexandrina (Kotwocki 1994). Measurement of sensible and latent heat fluxes were carried out using a GROB G109B research aircraft flying at 5-10 height above water surface. Evaporation from the lake was determined evaporation to be about 1m year. Another airborne hygrometry study was described by Silver and Hovde (1998)
3. Microwave Radar. This has been carried out by CSIRO, Australia and is described by Hill and Long (1995)
4. Large Aperture Scintillometry (LAS). This method is based on the analysis of intensity fluctuations (known as scintillations) of a near infrared (0.94µm) light beam (Gieske and Meijninger, 2003)
5. LIDAR (UV laser based scanning radar). Originally developed by the US Military, this is now a standard research instrument at several institutions eg. University of California Davis, Munich, Iowa & the Los Alamos Laboratory. LIDAR consists of a pulsed UV laser with Raman backscatter at 273nm. A 1 km range, 1m resolution and 95% accuracy is claimed

Figure 19 **Truck transportable LIDAR machine. The technology uses a scanning UV laser to detect humidity fields and thus deduce total evaporation rates over water bodies**

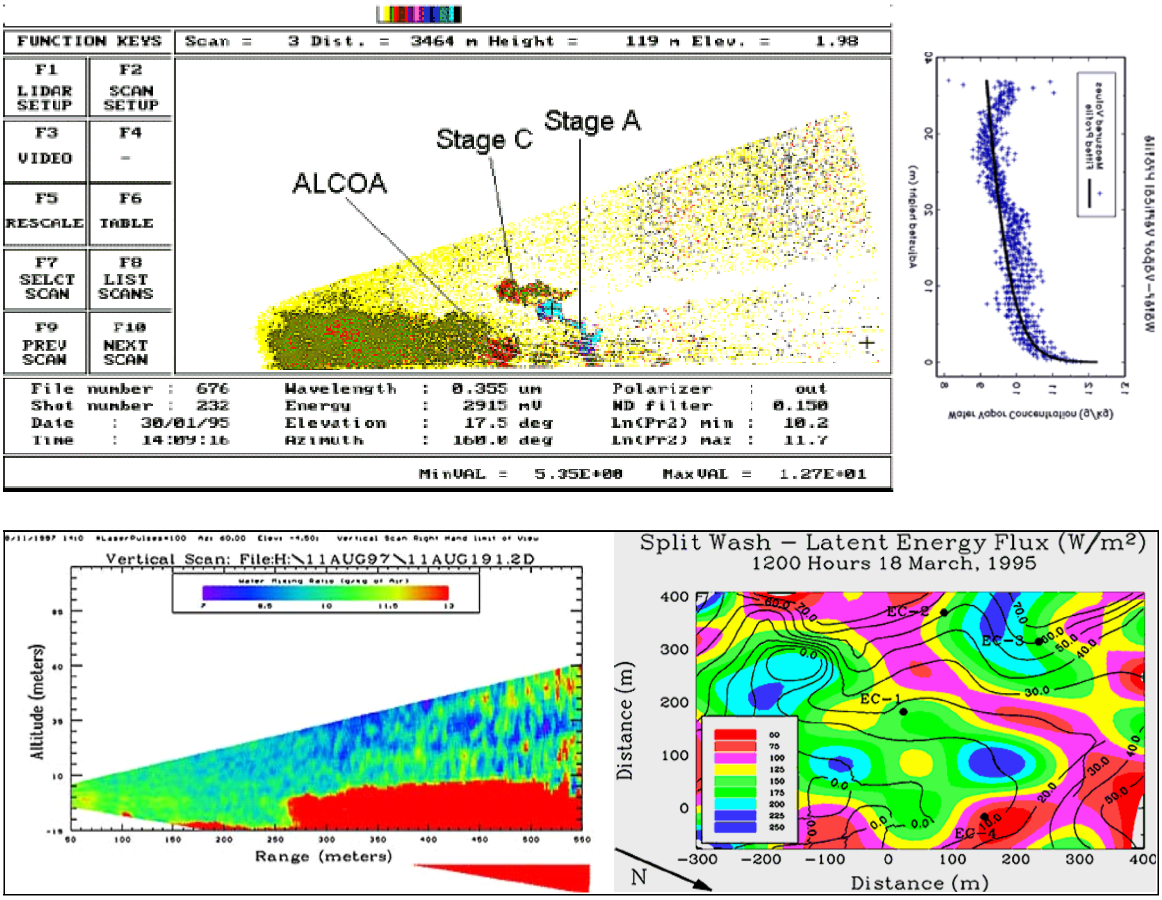

Figure 20 **Typical output data from the LIDAR unit**

4.8 Accounting for advective energy

In hot climates, advection plays a very important role in evaporation of water storages and therefore cannot be ignored. Hot dry cells or thermals form as a result of air passing over hot dry land. Inside the cells, the temperature may exceed 40°C and humidity may approach zero. As these cells pass over a water, extra energy is provided to locally increase evaporation rates at the upwind margin of the water body. This has the effect of depressing the mean humidity contours at the upwind margin of a waterbody (Figure 21)

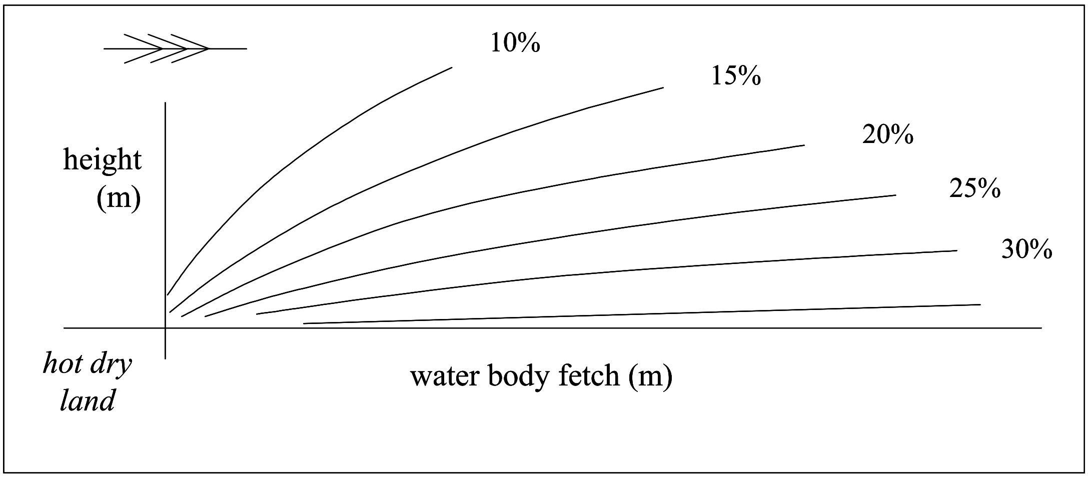

Figure 21 Principle of added evaporation energy due to the oasis effect. Relative Humidity contours predicted by the model of Webster and Sherman (1995) are depressed at the upwind margin of the water body, due to advection of hot dry air from an adjacent land mass.

For most evaporation measurements, the fetch (area upwind of point of measurement with similar surface characteristics) must be sufficiently long to develop a constant flux layer. This happens at some distance downwind from the upwind margin of a water body where equilibrium conditions are reached ie. temperature and humidity profiles do then not change significantly as one progresses further downwind across the waterbody. Some argument exists as to the minimum length of this fetch. Slatyer and McIlroy (1961) recommend an instrument height to fetch ratio of 1:100. This means that if the instrument measuring evaporation is set at a height of 1m above the water surface, then it should be situated at least 100m downwind from the bank of the water body. The problems with measuring evaporation using PM for water bodies less than a few hundred metres across is therefore highlighted.

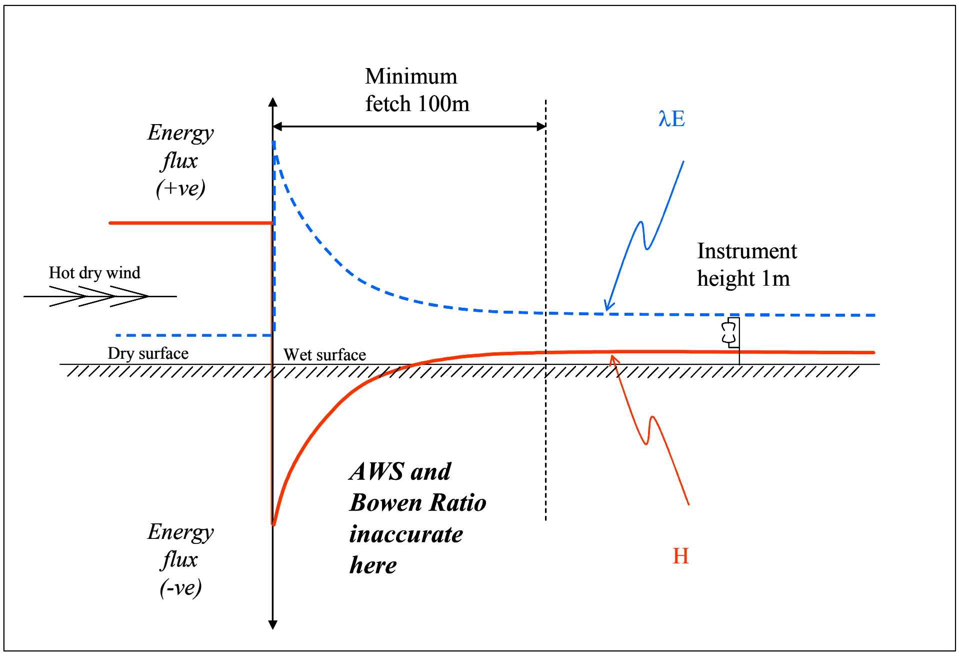

Figure 22 Simplified representation of local advection (after Oke, 1987)

For small water storages (less than a few hundred metres across), advective effects are taking place across the whole of the water storage. Temperature, humidity, windspeed and therefore evaporation will all vary second by second. Hourly or minute meteorological data is therefore of little use in this situation. To truly estimate evaporation over small water storages in hot climates, we therefore require meteorological data with millisecond resolution. The Eddy Correlation method is able to provide this temporal resolution. Additionally, air stability will vary markedly through the day in hot climates and this has an important effect on evaporation. The Eddy Correlation technique is able to calculate stability directly from the 3 axis wind direction and speed information gained from the sonic anemometer component of the apparatus. However, Eddy Correlation is still only a point measurement. Laser and remote sensing methods are really required to measure the spatial variability of humidity fields to fully take account of advective effects.

Under most climates that have sufficient rainfall to support ET, λE is generally some fraction of net radiation R_n. However, in areas where the air mass is strongly modified by dry desert conditions, the ratio of λE to R_n can exceed 1.5 (Allen 1999). In the case of an oasis in a desert environment, hot dry air moving sideways in the form of major eddies provides a major input of extra energy into the system (Webster and Sherman, 1995, Condie and Webster, 1997, Brutsaert and Stricker 1979, Brutsaert 1982). Where A_d is the extra energy due to advection, the sum of energies is now

$$R_n + A_d - G - H - \lambda E = 0 \qquad 28.$$

With fast response meteorological data, the Penman approach could still be used to calculate evaporation for rapidly fluctuating conditions. To remind us once more, the Penman Equation may be expressed as

$$\lambda E = \frac{\Delta R_n}{\Delta + \gamma} + \frac{\gamma E_a}{\Delta + \gamma} \qquad 29.$$

The first term is usually referred to as the radiation term and the second term the ventilative, aerodynamic or convection term. Brutsaert (1982) however prefers to call the first term the equilibrium term and the second term the non-equilibrium term, or the drying power of the air arising from large scale advection.

Consider a boundary layer (ie. air in close contact with the water) which is completely uniform and saturated. The second term of Eqn 26 is zero, but there is still some evaporation because of the first "radiation" term which represents the lower limit of evaporation from moist surfaces. The radiation term may be thought of informally as incoming photons knocking water molecules out of the surface of the water, which then knock other water molecules out of the boundary layer into the air above. More formally, the first term is considered as representing evaporation under equilibrium conditions, and the second term, the evaporation arising as a result of the departure from equilibrium conditions ie. advection (Brutseart and Stricker, 1979).

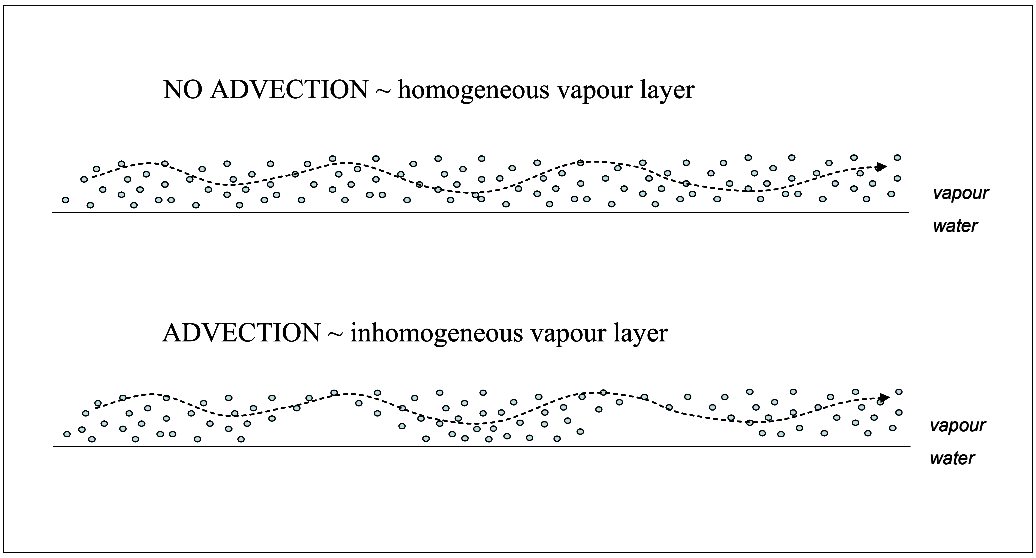

Figure 23 Concept of equilibrium and homogeneity associated with local scale advection

The atmospheric boundary layer however is almost never uniform but unsteady which tends to maintain a humidity deficit, even over the oceans. True equilibrium conditions are probably never encountered. Over a number natural surfaces described as saturated and essentially advection free, Priestley and Taylor (1972) noted that departure from equilibrium conditions produced evaporation values approximately 1.26 – 1.28 times greater than that predicted by the radiation term alone. This data was also supported by Davies and Allen (1973), Thompson (1975), Stewart and Rouse (1977). It is notable that land surfaces covered with vegetation, which is not wet but has ample water available, yields roughly the same evaporation as free water surfaces. This may be due to the larger roughness of the vegetative surface compared to the water surface. This is not true for wet canopy surfaces which are capable of evaporating at much greater rates (Watts and Hancock, 1984). This also may not be true in hot, dry, windy conditions experienced over water bodies in arid climates where waves on the surface of the water will increase roughness length of the surface.

4.9 Summary of methods

A summary of the advantages and disadvantages of the various methods and their appropriateness to the present study is described is presented in the following table.

Table 5 Advantages and disadvantages of the various assessment methods

Method	Brief description	Advantage	Disadvantage	Appropriateness to present study
Pan (Class A)	Simple pan of water, refill rate is a measure of the of evaporation rate. Related to crop ET via a simple "Pan" factor	Simple, robust, Pan factors have been widely used/ accepted for irrigation scheduling purposes	Difficult to keep clean & maintain, can give erroneous data, water/pan can heat up, complex windspeed effects associated with lip	Simple, easy to operate and maintain during short term trial. The three lined tanks (USQ) may be considered as well maintained large pans
Penman-Monteith (FAO 56)	Accepted standard method for estimating evaporation from standard (single height) meteorological data.	FAO 56 now widely established and used. FAO 56 considered superior to other ET formulae eg Blaney-Criddle, Priestly-Taylor	Few disadvantages, except not as accurate as Bowen ratio or Eddy Correlation.	Very appropriate to present study. FAO 56 P-M will be calculated using data from AWS. May require acquisition of accurate net radiation sensors.
Bowen Ratio (BR)	Measures temperature and humidity gradient across two heights close to evaporating surface.	Well established and can be very accurate if set up correctly with accurate sensors.	Humidity sensors of the required accuracy eg. cooled mirror hygrometer very expensive. Equipment can be temperamental.	Not appropriate as equipment impossible to acquire and set within time frame of project. Also, superceded by EC
Eddy Correlation (EC)	Uses 3 axis sonic anemometry and fast response infra-red sensors to detect the difference in upward verses downward moving air	Now a well established, affordable, up to date technique for evaporation assessment. Particularly suited to measurements close to open water surfaces.	Equipment still a little expensive for routine farm use, but affordable for researchers with a reasonable budget	Would be very appropriate for this study. The only method which is accurate in a fetch limited situations ie. most farm storages
Ground based laser	eg. Tunable Diode Fourier Transform InfraRed (FTIR), LIDAR (UV), Microwave Radiometry (CSIRO). Range about 1 km, resolution about 1m, about ±5% accuracy claimed	Lasers can scan horizontally and through the humidity plume. Widely used in volcanology. Can map variability of water vapour concentration across a water surface thus assessing fetch /advective effects.	Laser methods need the support of a well resourced university physics department (rare nowadays !). LIDAR type methods rather expensive. Only suited to large scale research projects.	Would be nice, but an expensive and possibly time / effort consuming option for this study
Remote Sensing / Airborne Survey	Spectral / thermal information obtained using aircraft or satellites	Good at assessing water surface temperature across large water bodies several km across.	Not so good at directly assessing evaporative flux from a water body	Would be nice, but an expensive and possibly time / effort consuming option for this study.

5 FULL LIST OF EVAPORATION CONTROL PRODUCTS

The following chapter represents a summary of information gathered from carrying out an internet search with "Evaporation Control Product" as the main search term.

Table 6 Summary of evaporation mitigation technology products referred to on the internet

Cover Type	Cover Name	Key Advantages	Cost
Chemical (Monolayer Covers)	***Water$avr**	Very low initial setup costs and relatively low ongoing maintenance costs.	$18.00/kg with an application rate of .5-1kg/ha.
	Hydrotect	Very low initial setup costs requiring minimal capital expenditure.	$ 5.00/kg with an application rate of 1.5kg/ha.
Floating Covers	***Evaporation Control System E-VapCap**	Reduction of salt build up, improved water quality, reduction in algae growth, reduction in wave action and reduced bank erosion.	$7.00/m^2 but these costs are dependant on transport costs and may be site specific.
	Aquaguard Evaporation Cover	Reduces algae growth, allows rainwater to enter the storage, reduces erosion from wind and wave action, slower salt build up.	The estimated cost is $6.00-$6.60/ m^2 installed. Cost subject to site location.
	CURV	The product is relatively cheap and long lasting.	The estimated cost is around $3.50/m^2 or more.
	C.W. NEAL Corp Defined Sump floating cover	Long lasting and prevents light from entering the storage and so eliminates algal growth and increases water quality.	The anticipated cost is $30/m^2 but this price is subject to size of site and the site conditions.
	Evap-Mat	Heat reflective, self-protecting in high winds (up to 150kph) whether empty or full and it is simple and easy to install, the cover is also suitable for all storage sizes, shapes and profiles up to 2 km wide.	$3.50/m^2 for complete installation.
	Fabtech	Reduces algae growth in the storage which can cause problems with irrigation sprinkler blockages, this is due to the fact that no light passes through the cover.	$7.00/m^2 but this price does not include any earthworks required for the installation.
	REVOC floating cover	The cover is able to be inflated for maintenance and inspection of the storage.	The anticipated cost is $30/m^2 but this price is subject to size of site and the site conditions.
	RTD Enterprises	Reduces algae growth and wave action.	$28.38/m^2-$63.86/m^2 or US $21.53/m^2- $48.44/m^2. The cost of this product is site specific and therefore it may vary.
Cover Type	**Cover Name**	**Key Advantages**	**Cost**
Shade Structures	***NetPro cabled shade cover**	The cover does not float on the water so there are no problems with changing water levels.	$7.00 - $10.00 $6.00-7.50/m^2
	Aquaspan	The structure is long lasting and the cover is not affected by changing water levels.	The cover costs approximately $33.00/m^2.
	MuzCov	The cover allows easy access to the storage for maintenance operations.	The anticipated costs are $7.50/m^2.

Modular Covers	***Raftex**	Easy to install and remove form the storage.	The anticipated cost of this product is $4.00-$5.00/m^2.
	AQUACAP	Minimal bank erosion and turbidity due to reduced wave action there will also be a reduced concentration of nutrients and salts in the water and possibly a reduction in algal booms.	The estimated cost is $17/m^2 installed.
	Euro-matic Bird Balls	Reduce light penetration and therefore algae growth and they are virtually maintenance free. They allow rainfall to penetrate the storage and they adjust with changing water levels.	The approximate cost is $22.80/m^2.
	Layfield Modular Cover	Maintenance is easy to carry out on the cover due to the fact that damaged modules may be removed independently and with ease.	Unavailable
	LemTec Modular Single Sheet Cover System	Reduces algae and also reduces the amount of total suspended solids in the storage and this product is relatively easy to install.	Information unavailable.
	HexDome™	It has been shown to greatly reduce the effects of wave action, and it is easily installed by the customer.	The anticipated cost is between $4.50-8.00/m^2
	MOD-E-VAP	Easy to install by the land owner and it is easy to remove the cover if necessary. There is no need for an anchor trench and maintenance costs are expected to be minimal.	The product has an estimated cost of $3.00-$3.50/m^2 depending on the catchment area shape.
	POLYNET	Quick and easy to install.	The anticipated cost is $2.50/m^2.
	QUIT Evap Modular Floating Cover	Lightweight and easy to install.	The estimated cost is around $6.00-$8.00/m^2 plus transport and installation.
Chemical (PAM)	***CIBA PAM**	PAM can reduce erosion and nutrient runoff in the field and also reduce seepage from the water storage.	It is expected to cost $25ML.

* Indicates the products evaluated in this project.
(Note information provided in this table is based on the promotion material provided for each product).

Water$avr

Description:

Water$avr is a white powdered product which is comprised of hydrated lime with a cetyl/stearyl alcohol flow aid which forms a film on the waters surface.
This product is made of food grade chemicals which are biodegradable in 2 ½ to 3 days and it is permeable to oxygen.

Manufacturer/Supplier:

ONDEO Nalco Australia Pty Ltd. and Flexible Solutions Int. Inc.
Flexible Solutions International Ltd.
615 Discovery Street
Victoria, BC
Canada V8T 5G4
Tel: 250-477-9969
Fax: 250-477-9912

Email: infowatersavr@flexiblesolutions.com
Website: http://www.flexiblesolutions.com/products/watersavr/

Performance as stated by the manufacturer:
Water$avr reduces evaporation by up to 30%.

Costs:
$18.00/kg with an application rate of .5-1kg/ha.

Durability:
Breaks down in 2 ½ to 3 days.

Installation:
Very easy to apply with a patented self applicator, by hand or with a boat. The wind direction must be taken into consideration when applying the product so as to gain an effective unbroken film.

Pros:
Very low initial setup costs and relatively low ongoing maintenance costs.

Hydrotect

Description:
Hydrotect is a water evaporation retardant which is an emulsion of 60% water and 40% aliphatic alcohols. This product is claimed to be non-toxic, biodegradable and suitable for application to drinking water.

Manufacturer/Supplier:
Swift and Co Ltd.
Neil Clifford
Business Manager
Tel: 61 3 8544 3159
Fax: 61 3 8544 3259
Mob: 0425 724 085
Email: nclifford@im.aust.com
Website: www.swiftco.com.au

Performance as stated by the manufacturer:
Hydrotect is claimed to reduce evaporation in larger storages by 25-35%.

Costs:
$ 5.00/kg with an application rate of 1.5kg/ha.

Durability:
The product has to be reapplied daily.

Installation:
Very easy to apply by machine or by hand with a boat. The wind direction must be taken into consideration when applying the product so as to gain an effective unbroken film.

Pros:
Very low initial setup costs requiring minimal capital expenditure.

Evaporation Control System E-VapCap

Description:
E-VapCap is a heavy duty polyethylene 'bubble wrap' style product with a white surface to reflex heat and a black bubble underside which provide flotation and stops light penetration. Both of the layers are UV stabilised and 10mm diameter holes are positioned at 1000mm centres to allow rainfall penetration and the release of gases from the storage.

Manufacturer/Supplier:
Sealed Air Australia Pty Ltd (SAA), Evaporation Control Systems Pty Ltd (ECS) and Darling Downs Tarpaulins Pty Ltd (DDT)

Evaporation Control Systems Pty Ltd (ECS)
Tel: 07 4665 6144
Fax: 07 4665 6395
Website: http://www.evaporationcontrol.com.au/index.1.htm\
Approved installers:
Darling Downs Tarpaulins Pty Ltd
Website: http://www.ddt.com.au/
C E Bartlett Pty Ltd
Website: http://www.bartlett.net.au/
Ertech Pty Ltd. Western Australia
Website: http://www.ertech.com.au/

Performance as stated by the manufacturer:
E-VapCap has been shown to reduce evaporation by as much as 90-95%.

Costs:
\$7.00/m^2 but these costs are dependant on transport costs and may be site specific.

Durability:
E-VapCap offers a 5 year warranty with and expected life of 12 or more years.

Installation:
The ease of installing this product is site specific and also dependant of the weather conditions as wind can create problems during installation.

Pros:
Reduction of salt build up, improved water quality, reduction in algae growth, reduction in wave action and reduced bank erosion.

Aquaguard Evaporation Cover

Description:
The cover is manufactured from a laminated polyethylene bubble with a beige/white top and black underside; the light top reflects heat while the black underside eliminates light. The material has positive buoyancy due to the "bubble" material and so floats on the waters surface.

Manufacturer/Supplier:
Fabric Solutions by PyramidDOME Australia Pty Ltd.

Fabric Solutions International
9A Production Avenue
Ernest Qld 4214
Tel: (07) 55633755
Email: info@fabricsolutions.com.au
Website: http://www.fabricsolutions.com.au/evaporative_covers.htm

Performance as stated by the manufacturer:
Up to a 90% reduction in evaporation.

Costs:
The estimated cost is $6.00-$6.60/ m^2 installed. Cost subject to site location.

Durability:
UV resistant long life material.

Installation:
The cover is installed by Fabric Solutions and the ease of installation is related to the site conditions, size and weather conditions.

Pros:
Significantly reduces algae growth, allows rainwater to enter the storage, and reduces erosion from wind and wave action, slower salt build up.

CURV

Description:
A new form of polypropylene sheet made in a patented process, the sheets are 0.3mm thick and they are attached to cables on either side of the storage. Smaller strips of the product can then be interwoven for stability. The product floats on the surface and is kept in tension by the cables.

Manufacturer/Supplier:
Still in its development stage.

Performance as stated by the manufacturer:
Unknown at this stage.

Costs:
The estimated cost is around $3.50/$m^2$ or more.

Durability:
It is expected to be highly durable and long lasting.

Installation:
Not known at this stage.

Pros:
The product is relatively cheap and long lasting.

C.W. NEAL Corp Defined Sump floating cover

Description:

The defined sump style cover is constructed with a polyester fabric reinforced geomembrane such as Hypalon or polypropylene with thicknesses ranging from 0.91mm to 1.14mm.The cover uses ballast tubes in the centre to keep it taught. The cover is also impermeable, so storm water collects in the ballast lines where a choice of either gravity removal through a network of hoses or electric pumps.

Manufacturer/Supplier:

C. W. Neal Corporation
8625 Argent St
Santee, CA 92071
USA
Tel: (619) 562-1200
(800) 377-8404
Fax: (619) 562-1150
E-Mail: info@cwneal.com
Website: http://www.cwneal.com/floatingcover.htm

Performance as stated by the manufacturer:

Reduce evaporation by up to 95%

Costs as at December 2004:

The anticipated cost is $30/m^2 but this price is subject to size of site and the site conditions.

Durability:

This product is said to last 20-30 years

Installation:

To install this product the storage is required to be empty and the cover is installed by C.W. Neal Corp.

Pros:

The cover is long lasting and prevents light from entering the storage and so eliminates algal growth and therefore increases water quality.

Evap-Mat

Description:

The cover is comprised of laminated 20 micron, stainless steel mesh and 0.4mm bubble HDPE sheet. The cover is anchored to the storage floor by cables attached to a buried polyethylene pipe. It is designed to only cover 90% of the waters surface area.

Manufacturer/Supplier:

Reservoir Covers Australia (Pty Ltd proposed extension).

Performance as stated by the manufacturer:

May reduce evaporation by up to 90% depending on the water level of the storage.

Costs:
$3.50/m^2 for complete installation.

Durability:
Life expectancy of 30 or more years. Resistant to UV and oxidation.

Installation:
Not available.

Pros:
Heat reflective, self-protecting in high winds (up to 150kph) whether empty or full and it is simple and easy to install, the cover is also suitable for all storage sizes, shapes and profiles up to 2 km wide.

Fabtech

Description:
High density polyethylene (HDPE) or unsupported polypropylene with a thickness of 0.5 to 1mm with flotation material attached and sand filled ballast tubes in the centre to take up the slack in the cover due to changes in the water level. The sand tubes also form sumps from which rainwater can be pumped into the storage using small submersible pumps. The cover is secured in a 600mm deep anchor trench around the storage wall.

Manufacturer/Supplier:
Fabtech SA Pty Ltd
53 South Terrace
Winfield SA 5013
Tel: (08) 8347 3111
Email: lorri@fabtech.com.au
Website: http://www.fabtech.com.au/Covers/covers.html

Performance as stated by the manufacturer:
Estimated to reduce evaporation by up to 95%.

Costs:
$7.00/m^2 but this price does not include any earthworks required for the installation.

Durability:
Design life of a minimum of 15 years.

Installation:
The storage is required to be empty.

Pros:
Reduces algae growth in the storage which can cause problems with irrigation sprinkler blockages, this is due to the fact that no light passes through the cover.

REVOC floating cover

Description:

Scrim reinforced Hypalon or scrim reinforced Polypropylene with flotation material attached and sand filled ballast tubes in the centre form sumps from which rainwater can be pumped into the storage using small submersible pumps. The cover is attached to patented self tensioners around the perimeter to keep the cover taught allowing people to walk all over the cover.

Access ports are also incorporated into the design to allow for maintenance and also to allow the cover to be inflated for ease of repair under the cover.

Manufacturer/Supplier:

C. W. Neal Corporation
8625 Argent St
Santee, CA 92071
USA
Tel: (619) 562-1200
(800) 377-8404
Fax: (619) 562-1150
E-Mail: info@cwneal.com
Website: http://www.cwneal.com/floatingcover.htm
Layfield Environmental Systems Corp
Dba CW Neal.

Performance as stated by the manufacturer:

Reduce evaporation by up to 95%

Costs as at December 2004:

The anticipated cost is $30/m^2 but this price is subject to size of site and the site conditions.

Durability as stated by the manufacturer:

The Hypalon cover has 30 year warranty.

Installation:

The storage is required to be empty.

Pros:

The cover is able to be inflated for maintenance and inspection of the storage.

RTD Enterprises

Description:

This floating cover is made from reinforced products such as Hypalon or polypropylene. This cover is typically incorporated with a liner to totally seal the storage.

Manufacturer/Supplier:

RTD Enterprises
P.O. Box 247, 196 Old Point Avenue

Madison, Maine 04950
USA
Tel: 207 696 3964
Fax: 207 696 0815
Email: info@rtd-enterprises.com
Website: http://www.rtd-enterprises.com/

Performance as stated by the manufacturer:
No information available.

Costs as at December 2004:
\$28.38/m^2-\$63.86/m^2 or US \$21.53/m^2- \$48.44/m^2. The cost of this product is site specific and therefore it may vary.

Durability:
The cover is made from long lasting product.

Installation:
Not available.

Pros:

NetPro cabled shade cover

Description:
High tension cable, incorporating long life 300g/m^2 90% plus black monofilament shade cloth. The cable design in essence acts as a giant spider web, with all cables spliced at crossover points to disperse the load evenly and also to eliminate product creep due to wind.

Manufacturer/Supplier:
NetPro Pty Ltd.
NetPro Protective Canopies
Lot 1 Sullivan Drive
Stanthorpe, Qld 4380
Free Call: 1800 501 337
Phone: +61 7 4681 6666
Fax: +61 7 4681 6600
Email: sales@netprocanopies.com
Website: http://www.netprocanopies.com/npcrd.php

Performance as stated by the manufacturer:
It has been shown to reduce evaporation by around 75%

Costs:
\$6.00-7.50/m^2

Durability:
It is expected that the shade cloth will have a life of over 30 years.

Installation:
The storage is required to be empty for the installation of the pole supports.

Pros:
The cover does not float on the water so there are no problems with changing water levels.

Aquaspan

Description:
Aquaspan is comprised of a patented polymer fabric which is suspended above the water storage via the use of steel support posts and cable. The fabric used is purpose designed and blocks 98% of light and reduces temperatures beneath by 31%. The fabric is a densely knitted membrane which reduces and stabilises the water temperature reducing vapour pressure adjacent to the surface and effectively insulating the water.

Manufacturer/Supplier:
Aquaspan Pty Ltd and Gale Pacific Limited.
Aquaspan Pty Ltd
Gary Gale
P.O. Box 367
Braeside Vic 3195
Australia

Performance as stated by the manufacturer:
Evaporation is reduced by 76-84%.

Costs:
The cover costs approximately \$33.00/m^2.

Durability:
The fabric is UV stabilised and supported by a 20 year warranty against UV breakdown.

Installation:
The cover is able to be installed regardless of the water level in the storage.

Pros:
The structure is long lasting and the cover is not affected by changing water levels.

MuzCov

Description:
The cover is comprised of high tension cables supported by poles with shade cover panels attached to the cables. The high tension cables give the structure stability while still allowing some natural movement. The structure is designed to allow heavy machinery access to the storage for maintenance and operational activities with minimal disruption.

Manufacturer/Supplier:
Designed at the Dalby Agricultural College and it is still in its initial concept stage.

Murray Choat
Dalby Agricultural College
PO Box 398
Dalby Qld 4405
Tel: (07) 4672 3100

Performance as stated by the manufacturer:
Unknown at this stage.

Costs:
The anticipated costs are $7.50/m^2.

Durability:
Unknown at this stage but it is expected to have a long life span.

Installation:
Unknown at this stage.

Pros:
The cover allows easy access to the storage for maintenance operations.

Raftex

Description:
Raftex modules comprise a fully enclosed rectangular plastic pipe frame with maximum dimensions of 12m x 2m. The plastic pipes are 2” or 3” diameter and are joined using force fit right angle joiners. The frames are also strengthened with plastic brace rods every 2 metres.
The frame is easily assembled on site with the pre-drilled holes for the brace rods.
Once the frame is assembled it is then machine wrapped in multiple layers of UV stabilised adhesive film which totally encloses the frame to form a raft. Holes are then drilled through the film and pipe to allow the raft to partially fill with water so as act as an anchor for the raft in windy conditions.

Manufacturer/Supplier:
IPEX Bulk Systems International Pty Ltd, Trading as F Cubed (F^3)
Peter Johnstone
35 Robins Avenue,
Humevale Victoria 3757
Tel: (03) 9716 1195
Mob: 0413 949007
Fax: (03) 9716 1541
Email: pjjohnstone@ipstretch.com

Performance as stated by the manufacturer:
This product is still in its trial stage.

Costs:
The anticipated cost of this product is $4.00-$5.00/m^2.

Durability:
The product is UV stabilised and the film has an anticipated life of 5 years. At the end of this time F^3 will provide complete refurbishment. However the frame is expected to have a much longer working life.

Installation:
This cover is easy to install and may be carried out by the owner.

Pros:
Easy to install and remove form the storage.

Aquacap

Description:
Aquacap is a free-standing floating modular cover with individual modules with a diameter of approximately 1m. These modules have specific design attributes to maximise their effectiveness in reducing evaporation loss from open water storages. The modules are used to cover up to 90% of the surface area of a water body.

Aquacap modules have unique suction properties that make them stable on a water surface.

Manufacturer/Supplier:
The product was designed by Ian Burston and it is not yet commercially available but it is expected to be sometime in 2005.
Website:
http://www.rmit.edu.au/browse/News%20and%20Events%2FNews%2FOpenline%2F1999%2FAquacaps%20to%20save%20water/

Performance as stated by the manufacturer:
Field studies have shown that Aquacap reduces evaporation by an average of 70% when 80% of the water surface is covered.

Costs:
The estimated cost is $17/m^2 installed.

Durability:
It is expected to have a long lifespan.

Installation:
The cover may be easily installed by the owner.

Pros:
Minimal bank erosion and turbidity due to reduced wave action there will also be a reduced concentration of nutrients and salts in the water and possibly a reduction in algal booms.

Euro-matic Bird Balls

Description:

Bird balls are hollow black balls that form a floating cover, they are made of high density polyethylene (HDPE) or polyethylene and they come in arrange of sizes ranging from10mm diameter to150mm diameter.

Manufacturer/Supplier:

Euro-matic Bird Balls
Head Office
Contact: Adrian Wilkes – Director
Euro-Matic Ltd
Clausen House
Perivale Industrial Park
Horsenden Lane South
Greenford
Middlesex UB6 7QE
United Kingdom
Tel: + 44 20 8991 2211
Fax: + 44 20 8997 5074
Email: sales@euro-matic.com
Website: http://www.enquip.com/BirdBalls.html

Performance as stated by the manufacturer:

They may reduce evaporation by up to 90%.

Costs:

The approximate cost is $22.80/m^2$.

Installation:

Bird balls are very easy to install and may be carried out by the owner.

Durability:

The balls are UV stabilised and are long lasting.

Pros:

Reduce light penetration and therefore algae growth and they are virtually maintenance free.

They allow rainfall to penetrate the storage and they adjust with changing water levels.

Layfield Modular Cover

Description:

A typical floating module would measure 50 x 50 feet (15.24 x 15.24m) or 100 x 100 feet (30.48 x 30.48m), the modules are floated out onto the storage and then lashed together by ropes or webbing. In storages with fluctuating levels special panels can be made to take up slack around the perimeter.

Manufacturer/Supplier:

Layfield Plastics Inc.
Head Office in Seattle, Washington USA
Tel: 425-254-1075
Email: international@layfieldgroup.com
Website: http://www.geotextile.ca/projectprint.cfm?productID=143&id=corC. W.

Performance as stated by the manufacturer:
Unavailable

Costs:
Unavailable

Durability:
The modules are made from long lasting material and so are expected to have a long working life.

Installation:
Modules are manufactured in ideal conditions in the factory and then installation is easily carried out by floating the modules into position on the storage. Installation does not necessarily require a trained professional.

Pros:
Maintenance is easy to carry out on the cover due to the fact that damaged modules may be removed independently and with ease.

LemTec Modular Single Sheet Cover System

Description:
The LemTec modular cover system uses 10 year UV resistant, High Density Polyethylene (HDPE) geomembrane sheets with encapsulated, closed-cell, lateral extruded-polystyrene insulation for flotation. These sheets are laced together during installation to form a complete cover. The edges of the cover are anchored to perimeter of the storage with LemTec's unique anchoring system.

Manufacturer/Supplier:
Lemna Technologies, Inc.
2445 Park Avenue South Minneapolis, Minnesota
USA 55404-3790
Tel: (612) 253-2002
Fax: (612) 253-2003
Email: techsales@lemna.com
Website:
http://www.lemnatechnologies.com/pdf/productSummaries/LemTecCoverProductSummary.pdf

Performance as stated by the manufacturer:
Information unavailable.

Costs:
Information unavailable.

Durability:
Made from long lasting HDPE material which is 10 year UV resistant.

Installation:
For installation of this cover fewer people are required than other products on the market. No heavy equipment is needed and the storage does not need to be empty.

Pros:
Reduces algae and also reduces the amount of total suspended solids in the storage and this product is relatively easy to install.

HexDome™

Description:
It is and independent modular system made from UV resistant recycled plastic. Each module covers one square metre.

Manufacturer/Supplier:
Indusium Pty Ltd and tested by the Queensland University of Technology
Stoph Vanwensveen
Email: stvn@bigpond.com

Performance as stated by the manufacturer:
Reduce evaporation by up to 90%

Costs:
The anticipated cost is between \$4.50-8.00/m^2

Durability:
Expected life of more than 25 years.

Installation:
This cover may be easily installed by the owner.

Pros:
It has been shown to greatly reduce the effects of wave action, and it is easily installed by the customer.

MOD-E-VAP

Description:
This product consists of simple and easy to install modular plate system of polyethylene pipe, fittings and sheeting.
Each modular has a rigid framework of high density polyethylene (HDPE) pipe and fittings restraining, via plastic sheet clips, linear low density polyethylene sheets (LLDPE). The individual plates are then inter-connected utilising manufactured polyvinyl chloride 'nuckle joints'.

Manufacturer/Supplier:
Merit Lining Systems Pty Ltd
6 Lombark Street
Acacia Ridge Qld 4110

Tel: (07) 3275 3950
Fax: (07) 3275 3960

Performance as stated by the manufacturer:
Not known at this stage.

Costs:
The product has an estimated cost of \$3.00-\$3.50/m^2 depending on the catchment area shape.

Durability:
It is expected to be long lasting.

Installation:
The modular cover is easy to install.

Pros:
Easy to install by the land owner and it is easy to remove the cover if necessary. There is no need for an anchor trench and maintenance costs are expected to be minimal.

Polynet

Description:
Polynet is a floating modular product that is comprised of expanded 20mm thick polystyrene sheets wrapped in a net and secured into pockets in the net in sections. Each section is prefabricated into 50m x 5m sections which can then be floated out onto the storage.

Manufacturer/Supplier:
The product was designed by Ken Gordon but it is still in its concept stage.
Ken Gordon
1 Euro Street
Gilgandra N.S.W
PO Box 33 2827
Tel/Fax: (02) 6847 1381

Performance as stated by the manufacturer:
Not known at this stage.

Costs:
The anticipated cost is \$2.50/$m^{2.}$

Durability:
It is expected to be long lasting.

Installation:
This product is relatively easy to install and could be done by the owner.

Pros:
Quick and easy to install.

QUIT Evap Modular Floating Cover

Description:

Quit Evap is a rectangular modular floating cover, manufactured from 0.5-.75mm thick polypropylene sheet with polystyrene floats. The modules are interconnected by Velcro straps. The full scale modules are up to 5m x 25-30m.

Manufacturer/Supplier:

SMEC Australia Pty Ltd.
Peter Chapman
1st floor, 105 Denham Street
Townsville Qld 4810
Tel: (07) 4771 6119
Fax: (07) 4771 6120
Email: Peter.Chapman@smec.com.au

Performance as stated by the manufacturer:

Can effectively achieve 90-95% coverage of the waters surface and reduce evaporation by 85-90%.

Costs:

The estimated cost is around \$6.00-\$8.00/m^2 plus transport and installation.

Durability:

The cover has a minimum life span of five years with a potential life of 8-10 years, the cover is also UV stabilised.

Installation:

Installation of this product is easy and may be done by the owner.

Pros:

Lightweight and easy to install.

CIBA PAM

Description:

PAM stands for polyacrylamide which is a chemical that is added to water in low concentrations to thicken it and therefore reduce evaporation.

Manufacturer/Supplier:

Ciba Specialty Chemicals Pty Limited
235 Settlement Road
PO Box 332
Thomastown 3074
Victoria
AUSTRALIA
Tel.: +61 3 9282 0600
Fax: +61 3 9465 9070
Email: customerservice.au@cibasc.com
Website: http://www.cibasc.com/ind-agr.htm

Performance as stated by the manufacturer:
The performance is not known at this stage.

Costs:
It is expected to cost $25ML.

Durability:
Not available.

Installation:
Very easy to apply to the water.

Pros:
PAM can reduce erosion and nutrient runoff in the field and also reduce seepage from the water storage.

6 CONCLUSION

Evaporation losses from on-farm storage can potentially be large, particularly in irrigation areas in northern New South Wales and Queensland where an estimated 40% of storage volume can be lost each year to evaporation. Reducing evaporation from a water storage would allow additional crop production, water trading or water for the environment. The NCEA study undertook a practical evaluation of current evaporation mitigation technologies (EMTs) on commercial sized water storages. In the case of the the majority of Australian agriculture, EMTs may be at present impractical due to cost and difficulty of implementation. It follows that any recommendation regarding water use efficiency might entail avoiding where possible the storage of water in surface dams, and the pumping where possible of water directly from bores only when required. In this way, excessive losses of water due to evaporation could be effectively minimised.

The Evaporation Control Project referred to in this review was initiated by the Queensland Government Department of Natural Resources and Mines (NRM) with the express aim of addressing this gap in our knowledge. Its focus was on;

- Assessment of the effectiveness of different EMTs in reducing evaporation from commercial storages across a range of climate regions.
- Assessment of the practical and technical limitations of different evaporation control products.
- Comparison of the economics of different EMTs on water storages used for irrigation.
- Preliminary assessment of the effect on water quality of the various EMTs.

This project in large part met all of its objectives resulted in;

- Detailed investigation of the evaporation mitigation efficiency of five products Water$avr (monolayer), E-VapCap (floating cover), NetPro shade cloth (suspended cover), Raftex (modular cover) and Polyacrylamide (chemical) on research tanks located at the University of Southern Queensland (USQ), Toowoomba.
- Field demonstrations and evaluations of evaporation reduction efficiency at four commercial storages (Capella (Water$avr), Dirranbandi (Water$avr), St George (E-VapCap) and Stanthorpe (NetPro shade cloth).
- Assessment of the mechanical durability, and practical and technical limitations, of the products evaluated at commercial storages.
- An economic assessment of the EMTs for a range of climate regimes, based on capital and operating costs and the anticipated evaporation reduction performance.
- An initial assessment on potential impact on water quality of each product.
- Substantial and significant interaction with agency representatives, farmers and EMT suppliers resulting in much interest in and support for the adoption of evaporation control products.

A major outcome of the project was increased awareness of the potential for evaporation reduction on water storages. The project has been highly successful in this regard, with significant interest being shown by landholders, agencies and private companies in the work undertaken. The combination of detailed experimentation at USQ, commercial scale demonstration sites and wide publicity, through field days, workshops, scientific papers and popular articles, has raised expectations on the potential for cost effective evaporation control solutions. Already a number of private companies, product suppliers and agency funding bodies are exploring the possibilities for further research, product development and commercialisation in this area.

An important outcome of the project has been the development of methodologies which allow the accurate measurement of seepage and evaporation rates, both from open water storages and storages with an EMT product in place. The methodology utilised accurate pressure sensors linked to data loggers and automatic weather stations. While further development and testing of this methodology is required, already a number of private irrigation consultants are investigating the use of this technology to provide recommendations to farmers on improved evaporation and seepage management.

Error! Reference source not found. indicates the range in measured evaporation reduction at the USQ research tanks for the products tested commercially. While efficiency in reducing evaporation was less favourable at commercial test sites, potential savings on commercial storages have also been given, based on the results and experiences of this study. A range of expected installation and operating/maintenance costs are also given and this has been translated into an estimated breakeven cost ($/ML water saved). It is anticipated that the low cost operating and maintenance scenario is most representative given good product installation and management.

Table 7 Summary table on product performance.

Product	Evaporation Reduction (%)		Installation Cost ($/m^2)	Operating & Maintenance Cost $/ha/yr	Breakeven Cost ($/ML saved)
	Measured Small Tanks	Potential Commercial Storage			
		High - Med - Low	Low - High	Low - High	Low - Med - High
E-VapCap	100% - 94%	95% - 90% - 85%	$5.50 - $8.50	$112 - $572	$302 - $319 - $338
NetPro	71% - 69%	80% - 70% - 60%	$7.00 - $10.00	$112 - $537	$296 - $339 - $395
Water$avr	40% - 10%	30% - 15% - 5%	$0.00 - $0.38	$826 - $4,050	$130 - $397 - $1191

1) Estimated breakeven cost is based on 2200mm potential evaporation, all year water storage, low cost scenario and range in evaporation reduction performance (Low- Med- High).
2) High operating and maintenance costs represent worst case scenario and are unlikely in most cases.
3) Evaporation reduction performance of Water$avr product has been shown to be highly variable and in some trials 0%.

Breakeven cost is shown to vary from $130 - $1,191 depending on product and evaporation reduction performance. Under situations where potential evaporation losses from storage exceed 2000mm/year and ‘medium’ evaporation reduction performance the breakeven cost is likely to range between $300/ML-$400/ML saved. The cost per ML water saved is influenced by the amount of time the storage holds water. Chemical monolayers can be selectively applied only in hot months or when there is water in storage which reduces cost per ML water saved. Considering the gross margin per ML water used of many crops ($100/ML - $1000/ML), it is likely that investment in these products will be viable in many situations. Investment in EMTs would also appear to be viable for high value crops in southern areas.

This project did not intend to recommend a single best evaporation control solution and it is envisaged that various EMTs would be appropriate in different situations, depending on the surface area, location and storage operational requirements. For example, floating covers are most appropriate on storages less than 1ha in size with all year water storage. Shade cloth structures would also be most viable on storages with permanent water and are likely to be limited to less than 5ha in size. Chemical monolayers would be most viable on large storages (greater than 10ha) and where the dam is likely to be dry for significant periods. Modular systems are likely to be best suited to intermediate storage areas less than 10ha.

While the volume of water in Queensland farm storages is not accurately known, one estimate from NRM (2,500,000ML) would equate to some 55,000ha of storage. With appropriate selection of different EMT products to storage area and some assumptions on storage size distribution potentially 300,000ML of evaporation loss could be saved with 100% adoption of EMTs. Even 10% adoption would save a significant amount of water (30,000ML). Only a preliminary water quality assessment was undertaken in this project and no significant negative impacts were evident. Reduced light penetration and lower temperatures occur under floating and shade cloth covers and dissolved oxygen is lower under floating covers. These factors will limit algal growth but may impact on other flora/fauna. The monolayer did not create any negative impact on the waters physical quality parameters measured, although a more comprehensive analysis would be required before this product can be widely accepted.

Given the large interest raised by this project further work will be required, particularly in the following areas;

- Fundamental research on evaporation processes for storage dams accounting for thermal storage in the water body and advection from surrounds, leading to improved prediction of evaporation losses from weather data and storage characteristics.
- Further testing of the instrumentation developed in this project for seepage and evaporation determination and methodologies to separate seepage and evaporation components of water loss.
- Further development of depth sounder systems developed at USQ for storage basin mapping to provide a cheap and accurate system for mapping the storage basin when filled with water.
- Information on the extent and area categories of storages in each state leading to information on likely water savings from EMTs.
- Fundamental research on the potential for monolayers particularly in terms of distribution characteristics, application methods, evaporation reduction performance and environmental impact.
- Further large scale testing of commercial products in conjunction with suppliers to assess evaporation mitigation efficiency and mechanical durability.
- Support for quality control, collection and analysis of data being collected commercially by a number of irrigation consultants to facilitate better understanding of factors impacting seepage rates and regional evaporation losses from storage.

- Extension and communication of results to a wide range of irrigators and stakeholders to ensure the current high level of interest is maintained.

The current interest by EMT product suppliers and landholders and operators in the agricultural, mining and municipal sectors needs to be supported by continued widespread publicity of the potential for evaporation water savings and cost/benefit of water savings.

In the report, a number of areas for further research and investment where identified. One of these was the development of a computer model ('Ready Reckoner') which allows site specific assessment of evaporation mitigation systems, whether it be a cover over the water, applying a chemical monolayer or modifying the shape of the storage dam. The 'Ready Reckoner' calculator (Heinrich and Schmidt, 2005) is a model which performs a simple, site-specific economic assessment of the viability of evaporation mitigation systems. The user enters appropriate data to customise the software to their particular site. The calculator then returns the volume of water saved (in ML) and the cost of the evaporation mitigation system used to save this water ($/ML/year).

The 'Ready Reckoner' requires a number of inputs from the user to evaluate evaporation mitigation systems for their particular storage. The inputs are grouped into six fields: Storage Type and Geometry, Evaporation, Average Amount of Water Stored per Month, Average Percentage of Years that the Storage Contains Water, Seepage Information and Evaporation Mitigation System Information.

To demonstrate the ready reckoner, an example 1 hectare square ring tank (100m x 100m) in 3 locations was assessed using 3 of the products available. The first example site is Dubbo in New South Wales (32.25 S 148.61 E) using the E-Vap Cap floating plastic cover. The results summary below is based on a number of assumptions including that the storage always has water in it, the storage is constructed on a clay soils, all batters are 3:1 and the wall height is 3m, the annual evaporation is 2024 mm/year, that the installation cost is $15.00/m^2 and the evaporation saving efficiency of the cover is 95%

DUBBO Rectangular Ring Tank		
Evaporation Mitigation System Used:	***Impermeable Cover***	
Water Saved From Evaporation	**18.2**	***ML each year***
Cost to Save this Water	**$963**	***per ML per year***
Calculated Storage Volume at Full Supply Level	**25.1**	***ML***
Surface Area at Full Supply Level	**1.00**	***ha***
Total Cost of Evaporation Mitigation System at Installation	**$150,000**	
Annual Operating and Maintenance Cost	**$200**	

Using a chemical cover on the same storage will have a much lower capital investment but a larger ongoing cost because the chemical product needs to be applied at least twice a week. The product is also much less efficient at saving evaporation but need only be applied during periods of high evaporation and only when there is water in the storage.

DUBBO Rectangular Ring Tank		
Evaporation Mitigation System Used:	***Chemical Monolayer***	
Water Saved From Evaporation	**2.9**	***ML each year***
Cost to Save this Water	**$188**	***per ML per year***
Calculated Storage Volume at Full Supply Level	**25.1**	***ML***
Surface Area at Full Supply Level	**1.00**	***ha***
Total Cost of Evaporation Mitigation System at Installation	**$1,000**	
Annual Operating and Maintenance Cost	**$500**	

If the same storage was located outside Darwin (12.46° S, 130.93° E in the Northern Territory (annual evaporation 2851 mm/year) with a shadecloth cover use to mitigate the evaporation from the dam then the cost to save each ML of water is reduced because the cover is saving more water from evaporation.

DARWIN Rectangular Ring Tank		
Evaporation Mitigation System Used:	***Shadecloth***	
Water Saved From Evaporation	**21.4**	***ML each year***
Cost to Save this Water	**$434**	***per ML per year***
Calculated Storage Volume at Full Supply Level	**25.1**	***ML***
Surface Area at Full Supply Level	**1.00**	***ha***
Total Cost of Evaporation Mitigation System at Installation	**$120,000**	
Annual Operating and Maintenance Cost	**$200**	

The Ready Reckoner can also be used to assess the evaporation saved per unit of surface area if the storage depth is increased. For example if the Darwin storage is doubled in depth to 6m and earthworks costed at $\$2.00/m^3$.

DARWIN Rectangular Ring Tank		
Evaporation Mitigation System Used:	***Increase Wall Height***	
Water Saved From Evaporation	**11.6**	***ML each year***
Cost to Save this Water	**$295**	***per ML per year***
Calculated Storage Volume at Full Supply Level	**25.1**	***ML***
Surface Area at Full Supply Level	**1.00**	***ha***
Total Cost of Evaporation Mitigation System at Installation	**$64,800**	
Annual Operating and Maintenance Cost	**$0**	
Total Extra Earthworks to Increase Wall Height	**32,400**	***m3***
Calculated Storage Volume at Full Supply Level after	**42**	***ML***

Increasing Wall Height	
Additional Water Lost to Seepage as a Result of Increasing the Wall Height	**0** ***ML***

With the various types of covers as well as changes to the storage depth, the Ready Reckoner can be used to determine the best possible approach to save evaporation based on site specific parameters and water use requirements.

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