Methods for Assessing Dam Evaporation – An Introductory Paper

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Abstract

An evaluation the effectiveness of chemical monolayers, floating covers and shade structures in reducing dam evaporation is being undertaken at the National Centre for Engineering in Agriculture at the University of Southern Queensland. Evaporation is being assessed using high precision pressure sensor transducers to measure small changes in dam height. The evaporation rate is calculated as the residual in the dam water balance, taking into account in-flows and out-flows, and seepage which is assumed to equal the nighttime loss. As night-time evaporation is minimal compared to relatively large daytime evaporation rates experienced in warm semi-arid environments, this method is proving a successful and robust standard method for assessing the evaporation of farm dams in Australia.

Alternative assessment methods include the use of evaporation pans, automatic weather stations, or more specialised Bowen Ratio equipment. However, these methods have a large fetch requirement (hundreds of metres) which makes them invalid and therefore of unknown accuracy for small farm dams. However, a method known as eddy correlation avoids the fetch requirement by directly measuring the upward flux of vapour from the water surface. Eddy correlation equipment is now readily available and may prove useful in routine assessments of small dam evaporation, and also in applied research to more fully understand the complicated array of aerodynamic and advective processes involved.
1. Introduction

The National Centre for Engineering in Agriculture (NCEA) at the University of Southern Queensland (USQ) is presently involved in a project to assess the relative effectiveness of three commercially-available evaporation control methods - namely chemical monolayers, floating covers and shade structures. The project is funded via the Rural Water Use Efficiency Initiative (RWUEI) and Natural Resources and Mines, Queensland (NRM). The project involves experimental trials on dams at Capella (5ha), Dirranbandi (120ha), St George (4ha), Stanthorpe (4ha) and Toowoomba USQ campus (10m) and is depicted in Figure 1.

1) Water$aver monolayer (Dirranbandi & Cappella)

2) EvapCaps floating cover (St. George)

3) NetPro shade cloth (Stanthorpe)

4) Three 10m ring tanks (USQ)

Fig. 1 Summary of the Evaporation Control Trials being carried out by the National Centre for Engineering in Agriculture (NCEA), USQ
Acknowledgements

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2. Evaporation Assessment Methods

Methods for assessment of evaporation are commonly classified according to whether they assess ‘potential’ evaporation or ‘actual’ evaporation.

**Potential evaporation** (commonly $E_o$ or $E_p$) assessment methods estimate what the evaporation would be from – very roughly – “an extensive area of uniform horizontal damp surface which is well supplied with water and is never allowed to dry out” (following the original definition of Potential Evaporation by Penman, 1948).

It is therefore tempting to assume that any open water surface will automatically meet this definition and therefore must evaporate at the potential rate: unfortunately this is not true (for reasons set out below).

**Actual evaporation** ($E_a$) assessment methods determine or estimate what the “actual evaporation is from a particular surface, which may have varying levels of water availability”. Common examples of limited water availability are when the water travels through the stomata of plants (transpiration) and the plants restrict the flow in response to their internal moisture stress; and ‘Stage II drying’ of soils, when the surface layer is no longer obviously wet. In both cases $E_a < E_o$. Water may also be ‘super-available’ e.g. when sprayed onto the surface of foliage during irrigation operations: here $E_a > E_o$, i.e. $E_o$ cannot be taken as a maximum.

In the case of open water evaporation, the ‘availability’ of the water varies with:
(i) the temperature of the uppermost layers; and
(ii) the ‘state’ of the surface, which is greatly affected by local wind causing waves, spray, etc.; and, of course,
(iii) the presence of any sort of surface covering (or other material, e.g. vegetation).

Hence, for the present application, the concept of potential evaporation has no relevance. What we require, of course, is ‘actual’.

2.1 Water Balance

In the present project, evaporation rate is being assessed as the residual in the dam water balance, i.e. by high-accuracy measurement of in-flows, out-flows and change in dam water level using sensitive pressure sensor transducers (accurate to ± 1mm). To account for wind piling effects, average readings are taken from typically four transducers per dam.

As noted above, measurement of all in-flows, all liquid out-flows and the consequent change in stored volume permits evaporation of the water storage to be deduced as the residual of the balance, for example, over the same time period,
\[ \Delta V = Q_{in} - Q_{out} - E - S \]  

(1)

where:  
\[ \Delta V \] is the measured change water volume  
\[ Q_{in} \] is the total water input including direct precipitation  
\[ Q_{out} \] is the total water output i.e. water used  
\[ E \] is the evaporation rate  
\[ S \] is the dam floor/wall seepage

With care taken, this approach is proving very reliable and robust and can be recommended as an “industry best practice” method for measuring the total evaporation from a particular farm dam. However, there are two points which should be noted with the method:

- **E** is usually a relatively small term compared with the other terms in equation (1). Therefore to achieve reasonable accuracy in **E**, high precision measurements are required for each of the other terms. *This has been achieved in the current project by ignoring data where \( Q_{in} \) and \( Q_{out} \) have values above zero, and the use of highly sensitive pressure transducers for measuring \( \Delta V \).*

- Seepage **S** is notoriously hard to estimate and the uncertainty in this term will often exceed the magnitude of **E**. *To account for this in the current project, the assumption is made that evaporation in the hours just before dawn is minimal, and any depth change then is due to seepage alone (Figure 2). This is supported by weather station data (windspeed and vapour pressure deficit values near zero).*

![Fig. 2 Typical pressure sensor transducer trace over a four day interval. The depth change in this dam is typically 10-20mm during daylight hours (clear regions) and approximately 2-4mm during the night (shaded regions) – although this night-time loss can sometimes be significantly higher – particularly in the early part of the evening. The minimum depth change rate obtained just prior to dawn is assumed to be due to the dam seepage alone.](image-url)
2.2 Evaporation Pans

In summary: pan evaporation methods are susceptible to large errors due to poor maintenance, fouling by vegetation and wildlife, heat exchanges within the pan, and aerodynamic effects.

Evaporation pans have been and still are used extensively throughout the world to estimate potential evaporation, particularly as a reference for crop evapotranspiration, or for evaporation from a bare soil. Likewise they seem ‘obvious’ for simulating the loss of water from a water storage, as illustrated in Figure 3.

![Fig. 3](image)

Fig. 3 The concept of using an evaporation pan to simulate dam (storage) evaporation. Evaporation from a pan is related to dam evaporation from a dam via a constant known as a pan factor.

Whilst this concept is very attractive, it is recognised that as regards evaporation, the two storages of Figure 3 – the pan and the dam – may perform differently. The reasons for the variability inherent with the practical use of pans include:

(i) dirt on the metal pan and contamination of the water
(ii) other inputs (rain, splash-in)
(iii) other outputs (bird and animal drinking, splash-out)
(iv) wave action and overtopping in windy conditions
(v) heat transfer through bottom and sides of pan
(vi) presence of birdguard (reduction of both radiation input and ventilation)
(vii) possible shade at low sun angles (e.g. surrounding trees)
(viii) aerodynamic changes at sides of pan (growth of vegetation)
(ix) aerodynamic effects associated with the pan lip (see Figure 4)
(x) warm water pooling (see Figure 4)

While some of these effects can be minimised by regular and careful maintenance, others are unavoidable. Almost universally a simple ‘pan factor’ \( K_{\text{pan}} \) is then introduced and where \( E_{\text{pan}} \) is the measured evaporation from the pan, the water storage evaporation \( E \) is then given by:

\[
E = E_{\text{pan}} \cdot K_{\text{pan}} \quad (2)
\]
hot dry air from area immediately upwind of pan causes increased evaporation here pooling of warm water due to wind drag causes increased evaporation here

Fig. 4 Aerodynamic lip / advective and warm water pooling effects associated with evaporative pans (not to scale)

Unfortunately experiments to deduce and validate an appropriate value for $K_{pan}$ almost universally report a wide range of values and these have ranged from 0.6 to 1.2 – see, for example Weeks (1983) for the major Queensland storages. The conclusion is unavoidable that a reliable $K_{pan}$ cannot be reliably determined.

1. exchange of:

- AIRFLOW
- MOMENTUM
- HEAT
- MOISTURE

2. ditto with soil beneath

3. distribution of heat WITHIN water body

Fig. 5 Interface fluxes required to be modeled to adequately characterise the rate of evaporation from an in-ground water storage

The need to site and maintain evaporation pans appropriately such that they yield 'valid data' is well recognised (for example, Allen et. al., 1998). However inspection of the siting of pans in Australia shows that some of the specified standard criteria, in particular the need to have the pan sited over an extensive area of actively-growing, well-mown grass, are difficult to meet. Perhaps because of this it is commonly assumed that pans can act as a reliable simulation of a major storage “as long as we maintain the pan properly”.

Unfortunately again this is not true. Results from regions in which large quantities of ‘good’ data are available from well-sited pans, particularly in USA (as reviewed in Allen et. al., 1998, for example) indicate that significant day-to-day variations in the
applicable pan factor $K_{\text{pan}}$ are unavoidable. In assessing the value of evaporation pan data (to determine a Potential Evaporation $ET_o$ as a reference for irrigation water calculation) Allen et. al. (1998 – Chapter 3) state:

“Pan evaporation methods clearly reflect the shortcomings of predicting crop evapotranspiration. The methods are susceptible to the microclimate conditions under which pans are operating and the rigour of station maintenance. Their performance proves erratic.”

The physical reasons for this result are illustrated in Figures 4 and 5. The ‘edge effects’ illustrated for the pan in Figure 4 will also apply to the dam in a similar fashion. And likewise there will be energy flows and energy storage which affect the evaporation from the pan and which require modeling similar to that of Figure 5, but very different results may be expected due to the major differences in scale, geometry, materials, meteorological conditions, etc. Hence it is not reasonable to expect that a reliable $K_{\text{pan}}$ can be always be deduced.

2.3 Automatic Weather Stations

In summary: Penman-Monteith, or FAO-56, is now recognised worldwide as the standard reference method for estimating potential evaporation for agricultural purposes.

‘Automatic Weather Stations’ (AWS), and other forms of personal computer-connected on-farm weather stations, commonly provide an estimate of Potential Evaporation. This is deduced, automatically, by use of a ‘combination equation’ embedded in the AWS/computer which combines simultaneous atmospheric measurements of (at least)

- radiation,
- humidity and
- windspeed

over a short time period (usually several minutes). The calculation performed on these data calculates the ‘evaporative flux’ at that moment, and the successive contributions over the day are summed to give the familiar value in units of mm/day. Commonly this is labeled as a “potential evaporation”.

Combination methods to calculate potential evaporation were first introduced by Penman (1948) and account for the energy required to sustain evaporation and the largely independent mechanism required to remove the vapour. The equation combining the two energy terms is usually written as:

\[
\lambda E = \left[ \left( \frac{\Delta}{\Delta + \gamma} \right) (R_n - G) + \left( \frac{\gamma}{\Delta + \gamma} \right) f(u)(e_v - e_o) \right]
\]

(3)
where $E$ is the evaporative flux
$\lambda$ is the latent heat of vapourisation
$R_n$ is net radiation
$G$ is the soil or water heat flux
$\Delta$ is approximately equal to the slope of the saturated
vapour pressure-temperature curve
$\gamma$ is the psychrometric constant
$f(u)$ is a function of windspeed, $u$
$e_s$ is the saturated vapour pressure (kPa)
$e_a$ is the atmospheric vapour pressure (kPa) at the height of
the windspeed measurement.

The Penman-Monteith Equation (Monteith, 1965)\(^1\) is the method of choice for
assessing evapotranspiration from a vegetated surface. This is because as well as
balancing energy inputs, water vapour transport from the plant surface is also
addressed. This is expressed in terms of a stomatal resistance constant which is
included as part of the windspeed function. FAO 56 Penman-Monteith (PM) is now
considered superior to all the other ET methods including Blaney-Criddle, Turc,
Shuttleworth-Wallace, Jensen-Haise, Priestly-Taylor, Doorenbos-Pruitt, Hargreaves
and Watts-Hancock (see Craig, 2004).

Details of the physics and how the data are combined is not significant for the present
application (but are set out, for example, in Allen et al., 1998, Chapter 2). However,
what is very significant for the valid use of an AWS and any Penman-type equation is
the requirement that there must be an *extensive* and *uniform* surface for some
considerable distance upwind of the point of measurement – this is known as having
‘adequate fetch’. The minimum fetch requirement is generally accepted as *at least* 100
times the height of the measurements above the surface, i.e. for a typical AWS with
sensors at approximately 1.5m, the *minimum* fetch requirement is 150m. *If this
criterion is not met the evaporation indicated by the AWS is simply not valid.*

The fetch criterion indicates obvious difficulties for the use of an AWS to measure
dam evaporation. However, the technique would appear to be applicable if, and only if:

- the dam is sufficiently large; and
- the AWS is sited in the dam, or at the edge of the dam downwind with
  respect to the prevailing wind direction.

This implies that we need one AWS in the centre of, say, a 400m diameter dam, which
is obviously not very convenient; or alternatively four AWS, distributed around the
dam to cope with the changes in wind direction. Recent work at USQ (Weick, 2003)

\(^1\) The Penman-Monteith (PM) Equation is able to calculate evapotranspiration (ET) from vegetated
surfaces by incorporating a bulk stomatal resistance term for that surface. The PM based FAO 56
method (Allen et al 1998) calculates reference evapotranspiration (ETo) for a reference surface
consisting of well watered grass 0.12m high with an albedo of 0.23, and constants of 70 s/m for
stomatal resistance, and 208/u s/m for the aerodynamic resistance. However in the present application,
evaporation from an open water surface, stomatal resistance is zero and the Penman-Monteith
Equation reduces to the original Penman (1948) Equation.
has demonstrated the variation in AWS-calculated evaporation across a 10m diameter ring tank.

In addition, there are two further serious limitations.

i. The measurement of radiation in most low-cost AWS is via a solarimeter which measures incoming sunshine only. (The reflected sunshine assumed to be a constant proportion\(^2\); and the longwave terrestrial energy exchange estimated from the surface temperature). However the penetration of solar energy into a body of water varies greatly with angle of incidence as well as wave action at the surface.

ii. It is likely that the raised dam walls will introduce major errors due to the modification of the airflow (analogous to those of Figure 4. AWS sited on or near these walls will be particularly exposed to these errors such that their readings would be questionable.

On a regional scale, dam evaporation can be related to dam water temperature and meteorological data obtained from large networks of low-cost automatic weather stations. In this endeavour, the National Centre for Engineering in Agriculture (NCEA) is pursuing collaboration with a wide range of partners, and specifically through post-graduate research, the Cooperative Research Centre for Irrigation Futures (CRC-IF) at University of Southern Queensland (USQ).

### 2.4 The ‘Bowen Ratio’ or ‘Energy Partition’ Method

*In summary: this method uses the temperature and humidity gradients present above the evaporating surface to estimate the evaporation rate*

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 (\(\lambda H\)). 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:

\[
R_n - G - H - \lambda E = 0 \quad (4)
\]

This may be rearranged as follows:

\[
\lambda E = \frac{R_n - G}{1 + \beta} \quad (5)
\]

where \(\beta\) 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 \(\beta\) is small (Brutseart, 1982, Angus and Watts, 1984). \(\beta\) is measured experimentally using Bowen Ratio apparatus which determines the temperature and humidity gradients over a height interval \(\delta z\).

\(^2\) called the ‘albedo’ of the surface.
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.). Figure 6 shows typical Bowen Ratio apparatus as used for high precision evaporation measurement. The requirement for placement above the evaporating surface with adequate upwind fetch applies similarly because its theory of operation is related to that of Penman-type AWS systems and, as illustrated, very high accuracy hygrometers/psychrometers are required. For this reason Bowen Ratio is usually regarded as a research-only technique.

Unlike the Penman-type (‘combination equation’) deduction of the evaporative flux, the Bowen Ratio method requires simultaneous measurements of temperature and humidity at two adjacent levels. The differences in temperature and humidity can then be used to ‘partition’ (i.e. split up) the total available energy (measured simultaneously) between that which is heat moving upward from the surface (‘sensible’ heat flux, \( H \)); and that energy which is moving upward with the water vapour (referred to as ‘latent’ heat flux, \( \lambda E \)). The Bowen Ratio \( \beta \) is defined as \( \frac{H}{\lambda E} \) and can be related to the temperature and humidity differences. (The aerodynamic theory and its relation to energy partition is beyond the scope of this paper – see for example Oke 1987 – Chapter 2).

Figure 7 illustrates the major significance of a change in evaporating surface, here from ‘dry surface’ to ‘wet surface’, which may be open water or irrigated cropping. Although the sum \( H + \lambda E \) may change only a little (increasing over the wet surface where the water is more ‘available’), the partitioning between \( H \) and \( \lambda E \) changes very greatly within the first few metres – indeed \( \lambda E \) is greatly increased just downwind of the boundary, using more energy than is provided by radiation alone (the extra energy is extracted from the airflow). The requirement for adequate fetch ensures that the airflow has been able to re-establish an equilibrium over the new surface.

Because of the fetch requirement, the applicability of the Bowen Ratio method to the present application is similarly limited unless the dam is very large or very small scale apparatus can be constructed. Recent work at USQ (Brier, 2003) indicates that this would be challenging and is unlikely to be cost-effective, even as a research tool.

\[
\beta = \frac{H}{\lambda E} = \gamma \left( \frac{\partial T/\partial z}{\partial e/\partial z} \right)
\]
Fig. 6  Left: typical Bowen Ratio apparatus with a pair of aspirated psychrometers mounted on an interchange system – they are exchanged for alternate measurements to cancel out errors. Right: a precision cooled-mirror hygrometer (an alternative to aspirated psychrometers).

Fig. 7  Theoretical variation of sensible heat flux $H$ and evaporative flux $\lambda E$ at a change of surface – hence the requirement for adequate fetch in the correct positioning of conventional meteorological instruments – if the instrument height is 1m it has to be located 100m into the dam (after Oke 1987)
2.5 The Eddy Correlation Method

In summary: this method uses state of the art instrumentation to physically measure the upward flux of water vapour molecules from the evaporating surface.

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. The method is offering an attractive alternative to other more cumbersome methods such as Bowen Ratio.

Developments in electronics in recent years have resulted in new sensors with the required speed and accuracy for Eddy Correlation. 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. Each parameter 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. Applying these assumptions and the rules of statistical averaging, the mean vertical flux for an averaging period longer than a few seconds becomes

$$\dot{\lambda}E = \rho \dot{\lambda} \overline{w'q'}$$

where $\dot{\lambda}E$ is the instantaneous latent heat flux (W/m$^2$), $\rho$ is the instantaneous air density, $\lambda$ is the instantaneous latent heat of vapourisation of water (J/g), $\overline{w'q'}$ is 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

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

where $H$ is the mean sensible heat flux (W/m$^2$), $C_p$ is the specific heat of air (J/kg$^\circ$K$^{-1}$), and $\overline{w'T'}$ is the covariance of vertical airspeed and temperature (K/m$^{-1}$) - see Monteith and Unsworth (1990) for further description.

The ‘vehicle’ for this transport is the arrangement of turbulent eddies caused by the friction (drag) between the surface and the prevailing wind blowing across it. This is illustrated in Figure 8. (The difference in concentration of the water molecules from high near the water surface, through to lower up in the evaporative plume, is the basis for the Bowen Ratio method, the Dalton Formula, and also the theory on which all combination equations are based.)
With sufficiently miniature (centimeter-sized) and fast response (milliseconds) sensors it is possible to measure within individual eddies. If instantaneous humidity and airspeed (eddy rotation) are repeatedly measured, statistical correlation techniques can be used to deduce the evaporative flux in units of (fraction of) millimeters per second. Once again these values can be summed up over time to produce the daily $E_{ws}$ value. (This is one application of the general ‘eddy correlation’ technique: the same approach can be used to deduce the flux of any quantity transported via the turbulent eddies.)
In general eddy correlation theory describes the turbulent transport of properties such as momentum flux, sensible heat flux and latent heat flux. The eddy correlation method relies on accurately measuring the fluctuations in airspeed, temperature and humidity and only in recent years have developments in sensor science and electronics resulted in new sensors with the required small size, speed of response and accuracy for this application. Likewise developments in microprocessor technology have permitted the logging and immediate on-line processing of the large volumes of data generated.

3. Recommendations for future research

As indicated above, the eddy correlation technique is thought to hold promise for more fully understanding the full complexity (ie. spatial and temporal variability) of the evaporation from small farm dams (less than about 200m across). Due to the rapid development of modern electronics, eddy correlation equipment is now relatively inexpensive, and is becoming a standard tool for researchers in the field.

The data provided by eddy correlation techniques may be compared to computer modelling outputs of evaporative plume behaviour. Such models may be based on Gaussian Diffusion (statistical) or Lagrangian (particle tracking) techniques or a combination of both. Computational Fluid Dynamics (CFD) software is now readily available which could be adapted to model the evaporative flux from small farm dams. This may be particularly relevant to the leading edge of the dam, where due to advection, the local evaporation may be expected to be significantly greater than that further downwind.\(^5\) (Figure 7).

The behaviour of the evaporative plume under various conditions of atmospheric stability also needs to be better understood – a parameter which can be directly measured with the eddy correlation instrumentation. In addition, the effectiveness of evaporation control techniques could be more thoroughly assessed if eddy correlation equipment was made available to the project.

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\(^5\) Wind driven water movement can change the distribution of water temperature (Figure 4). This has been described by Webster and Sherman (1995) and Condie and Webster (1997).
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