Comparison of precise water depth measurements on agricultural storages with open-water evaporation estimates

Craig, I.P. *

National Centre for Engineering in Agriculture (NCEA),
Faculty of Engineering and Surveying (FOES), University of Southern Queensland (USQ)
Toowoomba, Queensland 4350, Australia

* Corresponding author. Tel.: +61 7 46311980 fax: +61 7 46311870
Email address: craigi@usq.edu.au (I.P. Craig)

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Abstract

A simple technique to determine evaporation and seepage losses of agricultural water storages is described. Evaporation is calculated from Automatic Weather Station (AWS) variables using the Penman-Monteith equation, and seepage is determined as the difference between this and accurate water depth measurements made using a Pressure Sensitive Transducer (PST). The accuracy of the PST devices (±1mm) was far greater than any flow metering equipment available, so analysis only took place when there was no pumping in and out of the dam. Calibration tests were carried out during the summer of 2004/5 at a dam site where seepage was very close to zero, as total evaporation plus seepage loss over the winter months there was independently determined to be less than 1mm/day . Summertime PST depth traces were compared to the Penman 1948 equation, Penman-Monteith (PM) ETo calculated according to the FAO56 method and Penman-Monteith (PM) with surface resistance set to zero to simulate a open water surface. The first two produced the best correlations (within 10% agreement with the water depth trace), but PM open water over predicted by 40%. This technique has provided a useful tool to more accurately apportion total water loss into evaporation and seepage components. Similar to the evapotranspiration of different crop types, it is suggested that that the evaporation of open water can be similarly related to the international standard FAO56 PM via a simple dam factor.

Keywords : Evaporation, Penman Monteith, Pressure Sensitive Transducer, Seepage

Nomenclature

ET_0	reference evapotranspiration (mm/day)
Δ	slope of the saturated vapour pressure temperature curve
T	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)
$u*$	eddy or friction velocity
ρ_a	air density (kg/m^3)
c_p	specific heat at constant pressure 1.013 x 10-3 (MJ kg^{-1} °C^{-1})
P	atmospheric pressure 101.3 (kPa)
z	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)
RH	relative humidity
α	surface albedo (assumed 0.23)
R_s	total radiation from AWS (W/m^2)
R_l	long wave radiation (MJ/m^2/day)
R_a	average daily extraterrestrial solar radiation from tables (MJ/m^2/day)
R_{so}	average clear sky radiation (MJ/m^2/day)
σ	Stefan-Boltzmann constant = 4.903 MJ/m^2/K^4/day
E	evaporation (mm/day)
r_a	aerodynamic resistance (s/m)
r_s	surface resistance (s/m)
K_c	crop factor
K_p	pan factor
K_d	dam factor

1. Introduction

The loss of farm storage water due to evaporation and seepage is estimated to exceed several thousand GL/yr representing billions of dollars lost to the Australian economy (Queensland Natural Resources and Mines, 2002). This provides a strong incentive for research to be carried into how evaporation and seepage losses can be better assessed and reduced. The most common approach has been to deduce evaporation and seepage as residual terms in the overall water balance equation. In this study however, analysis of data only took place when there was zero water flow in and out of the dam, leaving evaporation and seepage as the only components of the water depth change. This had the significant advantage that only weather data and accurate water depth measurements were required, obviating the need for expensive high accuracy flow meters combined with surveys of the dam profile.

Evaporation is defined as the net movement of water molecules from water to air. The main driver of open water evaporation in warm countries is solar radiation during the day and this may be thought of simply as photons imparting an increased velocity to water molecules – enough to cause some to exit the water surface. This is the radiation energy component of evaporation may be expressed as

$$\lambda E = \left(\frac{\Delta}{\Delta + \gamma}\right)(R_n - G) \qquad 1.$$

Equation 1 multiplied by 1.26 is known as the Priestly-Taylor (PT) equation (Priestley and Taylor, 1972) and has been extensively used over large continental regions where detailed windspeed and humidity information is limited (Morton, 1986). However, there is no physical basis for the 1.26 factor, it is purely empirical and not universally agreed upon for different regions of the world. It is acknowledged that there are deficiencies with PT, particularly for very hot dry regions (McAneney and Itier, 1996).

Dalton (1802) on the other hand relates total ‘lake’ evaporation to aerodynamic or ventilation energy expressed as the product of a wind function, *f(u),* and the vapour pressure deficit

$$E = f(u)(e_s - e_a) \qquad 2.$$

Dalton essentially makes the same assumption as Priestley-Taylor, namely that the radiation and ventilation components are correlated such that measurement of only one is adequate. His windspeed function is analogous to the PT factor 1.26, to scale up from the ventilation component to total evaporative flux.

Brutsaert (1982) defines equation 1 as an energy equilibrium term and equation 2 as a non-equilibrium term, or the drying power of the air arising from advection. The aerodynamic or advection component is typically about one fifth of the total. This cannot be ignored as this is the mechanism for evaporation at night. In hot countries, hot dry air can blow across the water surface at night ensuring that the temperature of the air water interface remains well above the dew point. Due to this advective transfer of energy, night time evaporation can be a significant proportion of the daily total (Ham, 2002).

Combination methods for predicting evaporation are so called because they properly combine both radiation and aerodynamic energies into one equation. They were first introduced by Penman in 1948. The Penman (1948) equation is as follows

$$\lambda E = \left(\frac{\Delta}{\Delta + \gamma}\right)(R_n - G) + \left(\frac{\gamma}{\Delta + \gamma}\right) f(u)(e_s - e_a) \qquad 3.$$

The windspeed function in the above equation, $f(u) = 6.43(1+0.537u)$, incorporates aerodynamic resistance or concentration difference over flux. Doorenboss and Pruitt (1975 and 1977) developed a modified windspeed function and also a factor to adjust for local climatic conditions and this became the FAO24 method for grass reference evapotranspiration.

In 1965, interest in evapotranspiration (ET) of plants inspired Monteith to modify the Penman equation for a crop surface which incorporated an additional leaf surface or stomatal resistance term $r_{s.}$ The Penman-Monteith (PM) equation represented a major break though in the agronomic sciences because ET could now be directly linked to plant physiology and stomatal closure control of plant water loss. Workers were able to determine aerodynamic and stomatal resistances for their crop of interest and were more accurately able to predict ET values. It has been useful in this study too because it is useful to think of open water as also having a surface resistance to evaporation, which for example, could be increased by the addition of a chemical monolayer (Barnes, 1993).

The PM approach has three distinct advantages over other methods. Firstly, it is has a physical basis implying that the equation can be used on a global basis without the need for empirically derived constants relevant to specific regions and vegetation types. Secondly, the method does not rely on sophisticated meteorological instrumentation, as does for example the Bowen Ratio method (Bowen, 1926), which attempts to measure very tiny differences in temperature and humidity with height. Thirdly, the equation has received the most through experimental validation against other methods, mainly weighing lysimeters and soil moisture measurements.

There have been several validation studies (Ventura et al 1999, Hussein (1999), Al-Ghobari 2000, Kashyap and Panda 2001, George et al 2002) that have confirmed that the Penman-Monteith (PM) equation generally out performs all other empirically derived equations eg Blaney-Criddle (1945), Turc (1961), Jensen-Haise (1963), Priestly-Taylor (1972), Doorenbos-Pruitt (1975), Hargreaves (1985), Shuttleworth-Wallace (1985), Watts-Hancock (1985) and others (Burman and Pochop 1994).
The general consensus is that the PM method is superior to all the other methods. Kashyap and Panda (2001) have clearly indicated this in their study comparing 10 ET methods to grassed weighing lysimeter data obtained in India. However, calculating PM is a difficult process in which knowledge of micrometeorology is a prerequisite, and many workers have had several disagreements upon the precise methodologies to be used.

To solve this problem and provide uniformity and a working solution for the industry, Allen at al (1998) introduced the FAO56 method to calculate PM in which constants were set for aerodynamic resistance ($208/u_2$), stomatal or surface resistance (70 s/m) and surface albedo (0.23). The evapotranspiration of a particular crop is then related to the reference evapotranspiration (ET_o) by a crop factor, K_c. The method describes how the crop factor varies for different crop types and during the growth cycle. An extension to the FAO56 method is put forward in this paper, in that the evaporation of open water from a pan or dam could also be related to PM FAO56 ET_o by a simple “pan factor, K_p “or “dam factor, K_d.”. The suggestion is that this should suffice, at least until the research work is carried out to accurately determine aerodynamic and surface resistance values appropriate for open water surfaces.

The main trend in the past has been to compare all evaporation to USDA Class A pan data as the reference. Class A pan is highly variable, but despite this has been used extensively to represent the evapotranspiration across cropped or vegetated land surfaces. The evaporation of open water has been commonly quoted as roughly equivalent to $0.7A_{pan}$ (Burman and Pochop, 1984). It is suggested here that FAO56 is now regarded as the new reference level against which everything else is compared. Mean Class A pan evaporation would therefore be nominally expressed as approximately equal to $1.4ET_o$.

2. Methodology

2.1. Overview

As part of a Queensland Government Natural Resources and Mines (NRM) funded Rural Water Use Efficiency Initiative project, evaporation/seepage assessments took place from October 2003 to April 2005. A total of 25 PST units and six weather stations were purchased and installed at test storages located at Dirranbandi, Capella (near Emerald) , St. George, Stanthorpe and Toowoomba (Table 1 and Figure 1). The storage at Dirranbandi was used as the principal calibration site as it had very low seepage was considered large enough (120ha) to be fully representative of "open" water bodies. This is loosely defined here as having sufficient fetch to generate good wind driven mixing of subsurface cold water with warmer surface layers, producing a low or negligible "pan/dam factor" (see section 3.4). For full experimental and geographical details and the complete program of tests, the reader is referred to Craig et al 2005.

2.2. Instrumentation

Pressure sensitive transducers (PSTs) were used to precisely measure water depth and therefore accurately determine seepage and evaporation loss. The PST type used was a vented Druck (PMP 4030 350mbar sensor) with a stated accuracy of ±0.04% (±1.4mm) over a 3.5m range. The unit measures depth pressure according to the electrical resistivity of a deforming micro-machined silicon crystal, isolated from the water with a corrosion resistant diaphragm. Water pressure is measured relative to atmospheric pressure which is provided by a crushproof air tube inside the transducer cable.

The units were suspended just above the bottom surface of the test dams using a rope attached float-weight system (Figure 2). An Intech Nomad GP-HR 12 bit datalogger recorded PST outputs including time and date, instantaneous, minimum, maximum and average water depth over 15 minute time intervals. Environdata WeatherMaster 2000 automatic weather stations were set up to read every second and record 15 minute averages of solar radiation, temperature, windspeed, humidity and rainfall.

2.3. *Data processing*

The processing of data took place as depicted in the flowchart (Figure 3). PST and AWS data were downloaded from the data loggers every few weeks and imported into a spreadsheet for comparison against evaporation calculations. All four channel readings (point, average, minimum and maximum) were plotted initially. A visual check was made of the daytime max and min depth data to make sure that these readings were not too excessive, as this could generate a distortion in the average data. PST noise was thought to be due either to high windspeeds rocking the water surface, or electrical due to high cable temperature. Any noise distorted data was removed from the analysis.

Once an initial visual data checking procedure was completed, each graph was copied and all data removed except the average data (channel 2). If there were any portions of the curve where there was a sudden change to a gradient clearly too steep to be either evaporation or seepage, the data was not used due precipitation or pumping in or out of the dam. Prior to calculation of evaporation estimates, all AWS data was inspected to make sure that there were sensible readings from each sensor and that there was no precipitation during the period.

The equations used in the analysis spreadsheet were taken from Allen et al (1998) and are as follows :-

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \qquad 4.$$

$$\Delta = \frac{4098\left[0.6108\exp\left(\frac{17.27T}{T+237.3}\right)\right]}{(T+237.3)^2} \qquad 5.$$

$$\gamma = \frac{c_p P}{\varepsilon\lambda} = 0.067 \qquad 6.$$

$$P = 101.3\left(\frac{293 - 0.0065z}{293}\right)^{5.26} \qquad 7.$$

$$e_s = 0.6108\exp\left[\frac{17.27T}{T+237.3}\right] \qquad 8.$$

$$e_a = \frac{\overline{RH}.e_s}{100} \qquad 9.$$

$$R_n = (1-\alpha)R_s - R_l \qquad 10.$$

$$R_l = \sigma\overline{T}^4(0.34-0.14\sqrt{e_a})(1.35R_s/R_{so}-0.35) \qquad 11.$$

$$R_{so} = (0.25+0.5)R_a \qquad 12.$$

3. Results and discussion

3.1. PM comparison with a non-seeping dam

PST recorded water depth data was selected from a 120 ha dam located at Dirranbandi Queensland. It was decided to calibrate the software principally against this dam because it had a high quality compacted clay liner and effectively close to zero or nil seepage. The nil seepage value for the dam was confirmed by the fact that the depth gauge or ruler measured total evaporation plus seepage loss was less than 1.5 mm/day during the winter months, and that this loss was close to the predicted estimates for evaporation alone.

Over a seven day period during Oct/Nov 2004, the depth data from the nil seepage dam at Dirranbandi was compared against three estimates of open water evaporation, namely Penman 1948, Penman-Monteith with surface resistance set to zero to simulate open water (PM open water) and PM FAO56 ETo (Figure 4). It is evident from the graph that a very good correlation (within 10%) existed between the early season (cold water) PST recorded water depth data and the PM FAO56 model. The Penman 1948 equation predicted approximately 15% greater evaporation and PM open water over predicted evaporation by approximately 40%. The Dirranbandi datasets were therefore used as the zero seepage calibration benchmark for the PM FAO56 model (from here referred to as the ‘PM model’).

3.2. PM comparison with seeping dams

PST recorded water depth data was compared to open water estimates of evaporation for a 4ha storage at Capella (Figure 5) and a 3.7ha storage at St George (Figure 6). The graphs show that there was a good comparison between the PST data and the PM model at both locations when a 2mm/day correction for seepage was applied. Similarly, there was an equally good agreement between the PST data and the Penman 1948 model when a 1mm/day correction for seepage was applied. However, it was necessary to invoke a negative seepage to the PST data to obtain a fit with the PM open water estimate. This illustrates the relative magnitude of uncertainty for seepage and evaporation determination (approximately ±1mm/day) with the analysis technique described in this paper.

3.3. *Statistical agreement between PST data and model predictions*

PM model predicted evaporation (assumed correct for now) was compared with seepage corrected PST water depth data collected at Dirranbandi, Capella and St. George on selected days when noise in the PST data was at a minimum. The PST data underwent smoothing using a 4 hour rolling average to further reduce noise evident in the 15min average data. A plot of evaporation rate (in mm/hr) as calculated by the model versus PST data is provided in Figure 7.

The data then underwent further smoothing (24hr) to provide daily evaporation totals. The resulting Standard Error of Estimate (SEE) between the seepage adjusted and smoothed PST data y_i, and the model prediction y_i', was then computed according to Levine et al (1999) as

$$SEE = \sqrt{\frac{\sum_{i=1}^{n}(y_i - y_i')^2}{n-2}} \qquad 13.$$

In this case, the SEE for this 'selected' dataset was 0.36mm/day indicating that the smoothed PST data was within ±1.96x0.36 = ± 0.7mm of the model prediction 95% of the time. This 'best accuracy of agreement' between data and model compares well with degrees of uncertainties of between 0.3 – 1.2mm/day reported by Ham (2002) in his water balance studies on waste lagoons using floating recorders.

With other PST data obtained in the NRM program (Craig et al 2005), the correlation between PST data and model predicted evaporation was generally not as good. This was mainly due to temperature related PST cable and other noise, but despite this problem calculated accuracies were still generally of the order of ±1mm/day. This means that for a typical daily evaporation rate of 5mm/day, there was a 95%

probability that the daily evaporation recorded by the PST will be between 4 and 6 mm/day. The “nominal accuracy” of the PST can therefore be stated as approximately ± 1mm, roughly equivalent to ±20% of a typical daily evaporation of 5mm.

3.4. Variation in dam factor with size of water storage

Similar experiments were repeated at USQ with three plastic lined tanks (10m diameter and 0.8m high) and also with two galvanized steel Class A pans (1.3m diameter and 0.25m high). Evaporation from the 10m diameter tanks was on average approximately 1.2 ETo, although could be somewhat higher with increased water temperature. The USQ Class A pan evaporation data proved to be highly variable, concurring with analysis across several reports in the literature by Watts (2005) and also Allen et al (1998) which indicate that Class A pan evaporation typically varies from 1.3 to 2.1 ETo. A rough guide to expected dam factors in relation to size of the storage is provided in Figure 8. The inference from this diagram is that for a small dam of say 50m typical dimension or less, evaporation might be approximately 1.1 ETo or 1.2 ETo, which would correspond well with the Penman 1948 prediction.

4. Conclusions

This technique will enable irrigators and managers of stored water to more accurately determine the magnitude of losses due to evaporation and seepage. It represents a rapid relatively low cost method (less than a few thousand dollars) and is already being implemented by consultants working the area of agricultural water use efficiency in Australia. It eliminates the requirement to attempt to and assess total dam seepage via soil moisture or other measurements. The method does not require the use of sophisticated and expensive meteorological equipment.

The PST/AWS method was adopted because it proved to be the most accurate and reliable amongst a broad range of other possible approaches (Craig and Hancock 2004). The central finding of this study is that PM FAO56 correlates reasonably well with PST recorded evaporation of water from storages and can be related to it via a simple dam factor. It can be assumed that the magnitude of this factor is relatively small (<1.2) for storages with reasonable depth and greater than one hectare in size.

For pans and very small or shallow storages, water heating and geometrical effects become important and so experimentally determined pan or dam factors need to be applied. To more precisely confirm the effect of storage geometry on required dam factor values, further experimental work using lower noise PST units (possibly equipped with a digital radio frequency data transmission system) would be required.

It is proposed that this assumption will suffice until further detailed research is carried out to incorporate heat storage effects and assign appropriate aerodynamic and surface resistance values to an open water surface with waves. Computational Fluid Mechanics (CFD) based work is required to theoretically predict dam factor according to dam geometry, heat storage and boundary layer physics (Lakshman, 1972, Quinn 1979, Webster and Sherman, 1995, Condie and Webster, 1997). Experimental validation of theory is also required via measurements of advection driven temporal and spatial variability of open water evaporation using eddy correlation (Sene et al 1991) or optical techniques (Edwards et al 2000).

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Table 1 Details of the storages used in this study

	Dirranbandi	Capella	St George	Stanthorpe	Toowoomba
Surface area (ha)	120	4.0	3.7	0.8	78m^2
Capacity (ML)	7200	240	160	40	0.055
Wall height (m)	5.0m	5.0m	5.0m	3.0m	1.0m
Shape	Rectangle	Rectangle	Rectangle	Triangle	Circle
Siting	open flat	open flat	open flat	few trees	open flat
Mean daily max temp (January)	34.5°C	34.2°C	34.5°C	26.4°C	27.6°C

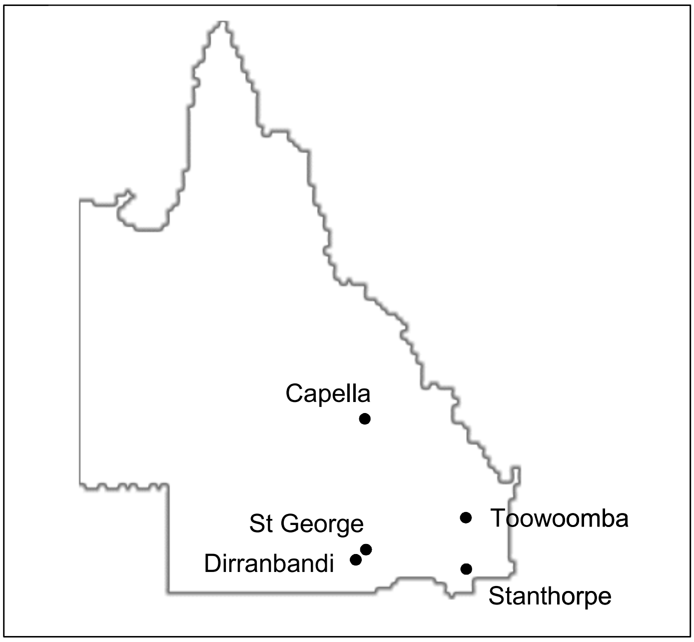

Figure 1 **Map of Queensland Australia showing the location of the various trial sites used in this study**

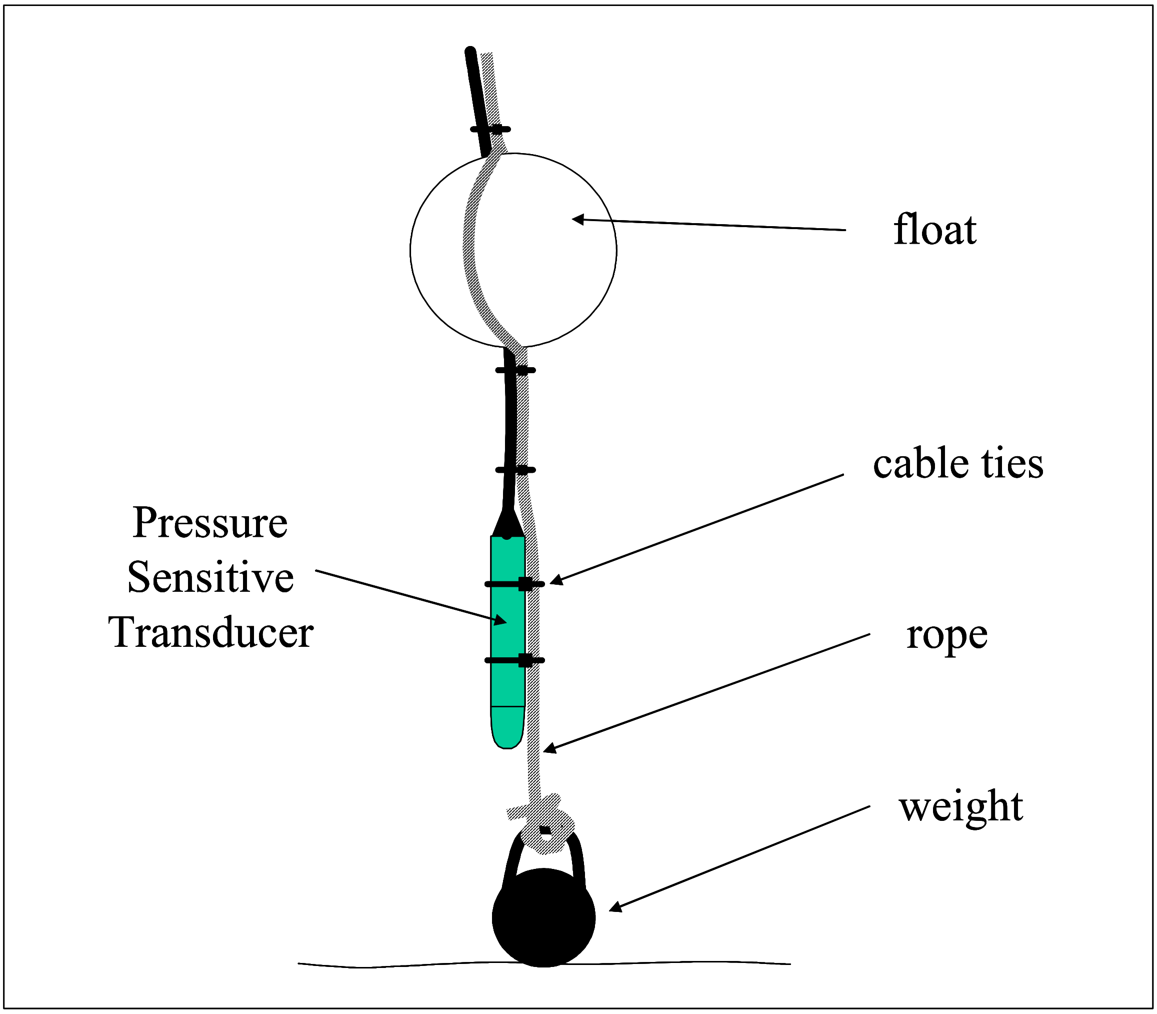

Figure 2 Diagram illustrating PST suspension mechanism

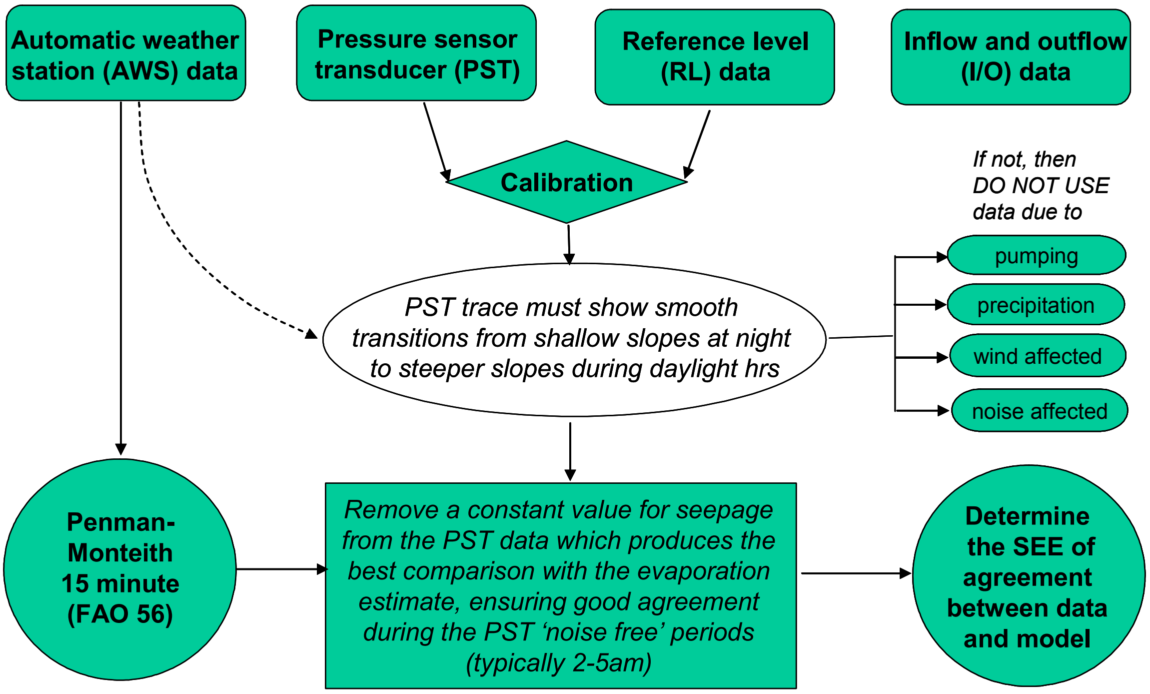

Figure 3 Flowchart illustrating PST-PM analysis procedure

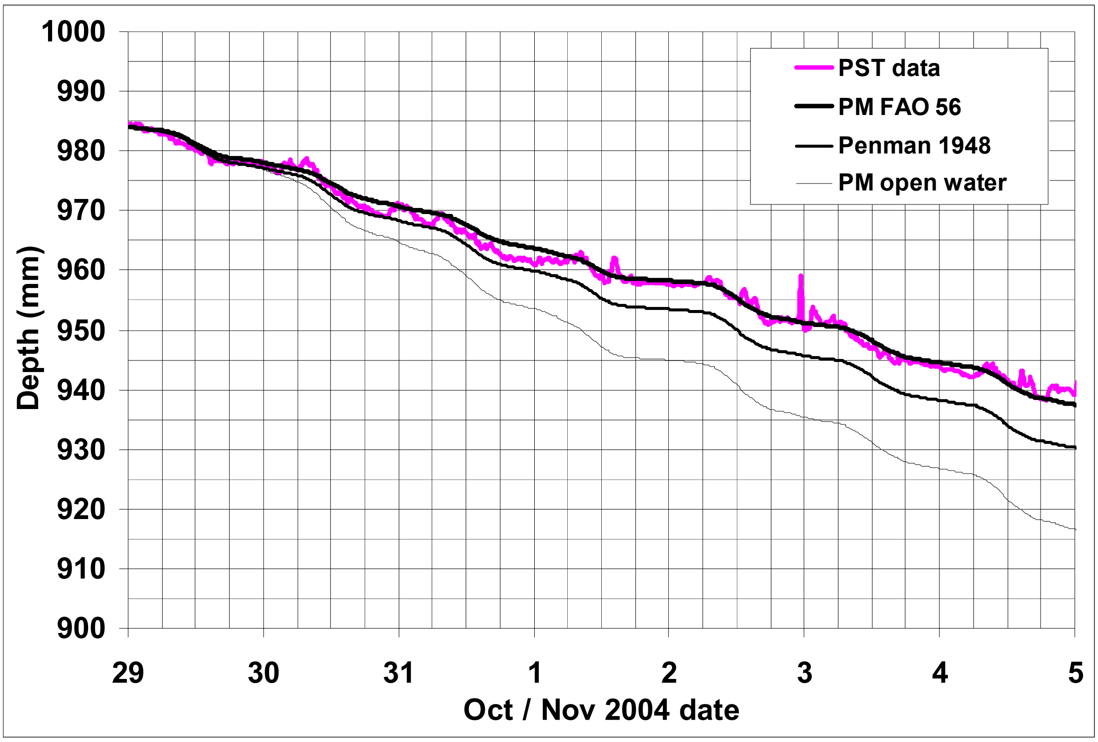

Figure 4 Agreement of PM FAO56, Penman 1948 and PM open water estimates with PST depth data for a farm storage near Dirranbandi with nil seepage

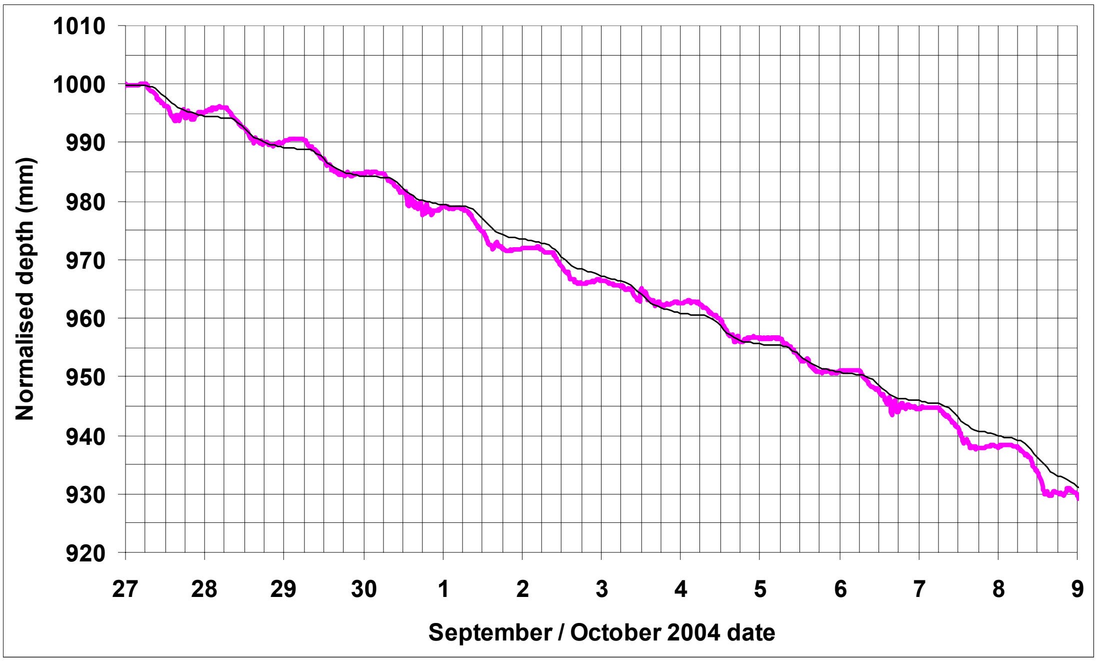

Figure 5 Agreement of FAO56 PM predicted evaporation (thin line) versus PST data (thick line) for a storage at Capella with 2mm/day seepage

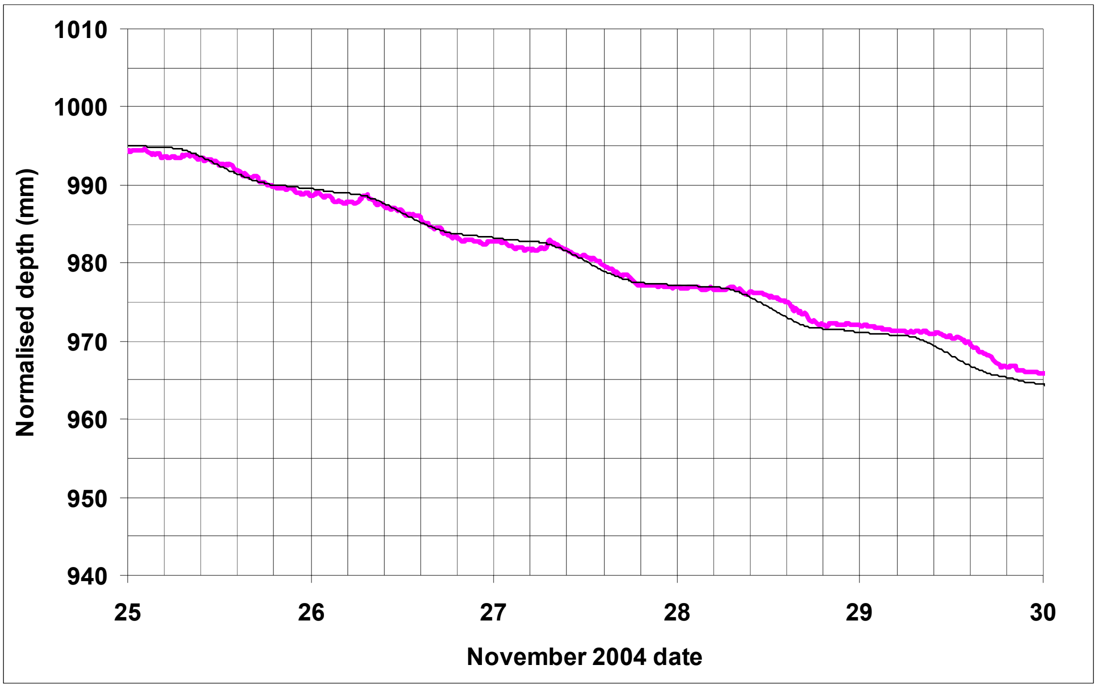

Figure 6 Agreement between FAO56 PM model predicted evaporation (thin line) and PST data (thick line) for a farm storage near St. George with 2mm/day seepage

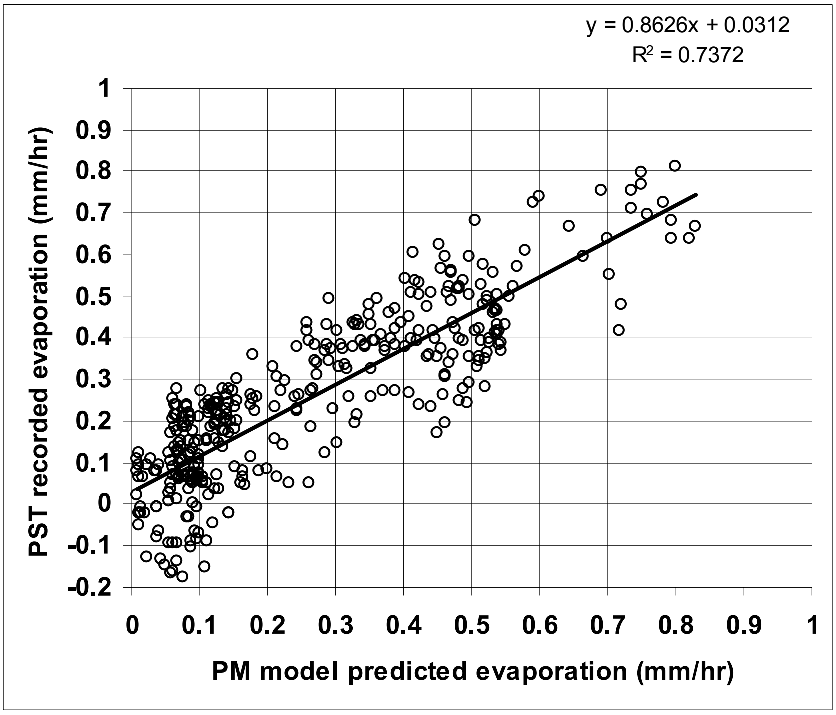

Figure 7 **Plot of model predicted evaporation rates versus PST data with seepage removed and smoothed with a 4 hour rolling average.**

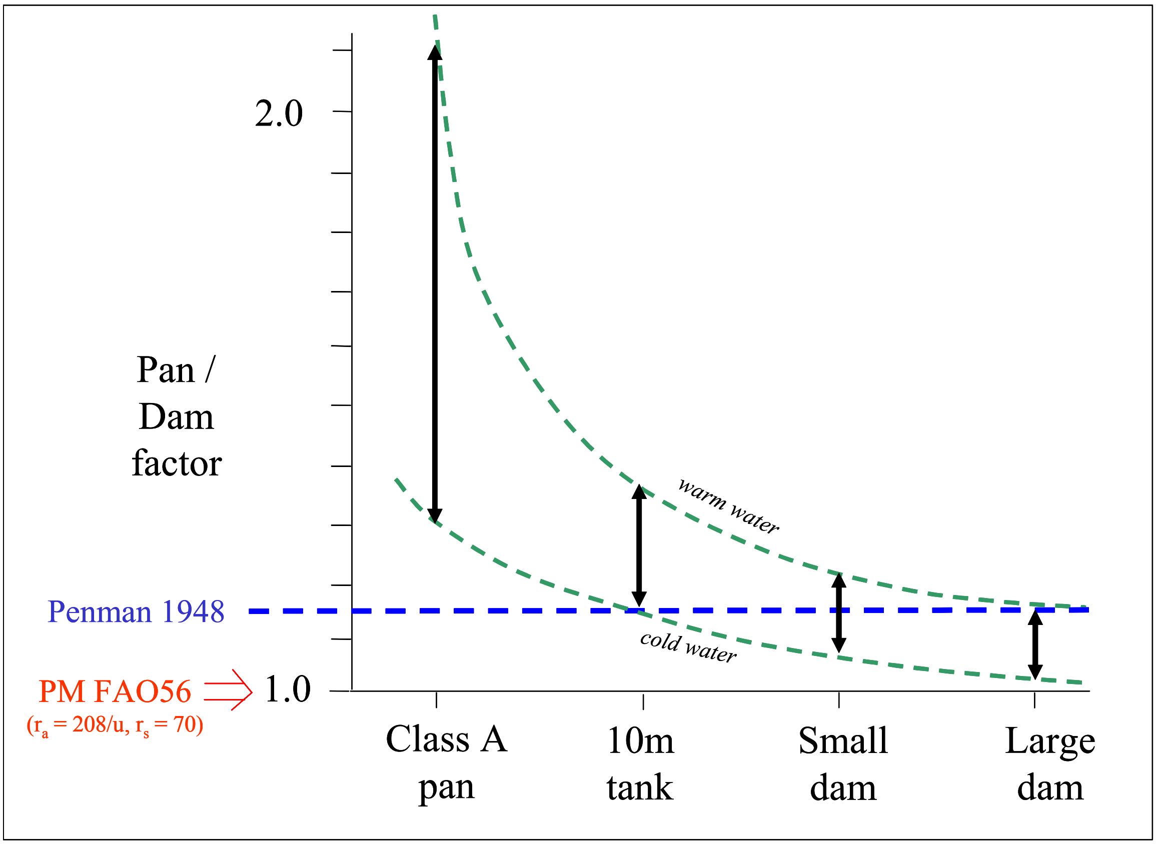

Figure 8 Inferred effect of storage size/depth/water temperature effects on required dam factor