International Symposium On Environmental Health
Climate Change and Sustainability

Development of a CFD based Dam Evaporation Model

Craig, I.P., Mossad, R., and Hancock, N.

Australian Centre for Sustainable Catchments (ACSC),
University of Southern Queensland (USQ)

Abstract

Current trends of increased temperature and reduced rainfall in primary areas of agricultural production are driving Water Use Efficiency (WUE) research in Australia. Irrigation accounts for approximately 70% of fresh water use. Much of this stored in a million or so small dams, accounting for 9% of the total stored or 7000 GL. Approximately one half of this may be lost due to evaporation, but precise figures are unknown due to a lack of understanding of the relevant dam thermodynamics and associated evaporation physics. Work has commenced through an Australian Centre for Sustainable Catchments (ACSC) grant to develop a Computational Fluid Dynamics Dam Evaporation Model (DamCFD) to adequately quantify this loss, which constitutes a major economic limiting factor to Australia, and also gross inefficiency in terms of the environmental sustainability our fresh water resource. The aim of the project is to use CFD modeling to incorporate aerodynamic, heat transfer and thermodynamic theory to predict the evaporation of agricultural water, with storage morphology and characteristics of the surrounding terrain treated as important input parameters. Consideration of the flow of air, water and heat is required principally to simulate the vertical temperature profiles, air stability and the advective accumulation of warm surface water at the downwind end of the dam. It is intended that the development of this research capability at USQ will promote increased understanding of the complexities involved in open water evaporation. This will lead to more accurate estimates and better strategies for managing and controlling the evaporative loss of fresh water in Australia.

Introduction

The present concern over global climate change is bringing water sustainability in Australia into sharp focus. Increasing temperatures and decreasing rainfall are the main threats to profitable agricultural production. Irrigated agriculture consumes approximately 70% of fresh water captured, but this resource is declining. Much water, if captured, is stored in a million or so small dams, accounting for 9% of the total stored or 7000 GL. Up to one half of this may be lost due to evaporation, but precise figures are unknown due to a lack of understanding of the relevant dam thermodynamics and associated evaporation physics. There is, therefore, an urgent need to accurately quantify the rate of this loss for a variety of situations, as it represents a major economic limiting factor to Australia and also a gross inefficiency in terms of the environmental sustainability of our fresh water resource.

Simple evaporation models

Evaporation is defined as the net movement of water molecules from water to air. The simplest modelling approach comes from the work of Dalton (1802) in which he describes lake evaporation E_{lake} in terms of aerodynamic or ventilation energy expressed as a function of the windspeed $f(u)$ and vapour pressure deficit or dryness of air. Where e_s is the water vapour pressure at the water surface and e_a is the water vapour pressure in the air at a fixed height above the water

$$E_{lake} = f(u)(e_s - e_a) \qquad 1.$$

More generally the water vapor flux E over any surface can be similarly described by:

$$E = f'(u)(e_{a2} - e_{a1}) \qquad 2.$$

where $(e_{a1} - e_{a2})$ is the vapour pressure difference between two levels *1* and *2* appropriate to the windspeed function $f'(u)$.

In an alternative approach the main driver of evaporation is recognised as 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. Where R_n is the net radiation (short wave and long wave, incoming minus outgoing), G is energy not used in evaporation (predominantly heat flux), λ is the latent heat of vapourisation of water, and Δ and γ are constants related to the saturated vapour pressure curve for water, the radiation energy component of evaporation E_r which may be expressed (in energy units) as :

$$\lambda E_r = \left(\frac{\Delta}{\Delta + \gamma}\right)(R_n - G) \qquad 3.$$

Equation 3 multiplied by 1.26 is known as the Priestly-Taylor (P-T) equation (Priestley and Taylor, 1972) and has been extensively and successfully over large continental regions where detailed windspeed and humidity information is limited (Morton, 1983). However, there is no specific physical justification for the factor 1.26 but differing values have not met with general acceptance.

Combination equations utilise both aerodynamic (equation 2) and radiation (equation 3) approaches to produce a physical description which is generally applicable, ie. including non-continental situations where the ratio of 'radiation energy' E_r to 'ventilation energy' (E_a=E–E_r) is not constant. Combination equations thus have the important practical advantage of not requiring the measurement of very small humidity differences between two levels and were first was introduced by Penman (1948) :

$$\lambda E = \left(\frac{\Delta}{\Delta + \gamma}\right)(R_n - G) + \left(\frac{\gamma}{\Delta + \gamma}\right) f(u)(e_s - e_a) \qquad 4.$$

This was later developed by Monteith (1965) into the Penman-Monteith (P-M) formula with the incorporation of a surface resistance to describe the restricted 'availability' of water from plants – transpiration – hence the term 'evapotranspiration' ET. The general P-M equation has been accepted as a world standard for estimating reference evapotranspiration (ETo) as the basis for agricultural water and crop water use calculation, and is fully described by Allen *et al* (1998). The Penman-Monteith formula has also been successfully utilised by Jensen (2005) for predicting the evaporation from open water surfaces.

However, the models so far described are 'one dimensional' in the sense that areal homogeneity is assumed. Hence they do not account for advection, the sideways movement of energy which results from differing energy and aerodynamic performance of differing soil/vegetated/water surfaces. In hot countries such as Australia, it is clear that the evaporation of a small farm dam will be heavily influenced by hot dry air blowing from land upwind of the dam and therefore the large proportion of advected energy may be expected.

The problem of advection effecting the evaporation of a small dam

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 as illustrated in Figure 1.

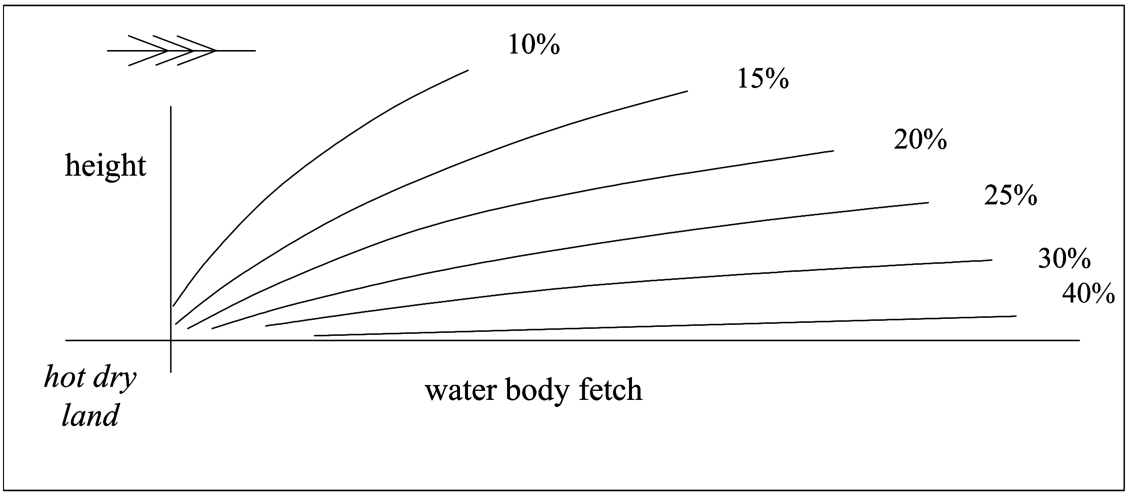

Figure 1 **The manifestation of added evaporation energy due to the oasis effect – relative humidity contours predicted by the model of Webster and Sherman (1995) are depressed at the upwind margin of the water body, due to advection of hot dry air from an adjacent land mass.**

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 1982). Where A_d is the extra energy due to advection, the sum of energies is now :

$$R_n + A_d - G - H - \lambda E = 0 \qquad 5.$$

However, unfortunately, the magnitude of A_d is difficult to determine in any simple or generic sense.

Application of Computational Fluid Dynamics – the 'DamCFD' model

Many parameters affect the evaporation from a body of water such as a lake to the surrounding air; these are the temperature of the water, size of the water body, the terrain surrounding the water body that affects the air flow over the lake surface, surface roughness of the water body, the air temperature, velocity and humidity. To account for all these parameters, the process of estimating the evaporation becomes very involved. A numerical approach is being used to predict evaporation from a specific chosen ring tank with the dimensions of 100 mx100 m square shaped with a ridge of about 25 m surrounding the ring tank, shown in figure 2. To permit description and consequences of advective energy flows a two-dimensional model has been constructed using the finite control volume approach on a vertical section through a typical Australian farm dam (or 'ring tank') with dimensions provided in Figure 2. A computational grid was established using GAMBIT software and computational fluid dynamics (CFD) was then performed using FLUENT version 6.2 software.

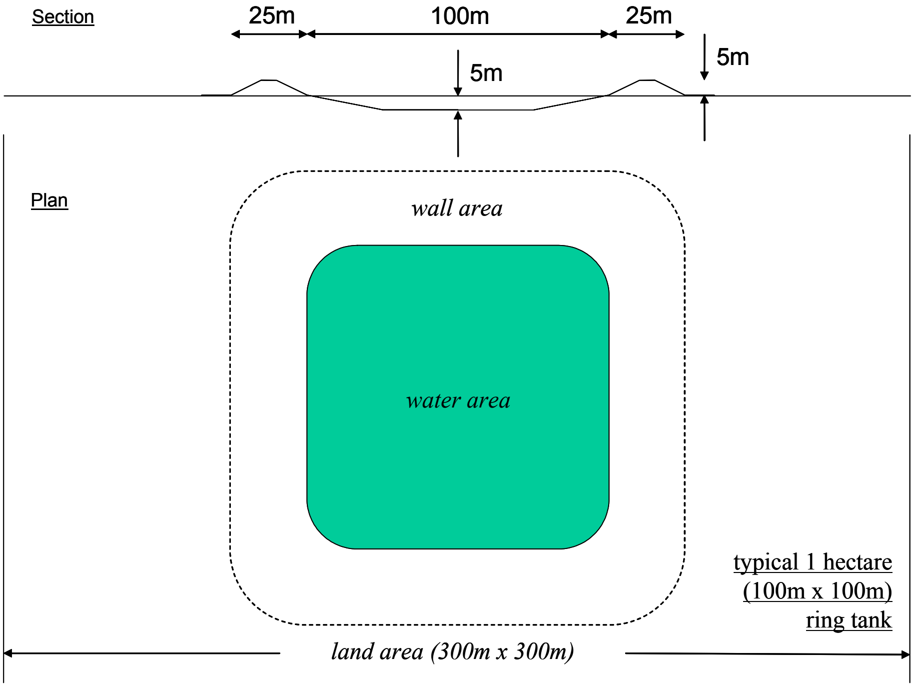

Figure 2 Dimensions of the ring tank modeled

Three cases have been examined, namely

- a hot summer day with air temperate of 35ºC, velocity of 2 m/s and 45% humidity, and water initially at 20º C,
- a cooler day with air temperate of 20ºC, velocity of 2 m/s and 45% humidity, and water at 35ºC with solar radiation (to represent late afternoon hours); and
- similarly without solar radiation to represent early evening/night hours.

Solar radiation incident were taken as 1000 W/m2 and water absorbs 85% of the incident solar radiation. Due to the complexity of the model small time steps have been used in order to achieve a stable solution. An example of the night time case at around 9s is provided in Figures 2 to 5 below.

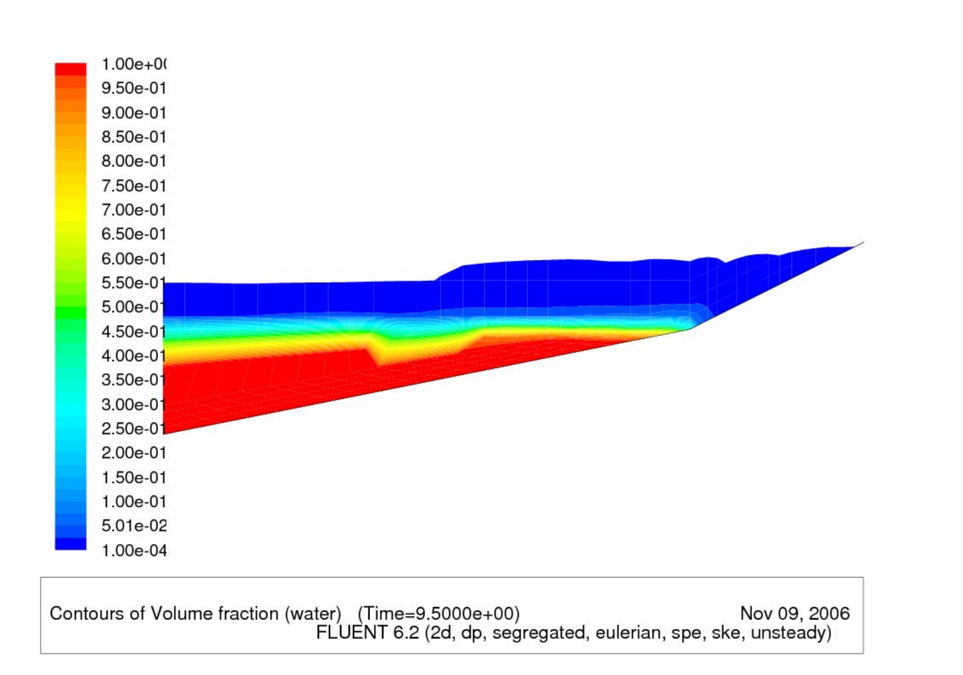

Figure 3 **Contours of humidity obtained at the downwind boundary of the dam**

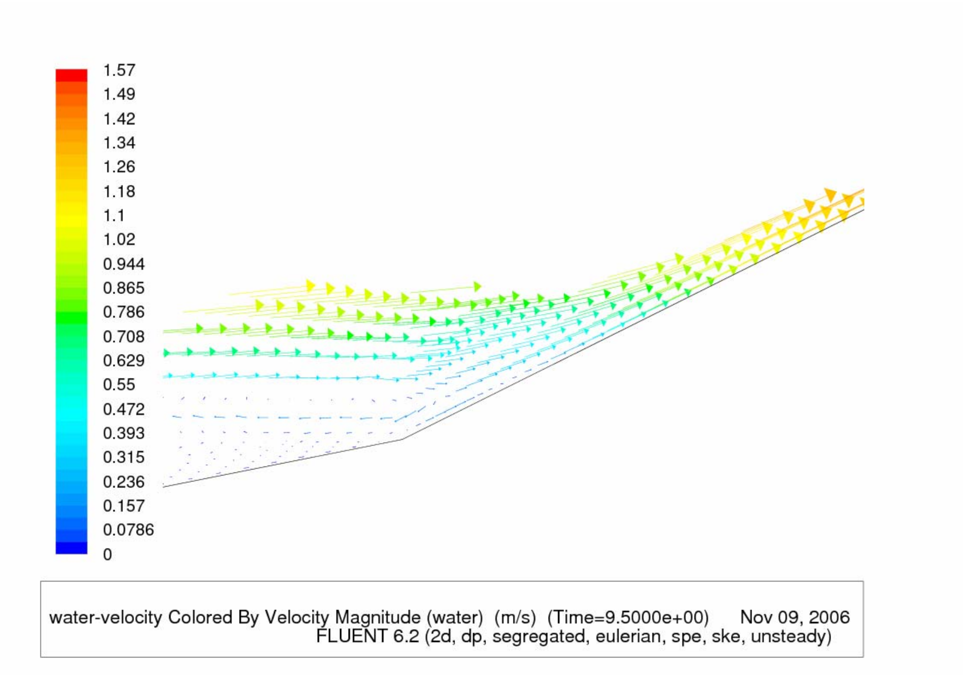

Figure 4 **Vectors of velocity obtained at the downwind boundary of the dam**

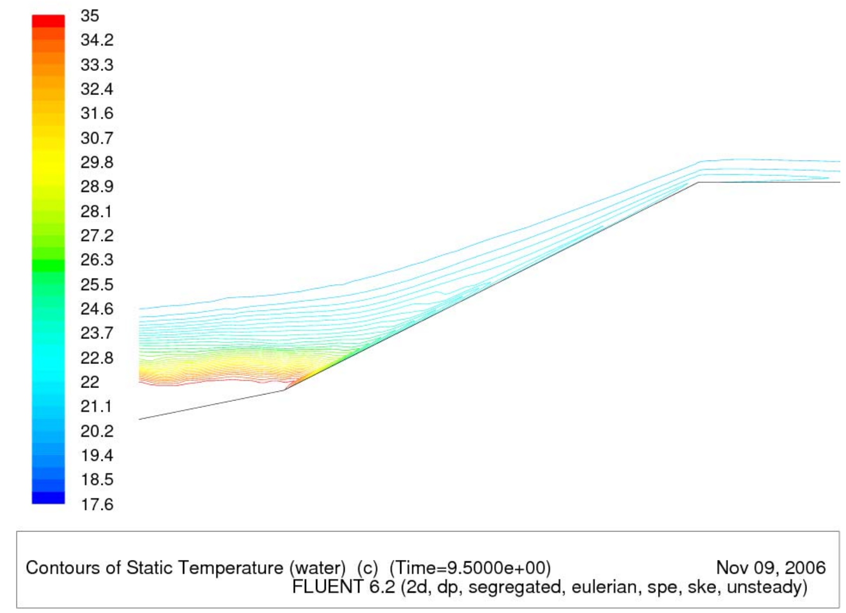

Figure 5 **Contours of temperature obtained at the downwind boundary of the dam**

Conclusion

A 2-D Computational Fluid Dynamics (CFD) approach to dam water evaporation has been initiated at the Faculty of Engineering and Surveying - University of Southern Queensland (FOES-USQ) to investigate evaporation of small farm dams, and in particular the advective effects.

The modelling is only in its very early stages but it is hoped that eventually DamCFD will be able to incorporate existing aerodynamic, thermodynamic and heat transfer theories into a technique to predict the rate of evaporation of agricultural water, with climate and morphometry of the storage and surrounding terrain as input parameters.

Consideration of the flow of air, interaction with the water stored, climate changes and solar heat absorbed is required, principally to simulate the vertical temperature profiles, air stability and the advective accumulation of warm surface water at the downwind end of the dam. Data collected from DamCFD for a variety of situations will provide the basis for a simple ‘dam factor’ algorithm to relate to simple indices of evaporation such as the P-M formula.

It is intended to validate experimental results produced by DamCFD using remote sensing, laser or eddy correlation techniques. These will be used to obtain real time non-equilibrium measurements of evaporative flux within the dry to wet boundary transition region and across the dam as a whole. This will validate results produced by DamCFD and also transition algorithms for small ponds suggested by Morton (1983) and Sartori (2000).

Acknowledgements

The authors are grateful to the Australian Centre for Sustainable Catchments (ACSC) of the University of Southern Queensland for funding this initial work.

References

Allen, R.G., Pereira, L.S., Raes, D., and Smith, M. 1998 "Crop evapotranspiration – guidelines for computing crop water requirements" FAO Technical Paper 56, Food and Agriculture Organisation of the United Nations, Rome.

Brutsaert, W.H. 1982 Evaporation into the atmosphere. Dordrecht, Holland. D. Reidel Publishing Co.

Condie, S.A and Webster, I.T. 1997 The influence of wind stress, temperature, and humidity gradients on evaporation from reservoirs. Water Resources Research 33 12 2813-2822

Craig, I.P. 2006 Comparison of precise water depth measurements on agricultural storages with open-water evaporation estimates. Agricultural Water Management 85 193-200.

Dalton. 1802 Experimental essays on the constitution of mixed gases, …., on evaporation and the expansion of gases by heat. Mem. Manchester Lit. and Phil. Soc. 5 535-602

Jensen, M.E., Dotan, A. Sanford, R. 2005. Penman-Monteith estimates of reservoir evaporation. ASCE Library. Fort Collins, CO.

Morton, F.I. 1983 Operational estimates of lake evaporation. J. Hydrol. 66 77-100

Monteith, J.L. 1965 Evaporation and the environment. The state and movement of water in living organisms. XIXth symposium, Society for Expt Biology, Swansea, Cambridge Univ. Cambridge, England 205-234

Oke, T.R. 1987 Boundary Layer Climates 2nd Ed. Routledge - London and New York

Priestley, CHB and Taylor, R.J. 1972 On the assessment of surface heat flux and evaporation using large scale parameters. Mon. Weather Rev. 100 81-92

Sartori, E. 2000 A critical review on equations employed for the calculation of the evaporation rate from free water surfaces. Solar Energy 68 77-89

Webster, I.T., and Sherman, B.S 1995 Evaporation from fetch limited water bodies. Irrig Sci 16 : 53-64