

A Note on Minimising Temperature Rise by Restricting Evaporation From Small Open Water Surfaces

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Abstract

In countries situated at certain (low) latitudes high daily insolation results in high rates of evaporation from open water surfaces. A cheap and efficient method to minimise evaporation from small water bodies is to cover the surface of the water completely with small, floating polystyrene spheres. Furthermore by consideration of the surface energy budget, it is shown that, in general, the temperature rise of the water is restricted. The lower temperature of the stored water (in comparison with that of a free water surface) permits higher concentrations of dissolved oxygen at saturation, discourages unwanted growths and makes for a more palatable water.

Introduction

One of the biggest problems in many low latitude semi-arid areas is the high rate of evaporation from open water surfaces. In countries (industrialised or developing) where water is scarce it is of paramount importance to the inhabitants to preserve water once collected. Containers open to the atmosphere specifically to collect precipitation are particularly prone to evaporation losses. Covered containers may not be economically feasible (especially in Third World countries) and the restricted availability of oxygen in the closed air space above the water surface may well lead to a poor quality of the stored water and provide a breeding ground for insects. One compromise is to use a floating lid, which will still permit direct infiltration of rainwater. To accomplish this it would be technically feasible and economically acceptable to "carpet" the open water surface with small, floating polystyrene spheres. (Experiments using one metre polystyrene hexagons have been undertaken on storage reservoirs with great success; Pereira, 1973). However, on this scale a carpet of spheres may suffer from accumulation downwind under windy conditions. The application of such a technique to small containers (e.g. water butts) will not suffer this effect.

As well as permitting infiltration, there will be some restriction on the particulates (deposited from the air) entering the water (especially if the spheres are weighted slightly to retain their orientation and stability). This lid will physically prevent evaporation. In addition, it will be shown, by consideration of the surface energy budget, that the temperature rise (over the year) of the water in the container is constrained, if there is a negligible heat flux through the sides of the container. This permits a greater concentration of dissolved oxygen to remain in the water (Henderson-Sellers, 1979a, b) and does not encourage algal growths and insect and bacterial breeding that may well occur at a higher temperature (e.g. Moss, 1980).

In this paper a theoretical analysis of the surface energy budget is undertaken to calculate the effect on water temperature and evaporation.

Surface Energy Budget

(a) Without Polystyrene Spheres

The surface energy budget of an open water surface must take into account incident solar radiation Φ_s , incident long-wave (atmospheric) radiation Φ_{r2} , long-wave radiation losses Φ_{r1} , latent heat flux Φ_c and sensible heat transfer Φ_e (where all energy values are in $W m^{-2}$). The reflectivity of the surface for both short and longwave radiation (A_s and A_L respectively) are also required. Here the energy budget is considered on an annual time scale so that all energy fluxes are expressed as mean daily values i.e. variability on a diurnal scale is ignored.

The net energy flux, Φ_{Nb} , available to the water body is then given by

$$\Phi_{Nb} = \Phi_s(1-A_s) + \Phi_{r2}(1-A_L) - \Phi_c - \Phi_e - \Phi_{r1} \quad (1)$$

where the subscript b indicates calculation before the introduction of the spheres.

All the energy fluxes on the right hand side of this equation can be computed using empirical or semi-empirical formulae. These are discussed in detail by Ryan and Harleman (1971) and Henderson-Sellers (1976). The recommended formulations (Henderson-Sellers, 1980) are given in Table 1.

If it is assumed that this energy is mixed evenly throughout the volume V of the water, where the surface area is A, then the rate of increase of temperature T is given by

$$\frac{\partial T_{wb}}{\partial t} \rho c_p V = A \Phi_{Nb} \quad (2)$$

Over an annual period the maximum temperature occurs (in late summer) when $\frac{\partial T}{\partial t} = 0$. This is given by a zero net flux i.e. (from equations 1 and 2).

$$\Phi_s(1-A_s) + \Phi_{r2}(1-A_L) - \Phi_c - \Phi_e - \Phi_{r1} = 0 \quad (3)$$

The two long-wave radiative fluxes Φ_{r1} , Φ_{r2} are given in Table 1.

Hence, substituting these expressions into equation 3, gives an expression for T_{wb} ;

$$T_{wb}^4 = \frac{\Phi_s(1-A_s) + \epsilon_a \sigma_a T_a^4(1-A_L) - \Phi_c - \Phi_e}{\epsilon_w \sigma} \quad (4)$$

(Note in some situations Φ_c is sufficiently small to be neglected in this equation.)

(b) With Polystyrene Spheres

Figure 1 depicts the energy fluxes needing consideration when

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TABLE 1
EMPIRICAL EQUATIONS USED TO CALCULATE ENERGY FLUX TERMS

Parameter	Symbol	Equation	Source
Incident solar radiation at top of atmosphere	Φ_{∞}	Astronomical data	e.g. Sellers (1965)
Radiation incident at ground level	Φ_s	$\Phi_s = \Phi_{\infty} (0.18 + 0.55n/D)$	Penman (1948)
Long-wave radiation loss	Φ_{r1}	$\left. \begin{aligned} \Phi_{r1} &= \epsilon_w \sigma T_w^4 \\ \Phi_{r2} &= \epsilon_a \sigma T_a^4 \end{aligned} \right\} \text{blackbody radiation}$	
Incident long-wave radiation	Φ_{r2}		
Latent (evaporative) heat flux	Φ_e	$\Phi_e = \{\lambda(T_{wv} - T_{av})^{1/3} + b_1 u_2\} (e_{sw} - e_a)$	Ryan <i>et al</i> (1974)
Sensible heat flux	Φ_c	$\Phi_c = 0.61 \times 10^{-3} p [(T_w - T_a)/(e_{sw} - e_a)] \Phi_e$	e.g. Dake (1972)
Emissivity of atmosphere	ϵ_a	$\epsilon_a = 0.688 + 0.125 (1 - \frac{n}{D}) + 0.443 \times 10^{-4} \psi e_{sa}$	Best fit approximation (Henderson-Sellers, 1976) to graphical data (Raphael, 1962)

Associated nomenclature

e_a	vapour pressure at temperature T_a
e_{sw}	saturated vapour pressure at temperature T_w
n/D	cloud factor (number of hours of sunshine divided by maximum possible number of hours of sunshine i.e. day length)
p	atmosphere pressure
T_a, T_w	air and water temperature
T_v	virtual temperature
u_2	wind speed at a height of 2 m
ϵ_a, ϵ_w	emissivities of air and water
λ, b_1	constants $\lambda = 2.7 \times 10^{-2} W_m^{-2} (N_m^{-2})^{-1} K^{-1/3}$ $b_1 = 3.2 \times 10^{-2} W_m^{-2} (N_m^{-2}) (m s^{-1})$
σ	Stefan-Boltzmann's constant = $5.67 \times 10^{-8} W_m^{-2} K^{-4}$
ψ	relative humidity

the water surface is covered by polystyrene spheres of depth d . Indicating values related to spheres by an asterisk and values for the underlying water by a subscript a , it can be seen that the energy balance of the spheres is given by

$$\Phi_{Np} = \Phi_s (1 - \check{A}_s^*) + \Phi_{r2} (1 - \check{A}_L) - 2 \check{\Phi}_{r1} - \check{\Phi}_c - \check{\Phi}_{c2} + \Phi_{r3} \quad (5)$$

and for the water

$$\Phi_{Na} = \check{\Phi}_{r1} + \check{\Phi}_{c2} - \Phi_{r3} \quad (6)$$

By analogy with equation 2, the rate of heating is given by:

$$\text{Spheres: } \frac{\partial \check{T}}{\partial t} \rho^* c_p^* d = \Phi_{Np} \quad (7)$$

$$\text{Water: } \frac{\partial T_{wa}}{\partial t} \rho c_p V = A_s \Phi_{Na} \quad (8)$$

Assuming that the maximum temperatures for both spheres and water occur at the same time of the year as for an open water surface

$$\begin{aligned} \text{Spheres: } & \check{\Phi}_s (1 - \check{A}_s^*) + \Phi_{r2} (1 - \check{A}_L) - 2 \check{\Phi}_{r1} - \check{\Phi}_c - \\ & \check{\Phi}_{c2} + \Phi_{r3} = 0 \end{aligned} \quad (9)$$

$$\text{Water: } \check{\Phi}_{r1} + \check{\Phi}_{c2} - \Phi_{r3} = 0 \quad (10)$$

Again substituting for the blackbody fluxes we find

$$\Phi_s (1 - \bar{A}_s) + \epsilon_a \sigma T_a^4 (1 - \bar{A}_L) - 2 \epsilon_p \sigma \bar{T}^4 - \Phi_c - \Phi_{c2} + \epsilon_w \sigma T_{wa}^4 = 0 \quad (11)$$

$$\Phi_{c2} + \epsilon_p \sigma \bar{T}^4 = \epsilon_w \sigma T_{wa}^4 \quad (12)$$

where ϵ_p is the emissivity of the polystyrene spheres. Elimination of \bar{T} between these two equations gives

$$T_{wa}^4 = \frac{\Phi_s (1 - \bar{A}_s) + \epsilon_a \sigma T_a^4 (1 - \bar{A}_L) + \Phi_{c2} - \Phi_c}{\epsilon_w \sigma} \quad (13)$$

Alternatively if it is noted that since the temperature difference between the bottom of the spheres and the water is very small, then the energy fluxes Φ_{r3} and Φ_{r1} can be considered equal. In that case equations 9 and 10 become

$$\text{Spheres: } \Phi_s (1 - \bar{A}_s) + \Phi_{r2} (1 - \bar{A}_L) - \Phi_{r3} - \Phi_c - \Phi_{c2} = 0 \quad (14)$$

$$\text{Water: } \Phi_{c2} = 0 \quad (15)$$

and equation 13 is simplified to read

$$T_{wa}^4 = (\Phi_s (1 - \bar{A}_s) + \epsilon_a \sigma T_a^4 (1 - \bar{A}_L) - \Phi_c) / \epsilon_w \sigma \quad (16)$$

Hence we have values for T_{wa} and T_{wb} and thus a value for the restriction imposed on the water temperature rise by the use of spheres (i.e. $T_{wb} - T_{wa}$) by inputting flux values appertaining to the period of highest water temperatures (usually about February in the Southern Hemisphere).

Results

The temperature increment (which will, in general, have a negative value) is given by

$$\Delta T = \left\{ \left[\Phi_s (1 - \bar{A}_s) + \epsilon_a \sigma T_a^4 (1 - \bar{A}_L) - \Phi_c \right]^{1/4} - \left[\Phi_s (1 - \bar{A}_s) + \epsilon_a \sigma T_a^4 (1 - \bar{A}_L) - \Phi_c \right]^{1/4} / \left[\epsilon_w \sigma \right]^{1/4} \right\}^{1/4} \quad (17)$$

Typical low latitude values (South Africa) are given in Table 2 although it must be noted that calculation of several of the fluxes (e.g. Φ_c , Φ_e) requires an input value for the water temperature. The calculation of ΔT (equation 17) is thus, strictly, an iterative procedure. These resulting maximum water surface temperatures and temperature increments for differing reflectivity values for the spheres are given in Table 3 (based in this first iteration only) together with the values for T . A reasonable range of reflectivity values, from 0,5 to 0,7, results in a range of values from a temperature decrement of between 8,6 K to a temperature increment of 0,6 K. It would be impossible to gain greater benefit by increasing the albedo to 0,8, say, since the calculated value of ΔT could be greatly moderated by heat influx through the sides of the water container resulting from a large temperature difference between the water temperature and the air temperature. In this case the first iteration based on a difference between T_a and T_w of no more than 2 K, is no longer valid.

Table 4(i) gives results based on a fully iterative solution. It is evident from these results that for spheres of low reflectivity, the water temperature is increased, largely a result of the initial retention of an increased absorption of energy which would normally be removed by an enhanced evaporation rate. This does

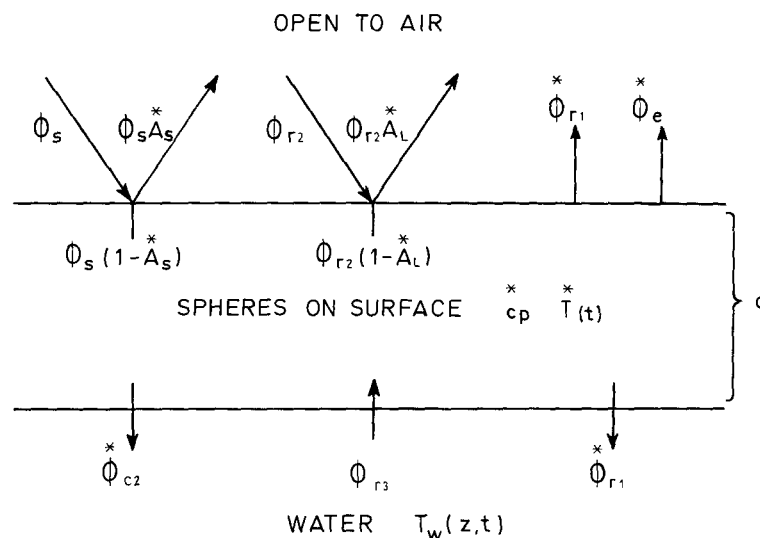


Figure 1
Energy Fluxes

TABLE 2
TYPICAL VALUES USED FOR CALCULATION OF TERMS IN EQUATIONS 4 AND 13

Symbol	Typical South African values	Sources
Φ_{∞}	500 W _m ⁻²	Sellers (1965)
n/D	0,64	Ellis (1978)
Φ_s	266 W _m ⁻²	Table 1
A _s	0,06	e.g. Parker and Krenkel (1970)
A _L	0,03	e.g. Raphael (1962)
$\therefore \Phi_s (1-A_s)$	250 W _m ⁻²	—
T _a , T _w	~ 300K with constraint that T _a - T _w = 0(2 K)	Scott <i>et al</i> (1977) Van As <i>et al</i> (1974)
ϵ_a	0,815	Table 1
Φ_{r2}	370 W _m ⁻²	Table 1
u _z	2,5 m s ⁻¹	Van As <i>et al</i> (1974)
Φ_e	125 W _m ⁻²	Table 1 (Ryan <i>et al</i> (1974))
Φ_c	0,32 Φ_e ~ 40 W _m ⁻²	Table 1 (Dake, 1976)
\ddot{A}_L	0,10	
$\ddot{\Phi}_{c2}$	negligible	
$\ddot{\Phi}_c$	~ 20 W _m ⁻²	(by analogy with Φ_e)
ϵ_w	0,97	

not occur if the reflectivity is higher when the resultant effect is that of a net decrease in available energy. With spheres of reflectivity of the order of 0,6 - 0,7, a temperature decrement of between 1 and 5 K is predicted (for complete coverage by the spheres).

TABLE 3
CALCULATED VALUES FOR WATER TEMPERATURES FOR A RANGE OF REFLECTIVITY VALUES (FOR SPHERES). VALUES GIVEN IN TABLE 2 ARE USED AND NO FURTHER ITERATION IS ATTEMPTED. (SURFACE IS ASSUMED TO BE TOTALLY COVERED BY SPHERES)

	\ddot{A}_s			
	0,5	0,6	0,7	0,8
T _{wb} = 300 K				
T _{wa} (K)	300,7	296,2	291,4	286,4
ΔT(K)	+0,7	-3,8	-8,6	-13,6

TABLE 4
ITERATED VALUES FOR WATER TEMPERATURE FOR A RANGE OF REFLECTIVITY VALUES

T_{wb} = 300 K.

(i) Total surface coverage (γ = 1,0)

	\ddot{A}_s		
	0,5	0,6	0,7
T _{wa} (K)	304,0	298,9	295,0
ΔT(K)	+4,0	-1,1	-5,0

(ii) Less than total coverage - values of T_{wa}(K).

	\ddot{A}_s		
	0,5	0,6	0,7
γ = 0,9	301,9	299,9	297,5
γ = 0,8	301,1	300,0	299,0

Discussion

The above analysis assumes that the spheres completely cover the water surface i.e. evaporation is prevented. It is perhaps more reasonable to assume that a large fraction γ of the surface is covered, in which case the value of T_{wa} is given by T_{wa}

$$\frac{\epsilon_w \sigma T_{wa}^4}{\gamma} = \epsilon_w \sigma T_{wa}^4 + \frac{1-\gamma}{\gamma} [(1-A_l) \epsilon_a \sigma T_a^4 + (1-A_s) \Phi_s - \Phi_e - \Phi_c] \quad (18)$$

where T_{wa}^4 is given by equation 13 or 16. The calculated values, given in Table 4(ii) for various coverage, show that, as expected, decreasing coverage tends to a temperature typical of an uncovered body of water ($T_{wb} = 300$ K) although the temperature difference between 80% and 100% coverage is no more than 4 K (for the range of sphere reflectivity values considered here).

It thus appears that for a reasonable coverage (although not necessarily total), the temperature change is related primarily to the reflectivity of the spheres and not to the percentage coverage. However, only a total coverage will prevent evaporation although a value of $\gamma = 0,8$ results in an approximately 80% saving of evaporation. Such a calculation suggests that even in a larger lake/dam considerable savings in evaporated loss can be accomplished (together with a diminished water temperature) even if the spheres are disturbed (e.g. by the wind) so that up to 20% of the surface is uncovered. Costs must be balanced — in countries with a water stress economy such costs may be considered justifiable.

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