Destratification and Reaeration as Tools for In-Lake Management

B. HENDERSON-SELLERS
Department of Civil Engineering, University of Salford, Salford M5 4WT, United Kingdom

Abstract

During the Summer, the water in many reservoirs (dams) exhibits a thermal stratification, which may have deleterious effects on water quality. The lower layer (hypolimnion) may become anoxic, permitting the release of reduced gases. The lack of oxygen affects the biota and also the water chemistry and it is often desirable to avoid such occurrences. To overcome this natural problem it is possible to aerate the water and/or prevent or destroy the stratification. Such techniques are described and theoretical aspects of one example (the Helixor unit) considered.

Introduction

When a lake becomes stratified many changes in the physical, chemical and biological characteristics of the water can occur. These changes are often undesirable for many reasons. In the hypolimnion (lower layer) of a stratified lake, oxygen levels are lower, nutrient concentrations higher and the temperature less than that in the epilimnion (upper layer). Water withdrawn from the hypolimnion for domestic and industrial usage needs more treatment to remove nutrients and add oxygen. Treatment costs are thus higher. Reducing conditions present in the hypolimnion change the chemistry: oxidation products are no longer released and instead large volumes of hydrogen sulphide and methane may be produced; anaerobic conditions may prevail such that aerobic bacteria and respiring organisms are replaced by anaerobic bacteria; the rate of release of phosphates from the sediments is increased by a large percentage.

These are some of the major reasons why a stratified lake is often considered undesirable. If it is possible to either destroy or prevent stratification, the lake is maintained at homogeneity throughout the year. Dissolved oxygen and nutrients are continually being recycled and the lake remains isothermal. For some water users there are drawbacks to destratification: the isothermal temperature, T_i, resulting from destratification must lie between the epilimnion temperature, T_e, and the hypolimnion temperature T_h, of the stratified lake, i.e.

$$T_h < T_i < T_e \tag{1}$$

In some countries the temperature of water abstracted for potable use must be below a legally specified maximum T_m. Since it is likely that $T_i > T_m$ whilst $T_h < T_m$, it is often more politic to reaerate, *in situ*, the cool hypolimnetic water rather than attempting destratification. Alternatively in a lake fished for cold water species, destruction of the thermocline (i.e. the boundary between the epilimnion and the hypolimnion) may well eliminate the habitat of such species. Furthermore, reducing the surface temperature from T_e to T_i may inhibit the growth rates of algae and restrict the amount of water lost by evaporation.

Reaeration/Destratification Devices

Many of the devices used for destratification can also be used for hypolimnetic reaeration (e.g. diffusers, bubble guns, Helixors). Introduction of air into the hypolimnion will increase the dissolved oxygen (DO) content of the lower layers. If the stratification is retained, then the reaerated hypolimnetic water can be used as a relatively cool potable supply: withdrawals are thus made from the lower levels. Many of the diffusers and other hypolimnetic reaeration devices use air bubble release. (Excellent reviews can be found e.g. Fast and Lorenzen (1976); Hydraulics Research Station (1978); Tolland (1977), who also considers aeration and destratification techniques in detail; Carr and Martin (1978) who assess the efficiency of aeration). The size and energy of these bubbles will determine whether the thermocline remains intact. Higher energy releases can thus be used for destratification; although initial experiments in South Africa (Scott *et al*, 1978) using diffusers in an attempt to destratify Hartbeespoort Dam were not wholly successful. One such method (the use of Helixors) will be discussed in detail later in this paper as a prelude to accurate assessment of the efficiency of these devices (in comparison with other techniques discussed here and evaluated by other authors).

One destratification tool which does not utilise air injection is "jetting". In a pumped storage reservoir where water is being transported by pipeline to form the inflow for the dam, it is possible to utilise the Venturi effect to create a jet. Jetting reservoirs is undertaken in many countries. Water entering the lake with additional momentum and/or buoyancy through a jet inclined at an angle to the horizontal will rise through the lake, entraining lake water and enhancing mixing.

Reaeration/Destratification Theories

Reaeration techniques (with or without destratification) do not as yet appear to be well understood theoretically. Since the destratifying effect is largely a function of the input energy and bubble size (together with the oxygen transfer effects), theories must be based on energy kinetics, bubble theory and diffusion concepts. Indeed in the use of bubble guns it is found that the large bubbles result in a low oxygen transfer coefficient because of their low surface to volume ratio. More successful methods are based on smaller bubbles which can be kept in "closer" contact with the ambient water as they rise.

Practical experience has shown that jetting can be successful in destratifying a dam. Many theoretical models exist to describe the trajectory of such a jet (which may also be buoyant). As it passes through the dam, the inflow mixes with ambient water, thus reducing both its buoyancy and momentum and may reach an equilibrium level below the surface, when these excesses have vanished. In order to maximise mixing and prevent local recirculation, a long trajectory is considered desirable (Steel, 1975).

Many models exist to simulate this phenomenon. Jet models have been devised to describe a vertical stream of water (e.g. Bourodimos, 1972), or a horizontal outflow, to detail a plume or a momentum dominated flow (e.g. Chan and Kennedy, 1975). Models employing curvilinear co-ordinates (e.g. Hoult *et al,* 1969; Hirst, 1971; Cederwall, 1975) have been developed by Henderson-Sellers (1978) by consideration of the conservation equations for mass, momentum and buoyancy described by Morton (1971). Entrainment is described in terms of an entrainment velocity, V_e, which is proportional to the axial velocity, W.

$$V_e = \alpha \mid W \mid \qquad (2)$$

The entrainment coefficient, α, is found to be a function of the Froude number (List and Imberger, 1973; Henderson-Sellers, 1978). This model has been successfully applied to the destratification of Farmoor Reservoir in the United Kingdom (Henderson-Sellers, 1978), by assuming that in the stratification model the jetted inflow can be replaced by an input of zero buoyancy and momentum at the calculated equilibrium height for the jet. A more sophisticated description of the physics of destratification can be attempted (see e.g. Graham, 1978).

Destratification by Use of Helixors

Another successful method of destratification and reaeration (for which no theoretical basis has as yet been fully developed) is based on small bubbles kept in contact with the water for a comparatively long period by circulation around a helix as the bubbles rise. Oxygen is thus dissolved in the water in the body of this "Helixor". At the top of the device the aerated water forms a plume which entrains more water, mixing as it rises.

The Helixor has been developed by POLCON*, first in Canada and the U.S.A., and then in Britain and South Africa for aeration of both wastewater and freshwater. Many of the installations in Canada are used for maintaining circulation and ice-free conditions in winter (Wirth, 1970; Lackey, 1972). In Britain, installations in storage reservoirs (for destratification) range from 1 to 12 in the number of Helixors used. They can be used to destroy or prevent stratification and use less energy in the latter mode (by a factor of 10 or more). Calculation of the number of Helixors and siting is undertaken by POLCON from previous experience; the rules of thumb used are

(a) 1 Helixor per 100 acres ($\simeq$ 40 ha = $4 \times 10^5 m^2$)

(b) Total volume of water moved by Helixor per day (i.e. including entrained water) = 1% of total volume of water in reservoir. (Valid for relatively isothermal lakes i.e. as a prevention rather than a cure).

These estimates are usually overestimates since it is often unnecessary to distribute Helixors evenly throughout the reservoir as only the deeper parts are likely to stratify. This is illustrated by applying the first rule to Britain's largest reservoir Rutland Water. ($A = 12{,}4 \times 10^6 m^2$, $V = 124 \times 10^6 m^3$) giving 30 Helixors whereas 12 Helixors are found to be sufficient in practice.

A theoretical calculation for n (the number of Helixors) needs to consider (i) the pumping rates of Helixors for a given air pressure, lake depth and length of Helixor, and (ii) the destratifying effect of the mixing. Progress towards the first part has been made by POLCON (undated) who use a semi-empirical equation to calculate the effective pumping rate QT (which includes entrainment) from the Helixor throughflow, QI:

$$QT = \frac{QI \times S}{6R} \qquad (3)$$

where S is the depth below the surface = z (total depth) − H (Helixor length), R is the radius of the Helixor and QI is related to the Helixor length by the pumping capacity curve shown in Figure 1. Equation 3 is a useful guideline in many cases, but is of more dubious validity as a plume model for large values of S. Better values for QT and hence n are derived when S is taken to be the depth below the thermocline – a reasonable assumption since it is likely to be at this level that the plume rise will terminate. For example consider Rutland Water.

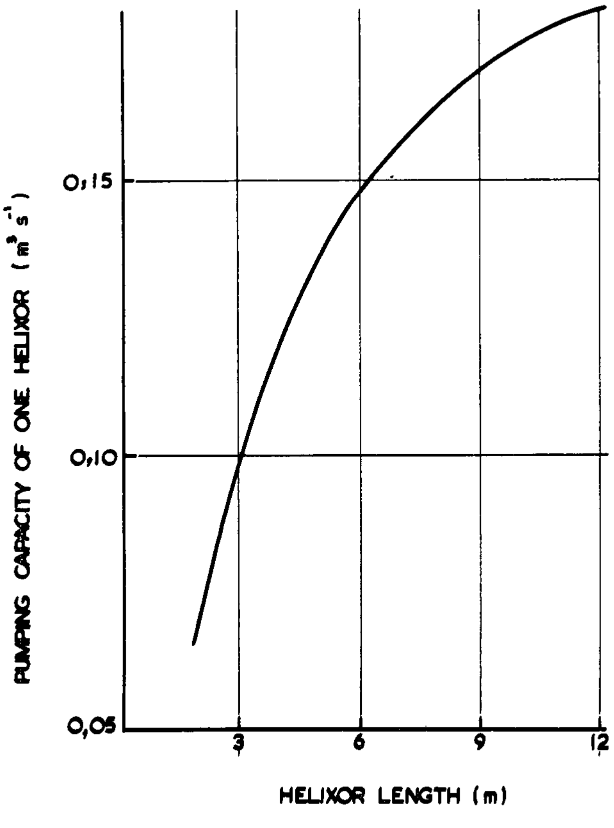

Figure 1
Pumping capacity curve for a single Helixor as a function of Helixor length

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$S = 24$ m, $R = 0{,}23$ m, $QI = 0{,}14$ m^3s^{-1} (from Figure 1 with a Helixor length 6 m)

Hence the value of QT is given by Equation 3 as 2,43 m^3s^{-1} (a factor of 17 greater than QI). Using the guidelines given above would imply only 6 Helixors for Rutland Water. However if S is the distance to the thermocline $\simeq 6$ m, $QT/QI \simeq 4$ and $n \simeq 25$. Noting that these calculations are valid as a preventative measure, then the value of 6, doubled for increased safety margins (e.g. anomalous meteorological conditions) would seem appropriate.

An alternative approach is to consider the volume entrained = $(QT - QI)$ m^3s^{-1}.

This is equated geometrically to the conical volume of the Helixor plume

$$QT - QI \simeq \frac{\pi Y^2 S}{3} \div \frac{S}{V_H} \tag{4}$$

where Y is the radius of the plume at the final height of rise and V_H is the mean vertical velocity (assumed constant here) given by

$$QI = \pi R^2 V_H \tag{5}$$

where R is the Helixor radius. It is known from plume theory that the ratio Y/S is of the order of 0,1 (Henderson-Sellers, 1980). Hence

$$QT - QI = \frac{\pi 10^{-2} S^2 V_H}{3} \tag{6}$$

Using Rutland Water data as before gives $V_H = 0{,}78$ ms^{-1} and hence $QT - QI = 4{,}72$ m^3s^{-1} ($S = 24$) or 0,30 m^3s^{-1} ($S = 6$), (Corresponding values for the ratio QT/QI of 35 and 3 respectively are in acceptable agreement with the values calculated by the first approach).

TABLE 1
VELOCITY OF RISING WATER/AIR PLUME, V_H, IN ms^{-1} AS A FUNCTION OF r and ℓ

		Compression ratio r		
		1,5	1,8	2,0
Constant of proportionality for entrainment of water by air bubbles ℓ	4	3,5	4,1	4,5
	10	1,7	2,8	3,0
	30	1,1	1,6	1,9
	100	0,6	0,8	1,0

Helixor Models

In the above modelling approaches, the velocities are deduced from a knowledge of QI(H) — from Figure 1. Independent calculation of V_H would ensure realistic Helixor velocities before modelling the volume throughput, QI, and effective flow, QT.

Model (a) Consider a compressor working at x watts with an efficiency of z. (Typically 12 Helixors would require a compressor of about 52 kW). The energy input by the compressor to the air is released as kinetic energy within the Helixor. If the pump compresses $C_A m^3s^{-1}$ of air from a pressure P to a pressure P_C and volume C, it can be shown that

$$zx = (P_C - P)^2\, 10^5 (C_A/P_C) \tag{7}$$

where P is in atmospheres.

If the compression ratio r is given by

$$P_C = rP \tag{8}$$

and if it is assumed that $C_A m^3s^{-1}$ of air entrains (at the base of the Helixor) $\ell C_A m^3s^{-1}$ of water (where ℓ is a constant of proportionality), then velocity, V_H, is given by

$$V_H = \left[\frac{2 \times 10^5 P (r-1)^2}{\ell r} \right]^{1/2} \tag{9}$$

Values for V_H are given in Table 1. Observed values are of the order of $r = 1{,}8$ (POLCON documentation) and $V_H \sim 0{,}8 - 1{,}2$ ms^{-1} which implies $\ell = 30 - 100$. Air:water ratios of the order of 30:1 are suggested by POLCON, but values as low as 4:1 by Fast and Lorenzen (1976) for other types of aerator. It seems unlikely that the coefficients r and ℓ should be independent, however no physical relationship has yet been formulated quantitatively.

Model b) Consider rising bubbles of air, released from rest, with velocity v at height s. The buoyant force on the air/water mixture is proportional to the density deficiency and hence depends on the mixing ratio ℓ (defined above). This gives

$$v^2 = \frac{2gs}{1+\ell} \tag{10}$$

However the entrained water is unlikely to rise as fast as the air bubbles. Assuming $V_H = \beta v$, where $\beta = 0{,}5$, then

$$V_H = \gamma \sqrt{2gs} \tag{11}$$

where $\gamma^2 = \beta^2 / (1 + \ell)$. It is found that for a constant value of $\gamma = 0{,}0746$, the curve of QI(H) given in Figure 1 is reproduced with a large degree of accuracy — see Table 2. Hence a relationship between ℓ and β is established i.e.

$$\beta^2 = 0{,}0056\,(1 + \ell) \tag{12}$$

The second objective of a Helixor model is to simulate the destratification process initiated by the jet issuing from Helixor top. Using the numerical forced plume model described above (for the case of jetting) it is possible to calculate the shape of the rising mass of air and water.

Neglecting any horizontal current, the plume centreline parameters (e.g. velocity) can be calculated. The equilibrium

TABLE 2
A COMPARISON OF VALUES OF THROUGHPUT CALCULATED USING EQUATIONS 5 AND 11 WITH VALUES FROM THE EMPIRICAL CURVE (FIGURE 1)

Helixor length H (m)	3,05	4,57	6,10	7,62	9,14	10,67	12,19
IQ (m^3s^{-1}) from Fig. 1	0,098	0,125	0,142	0,155	0,164	0,170	0,175
QI calculated from $QI = \pi R^2 \gamma \sqrt{2gH}$	0,096	0,117	0,136	0,152	0,166	0,179	0,192

height can be found; if this is greater than the depth of water above the top of the Helixor, then the air/water plume will rise to the surface. As it does so water is effectively withdrawn from the body of the lake (by entrainment) and reinput to the surface layer. This circulation of water is easily introduced into a numerical stratification model (for details, see Henderson-Sellers, 1978). The spread rate of the plume is given by

$$\frac{dR}{dz} = \alpha \tag{13}$$

where the value of α depends on the plumelike or jetlike characteristics of the air/water mass — the value is typically of the order of 0,08. (Hendrson-Sellers, 1980). This can be related to the half angle of the forced plume if desired, bearing in mind that the parameter values for the model discussed above implicitly assume a Gaussian cross-sectional profile in which the radius is ill-defined. Indeed the value of R in equation 13 is given as the radial distance at which parameters values (e.g. buoyancy, velocity) are 1/eth of the centreline value. A more realistic approximation to the physical radius is given where values are 1 or 10% of centreline values. The corresponding spread rates are thus found to be 0,18 and 0,12 respectively (Henderson-Sellers, 1980); thus stressing the importance of well-chosen definition for the radius R.

In a finite difference (multi-slice) model, the withdrawal from each slice, thickness dz is thus given by

$$\frac{\pi}{2}\left[R^2(z + dz) + R^2(z)\right] dz \tag{14}$$

and thus the input to the top slice is

$$\Sigma \frac{\pi}{2}\left[R^2(z + dz) + R^2(z)\right] dz \tag{15}$$

where the summation is applied over all the model slices above the Helixor top (i.e. from $z = H$ to $z = z$).

Discussion

Helixors are perhaps best suited to preventing stratification rather than destroying it and are certainly more efficient in energy usage in this mode. The calculations above have been made assuming this type of implementation.

A spin-off to destratification is that the surface temperature is reduced in summer. This affects the surface energy budget and will result in a decrease in the rate of evaporation. A first order approximation suggest that a (realistic) 2 K drop in summer surface temperature would result in a 10% decrease in evaporation losses. In an area where the annual evaporation is 1 800 mm per year (taking into account a summer stratification period of about 3 months) this gives a total water saving of about 50 mm.

Conclusions

Ways of destratification or reaeration have been discussed. Helixors appear to offer a viable alternative to diffusers, bubble guns, jets etc.and it is hoped that trial runs using these devices will be implemented in the near future in South African dams.

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