The Thermal Characteristics of Furzton Reservoir :- a preliminary desk study

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Introduction

One of the most important characteristics of a lake is its thermal structure. The heat content of a body of water is of vital importance to aquatic organisms, and of more than passing interest to those who sail or swim on its surface. In this report I attempt to predict the thermal characteristics of a lake that has yet to be built. Furzton reservoir will be a temporary storage/amenity water body near the town of Milton Keynes. Enviro Systems Ltd have been commissioned to install a heat pump system on this lake, and are currently evaluating its heat storage potential.

The operational characteristics of a heat pump installed on a lake are very different to those of a system installed on a river. In a river system there is an infinite supply of 'new' water flowing downstream. The heat capacity of a small lake is finite and a proportion of the water removed by the heat pump may well be reprocessed in subsequent cycles. In most rivers the temporary abstraction of water has little effect on water chemistry. Large capacity pumps installed on a small reservoir can however influence the mixing process and produce undesirable spatial or temporal changes in water quality. In this report I consider both the potential heat storage capacity of Furzton Reservoir and some of the environmental problems that could arise during pumping operations. The report is divided into three sections:-

1. An introductory section that describes the thermal characteristics of lakes in general and explains the difference between stratified and unstratified lakes.
2. A 'heat content' section that considers the likely seasonal variation in the heat storage capacity of the lake. This section has been written on the assumption that Furzton Reservoir will <u>not</u> become thermally stratified. If it does become thermally stratified the heat content will not be very different but the pumps will need to be operated in a different way.
3. A 'vertical mixing' section that considers some of the environmental problems that could arise if the lake does become thermally stratified. This will explain the chemical consequences of thermal stratification and use some empirical models to predict the depth of thermal stratification.

This report has been compiled as a desk study with no access to on site measurements. The results of the model simulations must therefore be treated with caution and the predictions validated by field observations at the earliest opportunity.

Section 1

The thermal behaviour of lakes

The thermal behaviour of lakes depends on the unique thermal properties of water itself. At normal atmospheric pressure water attains its maximum density of 1.000 at 4°C i.e. well above its freezing point of 0°C. This anomalous density-temperature relationship is a critical factor in the thermal behaviour of lakes.

It is convenient to begin a discussion of lake temperatures by considering a lake in a temperate region in early spring when the entire body of water is at a temperature of around 4°C. As spring progresses the surface water of the lake is warmed by the sun and becomes less dense. In lakes of sufficient depth the warm water near the surface becomes sufficiently buoyant to resist the mixing action of the wind. The lake then becomes divided into an upper region of turbulent water called the epilimnion and a deep, cold relatively undisturbed region called the hypolimnion. The region of rapidly decreasing temperature separating the epilimnion from the hypolimnion is called the thermocline. The term thermocline was originally defined as that layer of water in which the fall in temperature exceeds 1°C per metre. Such a definition is, however, quite arbitrary and the term is now more generally applied to the depth at which any substantial fall in temperature occurs. When such a thermocline has formed the lake is said to be thermally stratified. In late summer and early autumn wind-induced mixing and convective cooling gradually erode this vertical temperature structure and the lake again becomes isothermal. This sequence of events is illustrated schematically in Fig. 1. In the U.K. most lakes become thermally stratified towards the end of May and de-stratify sometime in October. The onset of summer stratification is usually a gradual process but the transition from summer stratification to complete mixing is sometimes quite dramatic and can occur after a few hours of strong wind. This idealised pattern of winter mixing and summer stratification is only found in reasonably deep lakes and in shallow lakes that are sheltered from the wind. Shallow lakes and lakes in very exposed locations may never become thermally stratified or stratify for only short periods in summer. From a water quality point of view isothermal lakes are much easier to manage than lakes that become thermally stratified. The problems associated with thermal stratification are most acute in biologically productive lakes that are rich in nutrients. Furzton Reservoir will almost certainly be enriched with agricultural drainage so it is very important to assess the likely incidence of thermal stratification. The physical characteristics of Furzton Reservoir are such that it will be very difficult to predict its thermal characteristics

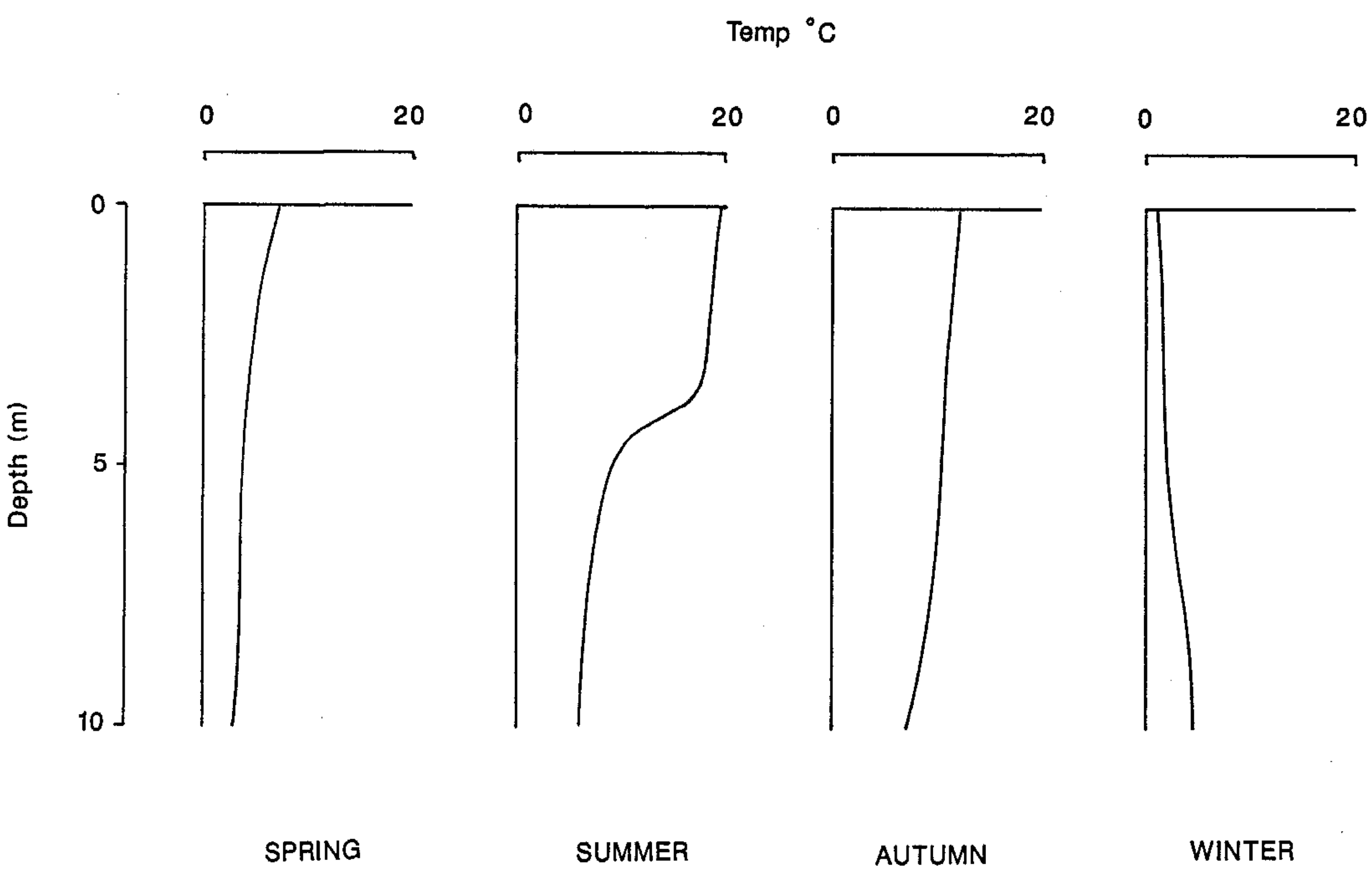


Fig. 1. The seasonal change in the temperature profiles of a thermally stratified lake.

without analysing the local meteorological records in some detail. The reservoir is almost certainly not deep enough to stratify throughout the summer, but thermoclines may form when the weather is warm and the winds are light. Such intermittent stratification is, however, relatively easy to destroy by mechanical methods. Some Water Authorities use Archimedes screws or bubble curtains to generate local upwellings, but the same effect can sometimes be produced by a careful siting of a jet outlet.

Section 2

The heat content of Furzton Reservoir.

The amount of heat stored in a lake varies throughout the year and depends on:-

1. The altitude of the lake
2. The latitude of the lake
3. The average depth of the lake.

In order to calculate the heat content of a lake at a particular altitude and latitude we need a detailed bathymetric map and some measurements of water temperature at different depths. In the case of Furzton Reservoir we can estimate the mean depth of the lake from site maps but can only draw some very general conclusions about the annual temperature cycle.

1. Estimating the mean depth of Furzton Reservoir

Fig. 2a is a bathymetric map of Furzton Reservoir drawn on the assumption that its average depth will be centred on the NWL (normal water level) shown in the site drawings. The mean depth of the lake can then be determined by drawing the hypsographic curve shown in Fig. 2b. A hypsographic curve is a graphical representation of the volume of water contained between set contour intervals. Flat bottomed lakes tend to have a U-shaped hypsographic curve whereas deep valley lakes have a hypsographic curve shaped like the letter V. By simple geometry we can estimate the mean depth of Furzton Reservoir as 2.6 m and its surface area as 148,000 m^{-2}. The dashed outline in Fig. 2b shows that the capacity of the reservoir could be increased by over 50% simply by raising the sluices to the top water level.

2. Predicting the seasonal temperature cycle

The results of world-wide limnological studies during the International Biological Programme (Le Cren and Lowe-McConnell 1980) showed that the annual variations in the surface temperature of temperate lakes could be modelled by a simple sinusoidal curve:-

$$T_t = A_0 + A_1 \sin (t + \vartheta_1)$$

where T_t is the temperature at day t of the year

A_0 is the mean annual surface temperature

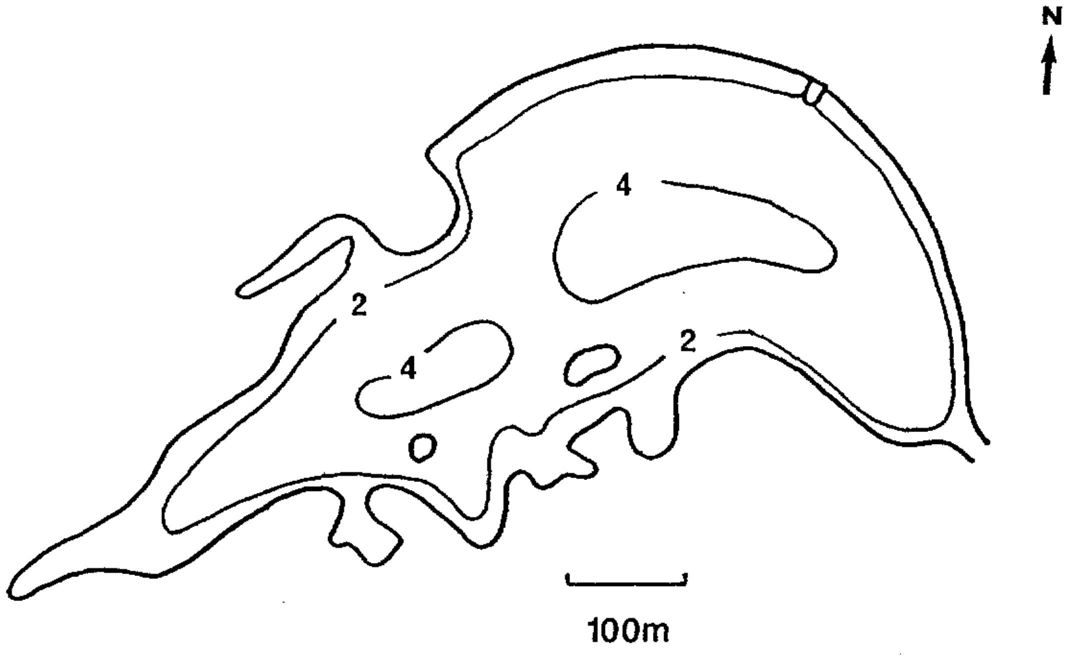
A_1 is the semi-amplitude of the seasonal variation

and ϑ_1 is a phase angle for temperature (degrees).

The terms A_0 and A_1 in this equation both vary systematically with latitude. Straskraba and Gnauck (1985) report that the relationship between A_0 and latitude can be defined by the simple linear equation:

$$A_0 = 28.1 - 0.34\ \emptyset$$

a



b

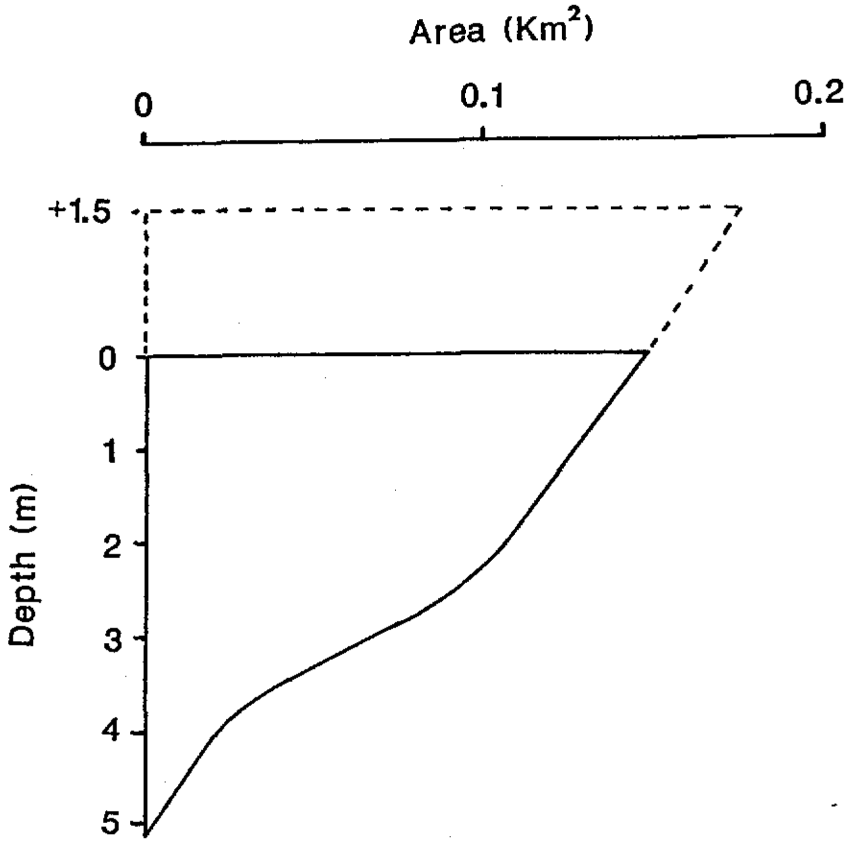


Fig. 2 (a) Bathymetric Map of Furzton Reservoir (2 m and 4 m contours shown).
(b) A hypsographic curve for Furzton Reservoir showing the potential volume increase if the water level was raised by 1.5 m.

when Ø is the latitude in degrees.

Similarly the relationship between A_1 and latitude can be defined by the polynomial approximation:

$$A_1 = 0.54 - 0.045\ Ø^1 + 0.0146\ Ø^2 - 1.97 \cdot 10^{-4}\ Ø^3$$

Fig. 3 shows the result of using these equations to generate an annual temperature curve for a low altitude lake at a latitude of 50°N. When an empirical phase shift term is introduced into the model the predicted annual cycle is very close to that recorded by Green (1966) in a shallow water body near London. Hampton Court Long Water, the lake studied by Green, was somewhat smaller than Furzton Reservoir and therefore cooled rather quickly in the autumn. In Furzton Reservoir the water at depth should be a degree or so cooler in summer and a little warmer in winter. The minimum winter temperature is, however, extremely difficult to predict and depends largely on the incidence of ice cover. When a lake becomes ice covered the heat exchange process changes fundamentally. Heat loss now occurs only at the surface of the ice by outgoing longwave radiation and by the sensible conduction of heat to the atmosphere. Sunlight penetrating the ice cover adds heat by absorption so the water may actually begin to warm up. With the addition of snow cover the heat exchange process becomes even more complex. Snow reduces the upward conduction of heat but also reflects more of the short-wave solar radiation. Latent heat is also stored in the ice and snow so many more storage terms are involved in the energy flux equations. A detailed analysis of the effects of ice cover is outside the scope of this report but could be investigated further given some local meteorological data.

3. Estimating the heat content of Furzton Reservoir

The amount of heat stored in a lake is simply a function of the water temperature at all depths. Since the density of water is generally close to 1.000 we can assume that the volumetric heat capacity of water is 1.0 cal/cm^3/°C. In an isothermal lake we can estimate the heat content by multiplying the average depth of the lake with the average temperature of the water. Conventionally all heat budget calculations are based on a "unit lake" which is a column of water with a surface area of 1 cm^2 which tapers down to some small fraction of a square centimeter at the deepest position of the lake. The heat content/cm^2 can be converted to a 'whole lake' total by multiplying this unit estimate with an appropriately chosen lake area.

Fig. 4 shows the result of converting the surface temperature estimates in Fig. 3 to equivalent heat content values. Table 1 summarises the annual trend as a series of monthly means. These tabulated values almost certainly

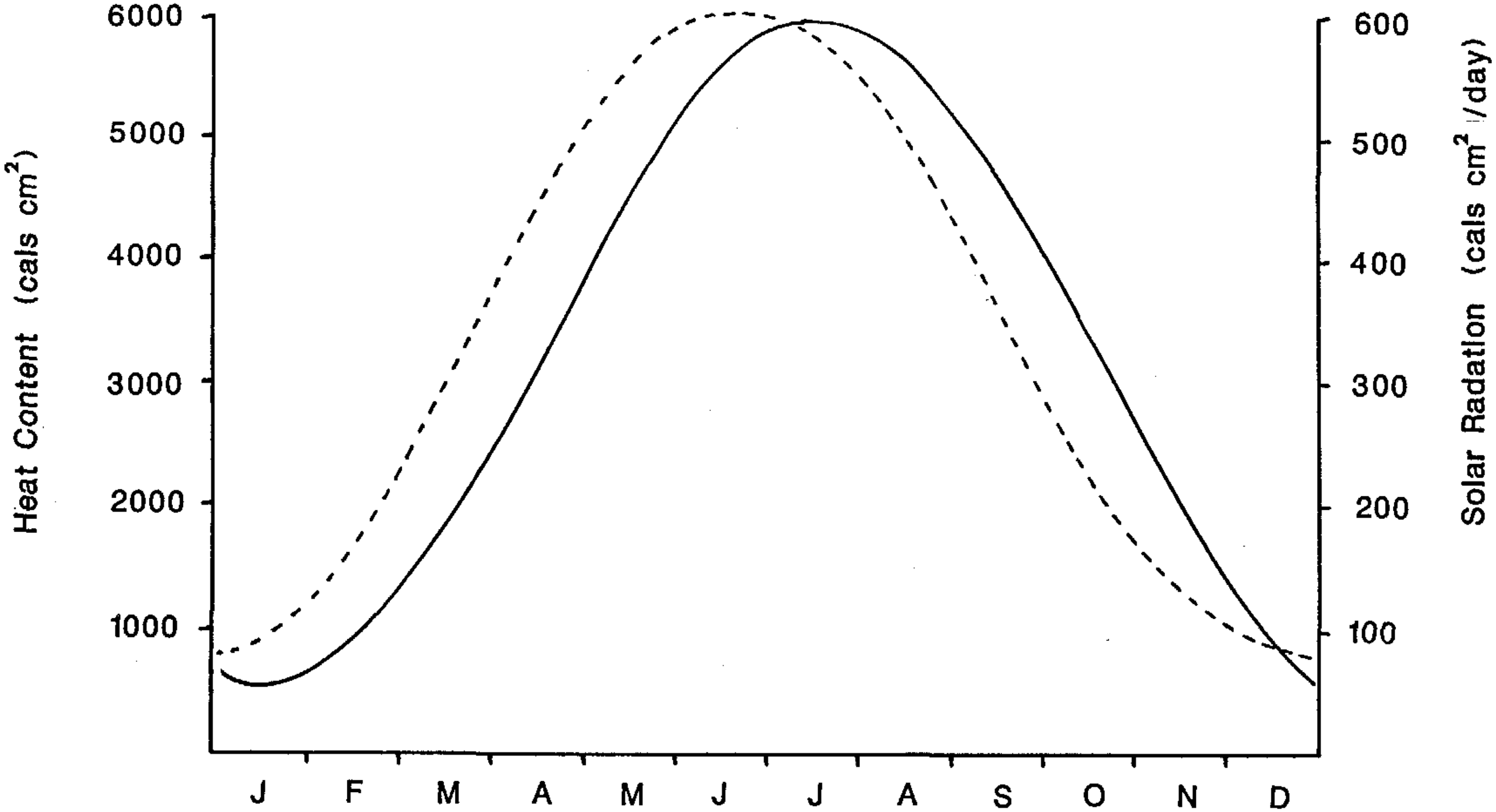


Fig. 4. Predicted heat content curve for Furzton Reservoir. The dashed line shows the expected input of solar energy under clear sky conditions (from Straskraba & Gnauck 1985).

Table 1. The predicted seasonal change in the heat content of Furzton Reservoir. The predictive model assumes that the lake does not become thermally stratified in summer or freeze in winter.

Month	Estimated Heat Content (cals cm^2)
January	600
February	900
March	1800
April	3100
May	4500
June	5500
July	5900
August	5600
September	4700
October	3500
November	2100
December	1000

overestimate the summer heat content and underestimate the winter minimum. The dashed line in Fig. 4 shows the idealised annual variation in the solar energy reaching the ground on clear days. This curve has been derived by sinusoidal simulation (Straskraba and Gnauck 1985) and must be regarded as an 'upper limit' given the scarcity of cloud free days in the U.K.

If Furzton Reservoir becomes thermally stratified more complicated 'depth weighted' methods will have to be used to calculate the heat content. The heat capacity estimated by such methods is likely to be quite close to that suggested in Fig. 4 but there may then be chemical constraints on the efficient operation of the plant.

Section 3

1. The chemical effects of thermal stratification

In deep impoverished lakes thermal stratification has relatively little effect on the concentration of oxygen and other chemical components in the water column. When a productive lake becomes thermally stratified, however, the oxygen concentration in the hypolimnion is soon depleted by oxidative processes. If stratification is maintained for a long enough period major changes in deep water chemistry then occur. The concentration of soluble reactive phosphorus and ammonia nitrogen in the hypolimnion typically increases soon after stratification. If stratification is prolonged some production of hydrogen sulphide may also be expected. In extreme cases the concentration of H_2S in the water above the mud can exceed 10 mg l^{-1}. If such high concentrations of H_2S ever entered the heat exchange system the corrosive effects could be devastating. Fortunately such local concentrations of H_2S take a long time to form and can readily be monitored with in situ sensors. Enviro Systems Ltd should nevertheless consider the potential problems posed by thermal stratification and plan their operations accordingly. If there is a serious risk of prolonged thermal stratification the inlet/outlet pipes to the plant may need to be resited. Short periods of thermal stratification are less serious and it may even be possible to position the discharge jet so as to assist complete vertical mixing.

2. Predicting the vertical mixing regime in Furzton Reservoir

In this section I show how two closely related empirical models can be used to predict the likely incidence of thermal stratification in Furzton Reservoir. The first method relies on simple morphometric measurements and largely ignores the shape of the lake basin. The second method involves some rather more complex fetch calculations which quantify the relative exposure of the lake to winds from different directions.

(a) Mixing depth in relation to lake size.

The mixing depth z_{mix} can conveniently be considered to be the depth at which the thermocline is located in July and August. Empirical observations suggest that z_{mix} can usually be related to lake size as expressed by the maximum length of lake (L) or the effective length of the lake axis (L'). The maximum length of a lake is usually defined as the straight line distance over open water. The effective length also includes a factor for lake width, and is usually taken to be 0.5 (maximum length + maximum width). Table 2 lists three equations that have been used by various authors to predict z_{mix} from morphometric measurements. The z_{mix} depths predicted by the three models are

Table 2. Estimating the depth of the thermocline from morphometric measurements. z_{mix} is the summer mixing depth and L is the maximum length of the lake. (from Le Cren and McConnell 1980).

Region	No of lakes studied	Equation	R^2	Reference number
Poland	53	$z_{mix} = 3.79\ L^{0.45}$	0.88	1
Canada	67	$z_{mix} = 4.98\ L^{0.38}$	0.72	2
Scotland	59	$z_{mix} = 4.66\ L^{0.55}$	0.41	3

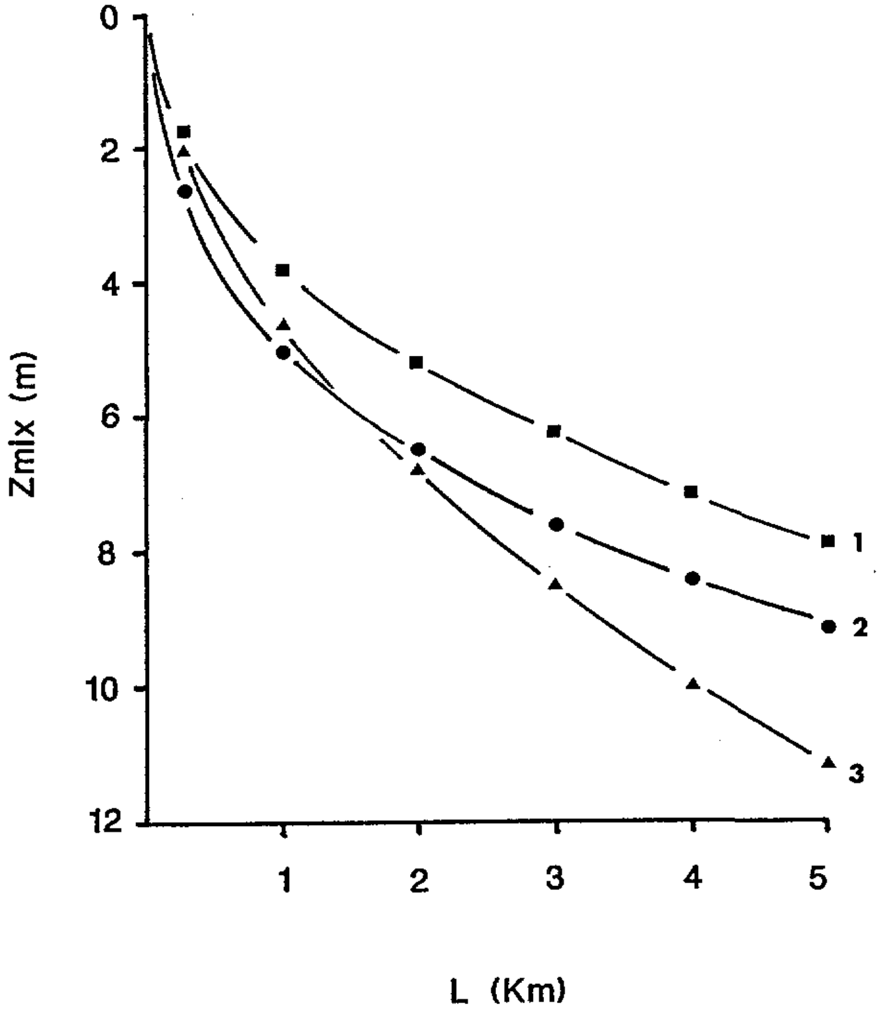


Fig. 5. Estimating the depth of the thermocline from morphometric measurements. The numbered curves refer to the equations in Table 2.

illustrated graphically in Fig. 5. For Furzton Reservoir all three models suggest a mid-summer thermocline depth of between three and four metres. In most lakes the thermocline is much shallower in early summer, so a z_{mix} depth of 2-3 m is quite possible in late May and early June.

(b) Mixing depth in relation to wind exposure

The predictive curves in Fig. 5 do not take into account the orientation of the lake in relation to the prevailing wind. A wind blowing across a narrow lake is obviously less likely to mix the water column than a wind blowing along its long axis. The wave generating (i.e. mixing) effect of a wind is not simply a function of linear distance but is related to the fetch. The fetch (Smith and Sinclair 1972) is a weighted measure of the distance the wind has travelled over open water. A detailed account of the method used to calculate fetch is given in Håkanson (1981). Ragotzkie (1978) has published some empirical data relating z_{mix} to fetch but more specific 'depth of wave mixing' calculations could also be performed if local wind speed records were available. Fig. 6 shows the fetch values calculated for selected locations in Furzton Reservoir when the wind was blowing (a) from the SW and (b) from the NE. These estimates show that a wind blowing from the SW would be more likely to mix the deepest water than a wind blowing from the NE. Fig. 7 shows the likely effect of this wind exposure on the predicted depth of the thermocline. A fetch of 0.5 km produces a z_{mix} depth of 3.8 m but a fetch of 0.3 km could result in a z_{mix} depth of only 3.1 km.

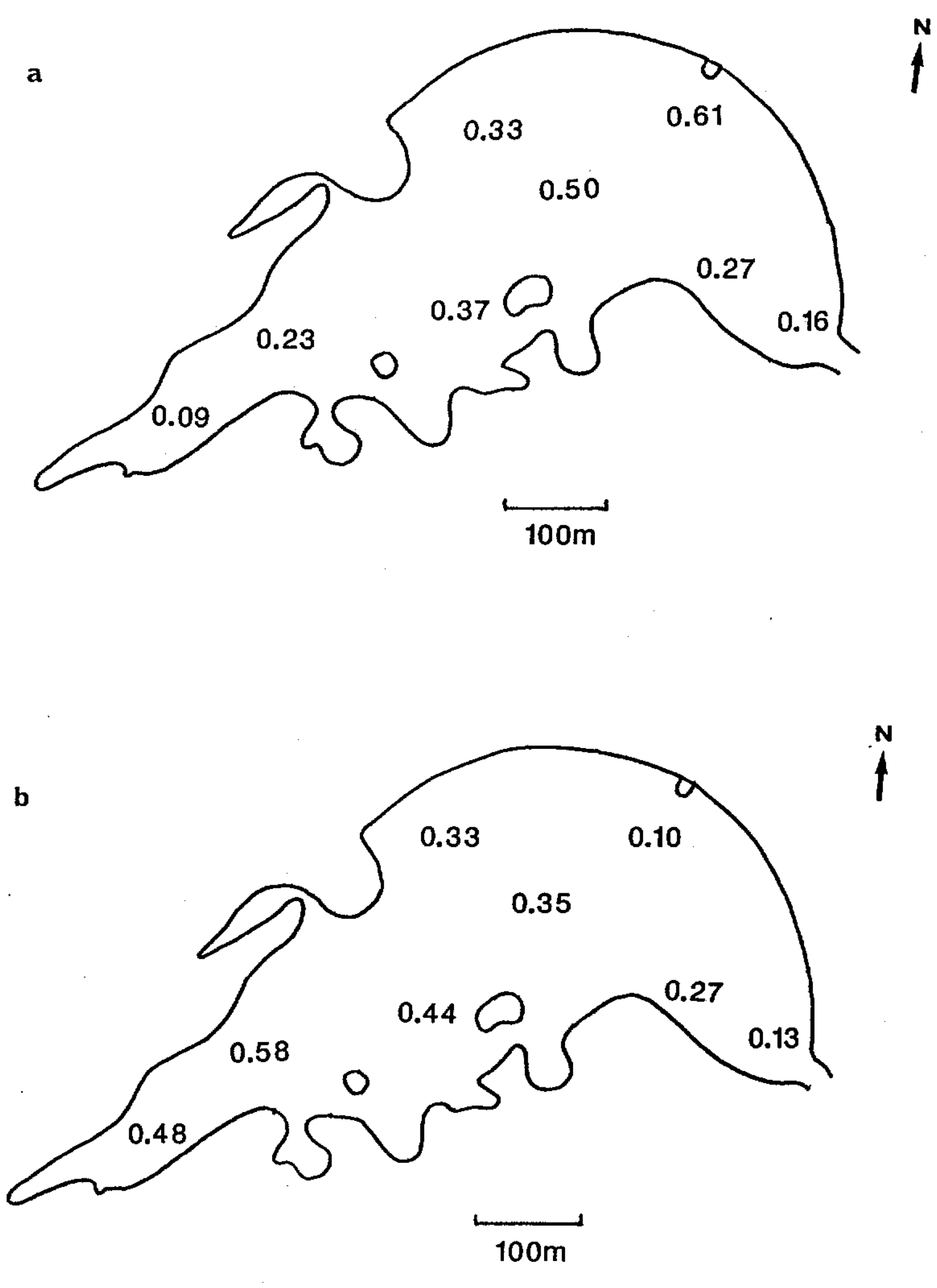


Fig. 6. Some illustrative fetch calculations for Furzton Reservoir.
(a) With south westerly winds (b) With north easterly winds.
(Fetch estimates given in km).

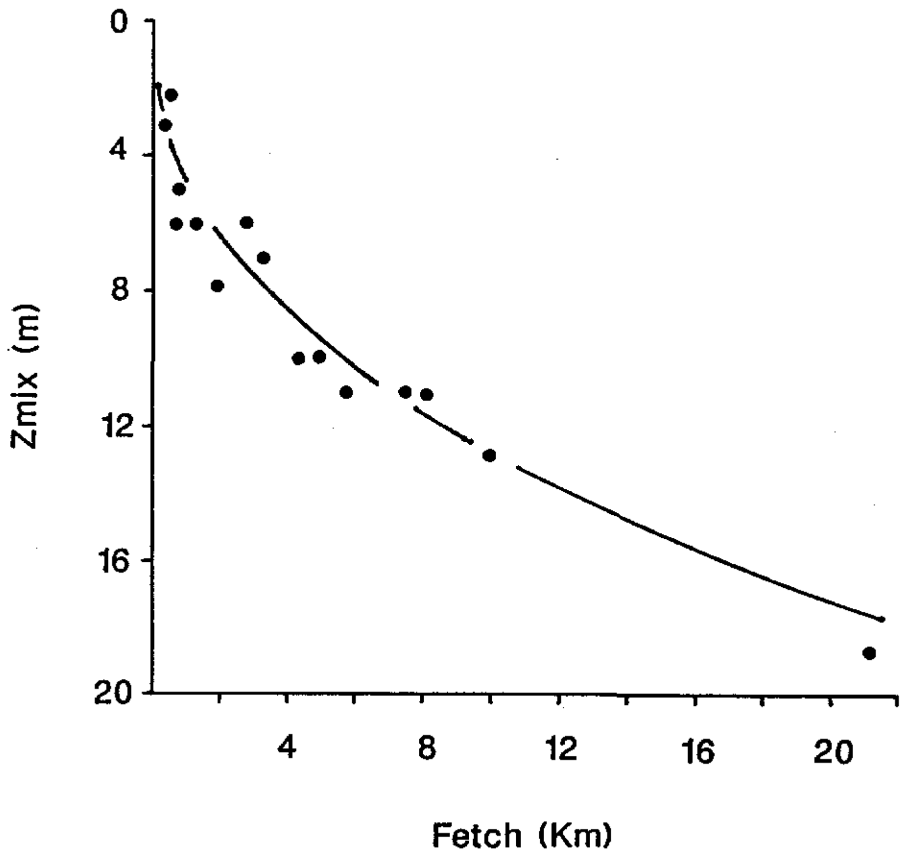


Fig. 7. Estimating the depth of the thermocline from the average fetch. Predictive equation : $z_{mix} = 5.05\ F^{0.41}$ (where F is the fetch in km).

Discussion

1. Furzton Reservoir as a heat source/heat sink

Furzton Reservoir is relatively small so any extensive pumping operations will influence the mixing pattern and the local temperature/density structure. Enviro Systems Ltd will need to consider the hydraulic implications of their pumping operations in some detail. The engineers should ensure that there is no 'short circuiting' between the inlet and outlet pipes, and that suitable diffusers are fitted to the discharge pipe to minimise scouring and sediment resuspension. If beds of submerged macrophytes appear in the lake, the inlet pipes may also need to be screened to protect them from floating debris.

The winter heat content of the lake is at present difficult to predict. Much will depend on the relative proportion of '4°' water and the period of ice cover. If pumping operations delay the freezing process it may be advisable to stop pumping on cold, calm nights to allow a thin cover of ice to form.

In summer the additional heat introduced into the lake by the plant should be encouraged to dissipate by vertical mixing. Whenever possible, all warm water should be discharged into deep water to generate local convective circulations. If there is a risk of deep water anoxia this warm water should be charged with oxygen by incorporating an aerating column in the return pipe run.

2. Design Considerations

Enviro Systems Ltd should now be in a position to specify the general heat exchange requirements of the plant. At this stage the design of the inlet/outlet system should be kept as flexible as possible. In practice it may be necessary to change the relative positions of the inlet and outlet pipes from season to season according to the following scenarios:-

Scenario 1. The lake remains well mixed throughout the year and freezes over for several weeks in winter.

Action required: The inlet and outlet pipes to the heat exchanger can be positioned where convenient. Care must be taken not to draw large amounts of suspended sediment into the plant or mobilise soft sediment with the discharge jet. Winter freezing reduces the heat loss to the atmosphere but a prolonged cold spell could overload the plant.

Scenario 2. The lake becomes thermally stratified for short periods in summer and freezes over for short periods in winter.
Action required: In winter it makes sense to draw water from the deepest part of the lake where the temperature may still be around 4°C. The cooled water should then be discharged near the surface to minimise any convective mixing. In summer the inlet pipes should be positioned in mid-water and the warm water discharged at depth to encourage vertical mixing. If there is a risk of prolonged thermal stratification the pumps should be operated at full capacity to destabilise the water column.

Scenario 3. The lake remains thermally stratified throughout the summer and seldom freeze over in winter. In winter water should again be drawn from the deepest part of the lake. If a permanent thermocline develops in summer all pumping operations should be confined to the epilimnion. A gradual erosion of the thermocline is less damaging than an artificially induced upwelling, so a sudden surge of pumping should be avoided at all costs. If pumping operations cannot be confined to the epilimnion Enviro Systems Ltd will have to consider installing a separate 'de-stratifying' system in the lake.

3. Recommendations for Future Work

1. Analyse the local meteorological records to estimate the likely periods of winter ice cover. Limnologists in North America have found that it is possible to predict the date of freezing by analysing running means of the daily air temperatures. If the lake remains frozen for several weeks in winter a detailed analysis of winter heat storage would require direct measurements of ice thickness, snow cover and albedo.
2. Produce more detailed calculations of the depth of wave mixing using local wind speed records. Investigate factors influencing the stability of the water column in rather more detail. Review existing techniques of artificial destratification and evaluate potential cost.
3. Produce a detailed heat budget for Furzton Reservoir both before and after the installation of the plant. Since this will be the first lake based heat storage system in the UK Enviro Systems Ltd should consider installing a sophisticated environmental monitoring system to 'fine tune' operations. The F.B.A. can provide a range of instruments that can be installed in situ to monitor critical parameters. Such a system could be controlled by an 'intelligent' logger and the data downloaded by telephone to our Windermere Laboratory.

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