Institute of Freshwater Ecology

Contributions to the Scotland and Northern Ireland Forum for Environmental Research (SNIFFER) Programme on Eutrophication Risk Assessment:
I. Effects of Light Attenuation by Humic Colouring and Turbidity on Chlorophyll Production
II. Factors Controlling Lake Stratification

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Final Report to the Water Research Centre
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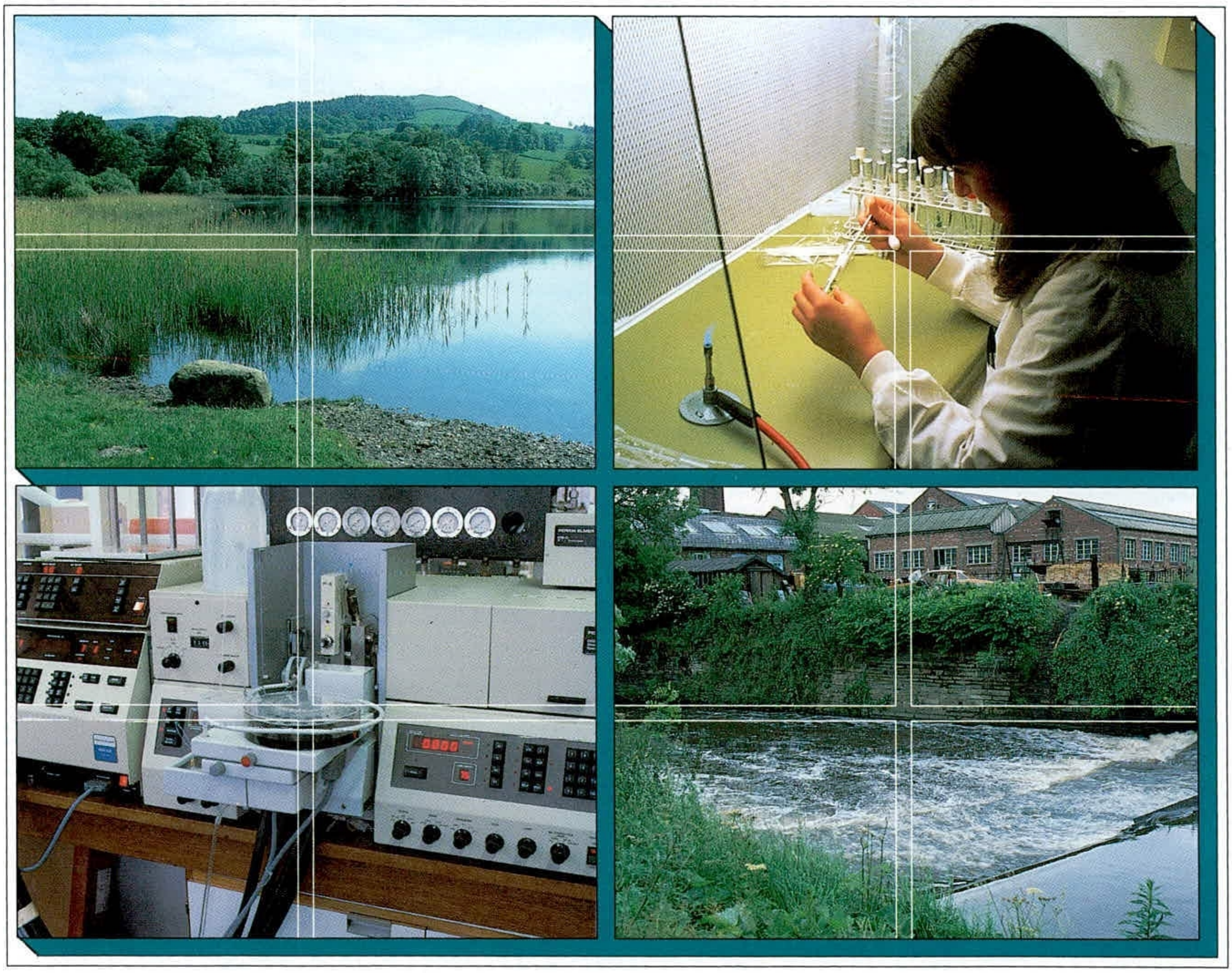

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Project Manager: A E Bailey-Watts

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Contents

1. INTRODUCTION

As a contribution to the SNIFFER programme on 'Eutrophication Risk Assessment', this report concerns (i) light attenuation by humic matter and turbidity, and (ii) thermal stratification. The extent to which light penetrates a lake or reservoir, and a water becomes layered due to density differences in summer, determine the amounts of plant material produced per unit of nutrient supply, and the species composition of the aquatic flora (Bailey-Watts *et al* 1992a, b, 1993). Factors affecting light attenuation and stratification are 'sensitivity factors' along with e.g. flushing rate and lake mean depth; they all have to be taken into account when decisions are being sought over catchment developments that may lead to enhanced inputs of nutrients to a lake or reservoir - and indeed, in the very planning of new reservoirs.

Both factors influence primary production in standing waters, not least by controlling the underwater light climate perceived by phytoplankton (the main focus of this study) and rooted vegetation. In addition to water itself, dissolved humic colouring and particulate turbidity control how far light reaches, and the spectral composition of the light field. Meanwhile, stratification determines the degree to which water is mixed, and thus the light 'dose', and its periodicity, experienced by organisms in the upper illuminated layers.

There are mechanisms whereby humic matter can affect primary production other than by their influence on light conditions. Jones, Salonen and De Haan (1988) show that humic material can bind phosphate, and De Haan (1992) suggests that this mechanism could counteract the effects of eutrophication. De Haan (1992) also points out, however, that humics may be more rapidly mineralised in eutrophic waters, owing to the elevated levels of organic substrates and the numbers of bacteria utilising them.

Light energy along with water, inorganic carbon (C) as carbon dioxide (CO_2) or bicarbonate ions, and mineral substances including nutrients, are vital for plant growth. They thus, also control the productivity of higher organisms feeding on plant material. In this respect the performance of plant communities in all freshwater ecosystems can be considered 'light-limited'.

Light inputs are especially important in governing the conversion ('fixation') of CO_2 and the manufacture of the carbon structure of the cells for metabolism and growth; this is the process of photosynthesis, summarised by the following equation:

$$6CO_2 + 6H_2O \xrightarrow{\textbf{light}} C_6H_{12}O_6 + 6O_2$$

It follows that light plays a major role in the potential of a waterbody to produce troublesome overgrowths of rooted vegetation, planktonic algal blooms or dense mats and swathes of attached algae. These all come quickly to mind when the term 'risk' is being considered in the context of the current SNIFFER programme.

Where possible, this report uses Scottish and Irish data to illustrate the various points raised. It is stressed, however, that rather little information exists on light conditions in Scottish waters in particular, and the study concludes with a proposal for much more work to characterise waters in terms of light attenuation and stratification patterns.

2. THE EFFECTS OF LIGHT ATTENUATION BY HUMIC COLOURING AND TURBIDITY ON CHLOROPHYLL PRODUCTION

2.1 Light attenuation - some general considerations

Much of the light impinging on the water surface (itself a function of daylength varying with latitude and aspect) is attenuated or absorbed such that with increasing depth, light intensity (irradiance) decreases - even in pure water. At the same time, the colour or spectral composition of the light field changes. For example, light quanta in the blue band 420nm to 490nm, penetrate furthest in clear waters i.e. those with low algal biomass. This favours algae with pigments capable of harvesting light in this region of the spectrum. Examples are cyanobacteria with biliprotein, diatoms with chlorophyll_c and fucoxanthin, and cryptomonads and chrysophytes with chlorophyll_c or carotenoids (Darley 1982).

In addition to the water itself, two other components affect the rate of decline in light and the shift in colour. These are (i) dissolved yellow humic substances ('Gelbstoff' or gilvin - Kirk 1983), and (ii) particulate matter or turbidity. Humic matter is derived from the breakdown of organic material, and apart from the particulate *humin*, there is a complex of dissolved compounds, which are broadly classified into *humic acids* which are alkali-soluble and are precipitated on acidification, and the *fulvic acids* which are also alkali soluble, but do not precipitate with acid. Particulate matter consists of an enormously diverse set of materials including particles which might be variously termed inanimate, non-living, mineral, organic, or living. A main component of the last-mentioned, in lakes and reservoirs, is phytoplankton, and this is commonly considered separately from the other light-attenuating particles.

Each of these components has different effects on both the penetration of total light energy, and the spectral characteristics of the underwater light field, and thus, the productivity of chlorophyll-bearing organisms (e.g. Kirk 1983; Grobbelaar 1989); they can thus be considered as competing for light. So, the greater the abundance of gilvin and/or suspended soil or sediment, for example, the less the availability of light for phytoplankton. Although rooted and attached plant communities are not the main concern of this report, their abundance and distribution are also strongly influenced by the nature of the underwater light climate (Spence 1967, 1976; Sheldon and Boylen 1977; Bailey-Watts and Duncan 1981b). **Figure 1** (from Vant and Davies-Colley 1984) relates the constituents of water which attenuate light, to various optical properties.

The rate at which light intensity declines exponentially with depth, is usually expressed as an attenuation coefficient (**k**) in units of natural logarithms (ln) per metre i.e. ln m^{-1}. [Natural logarithms are to the base 2.7183 as opposed to ordinary logarithms which are to the base 10; irradiance values expressed as natural logarithms are linearly related to depth, except where sharp discontinuities in the distribution of light-attenuating materials with depth occur.] The particular component (gilvin etc.) to which a coefficient refers, is denoted by a subscript thus: $\mathbf{k}_{gilv}$, $\mathbf{k}_{phyto}$, $\mathbf{k}_{turb}$, $\mathbf{k}_{water}$, $\mathbf{k}_{red}$. Attenuation coefficients are also used to describe the rate of decline in light of a particular wavelength or band. Where photosynthetic organisms are concerned, the main attention is often on light over, or within the wavelengths between 400nm and 700nm (1nm = 1mμ = 10^{-9}m). This is termed photosynthetically active radiation (PAR), and where the attenuation coefficient concerns the whole range, $\mathbf{k}_{PAR}$ is used. The wavelength which is the least rapidly attenuated (i.e. the most penetrating) in any given waterbody or situation, is also of interest, and $\mathbf{k}_{min}$ is used to denote this. Kirk (1983) and others also employ the term $\mathbf{k}_d$ for the total vertical attenuation coefficient for downward irradiance of PAR i.e. that portion of the irradiance that is not reflected back up to the surface. Since the extinction of PAR is an additive function, $\mathbf{k}_d$ is made up of the following:

$$\mathbf{k}_d = \mathbf{k}_{water} + \mathbf{k}_{gilv} + \mathbf{k}_{turb} + \mathbf{k}_{phyto}$$

In the vast majority of freshwater situations, $\mathbf{k}_{water}$ can be ignored. In all probability, almost any water is dominated by turbidity, plankton, peat-staining, or a combination of these features. For example, in certain shallow, turbid Canadian lakes, the attenuation of PAR could be reasonably partitioned between that due to phytoplankton and that due to particles resuspended from sediments (Hickman 1979a, b).

2.2 General relationships between light and phytoplankton photosynthesis

In spite of the paucity of information on the relative importance of the various light-attenuating components on light penetration into Scottish lochs and Northern Ireland loughs, there are sufficient data (see below) to suggest that the general relationship between the photosynthetic activity of chlorophyllous plankton to light gradients in these waters is the same as that established from studies elsewhere (Straskraba 1980; Westlake 1980; and Darley 1982). Photosynthetic rate expressed as mg O_2 evolved per mg chlorophyll$_a$ per day, or as a fraction of the maximum rate measured in the water column, relate to PAR (in J m^{-2} s^{-1}) as shown in **Figure 2** (modified from Westlake 1980). Classically, the rate is suppressed at high light intensities at the water surface due to photo-inhibition. The approximate irradiances expressed as percentages of surface irradiance, are shown in the Figure, for the boundaries of the depth zones corresponding to light inhibition, light saturation, a transition zone, and (at the base of the column) light limitation. Although the zones of inhibiting and saturating light levels cover wide ranges of irradiances, the light-limited region spans a minor light range. This is due to the exponential nature of the attenuation of light underwater as outlined above. While very high light is inhibitory, very low light limits photosynthesis by slowing down photochemical reactions which depend on the number of available quanta, and thus the quantum absorbance capacity of the cells (Darley 1982). These reactions are controlled by temperature and cell metabolism. Contrastingly, at saturating light intensities, photosynthetic capacity is a function of the 'dark' reactions of photosynthesis. As these are controlled by enzymes, however, they are also influenced by temperature.

In northern Britain, where light impinging on the water surface for much of the year is diffuse, and stems from dull cloudy skies, surface inhibition may not be apparent. For example, some of the photosynthesis-depth profiles measured by Bindloss (1974) at Loch Leven in 1971 (**Figure 3**), show the maximum rate of photosynthesis right at the water surface.

2.3 Gilvin and turbidity effects on light attenuation

Yentsch (1980) is one of many writers to show that yellow substances compete with algae by absorbing blue light, but he points out that the humic colouring may also offer protection by absorbing UV. Radiation absorbance by gilvin is strongly wavelength-dependent, increasing rapidly with decreasing wavelength. Gilvin levels can be assessed by measuring the spectrophotometric absorbance of filtered water at 340nm, and data of Jewson and Taylor (1978), indicate that some Irish lakes are extremely heavily stained i.e. with absorbance values exceeding 0.7 being by no means uncommon.

There is nothing to suggest that Scotland would not furnish many further examples of this type, although few detailed optical measurements have been made. WRc data from 5 Scottish lochs give mean and standard deviation values of 20 ± 6 to 110 ± 53 Hazen units, while 10 reservoirs gave 31 ± 9 to 219 ± 68; no information on sampling frequency/timing, however. Some valuable measurements of light penetration into 5 of Scotland's largest lochs (**Figure 4**), highlight the distinction between the peaty Lochs Ness and Awe, and the much clearer Morar, Lomond (north basin only) and Shiel (Bailey-Watts and Duncan 1981a). While light recorded with a Schott glass filter with an optical mid-point of 460nm was the most rapidly attenuated in all of these lochs, the depths at which 1% of the surface intensity were recorded, were considerably less in Ness (1.3m) and Awe (1.2m), than in the other 3 waters (2.2m in Shiel and Lomond, and 3.4m in Morar). As none of these waters is rich in plankton or other particulate matter, the relative extents to which light at other wavelengths penetrated were much the same as for blue light, although there were some differences in the colour of the most penetrating band. Morar was the clearest overall, and Awe was the darkest, but $\mathbf{k}_{min}$ was recorded by an orange filter (optical mid-point 590nm) in Morar and Shiel (registering 1% of the surface intensity at 9.5m and 8.4m respectively), a red filter (630nm) in Awe (4.3m) and Ness (4.7m) as in many peaty Finnish waters (see Jones and Ilmavirta 1978), and a green filter (540nm) in

Lomond (6.3m).

Humic colouring often constitutes the major part of the dissolved organic carbon (DOC) in stained waters (Jones and Arvola 1984), and the DOC concentrations also correlate well with light absorbance measurements (Davies-Colley and Vant 1987). In the best-researched water in Northern Ireland - Lough Neagh - light is usually attenuated primarily by particulate material in the form of phytoplankton, but also by gilvin which reflects the peaty nature of its catchment (Jewson 1977).

The relationships between **k** values and the levels of the materials determining them, are extremely complex where the particulate components ('turbidity') are concerned. These cannot be characterised in the comparatively abstract manner sufficient for gilvin. Light attenuation may relate well to the concentration of particulates where the material is uniform in nature and plainly dominates the light field as in e.g. very shallow, turbid systems such as the billabongs described by Walker and Tyler (1984); there, phytoplankton and gilvin have little effect on the underwater light field. Otherwise, the attenuation coefficients generally depend on the colour (surface properties) and the size distribution of the material (see Harris 1978 for phytoplankton). Grobbelaar (1989) points out that the effects of turbidity on productivity depends on whether the particles are organic or inorganic. Crystalline inorganic particles commonly scatter light, while organic materials absorb light. Bowling (1989) found that the reflectance (the ratio of upwards irradiance to downwards irradiance) was greatest in turbid waters, i.e. >1.5% *cf* dystrophic systems. Dystrophic lakes are waters where large amounts of the allochthonous organic matter supply contain a high humic content, often leading to heavy staining. Particles with adsorbed humic substances also absorb the shorter wavelength light in the PAR band, and scatter the light. Moreover, in situations such as the billabongs described by Walker and Tyler (1984), humic materials adsorbed onto particles can result in a blue-green deficient spectrum, which is optically similar to that produced by dissolved gilvin alone i.e. in non-turbid systems. Bowling (1989) thus found that the average **k** values were highest in turbid and dystrophic New South Wales lentic waters, and that light in the band 580nm to 660nm transmitted best in clear waters, while that in a narrow band of 680nm to 700nm transmitted best in turbid **or** gilvin waters.

Edmondson (1980) provides a simple example to illustrate one of the complex relationship between $\mathbf{k}_{turb}$ and the weight or volume concentration of particulate material. He pointed out that if a stick of blackboard chalk is placed in a jam jar of clear tap water, the water still appears clear. However, if that same stick of chalk is crushed to powder, the water becomes cloudy. So, the size distribution of the particulate material is important. Certainly, Davies-Colley *et al* (1992) and Quinn *et al* (1992) showed that fine inorganic suspensoids e.g. clays, 0.55-1.0μm, attenuate light very quickly and severely degrade the underwater light field; for example, values of 2.4 NTU (nephelometric turbidity units) and 340 μE m^{-2} s^{-1} (irradiance integrated over a 12-hour period) were measured upstream of a clay discharge stemming from gold-mining, compared to >100NTU and 80μE m^{-2} s^{-1} downstream. This effected considerable decreases in (i) the autotrophic content of the epilithic microflora (ii) benthic primary productivity (iii) the quality of food for the zoobenthos, and (iv) the species diversity and overall abundance of the invertebrate benthos - all in waters in which normally, only gilvin is important. Primary production differed between material enclosed in stationary glass bottles and that kept in rotated bottles in Madden and Day's (1992) experiments with turbid lagoon water. This was due to the settling of particulates and the affects on the light climate of the photosynthetic organisms present; mixing resulted in photo-inhibition under high light conditions, while it enhanced production under low light by improving on the average irradiance.

Bailey-Watts (1988) and Bailey-Watts *et al* (1993) have drawn attention to the affects of algal size on light penetration, and its effect on the general perception of different types of algal blooms. At Loch Leven, late winter-early spring diatom populations commonly exceed the biomass (in lake-wide terms) achieved by summer blue-green algae. Yet, the diatoms which are usually <15μm in greatest dimension generally occur under well-mixed conditions and simply cloud the water ('chalk powder' situation), and pass more or less unnoticed. Contrastingly, the blue-green algae, which are considerably larger (mm dimension), can float to the surface under calm conditions and form unsightly scums; otherwise i.e. under mixed conditions the water is quite clear ('chalk stick' situation). In this connection, it should be pointed out that phytoplankton components dominate the attenuation patterns in Loch Leven, although re-suspended sediment is also important on some occasions. In contrast to Lough Neagh, the Leven water itself absorbs very little light, there being virtually no humic component (Bindloss 1974, 1976). This feature, along with a mean depth of 3.9m, a commonly well-mixed column, and a moderate flushing rate (long-term mean value of 1.8 loch volumes y^{-1}), undoubtedly contributes to the very highly phytoplankton productivity in this loch. In systems here dissolved colour and/or inorganic or detrital turbidity are high, large phytoplankton crops cannot develop very extensively even where nutrients are abundant.

The PAR absorbance spectra of filtered and unfiltered water from different types of lake contrast in absolute and relative terms. **Figure 5** (taken from Howard-Williams and Vincent (1985), illustrates this with data from a variety of systems: eutrophic (moderately low absorbance values), turbid (moderately high absorbance), humic (very high levels) and oligotrophic (very low absorbances). In the eutrophic and turbid systems the absorbance values for the filtered water are naturally very much lower than those for the unfiltered water, while the plots are very similar for filtered and unfiltered humic and oligotrophic lakes. All waters, however, exhibit an exponential decline in absorbance with increasing wavelength. In spite of the complex interrelationships between the concentrations of different materials and the underwater light conditions, Brezonik (1978), found that some 80% of the variation in water clarity (expressed as the reciprocal of the Secchi Disc transparency - m^{-1}) in 55 Florida lakes was associated with the variation in the measures of turbidity (in Formazin units - FTU) and colour (measured in Pt units), thus:

$$1/SD = 0.106 + 0.128FTU + 0.0025Pt$$

Vant and Davies-Colley (1984) also found a good relationship between secchi depth (z_{SD}) and the reciprocal of k_d + c (where c is the intercept on the y axis) for a series of New Zealand lakes:

$$z_{SD} = 8.25/(k_d + c)$$

Equally, however, some situations are not so simply described. Grobbelaar's (1989) plots of $\mathbf{k_{PAR}}$ (measured as a downwelling coefficient) on chlorophyll concentration are very scattered, with correlation coefficients of 0.183 for one of his study dams, 0.569 for another and 0.384 for the two sets of data combined. There are situations too, where light attenuation may be dominated by a different factor at different times. Carter and Rybicki (1990) found that chlorophyll concentration was the dominant factor in a vegetated reach and a non-vegetated reach of the tidal Potomac in some years, while chlorophyll and suspended particulates were more important in other years. In both situations blue light 'disappeared' first.

It is beyond the scope of the present report to discuss all the known factors contributing to the complexities of the relationships between light supply and algal growth, but as an example Schreurs (1992) found that most of the cyanobacteria in a number of generally very shallow lakes ($\mathbf{z}_{mean}$, 1.0m to 1.5m) were low light organisms. However, the light required for saturated (maximal) growth rates varied with species, and nutrient status e.g 28μE m^{-2} s^{-1} to e.g. >100μE m^{-2} s^{-1} for *Aphanizomenon* with ample nitrate present, and >180μE m^{-2} s^{-1} when fixing atmospheric N i.e. under conditions of low nitrate.

2.4 Partitioning the light-attenuating factors

Since the attenuation of light due to all factors is an additive function, it is possible to calculate the effects of each component. In many studies the main attention has been on the phytoplankton fraction. For example, Jones (1992) shows that the proportion of the attenuation of PAR ($\mathbf{k}_{PAR}$) due to phytoplankton ($\mathbf{k}_{phyto}$) is given by:

$$\mathbf{k_{phyto}/k_{PAR} = B_c.k_c/(B_c.k_c)+(WC.k_p)}$$

where $\mathbf{B}_c$ is the concentration of phytoplankton as mg chlorophyll$_a$ m^{-3}, $\mathbf{k}_c$ is the attenuation coefficient per unit of chlorophyll i.e. m^2 mg chlorophyll^{-1}, **WC** is water colour expressed in Pt units, and $\mathbf{k}_p$ is the attenuation coefficient of colour per Pt unit i.e. m^2 g Pt^{-1}. Values for $\mathbf{k}_c$ vary with algal type, but a typical mid-range value is 0.015 according to Kirk (1983), while Jones and Arvola (1984) give 0.011. From the above equation, it follows that the proportion of PAR which can be captured by phytoplankton increases markedly, especially when chlorophyll levels are less than say, 10mg m^{-3}. Under such conditions, species capable of floating or swimming up to the better-lit surface layers (epilimnion) are plainly at an advantage over non-motile forms. Hence the predominance of flagellates in humic lakes.

At Loch Leven, firstly Bindloss (1974) and much later Bailey-Watts (1988) related $\mathbf{k}_{min}$ which is in the orange-to-blue-green part of the spectrum in that lake, to chlorophyll concentration. Both obtained a $\mathbf{k}_s$ of 0.0086 ln units m^{-1} mg^{-1} chlorophyll$_a$ m^{-3}. This is low compared to many other values in the literature, and reflects the relatively small effects on light attenuation of materials other than phytoplankton. In contrast, for example in the very turbid Lake McIlwane, a value of 0.0207 ln units m^{-1} mg^{-1} chlorophyll$_a$ m^{-3} was obtained (Robarts 1979). Similarly, Hickman (1979a, b) found that, on average, 41% of light attenuation was due to non-algal components in his shallow Alberta lakes; for example in Cooking Lake ($\mathbf{z}_{mean}$ 1.6m) $\mathbf{k}_s$ was 0.03, and in the slightly shallower Joseph Lake it was 0.04. Talling (1960) calculated a value of 0.02 for Lake Windermere, and the same author (Talling 1971) determined a $\mathbf{k}_s$ of 0.011 for the more productive Esthwaite Water.

2.5 Light attenuation and the effect on the depth of the productive zone

In controlling the depth to which light penetrates, turbidity and gilvin determine the depth of the productive zone, i.e. the water layer over which photosynthesis can take place - or more specifically, the depth to which photosynthetic gains exceed the losses due to respiration of the algae. This is termed the euphotic zone the lower boundary of which is the euphotic depth ($\mathbf{z_{eu}}$). This generally corresponds to what is known as the compensation depth ($\mathbf{z_c}$) where (at any instant) irradiance is reduced to 1% of the surface water value. This intensity is the compensation intensity, $\mathbf{I_c}$, that is, the light strength at which respiration rate equals the gross photosynthetic rate i.e. where net growth, or net photosynthesis, is nil (see **Figure 2**).

According to Kirk (1983) and Jones (1977) $\mathbf{z_c}$ (in metres) is calculated as follows:

$$\mathbf{z_c} = [\mathbf{N}/(24.\mathbf{k_{PAR}}.\mathbf{r})].\ln(\mathbf{I}/0.5\mathbf{I_k})$$

where $\mathbf{k_{PAR}}$ is as defined already, **N** is daylength in hours, **r** is the ratio of respiration rate to the light-saturated rate of photosynthesis, **I** is the average sub-surface irradiance during daylight hours, and $\mathbf{I_k}$ is the equivalent irradiance at the onset of light saturation.

Within reasonable limits, $\mathbf{z_{eu}}$ relates to (i) the simplest index of light penetration - that measured with a Secchi Disc - and (ii) to the more precise descriptors of the extent to which light enters the system i.e. attenuation coefficients, such as that for the most penetrating waveband, $\mathbf{k_{min}}$. For example $\mathbf{z_{eu}}$ is often 2-3 times the Secchi depth (SD), and although Reynolds (1984) obtained the relationship $\mathbf{z_{eu}}$ = SD x 1.7, this was far from constant with e.g. values of 1.2 to 2.7 in the same lake. Tilzer (1988) quotes figures of 1.5

to 2.5 for clear waters, and generally higher values in turbid systems e.g. 2.3 to 2.6 in the Dutch Loosdrecht region.

Talling (1965) considered that $\mathbf{z_{eu}}$ in a wide range of waters approximates to 3.7/$\mathbf{k_{min}}$ while Bindloss (1976) obtained numerators of 3.2 to 3.4 for Loch Leven, Jewson (1977) 3.9 in Lough Neagh and 3.7 for other Irish lakes, and Hickman (1979a, b) 3.74 and 3.79 for his shallow Alberta systems. Jewson (1977) also found that an optical density reading at 630nm approximates reasonably to $\mathbf{k_{min}}$.

2.6 Euphotic depth/mixed depth ratios - the link with stratification

The euphotic depth to mixed depth ratio ($\mathbf{z_{eu}}$:$\mathbf{z_{mix}}$) is an important determinant of primary production. Firstly, it is a good estimator of light climate, but it assumes continuous mixing over the whole mixed depth. As long as one bears in mind the monthly variation in the depth of the thermocline ($\mathbf{z_{therm}}$), this can be used an approximation of the average summer $\mathbf{z_{mix}}$ (Reynolds 1984). However, if micro-stratification is ignored, the light climate will be underestimated.

If $\mathbf{z_{eu}}$:$\mathbf{z_{mix}}$ is 0.5, circulating organisms are exposed to PAR for only 50% of the day. Where the ratio exceeds 1, $\mathbf{z_{eu}}$ may extend to the hypolimnion or the bottom of a loch, so that autotrophic growth is possible there. But a $\mathbf{z_{eu}}$:$\mathbf{z_{mix}}$ ratio of 1 corresponds to the upper limit of the light periodicity factor. Schreurs (1992) found ratios of >1 in only 6% of 'lake-years' in his Dutch database. Values of <0.2 (with a minimum value of 0.07) were more than twice as common; assuming an average summer daylength of 16h, the light corresponding period is <3.2h i.e. 0.2 x 16. Under such conditions, hardly any substantial production can be expected. This is keeping with Talling's (1971) suggestion that the critical $\mathbf{z}_{mix}$ is 5 times $\mathbf{z}_{eu}$.

By reducing the depth of light penetration, humic material in particular, can give rise to abrupt thermal gradients, and more stability with surface warming associated with the rapid absorption of the incoming solar radiation (Bowling 1990). Thus, Jones (1992) found not only a strong negative correlation between $\mathbf{z}_{mix}$ and colour in sheltered, humic Finnish lakes, but a decrease in $\mathbf{z}_{mix}$ as well as $\mathbf{z}_{eu}$ with increased colour. In these waters phytoplankton growth potential will be little affected by variation in water colour. Contrastingly, in large lakes where wind-mixing independent of water colour is effective, z_{mix} is more likely to exceed z_c, and phytoplankton growth potential is decreased.

Jewson and Taylor (1978) studied a set of Irish lakes where chlorophyll$_a$ values ranged from 1 to 860 $\mu g\ l^{-1}$ and $\mathbf{z}_{eu}$ ranged from 0.7 to 20m. They found that an essential feature of the phytoplankton in turbid systems i.e. those where $\mathbf{z}_{eu}$ is shallow, is that it is likely to be subjected to rapid changes in the underwater light field during circulation, but the effect on gross photosynthesis is probably small whether the turbidity is due to phytoplankton itself or inorganic matter. The important factor to cell growth is the time course. At a moderate wind speed of 2.5 - 5.0 m s^{-1} in a 10-m column, mixing times would be *ca* 10-20 minutes, whereas in a 3-m water column, these times would be as little as 4-8 minutes (Reynolds 1984). Thus, phytoplankton cells may receive the same light dose at different periodicities. For example, Schreurs (1992) suggested that low light diatoms are found in a situation combining a deep $\mathbf{z}_{eu}$ with low biomass (strictly, concentration), while low light cyanobacteria are commonly found where z_{eu} is shallow and biomass is high (dense crops). Laboratory studies by Kromkamp (1992) shows however that the maximal photosynthetic capacity of certain filamentous cyanobacteria can change rapidly in response to shifts in the mixing regime (and alterations in the z_{eu}:z_{mix} ratio).

2.7 Conclusions and recommendations

A good deal is known about the influence of humic colouring and turbidity components on the extent to which light penetrates a water column, and on the changes in spectral composition of light field with increasing water depth. However, published data on the levels of humic matter, plankton and other light-attenuating materials in Irish waters are relatively few, and on Scottish lochs there is virtually nothing apart from information on the five largest waters and on Loch Leven. As a result, this review has drawn largely on studies carried out in other parts of the world, with the contribution from Australia and New Zealand being considerable.

There is an urgent need for synoptic surveys of the underwater light fields of standing waters (lakes and reservoirs) over what is likely to be a considerable range of situations in both countries covered by the 'SNIFFER' initiative. Seasonal surveys of overall optical quality and the relative proportions of different light-absorbing/scattering components are needed. These should be carried out on waters differing in e.g. phosphorus loading, nutrient/trophic status, and various physical features such as mean and maximum depths and flushing rate.

3. THERMAL STRATIFICATION

3.1 General considerations and definition.

Thermal stratification takes place in many lakes during the summer months - if they are of sufficient depth. In its simplest form, a stratified lake consists of three (horizontal) temperature/density layers **(Figure 6)**: the epilimnion, which is a warm, mixed layer at the top; the metalimnion, a thinner layer where temperature changes rapidly with depth and includes the thermocline which is the plane of maximum temperature discontinuity (Hutchinson, 1957); and the hypolimnion which is the deeper, cold and relatively undisturbed layer.

In late winter/spring most lakes are cool (*ca* 4-8°C) and of uniform temperature from surface to bottom. With summer warming this isothermal structure changes due to the influences of solar radiation and wind **(Figure 7)**.

Solar radiation warms the surface waters to its penetration depth which depends on water clarity. Without mixing, the thermal structure of lakes would reflect the profile of solar energy absorption with depth (Ragotskie, 1978) where there would be a very thin, warm surface layer and an exponential decline in temperature with depth. However, this situation is never found - even without wind influences convection currents caused by surface cooling due to evaporation and low night-time temperatures would ensure some mixing. (Conductive heat gain may also occur at the air/water interface if the air is at a higher temperature but this is regarded to be insignificant in comparison to that gained from solar radiation.)

Wind stress at the surface causes mixing through several processes including surface wave turbulence and circulation currents. This effectively stirs the surface water creating a buoyant top layer with a more even temperature distribution. The mixing depth is determined by the relationship between the force of the wind induced currents, and the resistive strength of the water density contrast. The rate of change in the density of water with temperature increases as temperature rises, so, a temperature discontinuity of say 1 Celsius degree m^{-1} is more stable at 25-26°C than at 15-16°C. All else being equal, cooler lakes should have deeper thermoclines. The thermocline depth at the onset of stratification may be quite shallow but progressively deepens throughout the summer (see also Section 3.5).

Heat loss in autumn/early winter reduces the epilimnion temperature (and buoyancy) such that there is little density difference between it and the hypolimnion. The stratified structure is unable to resist the mixing influences of wind stress and the lake reverts to its isothermal status.

This is a simplified description of the stratification process. Variable climate, severe weather events and complex basin morphometry can lead to complicated patterns of intermittent stratification and/or multiple thermoclines.

3.2 Predicting mixing depth

Mathematical models of thermal stratification processes in freshwater lakes may be considered in two categories. The first of these concerns analytical models which focus on the action of wind force and thermal energy exchange. These enumerate the values of frictional stress, density gradients and energy balance within the waterbody and analyse their effects on thermal structure and stability (e.g. Gorham and Boyce 1989; Henderson-Sellers 1985, 1989). Such models tend to complexity in explanation and application. They are perhaps best suited to specific site studies and to be of predictive value they require additional site-specific information which may not be readily available. For example, Gorham and Boyce (1989) present the following relationship for predicting thermocline depth (D_t) at the time of maximum heat content:

$$D_t \approx 2.0\ (\tau/g\Delta\rho)^{0.5}.L^{0.5}$$

where g, the gravitational acceleration, and L, the square root of surface area of the lake apply to any system, while τ is the wind stress associated with late summer storms in the region under consideration, and $\Delta\rho$ is the density contrast between epilimnion and hypolimnion typical for local lakes near the time of maximum heat content. Clearly the data required to evaluate the last two parameters requires extra effort to obtain, if available at all.

Similarly, while the thermal stratification model of Henderson-Sellers and Reckhow (1989) EDD1 (Eddy Diffusion Dimension 1) has produced close simulations of the thermal regime for lakes in three differing climatic zones, (north temperate maritime (UK), north temperate continental (Ontario) and subtropical (S. Africa)) it is of a higher sophistication than required here but also requires lake-specific information on bathymetry, water turbidity and local meteorological data.

The second category of models is based on the examination of empirical data and seeks to relate single (occasionally combinations of) lake morphometric parameters to basic features of stratification such as epilimnion depth (D_e) or D_t by regression analysis. (Some studies go on to consider the likelihood of stratification occurrence in relation to depth, e.g. Davis-Colley (1988), Gorham and Boyce (1989), Patalas (1984) (also see Section 3.4)). These models are simpler than those in the first category and require only basic morphometric data. Consequently they are better suited to provide appropriate application algorithms which are acceptable as correction factors to the phosphorus concentration model in question (Bailey-Watts *et al* 1992). Such analysis for different climatic, topographic and global regions, has established that epilimnion and thermocline depths are greatly dependent upon some measure of lake surface size.

A summary of predictive models is given in **Table 1** for different climatic, topographic and global regions. All of these incorporate a function of lake length, either measured or derived. Most commonly, length (or fetch) is represented by the square root of area, or, by the average of length plus width. This strong relationship with fetch indicates the importance of the wind-driven mixing force in establishing 'typical' mixing depths.

Hanna (1990) evaluated the predictive power of 17 empirical models and concluded that they were limited both by their regional character and predictive range. An 'improved' model was developed which incorporated data for 123 lakes within the northern temperate climatic zone and examined the relationships between epilimnion depth and thermocline depth for 14 morphometric parameters, both singularly and in combination. (It is interesting to note that altitude and latitude were also examined but were not found to be significant indicators of mixing depth.) The best single predictor of thermocline depth was found to be maximum effective length (MEL) ($r^2 = 0.85$) which is the maximum uninterrupted water length (see Hakanson, 1981) although surface area and shoreline length are not significantly inferior ($r^2 = 0.83$ for both). Slightly lower regression values were obtained in relating D_e to the above parameters. No improvement was found using combinations of any of the morphometric parameters included.

Table 1: **Summary of predictive models for epilimnion and thermocline depth as a function of lake fetch ($f = A^{0.5}$, A is in km^2; F = (length + width)/2 in metres; MEL = effective length in metres).**

Reference	Region	Regression	r^2	n
Epilimnion depth (m)				
Arai (1981)	Japan	$4.6\ f^{0.304}$	-	32
Patalas (1984)	Poland,	$4.6\ F^{0.41}$	0.85	88
Green *et al.* (1987)	Canada	$7.0\ MEL^{0.42}$	0.79	33
Davis-Colley (1988)	New Zealand	$7.69\ f^{0.463}$	0.94	22
	New Zealand	$6.85\ F^{0.446}$	0.918	22
Thermocline depth (m)				
Ventz (1973)	E. Germany	$4.72\ F^{0.39}$	-	30
Ragotskie (1978)	N. America	$4.0\ f^{0.5}$	-	18
Arai (1981)	Japan	$6.22\ f^{0.304}$	0.53	32
Davis-Colley (1988)	New Zealand	$9.52\ f^{0.425}$	0.954	22
		$8.58\ F^{0.408}$	0.928	22
Hanna (1990)	N. hemisphere	$0.569\ MEL^{0.336}$	0.85	123

However, Hanna's 'improved' model is for application over a wide geographic area and the perceived 'weakness' (in global terms) of earlier models because of their limited parameter ranges and parochial nature is a subjective judgement depending on the user's requirements. In this case interest concerns waters in the British Isles where a temperate maritime climate prevails. Characteristic of that is a windier and thermally less stable regime than is found in continental climates where the majority of Hanna's 123 sites are located. While Hanna's model is more generally representative of lakes in the northern temperate zone and covers a wide range of lake sizes, it is not necessarily that best suited for application to British lakes. For example, Gorham and Boyce (1989) find that English lakes (Cumbrian lake district) are at variance with continental lakes. Similarly, the model of Green *et al* (1987) for New Zealand lakes, shows that mixing depths there are generally deeper than elsewhere. Also, Davis-Colley (1988) notes that mixing depths in New Zealand are similar to those in Britain (i.e. deeper than in continental lakes) which has a broadly comparable maritime climate, with windy, cloudy and cool summers in contrast to the relatively calm, hot and cloudless summers of the temperate continental zone.

It is reasonable therefore, in the light of these observations and the absence of adequate analysis for British lakes, to associate the British situation in this respect with that of New Zealand which is an island nation of similar size and climatic regime to the British Isles. Consequently the prediction of mixing depths for this study should adopt the models developed for lakes in New Zealand.

From Green *et al* (1987) and Davis-Colley (1988) in **Table 1** there are five predictive expressions presented - three for epilimnion depth and two for thermocline depth. Since an estimate of epilimnion volume is the ultimate aim of this exercise the former are clearly more relevant here than the depth of maximum temperature discontinuity which may be some way removed from the freely mixed zone (the ratio of epilimnion to thermocline depth averages at 80% (Davis-Colley 1988)). The most appropriate expression is that of Davis-Colley (1988) which relates D_e in metres to the square root of surface area (A) in km^2.

$$D_e = 7.69\ (A^{0.5})^{0.463} \qquad r^2 = 0.94$$

This is preferred to the model using the average of length plus width, partly because of its higher correlation coefficient, but also because it is less arbitrary in lakes of convoluted shoreline and (since area is usually already available) is more easily calculated without recourse to additional measurements.

It should be remembered that this expression estimates epilimnion depth at the time of maximum heat content, which is July/August. Account has yet to be taken (if possible) of the progressive increase in depth of the epilimnion.

3.3 Likelihood of stratification

The models for predicting D_e and D_t discussed above have identified the importance of lake surface size. Whether a lake exhibits stable stratification depends on there being sufficient depth for such a structure to become established. As lake surface area increases, the minimum depth required also increases, but it is not simply the case that when mixing depth ≤ maximum depth then stratification will occur. As the ratio of mixing depth to maximum depth approaches unity and the hypolimnion is relatively 'thin', then friction forces from the lake bed acting on hypolimnetic currents are sufficiently strong to influence thermocline stability. Gorham and Boyce (1989) examined 150 stratified lakes and found that in no instance was $D_t/D_{max} > 0.7$, and that in 90% of these lakes $D_t/D_{max} < 0.5$. They proceeded to calculate from analysis of stress interactions that $D_t/D_{max} \approx 0.6$ was a limiting function and, if exceeded, stratification could not be sustained.

Similar conclusions were reached by Patalas (1984) and also by Davis-Colley (1988) but in these cases D_e was considered - which is of greater relevance here. The critical value which identifies lakes which consistently stratify against those which never do, or are intermittent, is when $D_e/D_{max} \leq 0.5$ and is supported by data for 94 lakes in New Zealand (Davis-Colley 1988).

From these studies an idealised method for classifying lakes by 'mixing type' can be adopted by comparing the ratio of **predicted** epilimnion depth to the maximum depth of the lake:

if $D_e/D_{max} > 2.0$	Turbulent, well mixed lakes
if $1.0 < D_e/D_{max} < 2.0$	Mixed, isothermal lakes
if $0.5 < D_e/D_{max} < 1.0$	Occasional unstable stratification

if $D_e/D_{max} \leq 0.5$	Stable seasonal stratification

Our concern here is with lakes in the latter category (boxed above) and, for the purposes of this study, it is proposed to adopt this criterion for defining stratified and unstratified lakes. (Additionally, the above classifications may be useful in relation to broad considerations of the phosphorus cycle, e.g. if $D_e/D_{max} > 2.0$ there will be considerable sediment disturbance.)

3.4 Period of stratification

What has to be decided here is the normal period (P_s) over which the surface mixing volume is reduced by thermal stratification, for British lakes in general. In the absence of any known study specifically on this aspect a decision must be based on what information can be derived from broader-based studies. However, the descriptive literature suggests generally that stratification commences in late spring/early summer and ends in autumn/early winter - a period of about six months.

Many water temperature observations were taken during the Bathymetrical Survey of the Fresh Water Lochs of Scotland (Murray and Pullar 1910) around the turn of the century, and data for 70 of these lochs was analysed by Gorham (1958). From this it is evident that stratification may begin as early as April but is not established in most lochs until May. Stratification continues throughout the summer months and generally breaks down during October. In large lochs (e.g. Loch Ness) the onset and destruction of stratification may be delayed by about one month, but the duration is similar.

Monthly temperature profiles taken at Lochs Lomond and Awe in 1978 (Smith *et al* 1981) show in each a deepening temperature discontinuity layer which starts in May and ends in October. In a study of the seasonal formation of thermal stratification in Llyn Gwellyn during 1965 and 1965 (Darbyshire and Edwards 1972) the thermocline is formed in late May and lasts until late October. In Lake Windermere in 1947 stratification was in evidence from May until November (Lund *et al* 1963).

Given these observations it is reasonable to accept that, although the apparent maximum time for stratification may be from April to November (8 months), the period of May to

October (6 months) is that most common for stratification in British lakes and should be adopted for this study, i.e.

$$\boxed{P_s = 0.5 \text{ yr}}$$

3.5 Epilimnion volume

The first question to be addressed is whether the epilimnion depth at the time of maximum heat content (July/August) can be considered as a mean epilimnion depth for the purpose of volume calculation.

Note that the prediction model adopted in Section 3.2 relates to D_e at the time of maximum heat content and that this occurs mid-way through the stratification period (May to October). However, we know that the mixing depth increases throughout the period of stratification, but the rate of increase is not necessarily consistent. For example, in Lochs Lomond and Awe (monthly measurements) there is evidence of a 'flattening' in the thermocline depth/time curve in July and August respectively (Smith *et al* 1981). In Llyn Gwellyn (weekly measurements), although vertical fluctuations in D_e are recorded throughout, the general rate of decline is much reduced from the period June to August in both years of observation (Darbyshire and Edwards 1972). The temperature records for those sites show that the difference between actual thermocline depth at 1st August and the mean thermocline depth (taken as the mid-point between onset and break up depths) was as follows; for L. Lomond 1.5 m, L. Awe 0 m, L. Gwellyn (1965) 5 m, (1966) 1 m. In the three cases of difference the actual depth was less than the estimated mean, but, with the exception of L. Gwellyn in 1965, the differences are small. However, we have no simple method for estimating epilimnion depth at the onset or breakup of stratification without recourse to analytical models which we are trying to avoid for reasons given earlier. So even an idealised calculation of the seasonal growth in epilimnion volume is unjustified. Therefore, particularly in the absence of a suitable alternative, it seems reasonable to assume that the epilimnion depth in July/August as predicted from Section 3.2 will be an adequate representation of that prevailing throughout midsummer and can be taken here as the mixing depth for the period of stratification.

For a site where adequate bathymetric information is available the epilimnion volume can be derived by constructing a volume/depth curve (**Figure 8**), or by direct measurement/calculation from a bathymetric map. This is a time- consuming process and to avoid having to take account of individual lake basin morphometry a mathematical solution is considered for general application.

Firstly basin shape is idealised to that of a cone represented by actual lake area and maximum depth. For any cone there is a constant relationship between the ratio of an 'epilimnion' volume (c_v) to the full cone volume (C_v) and the ratio of 'epilimnion' depth (in this case D_e) to cone depth (i.e. D_{max}) where:

$$c_v/C_v = 1-[1-D_e/D_{max}]^3$$

($C_v = 1/3\ A.D_{max}$ where A is in km^2 and C_v is $m^3.10^{-6}$)

so,

$c_v = (1/3\ A.D_{max})\ (1-\ [1-D_e/D_{max}]^3)$

However, few lakes can be adequately represented by the simple conical shape considered above, some adjustment for actual shape must be applied. Volume development (V_d) is an expression of lake basin form in terms of its volumetric deviation from that of an idealised cone based simply on surface area and maximum depth as above (Hakanson, 1981). Its value is defined by,

$$V_d = \frac{\text{lake volume}}{\text{cone volume}} = \frac{A.\bar{D}}{1/3A.D_{max}} = \frac{3\bar{D}}{D_{max}}$$

Where $\bar{D}$ is the mean depth of the lake.

For concave basins $V_d>1$ (eg Loch Ness, which lies in a deep U-shaped basin, has a V_d value of 1.72), and for convex basins $V_d<1$ (eg Loch Leven is a shallow basin around a deep kettle hole and has a V_d value of 0.54). These are extreme examples and most lakes will have a V_d value closer to 1.

V_d can now be applied as a correction factor to the expression for c_v to solve for the approximate epilimnion volume of the lake (V_e),

$$\boxed{V_e = V_d \cdot c_v}$$

so,

$$V_e = (3\bar{D}/D_{max})\ (1/3\ A.D_{max})\ (1- [1-D_e/D_{max}]^3)$$

or to continue so that the solution requires only the three basic parameters of A (km^2), $\bar{D}$ (m) and D_{max} (m),

$$V_e = (3\bar{D}/D_{max})\quad (1/3\ A.D_{max})\quad \left(1- \left[1- \frac{7.69(A^{0.5})^{0.463}}{D_{max}}\right]^3\right)$$

Volume development	Idealised cone volume	Ratio of 'epilimnion' volume to cone volume
V_d	C_v	c_v/C_v

3.6 Effect on the influence of flushing rate

Flushing rate (ρ) is the rate at which water passes through a system. It is expressed as the number of times a volume of water equivalent to the lake is replaced by inflow (runoff, V_r) per annum. Bailey-Watts *et al* (1990) suggested that the effect of flushing rate on phytoplankton abundance would be most marked during summer startification. This is because at this time the great majority of the actively growing population lies within the epilimnion - and not distributed by mixing over the whole depth of the lake.

From analysis of river flow statistics for 26 sites throughout Great Britain with a minimum of eight years of records, it has been estimated that as a general rule 1/3 of runoff occurs during the (hydrological) summer, i.e. April to September (Mr I R Smith *pers. comm.*). Examination of the data for the lake stratification period of May to October shows that there is little significant difference between two periods and that the 1/3 rule can be taken to apply here also. Therefore, flushing rate of the epilimnion while stratification is in existence (ρ_s) can be calculated from:

$$\rho_s = \frac{\text{1/3 runoff volume}}{\text{epilimnion volume}} = V_r/3V_e$$

Note: The calculation for runoff volume is not given in detail here but is based on long-term rainfall, average evapotranspiration, catchment and loch areas (see Bailey-Watts *et al* 1992).

Flushing rate of the loch for the winter six months (ρ_w) is therefore calculated from:

$$\rho_w = \frac{\text{2/3 runoff volume}}{\text{lake volume}} = 2V_r/3V$$

In a lake which satisfies the condition for consistent stratification (i.e. $D_e/D_{max} \leq 0.5$) then V and V_e are the effective flushed volumes which each exist for 0.5 yr. The effective annual flushed volume (or alternatively, the volume of the freely mixed zone) is therefore,

$$(V + V_e)/2$$

the effective annual flushing rate (ρ_{epi}) of that volume is therefore,

$$\rho_{epi} = V_r/([V + V_e]/2$$

$$\boxed{\rho_{epi} = 2V_r/(V + V_e)}$$

3.7 Application process

Step

1. Input data required,

   A - Lake area (km^2) $\bar{D}$ - lake mean depth (m)

   D_{max} - maximum lake depth (m) V_r - annual runoff ($m^3.10^6$)

   V - lake volume (from $A.D.10^6$) ($m^3.10^6$)

2. Calculate epilimnion depth (D_e),

   $D_e = 7.69\ (A^{0.5})^{0.463}$ (m)

3. Determine likelihood of stratification, i.e.,

   is $D_e/D_{max} \leq 0.5$ if NO - END (dimensionless)
   if YES - Step 4

4. Calculate 'idealised (cone) epilimnion' volume (c_v),

   $c_v = (1/3\ A.D_{max})\ (1-\ [1-D_e/D_{max}]^3\ )$ ($m^3.10^6$)

5. Calculate lake volume development (V_d)

   $V_d = 3\bar{D}/D_{max}$ (dimensionless)

6. Calculate 'actual epilimnion' volume (V_e)

   $V_e = V_d\ .c_v$ ($m^3.10^6$)

   (this is taken to be the mean epilimnion volume for 0.5 yr)

7. Calculate effective annual flushing rate (EF)

   $EF = 2V_r\ /(V + V_e)$ (dimensionless)

The process above is constructed for application in studies where there is limited input data, to provide a generalised description of the influence of stratification on the hydrological structure. The process can be improved at different stages if appropriate additional information is available and extra analytical effort can be applied. For example, at:

<u>Step</u>

2. <u>Epilimnion depth</u> - Empirical data may be available, but this should be averaged over a number of years. Timing of measurements is important (see Section 3.5).

3. <u>Likelihood of stratification</u> - Where D_e/D_{max} is between 0.5 and 1.0 stratification may occur in deep holes. This may or may not be considered important on an individual site basis but would need to be confirmed by field data. In some cases normal climatic fluctuations may be critical.

4,5&6 <u>Epilimnion volume</u> - Whereas steps 2 and 3 are necessary without recourse to field measurements, the estimation of epilimnion volume in steps 4, 5 and 6 can clearly be improved on by actual volume measurement from a bathymetric map. Further improvements in the period of stratification and mean epilimnion depth would require field data, or perhaps the application of analytical models.

7. Effective flushing rate - The actual process of flushing is complex. Runoff is generally an estimate of long-term average and improvement could be made from examining local river gauging records for annual and seasonal flows.

3.8 Application process tests

The accuracy of the predictive model for epilimnion depth (D_e) in British lakes cannot be confirmed without the examination of empirical data - of which there is insufficient suitable information. However the mathematical solution for epilimnion volume (V_e) can be tested against volumes determined for D_e from available volume/depth curves (e.g. **Figure 8**). This has been done for eight selected lakes as given in **Table 2** where Steps 1-6 of the model have been carried out irrespective of whether D_e/D_{max} in any lake is >0.5 and would therefore not be expected to sustain stable seasonal stratification.

For most sites the percentage error between V_e and the volume/depth curve value is within reasonable limits considering the generalised approach of the method. However, for Lochs Lomond and Ness the errors are too high - 31% and 58% respectively. In both cases the ratio of D_e/D_{max} is very small (0.11 and 0.09) so the influence of the whole basin form as expressed by their volume development (V_d) is much less relevant - and in both cases V_d departs significantly from unity, i.e. 0.59 and 1.72. Consequently, for both lochs the error can be reduced by considering the calculated 'cone epilimnion' (c_v) values which are closer to those determined from the volume/depth curves than their calculated V_e - 16.3% and 8% error respectively. For Loch Ness, because of its very high V_d, the least error (0.4%) results simply from the product of area and epilimnion depth (i.e. A x D_e)).

Table 2: Comparison of calculated epilimnion volumes (V_e) to measured values for eight selected sites.

Step		Leven	Ness	Lomond	Insh	Esthwaite	Windermere	Crosemere	Neagh
1.	A	13.3	56.4	71.1	1.14	1.0	14.7	0.15	396.0
	D_{max}	25.5	229.8	189.9	30.5	15.5	66.8	9.2	31.0
	D	3.9	132.0	37.0	11.4	6.4	23.9	4.9	12.2
2.	D_e	14.0	19.6	20.6	8.2	7.7	14.3	5.0	30.7
3.	D_e/D_{max} if < 0.5	0.55 No	0.09 Yes	0.11 Yes	0.27 Yes	0.50 Yes	0.21 Yes	0.54 No	0.99 No
4.	c_v	102.6	1013.8	1311.5	7.06	-4.51	168.4	0.416	4092.0
5.	V_d	0.46	1.72	0.59	1.12	1.24	1.07	1.56	1.18
6.	V_e	47.2	1743.7	773.8	7.9	5.6	180.2	0.65	4828.6
V/D curve		49.4	1101.5	1127.9	7.0	5.0	172.9	0.55	*ca* 4831
% error		-4.4	+58	-31	+13	+12	+4.2	+18	*ca* 0.0

It would seem therefore that for very large and deep lakes when D_e/D_{max} is approximately 0.1 or less that Step 5 of the model could be omitted and c_v can be taken to represent V_e. There may be a more concise correction procedure for such sites based on some relationship involving D_e/D_{max} and V_d but there is insufficient information in **Table 2** to arrive at a definite conclusion about this. Lakes of this type require some individual consideration at present.

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FIGURES

Figure 1. The relationships between light-attenuating constituents and their optical properties. [Taken from Vant and Davies-Colley (1984).]

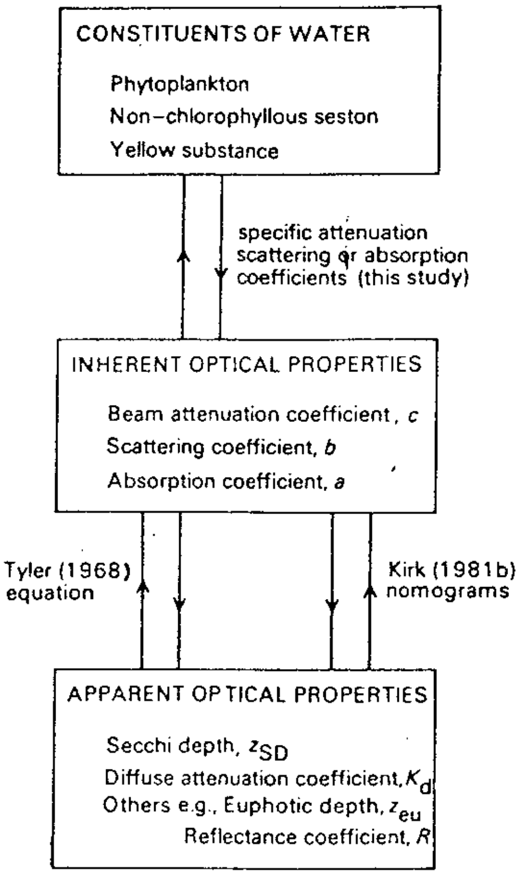

Figure 2. Generalised diagrams of specific photoassimilation in phytoplankton populations: (a) a typical profile for a mixed (i.e. homogeneous) population , and (b) a plot of photosynthesis expressed as a fraction of the maximal rate against actual irradiance values and the irradiances expressed as a percentage of the surface value. [Taken from Westlake (1980).]

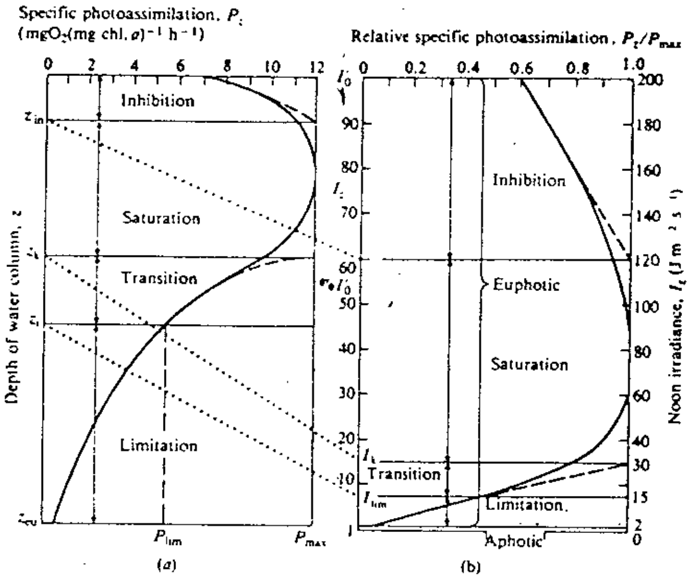

Figure 3. Depth profiles of the rates of photosynthesis per unit volume of water in Loch leven in 1971. The mean surface incident PAR light intensity (I_0) and the value at the onset of light saturation (I_k) are given where available; the units are kerg cm^{-2} s^{-1}. Arrows indicate the depth of the euphotic zone (z_{eu}).

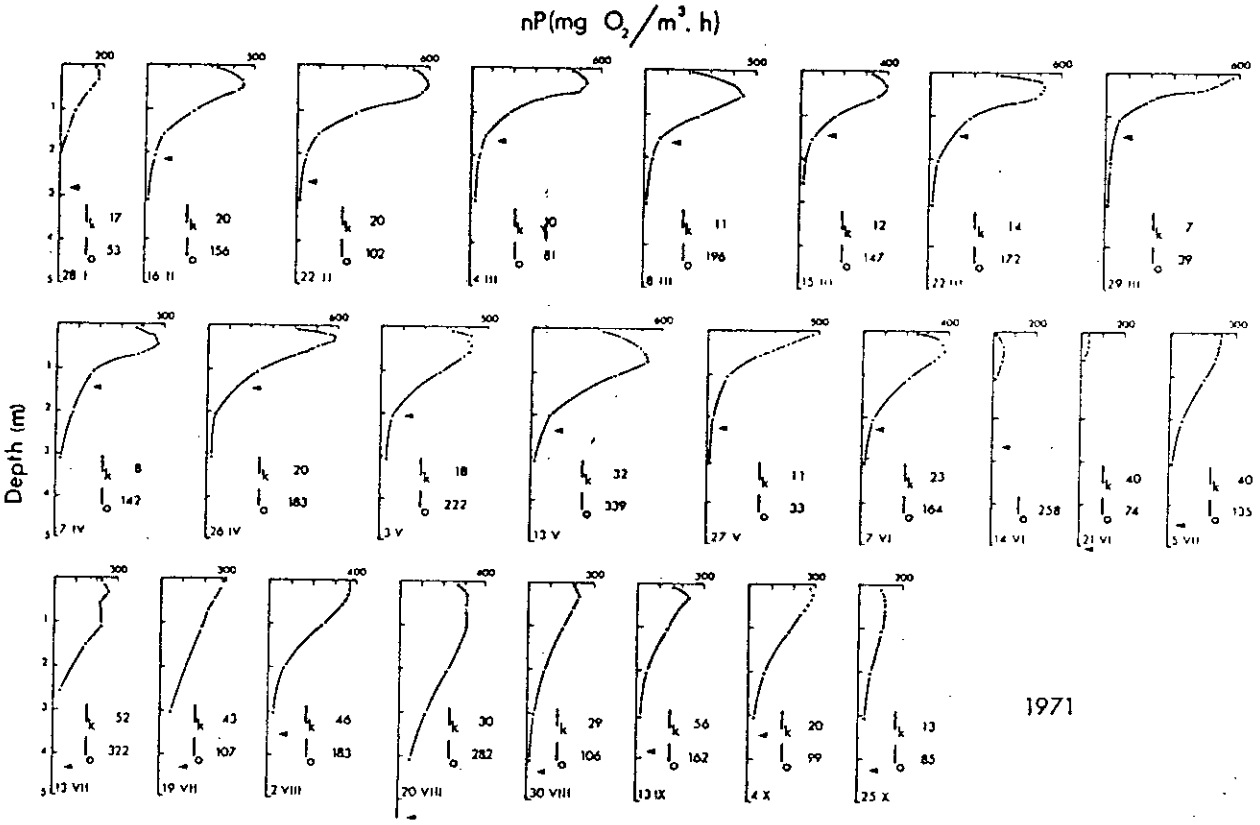

Figure 4. Underwater light conditions in Lochs Lomond (L), Awe (A), Ness (N), Morar (M) and Shiel (S). The penetration of light in the blue (○), red (■), orange (▲) and green (△) parts of the PAR spectrum are shown as percentages of the values at the water surface; lines have been fitted (by eye) only to the data for the colours showing maximum and minimum attenuation. The bottom right-hand graph shows the ranges in Secchi Disc Transparency recorded for each loch. [Taken from Bailey-Watts and Duncan (1981a).]

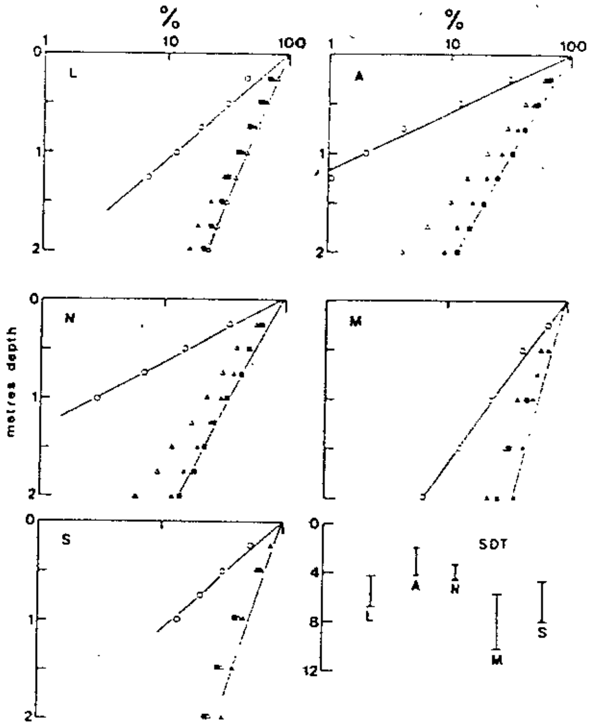

Figure 5. PAR absorbance scans (10-cm pathlength cuvette) of filtered (F - 0.22μm membrane) and unfiltered (U) water blanked against distilled water from lakes of different trophic status and type. [Taken from Howard-Williams and Vincent (1985).]

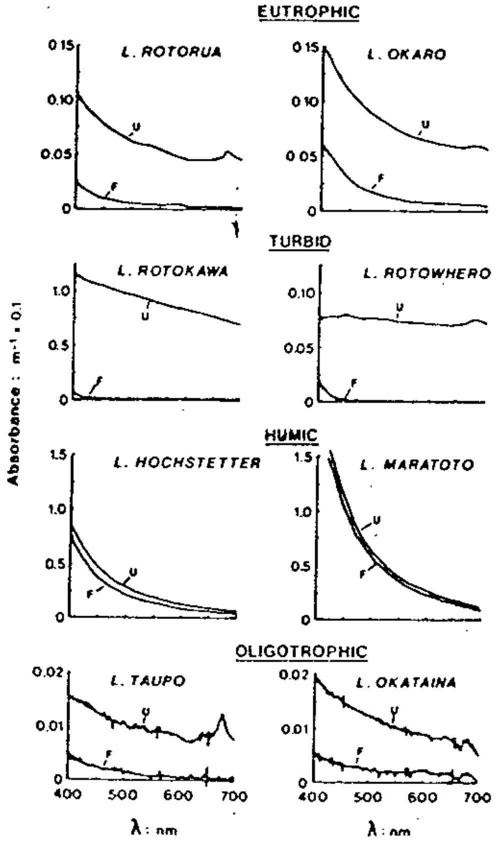

Figure 6. The basic three-layer structure of a thermally stratified freshwater lake in summer.

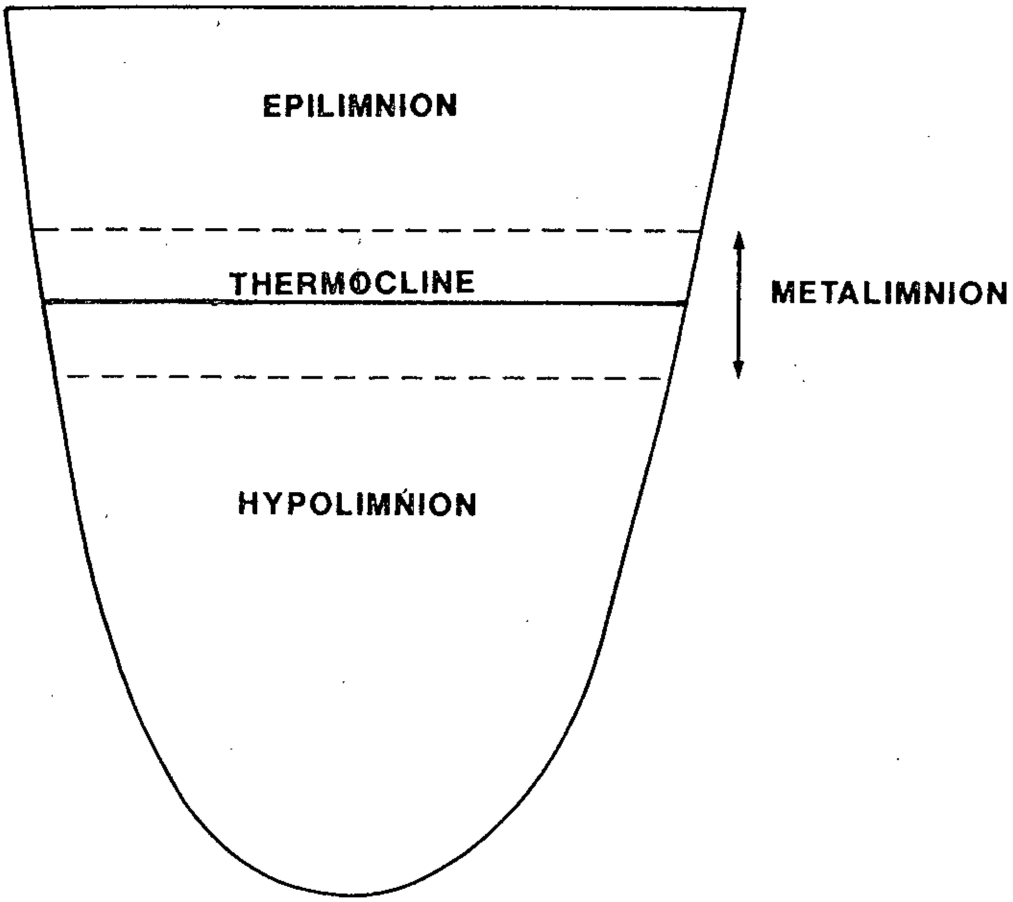

Figure 7. Idealised vertical temperature profiles in lakes: (a) winter isothermal conditions (b) the heating profile due to solar radiation only, and (c) the stratification profile resulting from the influences of solar radiation heating and wind-induced mixing.

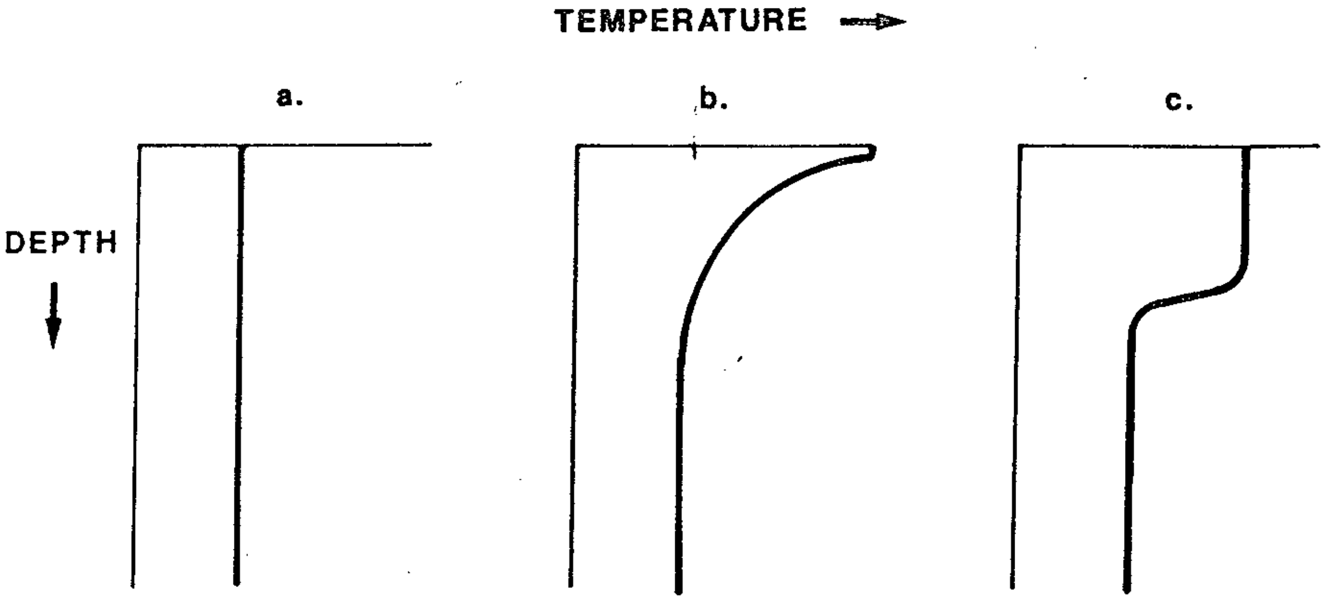

Figure 8. An example of a volume-depth curve (Loch Insh) used for the derivation of epilimnion volume (V_e) from epilimnion depth (D_e).