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6.—The Structure and Physical Environment of Loch Leven, Scotland.

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Synopsis

This paper describes the environment, structure and internal physical conditions of the loch. The first section deals with structure, land use and climate of the catchment area. The structure of the loch itself is then considered together with a brief description of the sediments. The bulk of the paper is devoted to the effect of sun, rain and wind on the loch, e.g., radiation and water temperature, water balance and hydraulic conditions. It ends with a summary of the influence of environmental factors on phytoplankton production and higher trophic levels.

Introduction

The object of this paper is to describe the environment, structure and internal physical conditions of Loch Leven. The loch lies about 35 km north of Edinburgh at a latitude of 56°10′N, a longtiude of 3°30′W and an altitude of 107 m above sea level. It covers an area of 13·31 km^2 and, since the mean depth is just under 4 m, wind has a considerable influence on conditions in the loch.

Topography and Climate of the Area

Structure of the catchment

The solid geology of the catchment can be divided into three zones (text-fig. 1). The western hills rise to a height of almost 500 m above sea level and are formed of volcanic lava and debris of the Old Red Sandstone Period, the detailed structure being complicated by faults and igneous intrusions. The lower hills of the smaller southern zones have a complex form with igneous sills intruding into carboniferous strata. A thin strip of similar geology occurs along the north-eastern watershed.

The topography of the plain in which Loch Leven is situated is dominated by glacial deposits which mask the underlying Old Red Sandstone strata. The loch itself is a drift basin in the classification of Hutchinson (1957), being formed in a shallow depression in sand and gravel deposits which overlie great thicknesses of boulder clay. There are two deep holes in the loch and it is believed that these are kettle holes, marking the site of large, detached ice blocks buried in the deposits (Kirby 1974).

There are thus no major aquifers within the catchment except for the sands and gravels so that, for the purpose of estimating the water balance, it can be assumed that the catchment is watertight. Some very small springs have been found near the south-east corner of the loch where the igneous rocks of the southern zone come very near to the shore and, at times of low flow, the water in some streams may disappear into the sand and gravel. The effect of these on the quantity of water entering the loch is considered to be negligible. The rock constituents are such that it is highly unlikely that river water entering the loch will have any abnormal properties.

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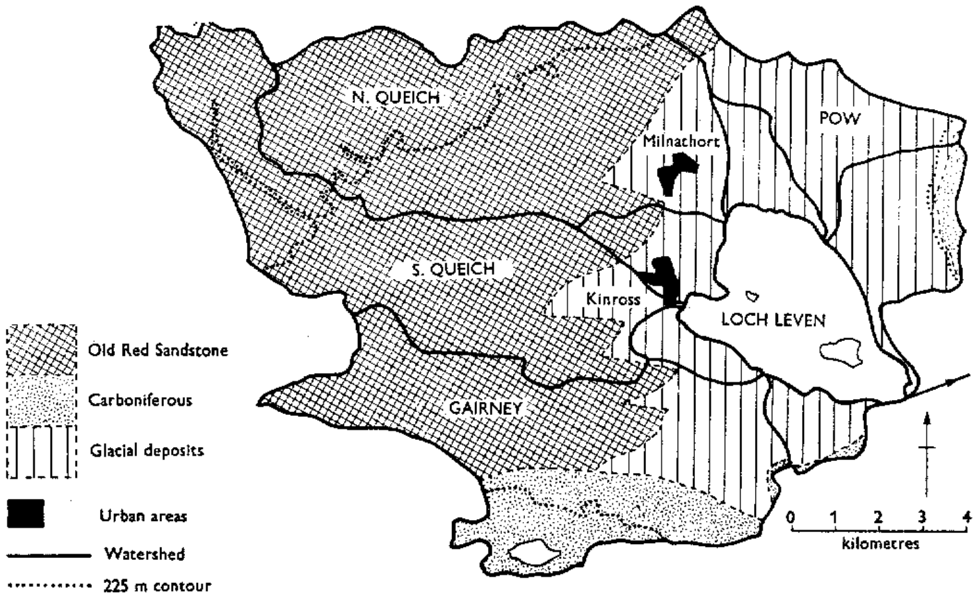


TEXT-FIG. 1.—The Loch Leven catchment.

Most of the 145 km^2 of the catchment is drained by four streams which are also shown on text.-fig. 1. The land is used predominantly for agriculture, an estimate of the proportional use being given in table 1. The figures are taken from statistics for the whole of Kinross County (Department of Agriculture and Fisheries for Scotland), which does not coincide exactly with the catchment. The area of rough grazing

TABLE 1

Land use within the Loch Leven catchment (145 km^2)

	% area
Urban area	1
Rough grazing (including small areas of coniferous plantations)	32
Other grass (supporting beef and dairy cattle)	39
Total grains (barley, wheat and oats)	18
Potatoes, other vegetables and fruit	10
	100

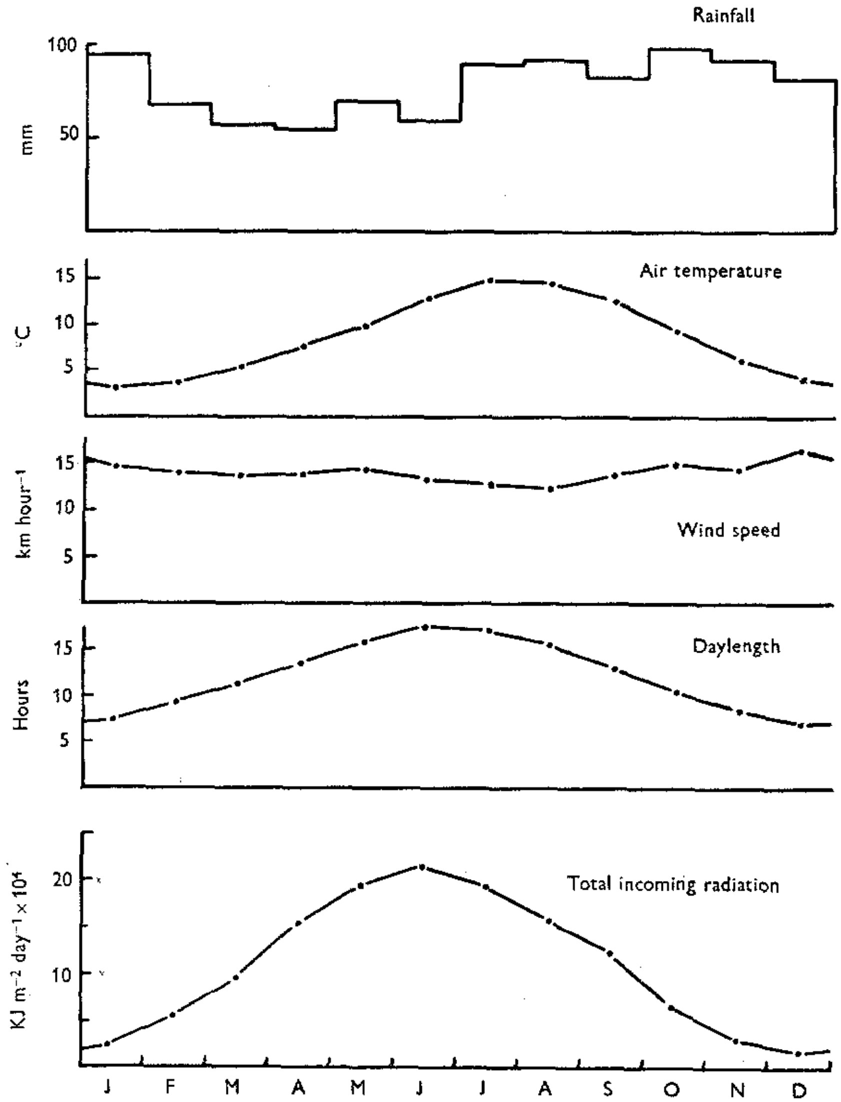
includes poorly drained lowlands as well as hill land. The extensive area of arable land to which nitrogenous fertilisers are applied results in high $N\text{–}NO_3$ concentrations in the inflow streams.

The Census indicates that the population within the catchment is a little over five and a half thousand, more than half being centred on the small towns of Kinross and Milnathort. The preliminary report on the 1971 Census indicates a slight fall in population since then. It appears that the sewage from about half this population is treated at sewage works, the remainder relying on septic tanks. The only industries are sand and gravel workings and a woollen mill in Kinross which has a marked effect on the phosphorus concentration in the River South Queich.

Climate of the Area

The climate of Britain, situated as it is on the eastern edge of the Atlantic Ocean, is dominated by maritime air masses. It is characterised by its lack of extremes—small range in temperature, rain at any time of the year and by the liability to wind at any time of year. During the passage of associated frontal systems, pronounced day-to-day changes in the weather can result. Sometimes, however, the influence of continental high pressure air extends over Loch Leven, usually accompanied by increased temperature range and reduced wind speeds.

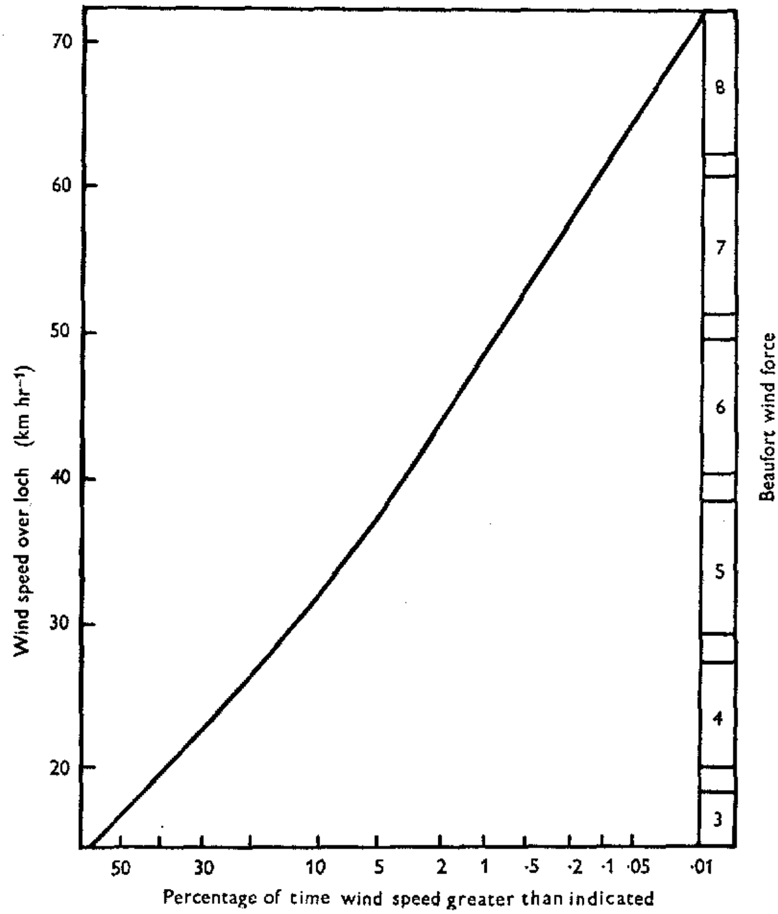
The question of the dominant air mass has some limnological significance for Loch Leven. During periods of maritime dominance the loch is well mixed and



TEXT-FIG. 2.—Climatic data for the Loch Leven area.

unstratified and stratification only occurs over the deeper parts of the loch during warm, calm weather. Similarly in winter ice cover only occurs when cold continental air is dominant.

The other basic climatic feature of the area results from the latitude, viz. 56°10′N. This results in a marked change in daylength and incoming radiation throughout the year.



TEXT-FIG. 3.—Frequency of strong winds at Loch Leven.

Climatic data for the area, shown in text-fig. 2, refer to long-term averages from Meteorological Office tables and not to the period of the IBP project. Air temperature data refer to Leuchars Airfield which lies about 35 km north-east of the loch. Wind data from the same site were used but adjusted to give wind speed over the loch using regression equations described by Smith (1973). Radiation data are calculated from hours of bright sunshine, checked against direct measuerment at Loch Leven (see Appendix).

Text-figure 3, derived from Smith (1973), shows the frequency of occurrence of strong winds, irrespective of direction. Two-thirds of the winds greater than force 5

($9{\cdot}5$ m sec^{-1}) are from a generally south-westerly direction, the proportion increasing as the wind force increases.

Marked changes in the weather throughout the whole of Eastern Scotland have occurred since 1971. Rainfall and hence river flow have been much below average, water temperatures have generally been higher and there has been some reduction in the number of days with strong winds.

The Structure of Loch Leven

The loch has been re-surveyed recently and a new bathymetric map published by Kirby (1971). The morphometric data in table 2 and text-figs. 4 and 5 are based on a preliminary map prepared by him and not on the final published map. The data are

TABLE 2

Morphometric data for Loch Leven

Mean depth	3·9	m
Maximum depth	25·5	m
Surface area	13·3	km^2
Volume	52·4	10^6m^3
Length	5·9	km
Breadth	2·3	km
Length of shore line	18·5	km
Shore line development	1·43	

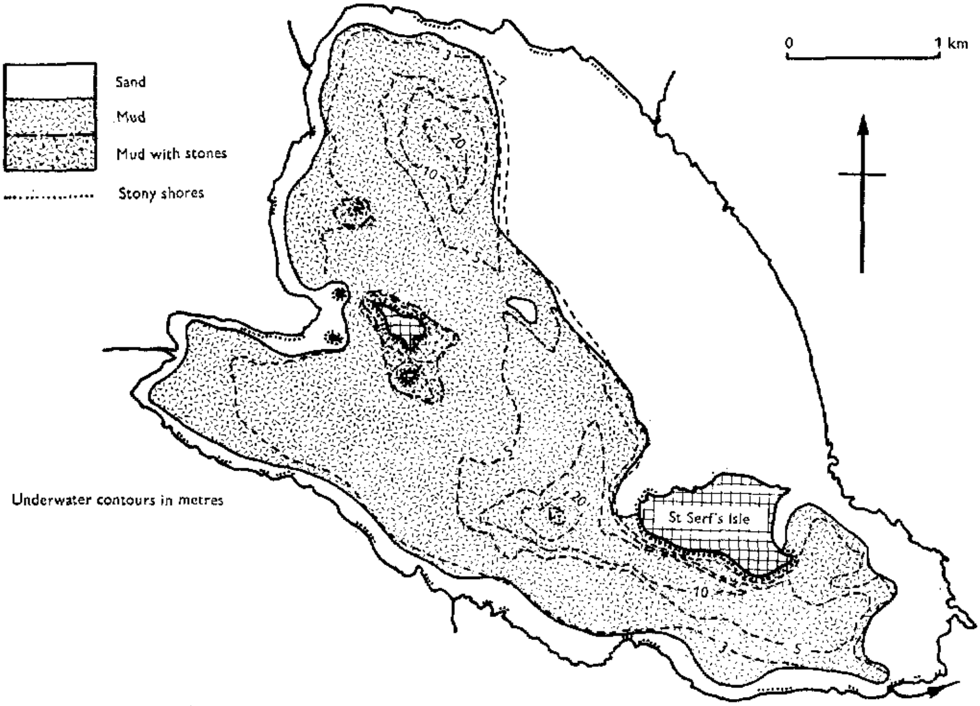
calculated on the assumption that the loch level is the same as the survey datum, i.e. 50 cm below spillway level. The pattern of water level fluctuations is shown in text-fig. 6. The dotted line on the volume-depth curve (text-fig. 5) is not based on survey data and is simply an extrapolation beyond the datum.

The form of the loch is rather like that of a dish, having a shallow rim round the edge and a central area of deeper water. The shallow rim is much more extensive along the north-east shore and there are two deep troughs in the middle of the dish. These are the kettle holes already referred to and it can be seen that the volume and lake bed area below 10 m are small in comparison to the totals. The sediments on the rim are predominantly sandy with some stony shores; clay and silty muds occur in the deeper water. The division between sand and mud, shown on text-fig. 4, corresponds to the divisions used in the zoobenthos work on the loch (Maitland and Hudspith 1974; Charles *et al.* 1974).

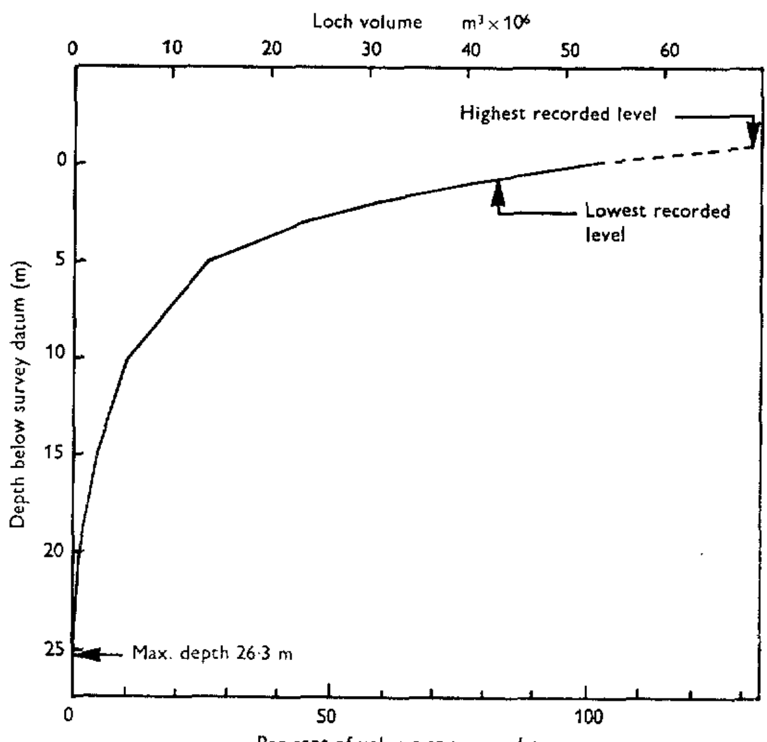
Radiation and Water Temperature

The radiation balance equation defines the disposal of the total incoming radiation and can be expressed as follows:

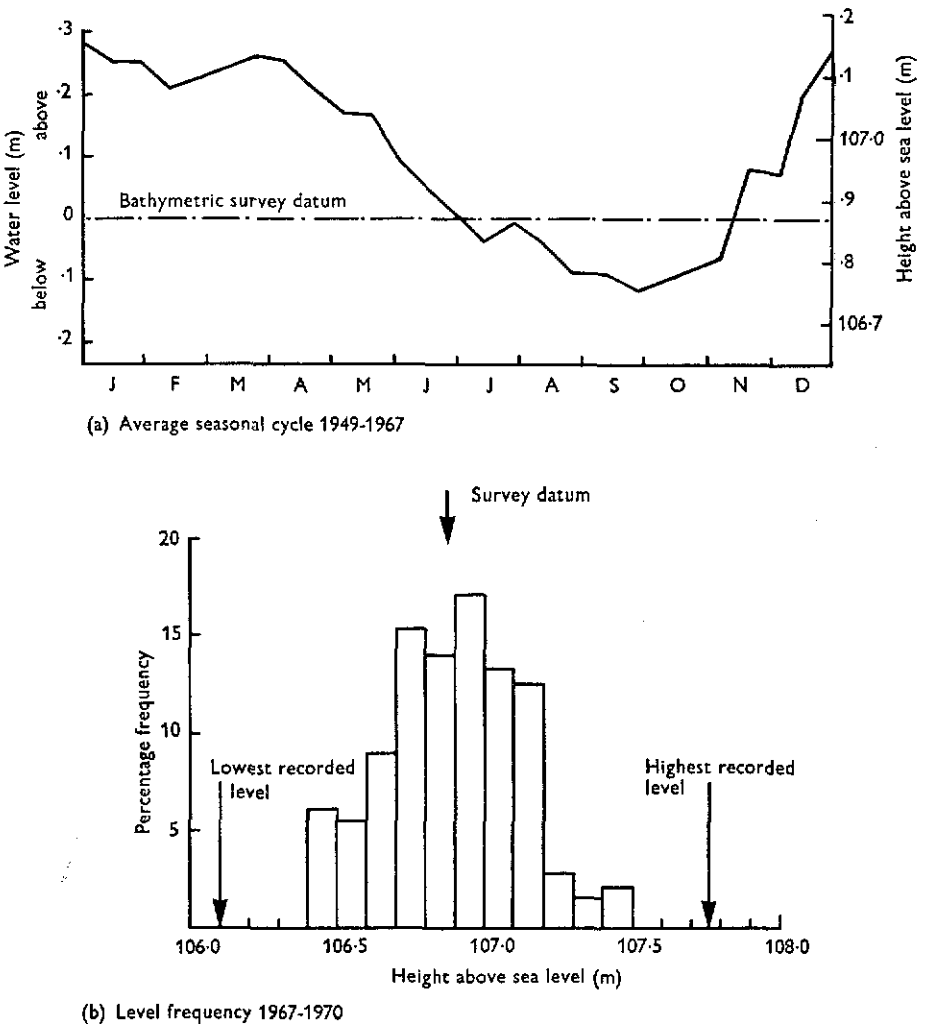
$$\text{total incoming radiation } (R_i) = \text{reflected radiation } (r) + \text{long wave back radiation } (R_b) + \text{energy used in evaporation } (E) + \text{heat transfer across the water surface } (H) \pm \text{change in heat stored in the loch } (S) + \text{photosynthesis } (P)$$



TEXT-FIG. 4.—Morphometry and sediments of Loch Leven.



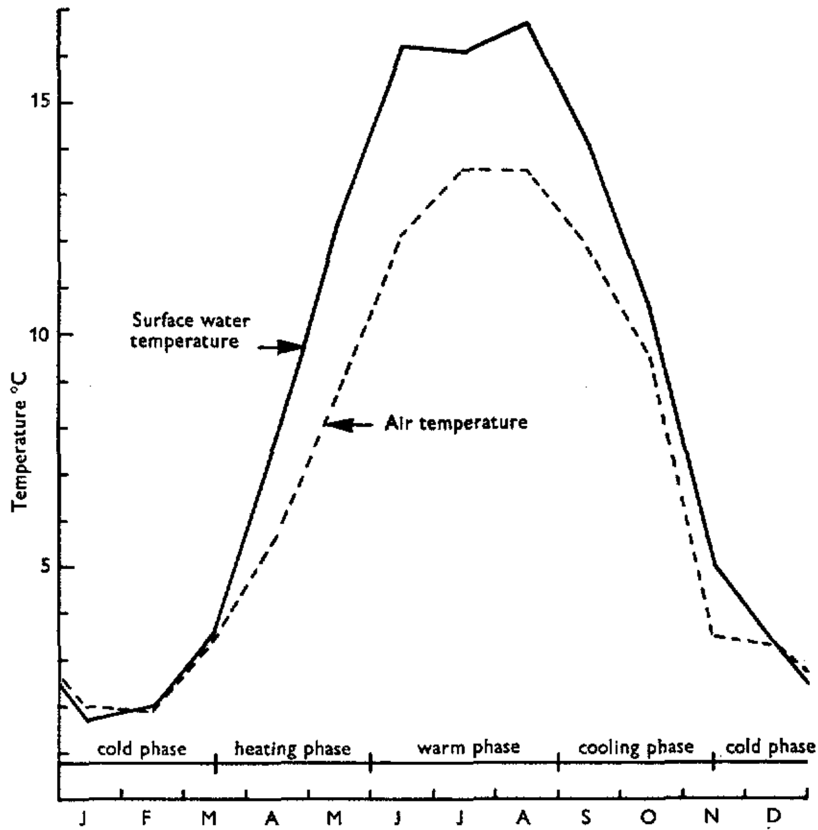
TEXT-FIG. 5.—Volume-depth curve for Loch Leven.



TEXT-FIG. 6.—Pattern of water level fluctuations at Loch Leven. (*a*) Average seasonal cycle of level fluctuation for the period 1949–67. (*b*) Level frequency histogram for the period 1967–70. The indicated extreme levels are those occurring since 1929.

The reflected radiation, *r*, was taken as 5 per cent of the total incoming and R_i, R_b and *E* were computed from meteorological data (see Appendix). *S* was calculated from water temperature data and the energy used in photosynthesis was assumed to be 1 per cent of the total incoming radiation. The heat transfer could, therefore, be deduced by difference.

Water temperature is continuously recorded on a mercury-in-steel thermograph installed on the end of the pier near the field station (text-fig. 7). The bulb, shielded from direct sunlight, is at a fixed level so that the actual depth at which temperature is being measured varies with water level. The instrument, therefore, only gives an approximate indication of the true loch surface temperature but tests show that the



TEXT-FIG. 7.—Average temperature cycles for the period 1968–71.

difference between the thermograph reading and the true surface temperatures elsewhere in the loch rarely exceeds 2°C even in warm, bright weather. The difference is generally less than this.

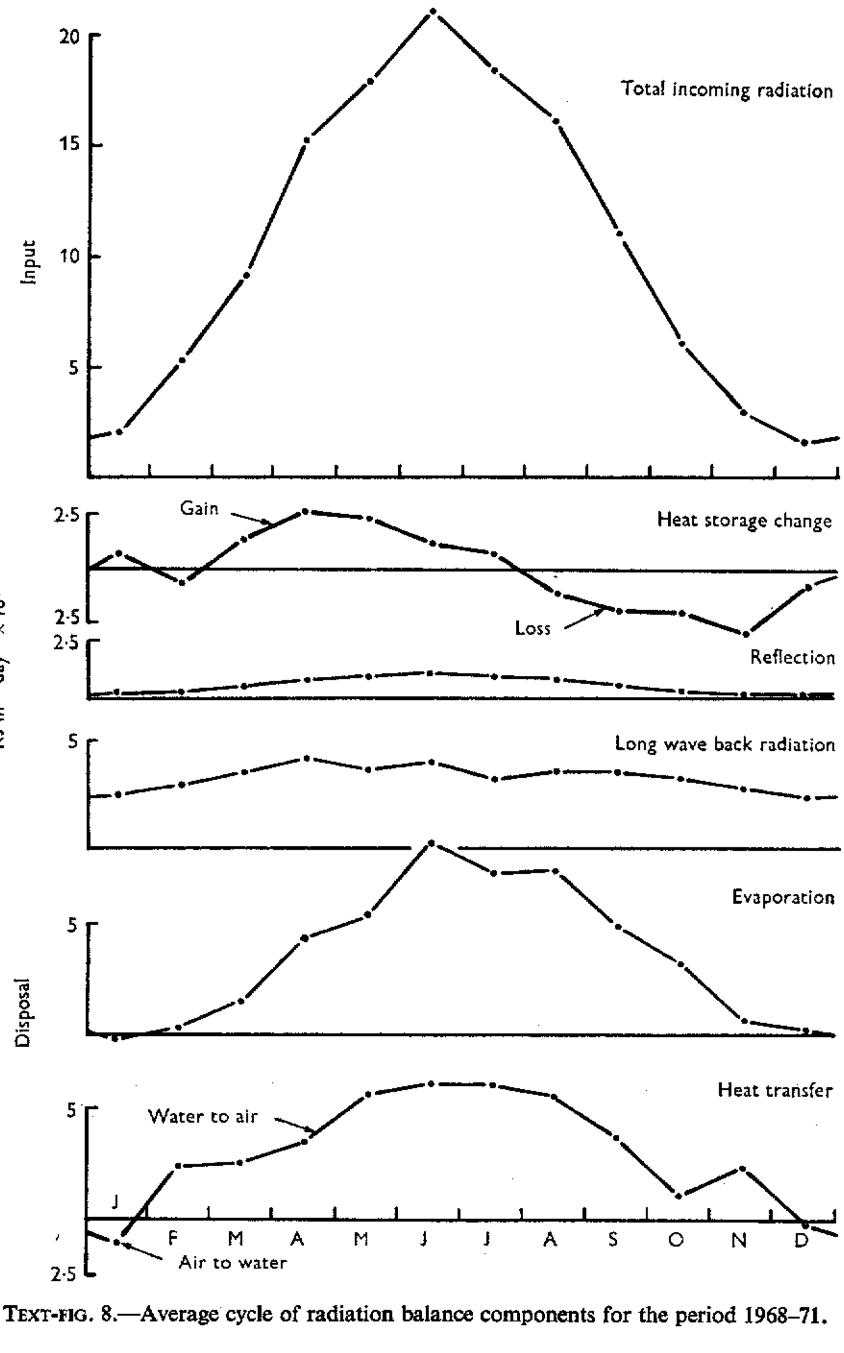
The radiation balance over the year, calculated from data averaged over the period 1968–71, is shown in text-fig. 8 and the annual totals are summarised in table 3.

TABLE 3

Annual total radiation balance components

	$KJm^{-2} \times 10^5$	%
Incoming radiation	*38·6*	*100*
Reflection	1·9	5
Back radiation	11·7	30
Evaporation	13·3	35
Net heat transfer	11·3	29 (water to air)
Photosynthesis	0·4	1 (assumed)

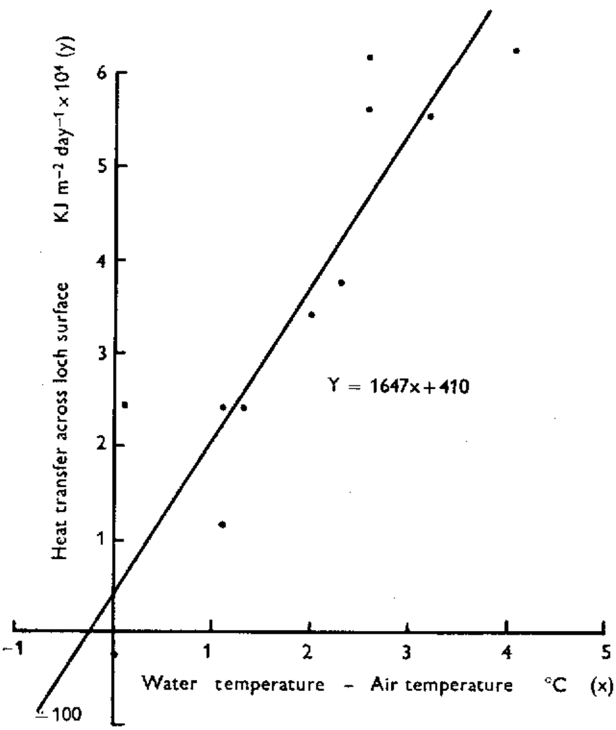
Besides forming the first stage in an energy flow diagram, the radiation budget gives an indication of the mechanisms influencing loch water temperature. In January, the average air temperature is higher than that of the water while, in December, the



TEXT-FIG. 8.—Average cycle of radiation balance components for the period 1968–71.

temperatures are equal. In all other months the average water temperature exceeds that of the air so that the net heat transfer over the year is from water to air. Text-figure 9 shows that approximately 1650 KJ m^{-2} day^{-1} are transferred across the loch surface for every one degree difference in temperature. The correlation coefficient between temperature difference and heat transfer is quite high ($r = 0{\cdot}92$) and increases confidence in the computed radiation balance.

The importance of atmospheric circulation to limnological conditions at Loch Leven has already been mentioned. Air temperatures in the maritime climate at Loch Leven are often affected by the origin and thermal condition of moving air masses, i.e. by horizontal heat flow as well as vertical radiation exchange. Because of the heat transfer across the loch surface, whenever there is a temperature difference between water and air, high water temperatures can only occur with more or less



TEXT-FIG. 9.—Heat transfer across loch surface.

static air, heated sufficiently to suppress the temperature difference. Since still air also implies the absence of wind-induced mixing in the water, stratification usually occurs in the deeper parts of the loch at the same time. Similarly, very low water temperatures and ice formation generally only occur with static air masses in winter.

Text-figures 7 and 8 suggest the division of the year into four thermal phases: a heating phase from March to May: a warm summer phase from June to August when changes in heat storage are small and the temperature is generally above 15°C: a cooling phase from September to mid-November: a cold phase from mid-November to the beginning of March when the temperature is almost always below 5°C.

Ice may be formed at any time during the cold phase (the varying immersion of the thermograph bulb means that ice may be formed when the thermograph temperature is above zero) but since stationery high pressure air is rarely over Scotland long enough for thick, extensive ice cover to develop, the period of continuous ice cover rarely exceeds 2 weeks. During the period of the IBP project there has only been one occasion when there has been complete ice cover thick enough to permit sampling by working from the ice. The previously mentioned change in weather pattern during the course of the project is clearly demonstrated by the ice-cover records. Maps showing the extent of ice cover, drawn by Mr A. Allison, the Nature Reserve Warden, have been used to estimate the number of days each winter when more than 50 per cent of the loch area was covered by ice (table 4).

TABLE 4

Records of ice cover at Loch Leven

Winter	First and last dates of recorded ice		No. of days with more than 50% ice cover
1967–68	8.12.67	17.1.68	11
1968–69	16.12.68	28.3.69	42
1969–70	26.11.69	28.2.70	35
1970–71	4. 1.71	6.1.71	1
1971–72	19.11.71	12.2.72	0
1972–73	18.11.72	27.2.73	5

Stratification of the water over the two deeps can occur during the warm phase but, as with ice formation, the appropriate meteorological conditions rarely last for periods exceeding 2 weeks. Stratification is more common in the North Deeps than in the South. This difference appears to be due to greater water current velocities in the South Deeps at a given wind speed. Temperature gradients are not strong but anaerobic conditions can occur in the first few metres above the sediment. The poorly defined hypolimnion resulting from this weak stratification generally forms in depths below 10 m.

Since, however, the extent of the loch below 10 m represents only 6·2 per cent of the loch area and 10·3 per cent of the loch volume, the significance of this weak, intermittent stratification is likely to be small. Because cloudy skies are common, particularly in autumn and winter, the incoming radiation and nocturnal heat loss are usually restricted and thus the daily temperature range is generally small. Table 5 shows, for 1968 only, the frequency of occurrence of different daily water temperature ranges in the four thermal phases. Loch Leven is typically isothermal with an oxygen content near to saturation.

TABLE 5

Percentage frequency of different daily temperature ranges in each thermal phase

Temperature range	Cold phase	Heating phase	Warm phase	Cooling phase
0 –0·5	61	22	24	77
0·6–1·0	27	35	29	19
1·1–1·5	7	25	12	4
1·6–2·0	4	6	14	—
2·1–2·5	1	1	6	—
2·6–3·0	—	3	6	—
> 3·1	—	8	9	—
	100	100	100	100

Water Balance

If, due to the absence of aquifers, the catchment can be considered watertight, the average inflow over a period of years can be estimated from meteorological data since runoff is equal to rainfall less evaporation. The results of such a calculation are shown in table 6. The rainfall data refer to the period 1916–50 and areal values were estimated from large-scale maps made available by the Meteorological Office, Edinburgh. The evaporation was taken as 420 mm for all areas, a figure based on data in MAFF (1967).

Table 6

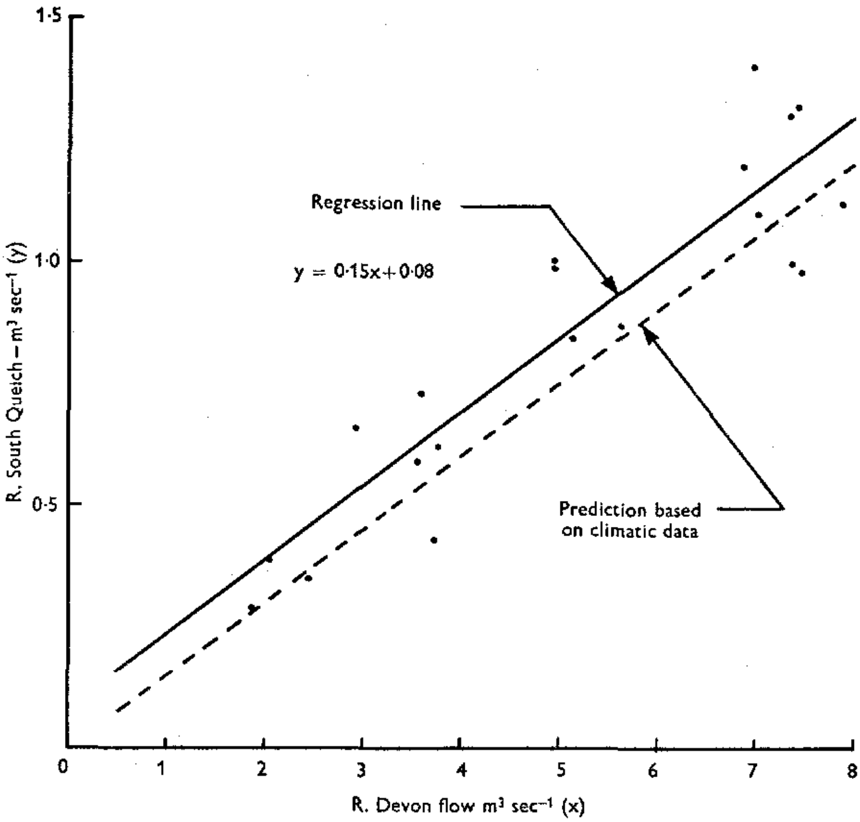
Average annual loch inflow calculated from meteorological data

Catchment	Drainage area	Rainfall	Runoff		Flow as % of S. Queich flow	
	km²	mm	mm	% total	computed	observed
N. Queich	41·6	1130	710	32·5	1·28	1·27
S. Queich	33·9	1100	680	25·3	1·0	1·0
Gairney Water	37·8	965	545	22·6	—	—
Pow Burn	11·1	1008	588	7·1	0·28	0·21
Secondary streams	21·0	961	541	12·5	—	—
Total	145·4	1050	630	100	4·0	—

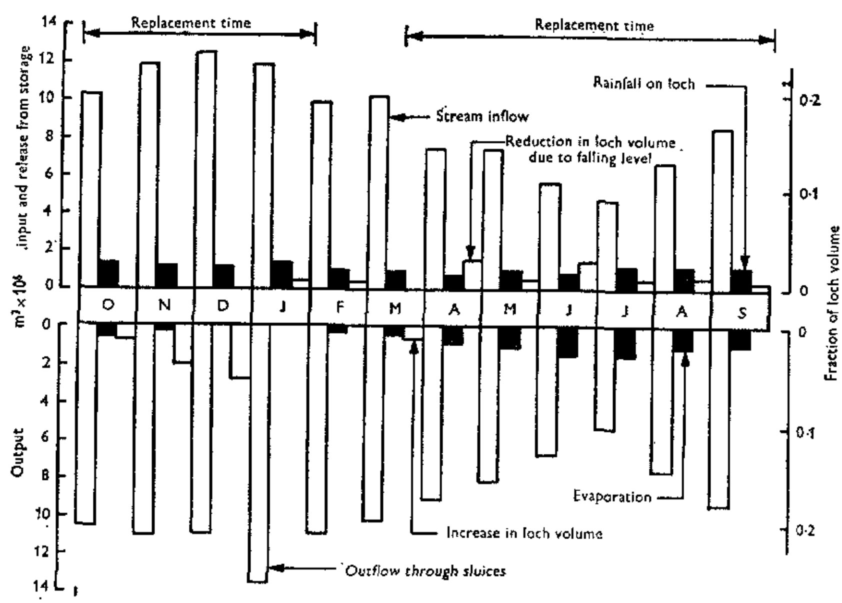
Not only does such a calculation provide an estimate of the total annual inflow into the loch, but it also indicates the relative contribution of each inflow stream. The observed flows in the North Queich and Pow Burn are based on the mean of at least 5 individual measurements using current meters. No suitable river reach for flow measurement could be found on the Gairney Water. The water level in the South Queich was continuously recorded and converted to rate of discharge using a water level/discharge calibration curve derived from current meter measurements. Since there is reasonable agreement between the computed and observed flow fractions it appears that the flow in the South Queich is approximately one-quarter on the total inflow.

Further confirmation of the flow proportion estimates was obtained by comparing the monthly flows recorded on the South Queich with those on a permanent gauging station operated by the Forth River Purification Board on the River Devon. The Devon catchment is adjacent to that of Loch Leven and the gauging station is about 25 km from that on the South Queich. Text-figure 10 shows the correlation between the Devon and South Queich Flows. Also shown on this figure is the prediction equation based on climatic data, calculated in the same way as the data of table 5. The regional consistency of river behaviour seems established and the assumption of a watertight catchment justified. Text-figure 10 can also be used to predict Loch Leven inflows for the period before the installation of the South Queich level recorder and to fill any gaps in the South Queich record.

An approximate long-term water balance for the loch has been calculated and is shown in text-fig. 11. The stream inflow refers to the period 1959–69 and is based on the Devon/South Queich correlation. The inflow volume is therefore, different from that indicated by table 6 since the periods are different. The direct rainfall on



TEXT-FIG. 10.—Correlation between Devon and South Queich flows.



TEXT-FIG. 11.—Average cycle of water balance components for the period 1959–69.

the loch refers to the period 1916–50. The changes in storage are derived from level records from 1949–69. The calculation of evaporation data which refer to the period 1950–64, is described in the Appendix.

Because of the irregular operation of the sluices controlling the outflow channel, no attempt was made to measure the outflow directly. It is estimated as the unknown in the balance equation, viz.

$$\begin{matrix}\text{stream}\\ \text{inflow}\end{matrix} + \begin{matrix}\text{direct rain}\\ \text{on loch}\end{matrix} = \text{outflow} + \begin{matrix}\text{evaporation}\\ \text{from loch}\end{matrix} \pm \begin{matrix}\text{change in water stored due to}\\ \text{level fluctuations}\end{matrix}$$

Since rainfall is more or less uniform throughout the year and there is no prolonged period with sub-zero temperatures, it is terrestrial evaporation and the resulting changes in soil moisture in the catchment that control the annual inflow cycle. The natural sequence of inflow and outflow is distorted by the erratic operation of the sluices.

The mean annual total inflow for the period 1959–69 is $120{\cdot}7 \times 10^6 m^3$ and this compared to a loch volume of $52{\cdot}4 \times 10^6 m^3$, results in a mean renewal time of 5·2 months. Within the period of record the actual renewal time varied from 3 to 9 months. These renewal times are equivalent to loss rates of between 0·3 and 1 per cent of the loch volume per day.

If the rate of mixing within a lake is rapid due to wind-induced turbulence (it will be shown later that this is the case in Loch Leven), then the renewal time, expressed simply as the ratio of lake volume to inflow rate, is an apparently deceptive measure of the time solid or dissolved matter stays in the lake. The outflow at any instant will include water of very recent age and, at the same time, some water will reside in the loch for a period greater than the renewal time.

As an example, it is simplest to consider a substance whose supply is not renewed. The decline in concentration of an accidental pollutant for steady flow conditions is defined by the following equation:

$$C = C_0 e^{-Et/V},$$

where C_0 = initial concentration
C = concentration at time, t
V = volume of the loch
E = throughflow (volume per unit time).

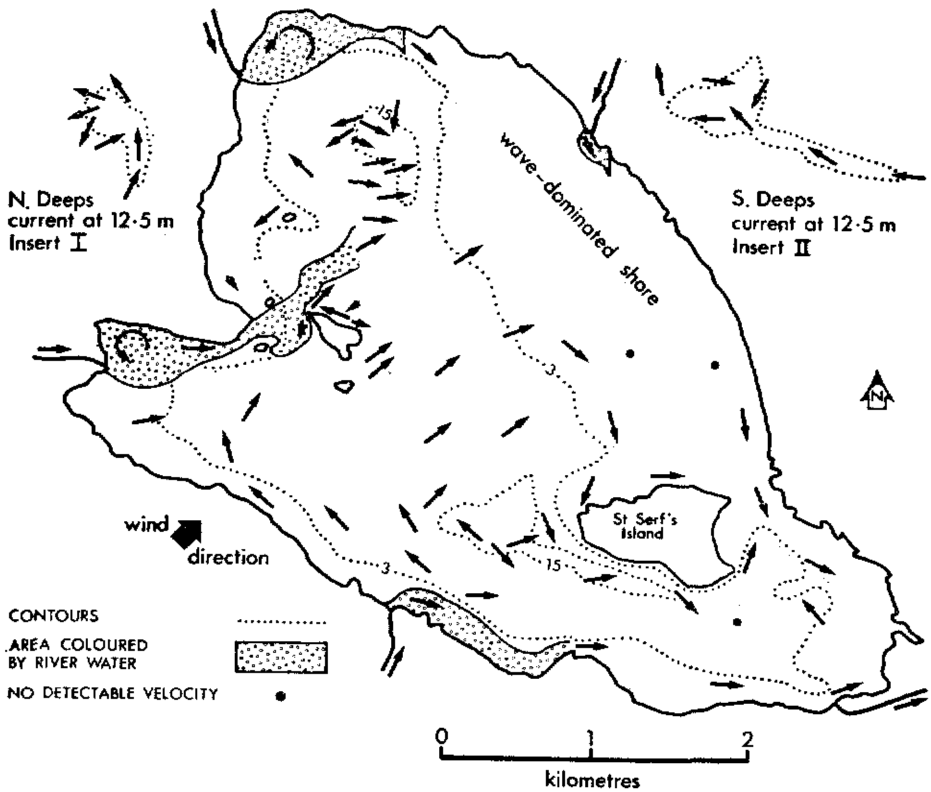
If it is expressed in months and the renewal time is 5 months, then $E = 0{\cdot}2V$, so that $C = C_0 e^{-0{\cdot}2t}$.

The half-life of the pollutant can then be calculated by setting $C = C_0/2$ so that $0{\cdot}2t = 0{\cdot}Y$, i.e. the half-life is 3·5 months and can be calculated from the renewal time. The asymptotic decline in concentration means that approximately 1 per cent of the original concentration will still occur in the loch after 2 years.

Hydraulic Conditions

The main features of the water circulation when a south-west wind is blowing are shown in text-fig. 12. Most characteristic are the large horizontal rotations or swirls on the surface and, only over the two deeps, are there return currents at depth flowing in contrary directions to those at the surface. The two deeps can in fact be considered as small deep lakes contained in a more extensive shallow one. The current direction at any point in the shallow-water rotational currents is generally, but not always, the same at all depths.

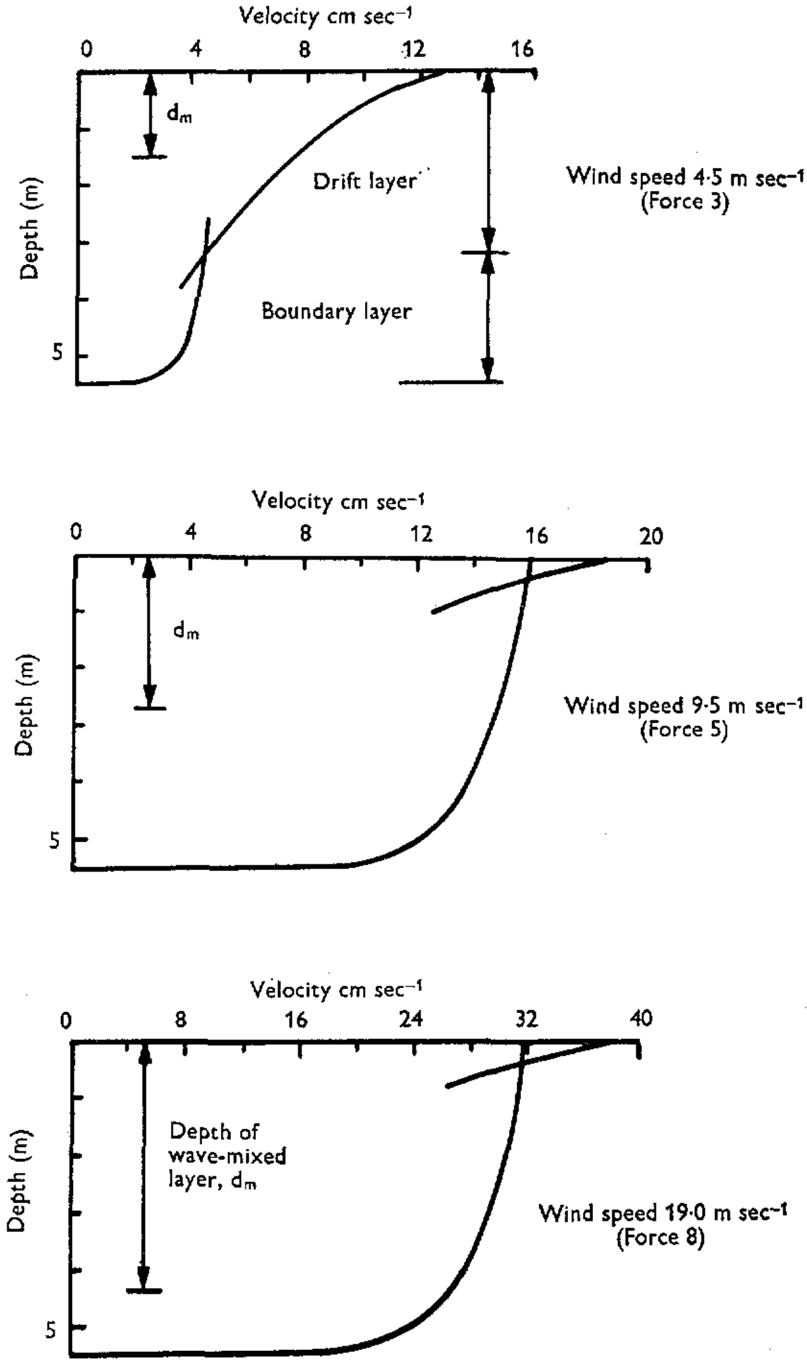
Work in progress on the analysis of the velocity depth profiles of currents in the centre of the loch where currents are more or less unaffected by distortions of the water surface suggests that they can be imagined as being composed of two layers:



TEXT-FIG. 12.—Circulation pattern in Loch Leven when a south-west wind is blowing.

an upper layer having an exponential change in velocity with depth: a lower boundary layer having a logarithmic profile as in a river. Text-figure 13, showing the theoretical form of profiles for a station in the middle of the loch, indicates the complex relation between wind speed and current speed at different depths. The theory takes no account of the turbulent transfer across the interface between the layers. This would tend to remove the abrupt discontinuity in the profile.

For winds of force 5 (9·5 m sec^{-1}) and above the profile form remains constant and doubling the wind speed results in a doubling of the current speed at all depths. At lower wind speeds, the change in surface velocity is relatively small but there are considerable differences in velocities near the bed. These computed profiles take no account of wave action which cannot, in the loch, be separated from the motion due to wind-induced currents. The most obvious effect of the orbital water particle motion beneath the waves is to increase the mixing rate near the surface and so



TEXT-FIG. 13.—Theoretical form of velocity-depth profiles for currents in the central area of Loch Leven.

accelerate the destruction of the abrupt discontinuity in the velocity/depth profile near the surface.

The rate of mixing within the water column, particularly lateral mixing and the resulting uniformity or otherwise of samples taken from different points on the loch, is dependent mainly on the velocity near the surface and the profiles show that this does not drop rapidly at lower wind speeds. The uniformity of water samples, already discussed in relation to temperature and considered by Bailey-Watts (1974) in relation to phytoplankton, does not, therefore, demand high wind speeds. Examination of wind records shows that prolonged periods of absolute calm are very rare and there is little opportunity for the formation of separate water masses.

One of the most important consequences of wind-induced turbulence concerns the possible mechanical release of nutrient-rich interstitial water into the water column. If there is a difference in concentration of any substance between interstitial and lake water, diffusion will occur and this will continue provided the turbulent mixing is sufficient to maintain a concentration gradient across the sediment/water interface. Much greater quantities are released if there is physical disturbance of the sediment so that the interstitial water is carried in bulk into the water column. The mechanism for this must depend on the velocity close to the loch bed and the profiles show that this increases steadily as the wind increases. Physical disturbance of the sediment is the subject of present research but, although it is likely that disturbance can occur, its extent and frequency is not yet known. Unless there is some long-term change within the loch, the quantities of nutrient released from the sediment must be balanced by accumulation due to the settling out of nutrients in particulate form during periods of calm weather.

The relation between windspeed, fetch (the distance over water along which the wind blows) and the wave characteristics of height, period and length has been considered by Smith and Sinclair (1972). The orbital radius and velocity of particles beneath the still water surface decrease with depth and the depth of water affected by wave action can be taken as half the significant wavelength. Significant in this context refers to the frequency distribution of wave characteristics and implies the average of the highest third of all wavelengths. Such a water depth not only defines the depth of the wave mixed layer where the total water depth is greater than half the significant wave length but also defines the depth limit of the shore zone, i.e. the bed inshore of this line is liable to be disturbed by wave action.

Superimposed on the current profiles on text-fig. 13 are the depths of the wave-mixed layers at the same wind speeds assuming a fetch of 1·5 km. By calculating the wave length at a number of points on the loch, the mean thickness and hence volume of the wave-mixed layer can be calculated for a given wind speed and direction. At the same time, by comparing wave lengths and total water depths, points on the shore zone limit can be interpolated. As might be expected, the north-east shore zone limit with strong south-westerly winds is very close to the boundary between sand and mud.

It is, therefore, possible to divide the total volume of the loch into a number of zones depending on the hydraulic conditions in each. Unlike the division of a stratified lake into epilimnion and hypolimnion, the volume in each zone varies with wind speed and direction. The figures in table 7 refer to winds of force 5 (9·5 m sec^{-1}) and 8 (19·0 m sec^{-1}) blowing from the south-west. Deep water defines the volume of water forming return currents in the two deeps which may occasionally stratify in the summer. It is taken as the entire volume of water below 10 m at both wind speeds. The middle water volume is all the water outwith the shore zone which lies below the wave-mixed layer but at depths less than 10 m.

TABLE 7

Volume of hydraulic zones in Loch Leven

	Force 5		Force 8	
	$10^6 m^3$	% total vol.	$10^6 m^3$	%total vol.
Shore zone	3·32	6·3	6·20	11·8
Wave-mixed layer	7·85	15·0	18·25	34·9
Middle water	35·82	68·4	22·54	43·0
Deep zone	5·41	10·3	5·41	10·3
Total loch volume	52·40	100	52·40	100

Environmental Conditions in Loch Leven

The environmental conditions in any lake result from the interaction between the external climatic factors, essentially sun, wind and rain, and the factors defining the geometry of the lake, viz., area and depth.

All five factors are important when the loch is considered as a tank for the culture of phytoplankton. The loch is well mixed so that a single sample is usually representative of the loch as a whole and the kinetics of the system can be based on the assumption of complete mixing. The flow through the system is, in comparison to those in other climates, fairly constant throughout the year and losses are moderate. Nutrient availability may at times be complicated by exchange between the sediments and the overlying water. There is considerable variation in the radiation input over the year although the temperature fluctuations are, in comparison, less pronounced.

The shallow depth of Loch Leven is the dominant factor when the environmental conditions of the higher trophic levels are considered since it reduces the ability of the loch to absorb externally applied stress. An obvious example of this is the effect of wave action on the shallow water benthos—large areas of the sandy sediments may become unstable during gale force winds. As far as temperature thresholds are concerned, the usual range of temperature fluctuations is relatively small but, when the atmospheric conditions are appropriate, heat transfer across the loch surface can be suppressed, resulting in very high or low water temperatures.

Acknowledgments

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Appendix

Method used for the Calculation of Radiation Balance Components from Meteorological Data

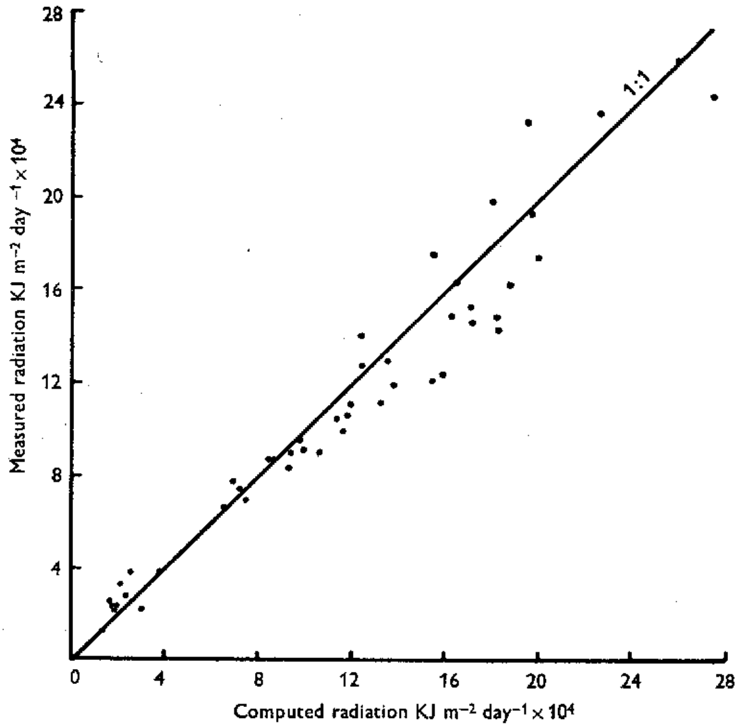
Total incoming radiation

Total incoming radiation, R_i, is measured directly at Loch Leven on a Kipp and Zonen solarimeter but, because of instrumental faults, the records are incomplete. The standard Meteorological Office equation relating R_i to the ratio of actual to possible hours of bright sunshine was found to underestimate incoming radiation. A similar discrepancy was found by Gloyne (personal communication) and it appears to be due to reduced atmospheric pollution. A slightly modified version of the equation in Vollenweider (1969) has been used, viz.

$$R_i = 0{\cdot}95\ R_a\ (0{\cdot}3 + 0{\cdot}7\ n/N)$$

where R_a = total incoming radiation at the top of the atmosphere,
n = actual hours of bright sunshine,
N = possible hours of bright sunshine.

A comparison of observed and computed incoming radiation using weekly data from each of the four years 1968–71 is shown in text-fig. 14. There are no consistent



TEXT-FIG. 14.—Comparison of computed and measured incoming radiation at Loch Leven.

errors and the actual accuracy of the estimate is probably greater than the apparent—the time intervals for points on the graph are not exactly the same and the exposures of both solarimeter and sunshine recorder, which are about 1 km apart, are imperfect.

Long Wave Back Radiation

This has been calculated from the following equation(M.A.F.F. 1967):

$$R_b = \sigma T_a^4(0{\cdot}47 - 0{\cdot}75\sqrt{e_d})\,(0{\cdot}17 + 0{\cdot}83\ n/N),$$

where σ = Stefan's constant,
T_a = air temperature (degrees absolute),
e_d = mean vapour pressure mm Hg,
n and N as before.

Evaporation

Tabulated data, for Kinross County, of potential transpiration from short grass is given in Ministry of Agriculture, Fisheries and Food 1967. These data, adjusted in summer for the difference between actual and average hours of bright sunshine were converted to evaporation from open water using ratios given by Penman (1948). The effect of the change in heat storage on evaporation from the loch was taken into account using the method described by Lapworth (1965). The justification for this simplified application use of Penman's theory (1948) is the accuracy of the estimates of evaporation from reservoirs illustrated by Lapworth (1965).