DEVELOPMENT AND COLLAPSE OF AN *OSCILLATORIA* BLOOM IN LOCH LEVEN DURING JULY 1994

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Introduction

Loch Leven lies in a glacial depression 35 kilometres north of Edinburgh, Scotland. It has a large surface area, 13.3 km^2, but is generally shallow with a mean depth of 3.9 metres, although there are two deeper "holes" where the depth reaches 25 metres. Land use in the 145 km^2 catchment draining to the loch is predominantly arable farming, with some rough grazing in the headwaters and with three small towns close to the loch. The physical characteristics of Loch Leven are fully described by Smith (1974); it is a National Nature Reserve, a Site of Special Scientific Interest, and is cited under the Ramsar Convention as a wetland site of international importance.

Because of its lowland situation the loch is naturally productive and algal blooms are common. Bailey-Watts et al. (1987) estimated the annual load of phosphorus entering the loch from diffuse sources in the catchment at 26 kilograms per day. Over the past ten years, point-source emissions of phosphorus have been steadily reduced from 32 kg per day to around 9 kg per day in 1994. However, there is a legacy of historically high phosphorus loadings held in the loch sediment, which can be released into the loch water under certain conditions.

In 1992 a particularly severe bloom of the blue-green algae *Anabaena* and *Microcystis* caused much publicity and considerable damage to the world-famous fishery in Loch Leven. As a result of this the Forth River Purification Board (FRPB) decided to supplement its spot-sampling of the loch and its tributaries with a buoy, moored in the loch and able to continuously monitor basic water quality parameters. The buoy was deployed in May 1994 and produced detailed data on the condition of the loch through the development and subsequent collapse of a bloom of another blue-green alga, *Oscillatoria.* This article briefly describes some important features and gives our initial thoughts on events in the loch during this period.

Sampling the loch

Sampling has been carried out in conjunction with Scottish Natural Heritage and the NERC Institute of Freshwater Ecology. During 1994, weekly spot-sampling of open water sites on Loch Leven took place from 16 March onwards, at the South Deep Hole (NCR NO 148 005), South of the Reed Bower (NO 138 012), and the Outlet at the Sluices (NT 168

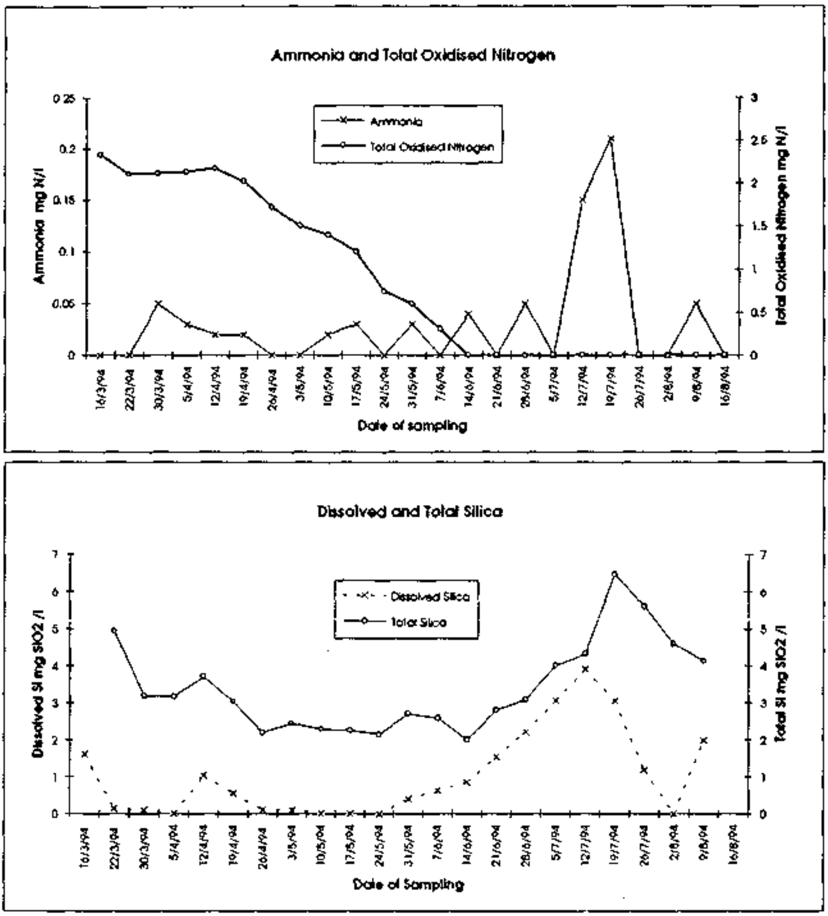


FIG. 1. Concentrations (mg per litre) for ammonia, total oxidised nitrogen, dissolved silica and total silica at the Outlet at the Sluices sampling site in Loch Leven, for the period 16 March to 16 August 1994.

995). When the weather prevented open water sampling, this was done on the shore at the Outlet at the Sluices and the Pier at Kinross (NO 127 017).

The samples from the South of Reed Bower and Sluices sites were taken from a 2-metre column of water whereas the South Deep Hole was sampled from a 15-metre column. From 12 July 1994, following thermal stratification, an additional site at the North Deep Hole (NT 141 031)

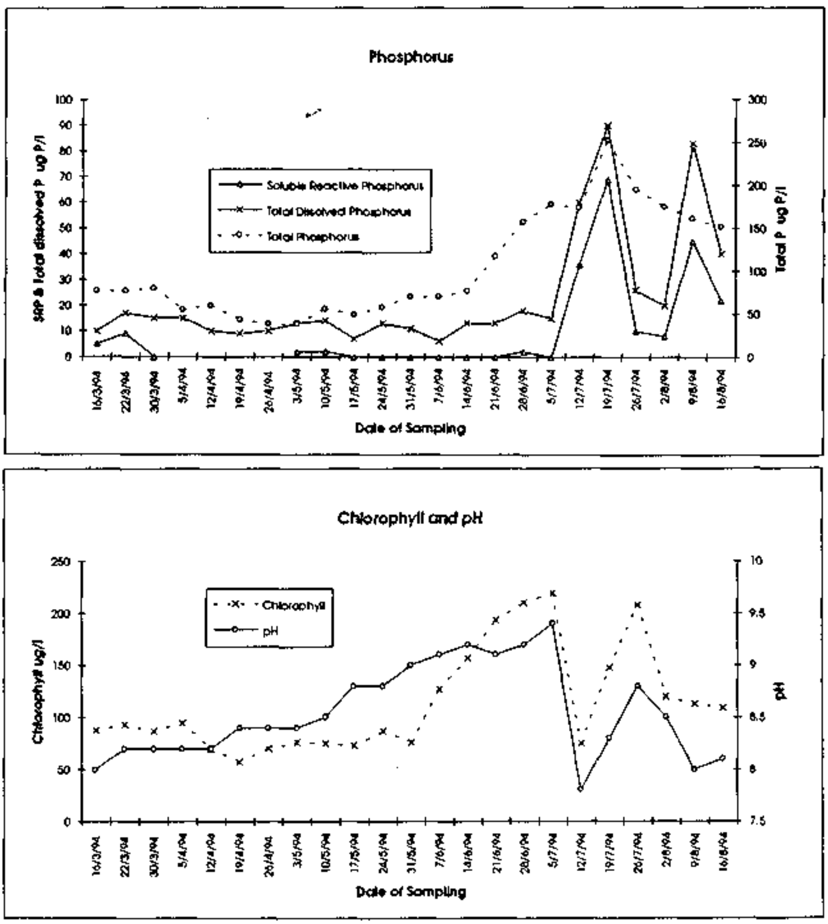


FIG. 2. Concentrations (µg per litre) for soluble reactive phosphorus, total dissolved phosphorus, total phosphorus, chlorophyll-*a* and pH at the Outlet at Sluices sampling site in Loch Leven, for the period 16 March to 16 August 1994.

was sampled. The Deep Hole sites were subsequently sampled using a 2-metre column for a sub-surface sample and a displacement water-sampler was used to take a grab sample at 20 metres depth. These spot-samples were analysed for the variables shown in Figs 1 and 2, plus electrical conductivity. Temperature, dissolved oxygen and Secchi disc depth were recorded at each site. Depth profiles of temperature and dissolved oxygen were recorded at the South and North Deep Hole sites.

The above water samples and recordings were all taken manually. Additional information on dissolved oxygen, temperature, pH, electrical conductivity and turbidity was recorded by a water quality monitoring buoy, comprised of a Hydrolab DataSonde 3, which performs the analyses and logs the data at 15-minute intervals, and a buoy with a solar panel and telemetry link. The sonde was deployed on 24 May 1994 and initially located at the South Deep Hole without a solar panel, so it was necessary to retrieve the sonde weekly and download data in the laboratory. From 28 June 1994 the complete buoy, including a solar panel, was installed at its permanent location, South of Reed Bower, and the sondes were changed fortnightly.

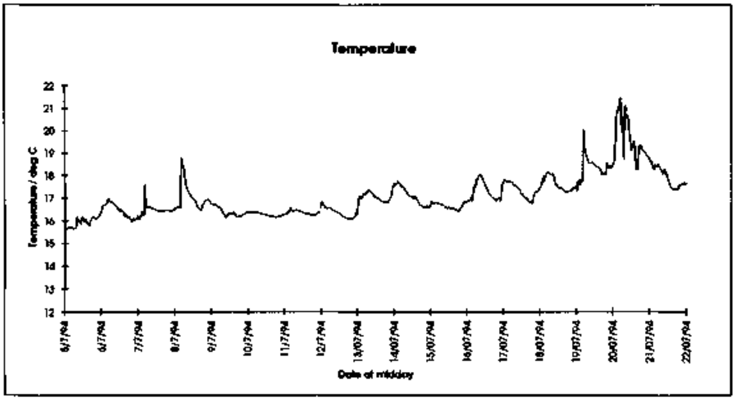
Checks on the quality of field and laboratory data were performed routinely. In the laboratory, independently prepared standards of known concentration were analysed along with the samples, and the sample results were accepted if they fell within a pre-determined range. No problems were encountered.

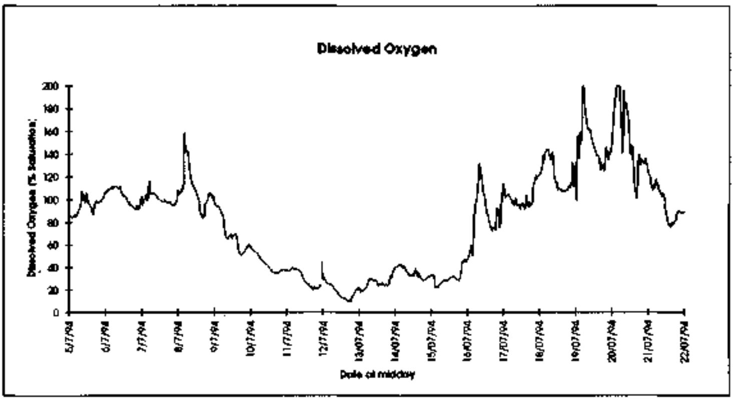
For field data the instrumentation was calibrated on a weekly or fortnightly basis. This included the field dissolved oxygen (DO) meter and the probes on the water quality sonde, which were calibrated prior to deployment; post-deployment calibration checks were made for calibration drift. The probe readings were also compared with the results for the spot-sample taken at about the same time. Winkler DO samples were taken at some sites as a check on the sonde DO readings. The sonde data were accepted if they passed these validation checks.

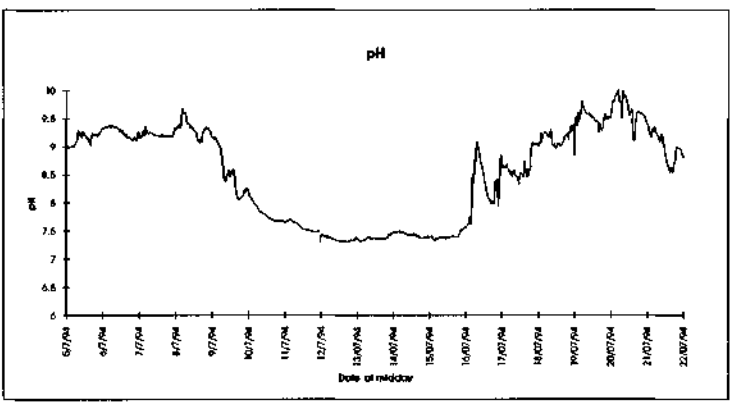
Changes in chlorophyll-a and nutrients during the period 16 March to 5 July 1994: development of the *Oscillatoria* bloom

Very little difference between spot-sampling sites was observed during this first period of observations, and data from one site have been chosen as representative of conditions in the loch (Figs 1, 2). Throughout April and May there was a slow increase in levels of chlorophyll-a, followed

FIG. 3. *(On page 207)* Plots of water temperature, dissolved oxygen and pH recorded by the water quality monitoring sonde on a buoy at the South of Reed Bower sampling site in Loch Leven, for the period 5 July to 22 July 1994.


Temperature
Temperature / deg C
22
21
20
19
18
17
16
15
14
13
12
Date at midday


Dissolved Oxygen
Dissolved Oxygen (% Saturation)
200
180
160
140
120
100
80
60
40
20
0
Date at midday


pH
pH
10
9.5
9
8.5
8
7.5
7
6.5
6
Date at midday

by a rapid increase through June, reaching a maximum of 230 micrograms per litre. This was mirrored to a considerable degree by the total phosphorus levels. A steady rise in the pH of the loch was also observed, with levels above pH 9 being recorded throughout June.

The dissolved nutrient status of the loch showed little change over the spring period, except for total oxidised nitrogen. Ammonia was consistently less than 0.1 milligrams of nitrogen per litre whereas total oxidised nitrogen displayed a steady decline from 2.5 mg N per litre in March down to less than 0.1 mg N per litre from mid-June. In the period of rapidly increasing chlorophyll-a levels the total and dissolved silica displayed a steady increase. Soluble reactive phosphorus was less than 2 micrograms P per litre on most sampling occasions from mid-May, whilst total dissolved phosphorus was between 10 and 20 micrograms per litre. As previously stated there was little difference in results from the three main sampling sites, suggesting that the water in the loch was well mixed. No marked difference in water temperature or dissolved oxygen was observed in the South Deep Hole profile prior to 12 July.

Throughout this spring period the water quality monitoring sondes provided a valuable insight into the behaviour of the loch. There was a clear diurnal pattern in pH, dissolved oxygen and temperature. The level of change varied according to climatic conditions. The most marked changes in pH and dissolved oxygen occurred with the biggest fluctuations in temperature. These changes were indicative of algal photosynthesis, which increased the saturation levels of dissolved oxygen in the water, whilst carbon uptake by the algae caused a drop in carbon dioxide levels and thus a rise in water pH.

Changes in chlorophyll-a and nutrients during the period 5 July to 16 August 1994: collapse of the *Oscillatoria* bloom

Through the telemetry link with the water quality monitoring buoy a marked decline in levels of dissolved oxygen was observed from 9 July onwards, heralding changing conditions in the loch. The events that took place in the summer of 1994, between 5 July and 16 August, are now described (Fig. 3).

On 8 July there was a very rapid rise in water temperature, with a corresponding increase in dissolved oxygen and pH. Over a 30-minute period the temperature rose from 16.9°C to 18.8°C, the percentage saturation of dissolved oxygen rose by 48% to a maximum of 158 per cent saturation and the pH, which was already high, rose from 9.36 to 9.68. These values appear to represent a peak in photosynthetic activity by algae.

The peaks occurred around 1600 hours, the approximate time of the diurnal peaks observed on previous days, but were much more marked than previously. An overnight decline was observed and the rise in values on 9 July was limited, and from 0915 hours there was a drop in all three variables. Over the following three days a diurnal fluctuation was observed but with an overall downward drift until the afternoon of 12 July, when dissolved oxygen was in the region of 20 to 30 per cent saturation and the pH was 7.35.

These changes were coincident with a marked reduction in chlorophyll-a values, which had climbed to 230 micrograms per litre by 5 July, falling to approximately 70 micrograms per litre on 12 July (Fig. 2). The low levels of dissolved oxygen and pH were maintained until 16 July, with dissolved oxygen levels as low as 10 per cent saturation occurring in the early morning (0500-0600 hours). The pH remained fairly constant at around pH 7.35 (Fig. 3).

On 16 July, after about a week with low levels of dissolved oxygen saturation and circumneutral pH values, evidence of a resurgence of photosynthesis was observed. Dissolved oxygen rose from 47 per cent saturation at 1200 hours to 132 per cent by 2000 hours, with a corresponding rise in pH from 7.55 to 9.05. This effectively marked the end of the perturbations caused by the crash of the *Oscillatoria* bloom.

Possible causes of the collapse of the algal bloom

The rising trend of chlorophyll-a values (Fig. 2) began to slow around 21 June, shortly after total oxidised nitrogen effectively became exhausted in the loch (Fig. 1). Like most phytoplankters, *Oscillatoria* is unable to fix atmospheric nitrogen (Steinberg & Hartmann 1988). The collapse of the algal bloom appears likely to have been caused by this factor, perhaps triggered by the peak of photosynthesis noted on 8 July. The conjunction of these two events appears to be similar to conditions in the summers of 1968 to 1971 when *Oscillatoria* was last present as a major component of the phytoplankton (Bindloss 1974; Holden & Caines 1974). The removal, from the water column, of a substantial biomass of *Oscillatoria* (and the other phytoplankters present - green algae and diatoms) was associated with order of magnitude increases in the concentrations of soluble reactive phosphorus, total dissolved phosphorus, and ammonia. Dissolved silica, in contrast, declined steeply from 12 July to 2 August. Whether this was due to uptake by rapidly growing diatoms or a chemical effect is not yet clear.

Following the crash of the algal bloom, both of the deep "holes" in Loch Leven displayed a sharp dissolved oxygen gradient, down to less than 5 per cent saturation at 20-metres depth. This persisted into early August. Under such conditions further increases in the dissolved phosphorus concentration might be expected, and samples from 20-metres depth did confirm significantly raised concentrations compared with surface samples.

The nutrients at the sluices have shown raised levels compared to other surface samples on some occasions since the algal crash; it may be that water flows from the South Deep Hole site directly to the sluices without much mixing. This may also explain the only noted fish kill that took place throughout this interesting period, in the afternoon of 13 July. This fish kill occurred downstream of the sluices after they had been raised, allowing a greater volume of water to flow out of the loch. Brown trout *(Salmo trutta)* and rainbow trout *{Oncorhynchus mykiss)* were killed in the long canal-like "cut" downstream from the loch; the actual number of mortalities is not known because some were carried away by the high volume of released water, but the total killed was probably less than a hundred fish. Brown trout within the loch presumably accommodated to the situation by seeking out areas with higher oxygen levels, e.g. near inlets or in turbulent areas, and by restricting their oxygen consumption for example, by reduced feeding and swimming.

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