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Deliverable No. 80

Using automatic monitoring to quantify the impact of short-term changes in the weather on the dynamics of lakes

Previous title: Report on the impact of short-term changes in weather patterns on lake stability focusing on extreme events and using high-resolution data from automatic monitoring stations in selected lake districts Task 2.1).

Now incorporating Deliverable 151: Report on the response of lakes to extreme events (Task 3.2)

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(Authors: D G George and I Jones, CEH. Additional material: M. A. Rouen, Lakeland Instrumentation)

<table>
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<th>Dissemination Level (tick appropriate box)</th>
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<td>PU</td>
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1. Introduction

It is now clear that the world’s climate is changing at an unprecedented rate. The globally averaged air temperature increased by 0.6 °C in the last century and is projected to increase by at least 1.4 °C by 2100. Weather patterns are also becoming increasingly variable with floods and droughts becoming more common. These changes have already influenced the physical dynamics of lakes throughout Europe and will have a major effect on the way we manage our water resources in the coming decades. Automatic monitoring systems provide the ideal means of recording the responses of lakes to short-term changes in the weather. In the 1990’s, engineers from the Institute of Freshwater Ecology (Windermere, UK) designed and built a range of automatic stations that could be deployed on lakes to monitor their response to short term changes in the weather (Rouen et al., 19xx). Upgraded versions of these Automatic Water Quality Monitoring Stations (the AWQMS Mk II) were later deployed in Europe to support two major projects funded by the European Commission. The first project (REFLECT) used these stations to study the climatic responses of lakes in the UK, Ireland, Sweden and Germany. The second project (CLIME) used the stations to support physical modelling studies in a number of different lakes. These AWQMS2 units have proved very reliable and are still being used to acquire data from a number of sites in Northern, Western and Central Europe. They were, however, technically quite complex and required visits to clean sensors and replace batteries at least once every month.

In 2002, the Centre for Ecology and Hydrology at Windermere were commissioned to design, build and install a network of automatic stations in the UK that were easier to use and required less maintenance. The cost of building and testing these Lake Dynamics Monitoring Stations (LDMS) was covered by a grant from the Natural Environment Research Council. The funds made available by Eurolimpacs were designed to provide scientific support for a series of Case Studies that would demonstrate how these systems could be used to study the dynamic responses of lakes to extreme weather events.

In this report, we describe the technical characteristics of these LDMS units and explain how they have been used to monitor the physical dynamics of a range of contrasting lakes. Particular attention has been paid to the factors influencing the regional responses of the lakes and their sensitivity to short-term changes in the weather. A detailed account of the AWQMS2 units deployed in Europe has been provided by Rouen et al. (2005). The design of the LDMS units is based on the same principles, but the new units consume less power and can be left unattended for longer periods of time. Since most of the staff associated with this development of these systems have now left CEH, the responsibility for the management of these stations is now shared by several research groups operating in the UK. At the time of writing, four of these stations have been allocated to Eurolimpacs sites and four to new sites in Wales and the north of England. The Eurolimpacs sites are Loch Leven, Loch Lomond and the Round Loch of Glenhead in Scotland and Llyn Conwy in Wales. Most of the examples presented here are based on data acquired in the English Lake District but we include some comparisons with a lake in Ireland and some example results from the Round Loch of Glenhead.

2. Objectives of Sub-task

1. To design and construct a prototype Lake Dynamics Monitoring Station (LDMS) that can be used to monitor the physical responses of a lake to short-term changes in the weather.
2. To construct, test and deploy a network of LDMS units and use these stations to support a range of climate-related studies in the UK.
3. To collate and analyse the high-resolution data acquired by the LDMS units.
4. To produce a report on the technical performance of the LDMS units to illustrate the value of automatic monitoring in freshwater lakes and reservoirs.
3. The development of automatic monitoring stations at CEH Windermere

In the past ten years, the Engineering team at Institute of Freshwater Ecology (then the Centre for Ecology and Hydrology) developed a number of automatic lake monitoring stations to support a range of scientific studies in the UK and mainland Europe (Table 1). The first stations (‘Automatic Water Quality Monitoring Stations’ AWQMS Mk I) were designed to support an EU ‘LIFE’ project where units were installed on two lakes in the UK, two loughs in Ireland and a reservoir in Spain. A few years later, upgraded versions of the stations (the AWQMS Mk II) were deployed on three European lakes to support the REFLECT projects (the Response of European Freshwater Lakes to Environmental and Climate Change). These stations were further enhanced for a second ‘LIFE’ project and used to support the Framework V project CLIME (Climate and Lake Impacts in Europe). In 2003, the Natural Environment Research Council (NERC) funded the development of the new low maintenance Lake Dynamics Monitoring Stations described in this report. Two of these units were deployed in Europe but most were used to expand the network of stations operating UK. The cost of building, testing and installing these stations was met by the NERC but the running costs were covered from a variety of sources including this ‘climate impacts’ study in Eurolimpacs. A preliminary report on the LDMS stations used in Eurolimpacs was prepared in 2005. This report included a more detailed technical description of these systems together with a series of examples to illustrate the way in which these systems are being used to support a number of climate-related investigations.

<table>
<thead>
<tr>
<th>Period</th>
<th>Instrument</th>
<th>Project</th>
</tr>
</thead>
<tbody>
<tr>
<td>1995 – 1997</td>
<td>Automatic Water Quality Monitoring Station (AWQMS Mk I)</td>
<td>LIFE I</td>
</tr>
<tr>
<td>1998 – 2000</td>
<td>Automatic Water Quality Monitoring Station (AWQMS Mk II)</td>
<td>REFLECT</td>
</tr>
<tr>
<td>1999 – 2002</td>
<td>Automatic Water Quality Monitoring Station (AWQMS Mk II)</td>
<td>LIFE II</td>
</tr>
<tr>
<td>2003 – 2005</td>
<td>Lake Dynamics Monitoring Station (Mk I)</td>
<td>CLIME</td>
</tr>
<tr>
<td>2004 – 2006</td>
<td>Lake Dynamics Monitoring Station (Mk II)</td>
<td>Eurolimpacs</td>
</tr>
</tbody>
</table>

4. The design of the Lake Dynamics Monitoring Stations

4.1. Design Aims

The station should be suitable for deployment in a range of lakes and be sufficiently rugged to withstand high winds and temperature extremes. It should be able to record readings a high frequency (at least every 5 minutes) from an array of meteorological and water quality sensors. It should be able to accommodate additional sensors/instruments using either analogue or digital interfaces. The station should not require frequent routine servicing, the power consumption should be minimised and controlled in such a way that selected sensors could be powered down between measurements and switched off under fault conditions. The station should be able to monitor its own performance and record this diagnostic information and relay this information to an engineer based at a remote site.
4.2. The overall design

The schematic diagram in Figure 1 shows the basic features of the Mk II version of the Lake Dynamics Monitoring Stations. In functional terms, the system is based on two components: the Buoy Station deployed on the lake and the Remote Station used to download the acquired data to a remote site. An operator can use the Remote Station (e.g. located in the laboratory) to contact the buoy station to retrieve recorded data or to examine measurements in real-time.

4.3. The Buoy Station

The Lake Dynamics Monitoring Station comprising the Remote Station and Buoy Station.

The schematic diagram in Figure 2 shows the Lake Dynamics Monitoring Station, Buoy Station.
Figure 2 shows the typical configuration of the buoy station. The buoy station comprises:

- A toroidal buoy secured to the lake bed using a three point mooring.
- Stainless steel housings mounted on the buoy containing rechargeable sealed lead-acid batteries to power the station and the stations electronic systems to record data and telemeter stored and real-time data via the GSM (cellphone) network.
- A mast supporting meteorological sensors and GSM Antenna
- A selection of water quality sensors suspended in the water column from the centre of the buoy.

The buoy

The buoy is custom manufactured by Trelleborg CRP Ltd. The mechanical design of the station is based on the proven configuration used in earlier versions. Some of the stations deployed under earlier projects have been deployed continuously for more than a decade, without any major mechanical failures. A schematic diagram of the buoy is shown in Figure 3. Its shape is toroidal with diameter of 1.70m. The diameter of the central opening is 1.00m and the height of the buoy is 0.50m. Its weight in air is 206kg. The buoy is made using closed-cell polymer foam and is coated in a durable elastomer. This coating is very unlikely to be punctured, but even if it were to be damaged, the closed-cell internal construction would prevent the buoy from losing significant buoyancy. The buoyancy is approximately 570kg (including all metalwork, but excluding the sensors and instrument assemblies).

![Figure 3](image)

**Figure 3** The mechanical design of the LDMS Buoy.
The toroid is fitted with a metal underframe which lowers the centre of gravity of the buoy and can also be used to support additional counter-weights (e.g. concrete blocks). The buoy is moored using a three point mooring where the chains/cables are attached to eyelets fixed to the bottom of the underframe. This configuration ensures that the centre of gravity of the moored station is lowered still further, minimises the rotation of the buoy and prevents the mooring chains from becoming entangled with the sensor cables.

The station is designed to be service from a small boat and the batteries can be changed and the sensors checked without boarding the buoy. Attention has been paid to the weight of batteries and any other items that may need to be retrieved on a service visit.

The selected sensors

Table 2 lists the range of sensors fitted to the LDMS. The combination used at a particular installation depends on the characteristics of the site and the scientific requirements. The sensors were selected from a range of commercial options, after careful evaluation supplemented in many cases by comparative tests. The current selection can be replaced with improved or additional sensors as and when these become available.

### TABLE 2 Specification of the sensors included in the Mk II version of the Lake Dynamics Monitoring Station

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>SENSOR TYPE</th>
<th>MODEL</th>
<th>MANUFACTURER</th>
<th>RANGE</th>
<th>ADAPTATION</th>
<th>NOTES</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Wind Speed</strong></td>
<td>Cup anemometer</td>
<td>A100L2</td>
<td>Vector Instruments</td>
<td>0 to 50m.s⁻¹</td>
<td>Military-grade connector fitted</td>
<td>Wind Speed is measured as a height of 2.5m above the water surface.</td>
</tr>
<tr>
<td><strong>Wind Direction</strong></td>
<td>Wind vane (Potentiometer)</td>
<td>W200P</td>
<td>Vector Instruments</td>
<td>0 to 360°</td>
<td>Military-grade connector fitted</td>
<td>The Wind Vane is aligned on deployment of the buoy station. Accuracy of readings depends on stability of buoy.</td>
</tr>
<tr>
<td><strong>Barometric Pressure</strong></td>
<td>Semiconductor strain gauge</td>
<td>PDCR1830</td>
<td>0 to 2000mBar</td>
<td>Military-grade connector fitted</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Air Temperature</strong></td>
<td>Platinum resistance sensor</td>
<td>SKI2012 (combined Air Temperature and Relative Humidity sensor)</td>
<td>Skye Instruments</td>
<td>-40°C to +60°C</td>
<td>Military-grade connector fitted. Internal wiring altered to remove ground loop in this application.</td>
<td>Prolonged exposure to very high humidity conditions may limit the life of the humidity sensor.</td>
</tr>
<tr>
<td><strong>Relative Humidity</strong></td>
<td>Semiconductor sensor</td>
<td>SKH2012</td>
<td>Skye Instruments</td>
<td>0 to 100%</td>
<td>Military-grade connector fitted</td>
<td></td>
</tr>
<tr>
<td><strong>Photo Flux Density</strong></td>
<td>Photodiode Quantum Sensor</td>
<td>LI-192SZ</td>
<td>Licor</td>
<td>0 to 3000 µmol.m⁻².s⁻¹</td>
<td>Military-grade connector fitted</td>
<td></td>
</tr>
<tr>
<td><strong>Solar Radiation</strong></td>
<td>Pyranometer</td>
<td>CM6B</td>
<td>Kipp &amp; Zonen</td>
<td>0 to 2000 W.m⁻²</td>
<td>Military-grade connector fitted</td>
<td></td>
</tr>
<tr>
<td><strong>Water Temperature Structure</strong> (Water Column Stability)</td>
<td>Chain of Platinum Resistance sensors (up to 12 sensors)</td>
<td>-</td>
<td>Labfacility</td>
<td>-5 to ~40°C</td>
<td>Individual Sensors assembled into a chain and terminated.</td>
<td></td>
</tr>
<tr>
<td><strong>Conductivity</strong></td>
<td>4 Electrode Cell</td>
<td>CMCS/</td>
<td>LTH Electronics</td>
<td>0 to 100mS.cm⁻¹</td>
<td>Military-grade connector fitted. PVC cable replaced with polyurethane cable</td>
<td></td>
</tr>
<tr>
<td><strong>Water Temperature (for temperature compensation of Conductivity sensor)</strong></td>
<td>Platinum resistance sensor</td>
<td>-</td>
<td>Labfacility</td>
<td>-5 to ~40°C</td>
<td>Military-grade connector fitted</td>
<td></td>
</tr>
<tr>
<td><strong>pH</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Dissolved Oxygen Sensor</strong></td>
<td>Clark Cell</td>
<td>Quanta</td>
<td>Hydrolab</td>
<td>pH 1 to 14</td>
<td>Military-grade connector fitted</td>
<td>Station can operate with alternative models of Sonde (e.g. YSI 6000, YSI6600EDS, YSI6920)</td>
</tr>
<tr>
<td><strong>Chlorophyll a</strong></td>
<td>Fluorimeter</td>
<td>Minitracks (C)</td>
<td>Chelsea Instruments</td>
<td>0 to 1000 µg/L (in acetone)</td>
<td>Military-grade connector fitted</td>
<td>12V supply controlled by data logger</td>
</tr>
<tr>
<td><strong>Suspended solids</strong></td>
<td>Nephelometer</td>
<td>Minitracks (N)</td>
<td>Chelsea Instruments</td>
<td>0 to 100 FTU</td>
<td>Military-grade connector fitted</td>
<td>12V supply controlled by data logger</td>
</tr>
<tr>
<td><strong>Coloured Dissolved Organic Matter</strong></td>
<td>Fluorimeter</td>
<td>SUVF</td>
<td>Seapoint Inc</td>
<td>Configurable between 0 to 50 µg/L and 0 to 1500 µg/L</td>
<td>Military-grade connector fitted</td>
<td>12V supply controlled by data logger</td>
</tr>
</tbody>
</table>

The meteorological sensors

For certain parameters (e.g. wind measurements) some compromise in performance is unavoidable due to the nature of the buoy platform. The wind instruments manufactured by Vector Instruments are developments of the ‘Porton’ designs. In this design, the rotation of the cups is measured using a slotted optical disc arrangement. This type of sensor is very reliable and consumes very little electrical current.
The height at which wind speed is measured is of necessity different to that used in a land-based installation. The standard height of measurement for a terrestrial meteorological stations is 10m. The anemometer on the buoy is mounted at height of 2.5 m. This was considered to be high enough for uninterrupted measurement but low enough for servicing without compromising the physical stability of the buoy. Wind direction is recorded as the direction of the wind vane relative to the alignment of the instrument casing. At the time of deployment, the instrument casing is aligned using a compass to ensure that wind vane output coincides with wind direction referenced to magnetic north. Although the three point mooring constrains any rotation of the buoy around a vertical axis, it cannot eliminate this movement and hence the accuracy of the individual direction measurements is limited by this short-term variations.

There are two light measurements recorded by the station: the solar radiation measured using a pyranometer recording shortwave radiation (i.e. incident visible and infra-red radiation) as energy per unit area per unit time and photon flux density, the number of incident photons in the visible spectrum per unit area per unit time). Although these two measurements are related, they are not identical. Solar radiation is of particular interest for physical studies of heat transfer, while photon flux density is used by biologists when considering the light available for photosynthesis. Both sensors are mounted high on the mast to ensure that they cannot be shaded by any part of the station.

Air temperature and relative humidity are measured using PRT temperature sensor and semiconductor relative humidity transducer housed in a louvered solar screen. In common with all non-aspirated sensors, errors of several degrees Celsius can occur on very still days with bright sunlight due to solar heating of the louvered screen. Such conditions are quite rare in the UK but aspirated sensors could be fitted to stations deployed in very sunny locations. Tests have shown that prolonged exposure of the relative humidity sensors to high humidity conditions can result in a progressive decline in performance. This problem can be avoided if the sensors are exchanged from time-to-time and new units fitted when the units become unreliable.

Barometric pressure is recorded using a pressure transducer based on a semiconductor strain gauge, chosen for its reliability, accuracy and low hysteresis. No special concerns arise from this being buoy mounted rather than fixed at a terrestrial site.

The water quality sensors

The temperature structure of the water column if recorded using a chain of up to 12 temperature sensors. These are assembled specially for each site with the number of sensors and spacing between them chosen according to the depth of the water column and the mixing characteristics of the lake. The sensors are high-precision platinum resistance thermometers (PRTs), encapsulated in a stainless steel sheath. A PTFE cable connects each sensor to a termination box on the buoy station. This enables individual sensors to be replaced as necessary. A four-wire measurement of each sensor is made, which enables any measurement errors that could result from cable or contact resistance to be completely compensated.

One or two sondes (multi-parameter water quality instruments) can be fitted where high-resolution pH and dissolved oxygen measurements are required at a particular site. These sensors, however, require regular cleaning and recalibration so are only fitted at sites where the stations can be serviced at weekly or fortnightly intervals. The LDMS units in the UK were all fitted with Hydrolab Quanta sondes but the station can also accommodate a range of other sondes which use the SDI-12 data interface (e.g. most models manufactured by YSI Incorporated including the YSI 6000, YSI6600EDS and YSI 6920).

Although conductivity is offered as a standard option on the Quanta sonde the resolution of these sensors is too low for most of the lake sites selected in the UK. All the units have therefore been fitted with a separate, high-resolution conductivity. This is a simple sensor containing 3 graphite ring electrodes
mounted within an epoxy housing. The cell constant is 1.0 meaning that the measured conductance corresponds directly to the conductivity of the sample. A dedicated PRT sensors is attached to the conductivity sensor to record the temperature of the water at the sampling depth to enable the conductivity measurements to be corrected to a particular temperature (25°C).

The station also supports sensors that provide three types of optical measurements:

- **A nephelometer** that measures the optical scatter of light at a wavelength 470nm - used as a general measure of the concentration of all suspended particles.
- **A chlorophyll fluorometer** that measures the fluorescence of the water at a wavelength of 685nm when excited with light at 470nm - used as a measure of the biomass of phytoplankton.
- **An ultraviolet fluorometer** measuring fluorescence of the water at a wavelength of 685nm when excited with light at 370nm - used as a measure for chromophoric dissolved organic matter.

All these sensors require regular calibration with date-specific measurements. At most sites, the relationship between the optical measurement and the variable of interest will change from date to date to month and from year to year. A full discussion of these calibration procedures is beyond the scope of this report. They include the regular collection of water samples for phytoplankton counts and pigment analysis, the gravimetric determination of suspended solids and the measurement of dissolved organic carbon by established chemical methods.

**Storing the data**

Data is recorded using a Campbell Scientific CR10X data logger loaded with a custom written control program. In this logger, the memory used to store data is divided into two areas each configured as two ‘circular buffers’. One area is used to store hourly and daily summary data and the other to store high resolution data (measurements taken every four minutes). Once the allocated storage area is full, the oldest data is overwritten. In practice, several years worth of hourly and daily summary data can be stored before any such data is overwritten. In a typical installation, about three weeks of high resolution data can be stored before the overwriting process is initiated.

**Retrieving the stored data**

Stored data can be retrieved on-site by plugging a portable PC directly into a connector on the station. The portable PC runs a program supplied by Campbell Scientific that retrieves the data and stores it as a comma separated value (csv) file that can be imported into almost any spreadsheet or database software. Alternatively, the station can be contacted from any remote location where there is either a telephone point or a GSM (cellphone) link. A GSM data modem is fitted on the buoy, which can be called in a similar manner to a mobile phone. Rather than a voice call, however, the station is called using a PC equipped with a standard telephone modem and, once communication is established, data can be retrieved in the same manner as using a portable PC directly connected to the buoy station.

As well as retrieving data, a directly connected or remote PC connected by the GSM network can be used to examine measurements in real-time and (if necessary) to update the control software running on the buoy. A major advantage of this facility to connect to the station remotely is that engineers can also check the performance of the station and diagnose most problems without having to arrange a site visit.

**Powering the station**

The station is powered by 12 sealed, lead-acid batteries each housed in a carry case and equipped with a simple connector to enable them to be exchanged easily on a service visit. The retrieved batteries are then recharged for a subsequent visit. Optionally, a solar panel can be attached that will maintain the charge in the batteries, either eliminating the need to exchange them or greatly reducing the frequency.
Diagnostic features
In addition to recording measurements of scientific interest, the station also records a range of technical parameters (e.g. battery voltage, current consumption, operating temperature etc). These measurements can be invaluable for establishing the cause of any fault and for tracking any changes in the configuration of a particular installation.

Servicing the station
Most of the sensors fitted to the Mk II LDMS require relatively little servicing. For stations not equipped with any sondes or optical sensors the service interval can be as long as three months. Stations fitted with a sonde, a fluorimeter or a nephelometer require more frequent maintenance. If a sonde is fitted, the pH and dissolved oxygen sensors will regular cleaning and recalibration. The service interval for the optical instruments depends on the productivity of the lake, the depth of the sensor and the underwater light climate.

4.4. Remote Station
The remote station consists of a PC connected to a conventional telephone modem. The PC is used to run one of three software packages produced by Campbell Scientific Ltd: PC208W, PC400 or LoggerNet. All these packages allow the operator to establish a connection to the buoy station, to retrieve stored data and view measurements in real-time. The most sophisticated package (LoggerNet) has facilities for managing and checking the output from a network of recording stations.
5. **Testing the Lake Dynamics Monitoring Stations**

A prototype version of the Lake Dynamics Monitoring Stations was deployed on Bassenthwaite Lake (Cumbria) in 2004. The sensors and the logging system were very similar to those used in the final version but the instruments were mounted on a larger toroidal buoy reclaimed from another application. Figure 4 shows some of the high-resolution data acquired by this prototype unit.

![Diagram](image)

**Figure 4** Some example LDMS data from Bassenthwaite Lake (August 2004).

Bassenthwaite Lake is too shallow to remain permanently stratified during the summer. Short periods of stratification are, however, common and have important consequences for the chemistry and biology of the lake. The top panel in the figure shows the vertical variations in the water temperature recorded by the platinum resistance thermometers (PRT’s) suspended in the water column. The lower panel shows the corresponding variations in the air temperature and the wind speed. The results show the effect that a relatively short period of intense mixing had on the physical stability of the water column. On the 9th of August, the wind speed only started to increase at 03:30 hours GMT but the water column was effectively mixed by 12:00 hours GMT. By late afternoon, the wind speed was in decline and some temperature variations were again apparent in the water column.
6. The construction and deployment of the Lake Dynamics Monitoring Stations

In March 2004, the design team based at CEH Windermere was disbanded and the remaining staff transferred to a new site at the University of Lancaster. The workshop facilities at Lancaster did not become fully functional until September 2004 so the construction and testing of the LDMS units for the UK network was delayed by several months. Subsequent ‘health and safety’ problems with the new workshop resulted in further delays so a significant proportion of the assembly and testing work had to be allocated to sub-contractors (principally Duddon Electronics). Eight LDMS units were assembled in 2005 and some features of the design revised to meet new operational priorities. Figure 5 shows the distribution of the LDMS units currently delivered to sites in the UK. Seven of these sites (Loch Lomond, Loch Leven, Round Loch, Esthwaite Water, Windermere South Basin and Llyn Conwy) are Eurolimpacs sites three of which are still being managed by CEH.

By the end of 2005, three of these stations were fully operational and the remaining stations were delivered in 2006. Since many of these sites are in environmentally sensitive areas, acquiring planning permission for these installations has taken much longer than anticipated. All the remaining stations have now been delivered but the units delivered to CEH Bangor and the University of Glasgow have yet to be deployed. In logistic terms, the most difficult installation was that organized by the team from University College London at the Round Loch of Glenhead. This site is remote and located in very rugged terrain so transporting the toroid and its associated steel frame proved a major challenge. In the event, all the heavy equipment was airlifted to the site and the station serviced from a portable inflatable. Figure 6a shows an LDMS unit being lowered on to the loch by the helicopter. The anchors were constructed on site by filling heavy-gauge net bags with a collection of large stones. Figure 6b shows the LDMS with all the sensors installed. Since this photograph was taken, the station has been fitted with a solar panel to charge the batteries and reduce the service interval at this difficult site.
7. Some examples of the data acquired by the LDMS

7.1. Case Study 1: The influence of basin topography on the thermal responses of lakes

Lakes located in the same area frequently respond in a coherent way to seasonal variations in the weather (George et al., 2000). Their surface temperatures are often very similar and there is usually a high degree of synchrony in the mixing events that regulate the recycling of nutrients and the succession of phytoplankton. Lakes that are very different in size may however integrate the imposed climatic signal on different time scales and respond to the variations in subtly different ways. Esthwaite Water and Bassenthwaite are two lakes situated about 40 km apart the English Lake District. Esthwaite Water has an area of 1.01 km$^2$, a mean depth of 6.4 m and remains thermally stratified throughout the summer. Bassenthwaite a surface area of 5.2 km$^2$, a mean depth of 5.3 m and stratifies intermittently during the summer. Figures 7a and 7b compare the day-to-day variations in the surface temperature of the lakes on two different occasions in 2004. In May 2004 (Figure 7a), when the lakes were well mixed, the diel variations in the surface temperature were very similar in the two lakes. In June 2004 (Figure 7b), when Esthwaite Water was stably stratified, the diel variations recorded in this lake were very much greater than those recorded in Bassenthwaite where there was more intense wind-induced mixing. These results show the extent to which the development of the seasonal thermocline influences the vertical transfer of heat. On this occasion, the surface temperature of Esthwaite Water was almost 2°C higher than recorded in the more exposed lake and the short-term variations in the day-time versus night-time temperatures were more pronounced.
Using high-resolution monitoring to show the extent to which the physical characteristics of lakes can influence their response to short-term changes in the weather. (a) The day-to-day variations in the surface temperature of Esthwaite Water and Bassenthwaite when the two lakes were relatively well-mixed. (b) The day-to-day variations in the surface temperature of Esthwaite Water and Bassenthwaite when Bassenthwaite was still isothermal and Esthwaite Water was stably stratified.
7.2. Case study 2: The coherent responses of lakes to regional changes in the weather

Lakes located on the west coast of Europe are strongly influenced by the movement of high and low pressure systems over the Atlantic. George and Taylor (1995) showed that the trajectory of these storm tracks were also regulated by the north-south movements of the Gulf Stream. In Eurolimpacs, we compared the mixing characteristics of Esthwaite Water in the English Lake District with those of Lough Feeagh on the west coast of Ireland. Lough Feeagh has a surface area of 3.9 km$^2$ and a maximum depth of 45 m, while Esthwaite Water has a surface area of 1.0 km$^2$ and a maximum depth of 15 m. Although the two lakes are more than 300 km apart they often respond in a synchronous way to the observed seasonal variations in the weather. One of the key factors influencing these ‘coherent’ responses is the synoptic distribution of pressure over the British Isles. In 1972, Lamb designed a system of weather classification that was based on the subjective analysis of daily weather maps. This has since been replaced by a more subjective automated method (Jenkinson and Collison, 1977) which generates the same synoptic categories. The classification contains eight directional types, two non-directional types and an unclassified category. The directional types (N, NE, E, SE, S, SW, W and NW) are defined according to the general direction of the air flow. The two non-directional types (A – anticyclonic and C – cyclonic) occur when high or low pressures systems dominate the UK. In summer, the dominant circulation types are the anticyclonic and the westerly (Kelly et al., 1997). The time-series Figure 8 show the way in which the short-term variations in the surface temperature of the two lakes were influenced by the relative dominance of these ‘stationary’ and ‘directional’ weather types.

Figure 8a shows the high levels of ‘coherence’ when a stable high pressure system was centred over the British Isles. The record covers the two week period between 1 June and 15 June 2004. The absolute temperatures in Lough Feeagh are much lower than those in Esthwaite Water but the day-to-day variations and the diel fluctuations were very similar in the two lakes. Figure 8b compares the day-to-day variations in the surface temperature of the two lakes at a time when frontal system was moving in from the Atlantic. The record covers the two week period between 16 July and 31 July 2004 when the surface temperatures in the two lakes were very close to their summer maxima. For the first 5 days, the two records were relatively coherent but the temperatures then diverged as the front crossed the two islands from west to east. The diel variations recorded in the two lakes were then less regular and there was a very distinct cooling of the surface water in Lough Feeagh. Lough Feeagh is a simple trough-like basin where the episodic movements of the internal seiche can have a major effect on the vertical distribution of heat. The re-distribution of temperature observed on the 21st of July could well have influenced by this entrainment effect as well as by the transfer of heat across the air-water interface and its subsequent dispersion by turbulent mixing.
Using high-resolution monitoring to study the relative responses of a lake in Ireland and a lake in the UK to the movement of weather fronts across the Atlantic. (a) The day-to-day variations in the surface temperature of Esthwaite Water and Lough Feeagh when a high pressure system. (b) The day-to-day variations in the surface temperature of Esthwaite Water and Lough Feeagh when a similar high pressure system was replaced by a warm front.

Seasonal variations in the mixing depth of a lake have a major effect on the vertical distribution of oxygen and the recycling of nutrients. In 2005, a modified version of an LDMS was installed in Esthwaite Water to monitor the seasonal variations in the mixing depth of the lake. This lake has been sampled using conventional methods for a number of years but the temperature and oxygen profiles recorded during this routine monitoring frequently miss important weather-driven events. As the lake is eutrophic and strongly stratified, there is a progressive decline in the concentration of oxygen found in deep water through the summer. Periods of episodic wind mixing may, however, reverse this trend and introduce more oxygen into the upper layers of the metalimnion. The red line in Figure 9a shows the variation in the oxygen concentration at a depth of 7 m recorded by routine sampling during the summer of 2006. The oxygen concentration was already low on Julian Day 160 and continued to fall until Julian Day 220 when it rose to reach a maximum of 7.2 mg.L\(^{-1}\) on Julian Day 248. The broken blue line in Figure 9a shows the mixed depths calculated from the temperature profiles recorded during routine sampling. These measurements imply that the mixed depth never fell below 6 m so cannot explain the observed increase in the 7m oxygen concentration. The solid line in Figure 9a shows the mixed layer depth calculated from the water temperature data acquired by the automatic monitoring station. These measurements are taken at two minute intervals and then averaged to produce hourly means. Here, these values have been combined to produce a daily series of average mean depths. These high-resolution records show that the mixed depths were, in fact, almost continuously below 6 m for the critical period between Julian Day 220 and Julian Day 250. The reason for the re-oxygenation at 7 m depth is now clear; the waters there having been entrained into the mixed layer and the oxygen replenished through contact with the atmosphere. Similarly, the reasons for the continued depletion of oxygen between Julian Day 160 and Julian Day 220 also become clear. During this period, the mixing depth never exceeded 6 m and was frequently less than 4 m.

Figure 9b shows the percentage difference between the mixed depths estimated from the automatic station data and those estimated from the routine measurements. Here, daily mixed depths have been derived from the fortnightly measurements by simple linear interpolations. The percentage error, \( E \), of this estimate was then calculated by:

\[
E = \left[ \frac{z_{mi} - z_{mb}}{z_{mb}} \right] \times 100\%\, ,
\]

where \( z_{mb} \) is the daily mixed depth calculated from the monitoring station and \( z_{mi} \) is the daily mixed depth as interpolated from the fortnightly profiles. These estimates show that the error can either result in overestimates or underestimates. The average error calculated for the period of observation is approximately 25 % but differences in excess of 100% were recorded around Julian Day 185. This example highlights the danger of relying on infrequent measurements to quantify the physical and chemical characteristics of a lake. The measurements acquired at fortnightly intervals provide a reasonable measure of the average depth of the mixed layer but cannot resolve the mixing episodes that have such an important effect on the dynamics of the lake.
FIGURE 9

a) Time-series showing the fortnightly variation in the oxygen concentration at 7m, the fortnightly variations the mixed depth and daily estimated of the mixed depths acquired by automatic monitoring. (b) Time-series showing the percentage difference in the mixed depths estimated by routine and automatic monitoring. Measurements recorded in Esthwaite Water between the middle of June and the middle of September 2006.
7.4. Case Study 4: The impact of short-term changes in the weather on the Round Loch of Glenhead

Automatic systems, of the kind described here provide the only means of monitoring the responses of remote mountain lakes to short-term changes in the weather. These changes often have a disproportionate effects on the dynamics of such lakes. Periods of heavy rain can give rise to episodic changes in the chemistry of the water whilst a few hours of strong wind can re-suspend and re-distribution surface sediments from the shallow littoral. The Round Loch of Glenhead is one of the most intensively studied mountain lakes in the UK. Field visits to the site are normally organized at quarterly or, at best, monthly intervals. In November 2005, an LDMS unit was installed in the lake at a central location and has since provided a continuous record of the loch’s response to changes in the weather. The Round Loch of Glenhead (Figure 10) lies at 295 m altitude in the Galloway region of south-west Scotland. The loch covers an area of 12.5 ha, has a maximum depth of 13.5 m and drains a catchment of 95.1 ha. Although the loch is quite exposed to the effects of wind-mixing periods of intense thermal stratification have occasionally been recorded at the height of summer. In this CASE study, we used the LDMS to monitor the frequency and intensity of these stratification events and quantify their effect on the growth of phytoplankton.

Figure 11 shows a time-series of three measurements recorded by the Round Loch buoy during the summer of 2006 (1 May to 31 August). The figure shows the hourly variation in a) the mean square of the wind speed (a measure of the wind stress) b) the chlorophyll fluorescence (a measure of the biomass of phytoplankton) and c) the vertical variations in the temperature of the water column. The most striking feature of this long-term record is the intensity and duration of the stratification episodes. The most pronounced variations were those recorded between the 3rd and the 9th of July and between 16th of July and 31st of July. On both occasions, there was a marked increase in the surface temperature with temperatures in excess of 20°C being recorded for several consecutive days. The phytoplankton biomass measurements recorded during this period showed that these periods of intense stratification had a pronounced effect on the growth of phytoplankton. The highest chlorophyll concentrations were recorded in mid July when a well-defined thermocline was present at a depth of 3 m and the surface temperature reached an annual maximum of 24°C.
a) Mean squared Wind Speed (m$^2$.s$^{-2}$)

![Graph showing mean squared wind speed](image)

b) Chlorophyll fluorescence (arbitrary units)

![Graph showing chlorophyll fluorescence](image)

c) Temperature structure

![Graph showing temperature structure](image)

**FIGURE 11** Time-series for the summer months of 2006 (1 May to 31 August) at the Round Loch of Glenhead showing the hourly variation in a) the mean square of the Wind Speed, b) the Chlorophyll fluorescence and c) temperature structure of the water column shown as a surface chart.
7.5 Case Study 5: The impact of an ‘extreme’ mixing event on the seasonal succession of phytoplankton in Esthwaite Water

Year-to-year variations in the frequency and intensity of wind mixing have major effects on the growth and succession of phytoplankton in thermally stratified lakes. Reynolds (1993) has shown that this pattern can be explained by the interaction of two key processes:

a) An autogenic process, where a number of different ‘functional types’ dominate the phytoplankton community in an ordered sequence.

b) An allogenic process, where periodic disturbances disrupt this sequence and return the phytoplankton community to a less stable state.

In most lakes, the critical factor influencing the switch from an autogenic to an allogenic pattern of succession is the timing and intensity of wind-induced mixing. Automatic monitoring stations, like the LDMS, provide an ideal means of recording the changing frequency of these mixing events and quantifying their effect on the development of phytoplankton. In small lakes, like Esthwaite Water, quite short lived mixing events can have a major effect on the qualitative composition of the phytoplankton. It is therefore essential to acquire reliable, high-resolution records that can be downloaded and analysed in near-real time. Fig. 12 shows an example of the lake temperature / mixing records acquired from Esthwaite Water in 2004, a year when an ‘extreme’ mixing event had a major effects on the summer development of the phytoplankton. The raw measurements were acquired at 4 minutes intervals and the results stored as hourly averages. The multi-coloured lines show the temperatures measured at the different depths and the red line the stability of the water column.

![Fig. 12](image_url)
The stability values have been derived using the procedure described by Schmidt (1928) and show the effect that a relatively short period of wind-induced mixing had on the physical stability of the water column in mid-summer. A detailed account of the biological consequences of this ‘extreme event’ is outside the scope of this report. In mid-summer, the phytoplankton community in Esthwaite Water is typically dominated by the blue-green alga *Aphanizomenon flos aquae*. This species floats to the surface in calm weather and often forms dense patches that accumulate in the more sheltered bays (George, 1992). In 2004, high concentrations of *Aphanizomenon* were recorded in the lake on the 27th of June but these concentrations declined after the mixing episode and remained for the following weeks. On the 27th of June more than 2000 filaments of *Aphanizomenon* were counted in the routine samples but by the 11th of July the numbers had declined to around 900 filaments per ml. Since this decline was recorded several days after the mixing event, the collapse must reflect a real reversal in the normal successional process. The associated increase in the epilimnetic volume will also have had some effect but only in the first few days of the mixing episode. Phytoplankton succession patterns in Esthwaite Water have now been monitored for over forty years. Summer mixing events of this magnitude appear to be coming increasingly common in Esthwaite Water. Only one mid-summer mixing event was recorded in the 1970’s but at least three were recorded in the 1990’s.

Conclusions

The automatic monitoring systems described here are the culmination of more than ten years of intensive development work. Both the sensors, the control devices and the communication systems have been upgraded at regular intervals to take advantage of new technical developments. Eight LDMS units are currently operating in the UK and two more are ready for deployment. The latest version of these monitoring systems has proved exceptionally reliable and requires less frequent servicing than the original AWQMS units. The case studies presented here illustrate some of the ways in which these instruments are being used to support a range of climate-related studies in the UK. The first two case studies demonstrate how these systems have been used to quantify the sensitivity of lakes to short-term changes in the weather and explore the synchronous patterns that develop within particular geographic region. The third case study highlights the uncertainties associated with infrequent measurements whilst the fourth demonstrates the value of deploying these systems on a very remote lake site. Much of the short-term variability measured by these instruments can be directly related to changes in the frequency and intensity of ‘extreme’ weather events. The fourth case study provides a particularly good example of the limnological consequences of an ‘extreme’ mixing event. Short-lived events of this kind influence the seasonal dynamics of these lakes in direct and indirect ways. They have an immediate effect on the thermal characteristics of the lakes and the recycling of nutrients and an indirect effect on the growth of plankton and the stability of the ecosystem. Limnologists in the US have recently established a network of lake monitoring stations (GLEON) to explore the ecological consequences of these climate-related effects (www.gleon.org). The automatic monitoring stations described here already form part of an informal European network that could be formalized and expanded to meet the challenges posed by the changing climate.

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