Llyn Tegid Monitoring Station 2014

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NRW Evidence Report No. 62

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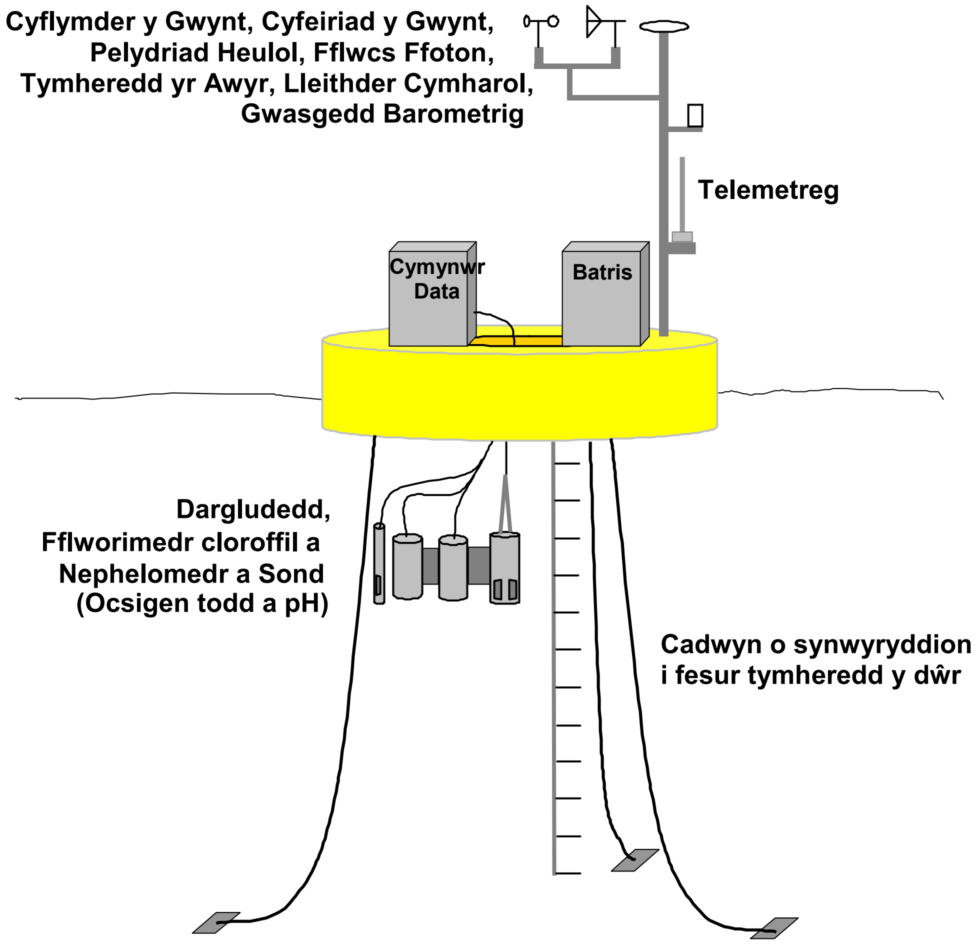
1. Crynodeb Gweithredol

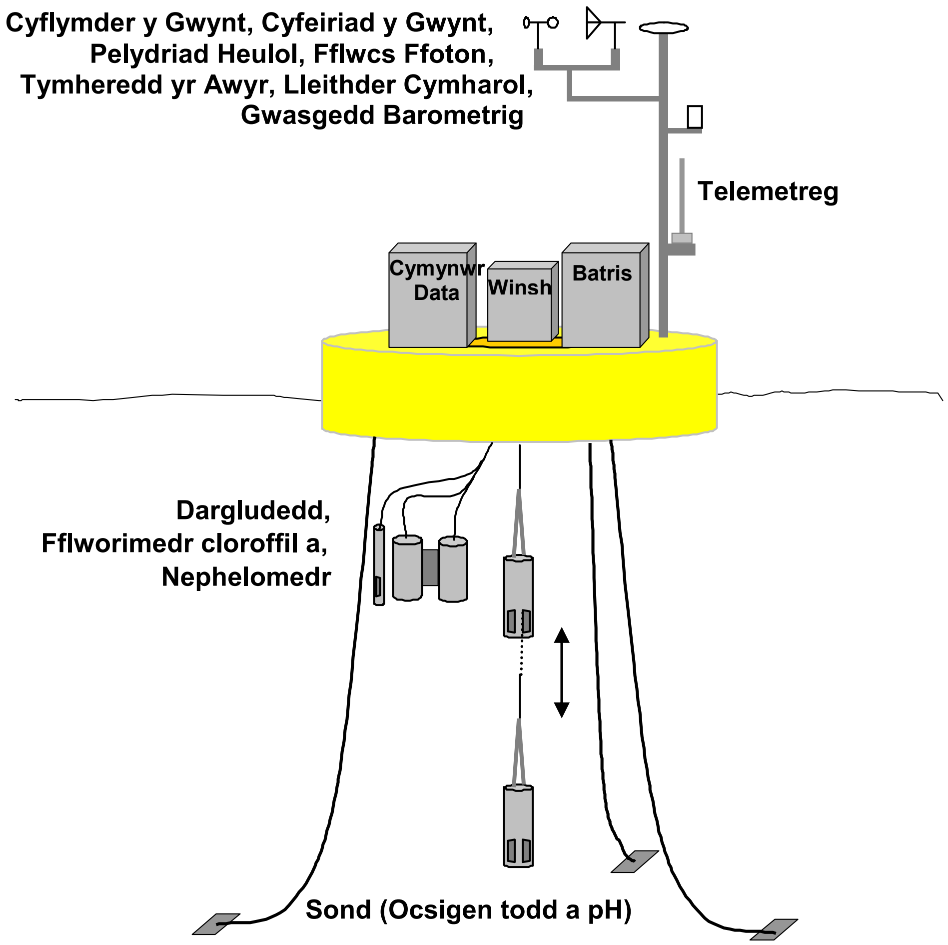
Y mae'r 'Lake Dynamics Monitoring Station' (LDMS) a osodwyd ar Lyn Tegid wedi bod yn ei lle ers 2006 ac yn dechrau dioddef o draul amser. Yn 2014 niweidiwyd rhai o'r sensorau a ddefnyddir i fesur tymheredd y dŵr wedi storm o wynt a dechreuwyd ar y gwaith o gynllunio gorsaf newydd. Ariannwyd yr orsaf newydd gan Gyngor yr Amgylchedd Naturiol fel rhan o'i chefnogaeth i Ganolfan Ecoleg a Hydroleg yng Nghaerhirfryn. Fe fydd nifer o'r gorsafoedd mesur a osodwyd ar lynnoedd y DU yn cael eu hadnewyddu yn y misoedd nesaf a, gan fod yr orsaf ar Lyn Tegid wedi ei niweidio, bydd hon ymysg y cyntaf i dderbyn sylw.



Ffigwr 1 Prif nodweddion yr LDMS

Dengys Ffigwr 1 nodweddion yr LDMS a osodwyd ar Lyn Tegid. Y mae gan yr orsaf sensorau i fesur y tymheredd y dŵr ar sawl level dyfnder ond y mae'r sensorau eraill yn gyfyngedig i wyneb y llyn. Dengys Ffigwr 2 nodweddion y system newydd. Fe fydd gan y system winsh i ollwng y sensorau trwy'r golofn ddŵr i ddarparu mwy o wybodaeth ar strwythur y llyn a'i newidiadau tymhorol.

Yn yr adroddiad, cynigir crynodeb effeithiau'r tywydd ar y llyn yn 2014, disgrifiad o'r system newydd ac enghreifftiau i ddangos sut y gellir defnyddio mesuriadau o'r fath i reoli'r llyn yn y tymor hir. Y mae yna arwyddion bod y cyfnod o hafau gwlyb, gwyntog ar ddod i ben felly rhaid derbyn bod problemau fel tyfiant algâu glaswyrdd a threuliant yr ocsigen yn y dŵr dwfn yn debygol o gynyddu.



Ffigwr 2 Prif nodweddion yr LDMS newydd gyda'r gyfundrefn proffilio

Yr amcanion yn ystod y cyfnod oedd:

- I gynnal yr LDMS a osodwyd ar Lyn Tegid trwy gyfuniad pwrpasol o ymweliadau ac arolygu tros y we.
- I arolygu perfformiad technegol yr LDMS a nodi unrhyw newidiadau a wnaed yn 2014.
- I lawr lwytho'r data a gasglwyd gan yr LDMS a'u dosbarthu i CNC a'u partneriaid yn y prosiect.
- I ddisgrifio patrwm y tywydd a welwyd yng Ngogledd Cymru yn 2014 a chymharu'r mesuriadau gyda'r patrwm hirdymor.
- I ddangos bod y cyfnod o gymysgu dwys a welwyd ym mis Awst wedi cael dylanwad mawr ar ddeinameg tymhorol y llyn.
- I ddisgrifio'r system newydd a dangos sut y gall y gall y data a gynhyrchir fod yn fodd o reoli'r llyn a'i dalgylch mewn ffordd fwy effeithiol.

Cyflawnwyd yr holl amcanion ac fe geir disgrifiad llawn o'r canlyniadau yng nghorff yr adroddiad.

2. Executive Summary

The Lake Dynamics Monitoring Station (LDMS) deployed on Llyn Tegid has been in operation since 2006 and is now showing signs of age. In 2014, some of the sensors used to measure the vertical variation in the water temperature were damaged by strong winds and work started on the design of a new station. Funding for the new station was provided by the Natural Environment Research Council as part of their ongoing support for the Centre of Ecology and Hydrology (CEH) at Lancaster. A number of lake monitoring stations in the UK will be upgraded in the next few months and, since the station deployed on Llyn Tegid has been damaged, this will be one of the first units replaced.

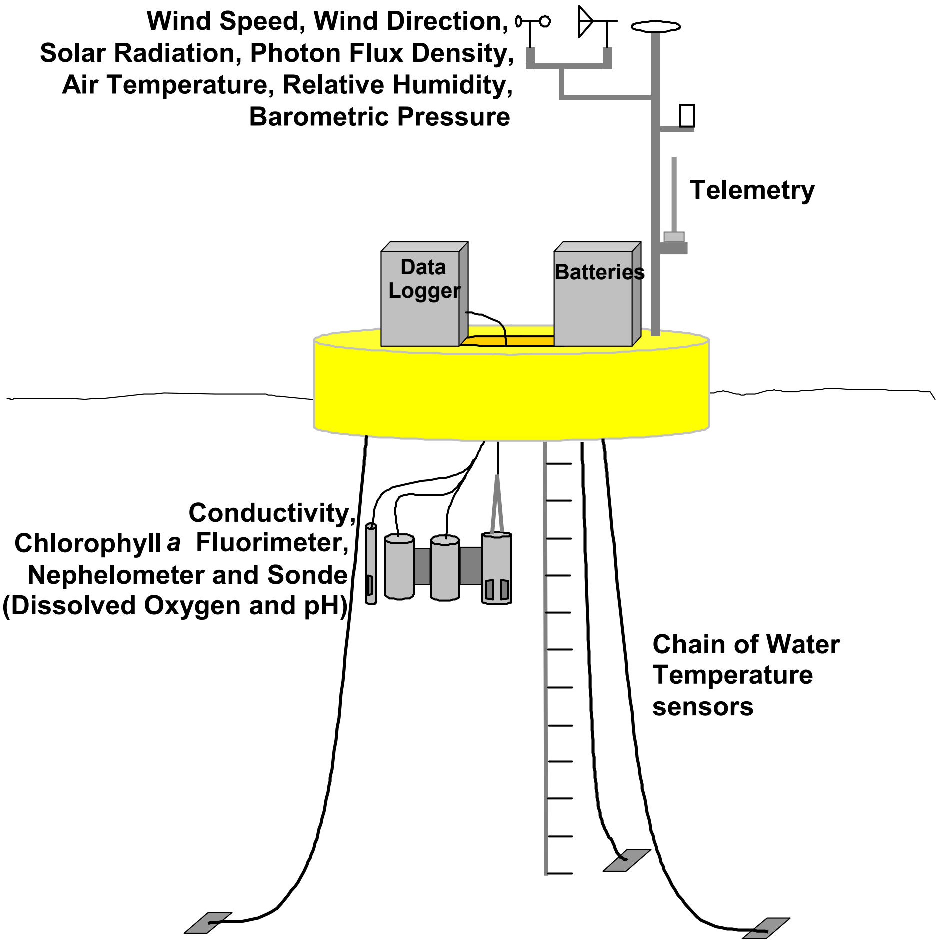


Figure 3 The basic features of the LDMS

Figure 3 shows the features of the LDMS currently deployed on Llyn Tegid. The station is fitted with sensors to record the temperature of the water at different depths but the remaining sensors are positioned quite close to the surface. Figure 4 shows the features of the new system. This will be fitted with a winch to lower the sensors through the water column to provide more detailed information on the structure of the lakes and its seasonal dynamics.

This report includes a summary of the weather-related changes observed in 2014, a detailed description of the new system and some examples to show how the information acquired can be used to support the management of the lake. There are indications that the period of wet, windy summers is coming to an end so problems like blooms of blue-green algae and the increased consumption of oxygen in deep water will become more common.

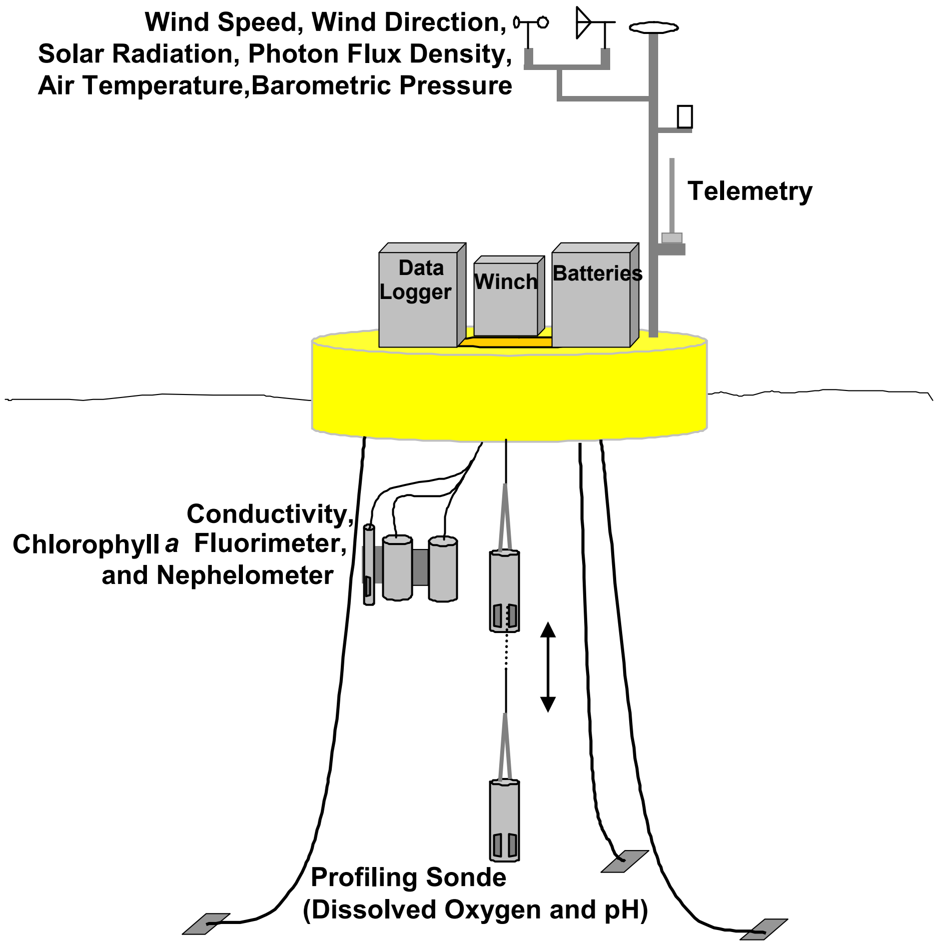


Figure 4 The basic features of the new profiling version of the LDMS

The objectives for reporting period were:

- To maintain the LDMS deployed on Llyn Tegid using an appropriate combination of site visits and internet checks.
- To review the technical performance of the LDMS and note any modifications made in 2014.
- To download the data acquired by the LDMS and distribute this information to NRW and its project partners.
- To describe the weather patterns experienced in North Wales area in 2014 and compare these with some long-term averages.
- To demonstrate that the period of intense mixing recorded in August 2014 had a profound effect on the seasonal dynamics of the lake.
- To describe the basic features of the new system and provide some examples to show how the data acquired can be used to better manage the lake and its surrounding catchment.

All of these objectives have been met and are described in the main body of the report.

3. The Maintenance and Servicing of the LDMS in 2014

3.1. Introduction

The station on Llyn Tegid was installed in October 2006 and, although showing signs of age, has continued to perform well. The station was visited by Lakeland Instrumentation Ltd in February 2014 and was found to have suffered some storm damage. An account of the work undertaken in that visit was presented in last year's report. In the coming year, a major upgrade is planned to the station at Llyn Tegid and five other stations in the UKLEON network that will see the buoy platform itself replaced as well as the addition of an automatic profiling system enabling many measurements to be taken at different depths in the water column.

3.2. The configuration of the LDMS in 2014

Figure 5 Photograph of the LDMS fitted on Llyn Tegid

The configuration of the station remained unchanged in 2014 and Lakeland Instrumentation Ltd (LI Ltd) monitored the performance of the station (pictured in Figure 5) regularly. The specification of the sensors connected to the stations are summarised in Tables 1 and 2.

Two sensors have remained disabled due to generic problems identified at a number of UKLEON sites. CEH have been developing revised methods to adapt the Vaisala atmospheric CO_2 sensor for use in water following several failures. It is expected that this will enable the sensor on Llyn Tegid to be deployed during 2015. Also the mount for the underwater light cell have proved to be susceptible to damage. A new design will be fitted to the new buoy platform.

Table 1 Details of the meteorological sensors fitted (Llyn Tegid)

PARAMETER	SENSOR TYPE	MODEL	MANUFACTURER	RANGE	ADAPTATION	NOTES
Wind Speed	Cup anemometer	A100L2	Vector Instruments	0 to 50m.s^{-1}	Military-grade connector fitted	Wind Speed is measured as a height of 2.5m above the water surface.
Wind Direction	Wind vane (Potentiometer)	W200P	Vector Instruments	0 to 360°	Military-grade connector fitted	The Wind Vane is aligned on station deployment. Accuracy of readings depends on stability of buoy
Barometric Pressure	Semiconductor strain gauge	PDCR1830	Druck Instruments	0 to 2000mBar	Military-grade connector fitted	
Air Temperature	Platinum resistance sensor	SKH2012	Skye Instruments	-40°C to +60°C	Military-grade connector fitted. Internal wiring altered to remove ground loop in this application	
Photo Flux Density	Photodiode Quantum Sensor	LI-192SZ	Licor	0 to 3000 µmol.m^{-2}.s^{-1}	Military-grade connector fitted	
Underwater Photon Flux Density	Photodiode Quantum Sensor	LI-190S	Licor	0 to 3000 µmol.m^{-2}.s^{-1}	Military-grade connector fitted	
Solar Radiation	Pyranometer	CM6B	Kipp & Zonen	0 to 2000 W.m^{-2}	Military-grade connector fitted	
Carbon Dioxide Concentration	Silicon based carbon dioxide senor	GMM222	Vaisala	0 to 7000ppm	Gas permeable membrane, waterproofing and military-grade connector fitted	Not operational

Table 2 Details of the water quality sensors fitted (Llyn Tegid)

PARAMETER	SENSOR TYPE	MODEL	MANUFACTURER	RANGE	ADAPTATION	NOTES
Chlorophyll a	Fluorimeter	Minitracka (C)	Chelsea Instruments	0 to 100µg/L (in acetone)	Military-grade connector fitted	12V supply controlled by data logger
Suspended solids	Nephelometer	Minitracka (N)	Chelsea Instruments	0 to 100 FTU	Military-grade connector fitted	12V supply controlled by data logger
Water Temperature (for temperature compensation of Conductivity sensor)	Platinum resistance sensor	-	Labfacility	-5 to +40°C	Military-grade connector fitted	
pH	pH	DataSonde 5x	Hydrolab	pH 1 to 14	Military-grade connector fitted	Station can operate with alternative models of Sonde
Dissolved Oxygen Sensor	Luminescent Dissolved Oxygen			0 to 500%		
Water Temperature structure	'Chain' of 12 Platinum Resistance sensors		Labfacility	-5 to +40°C	Special termination module supplied	12 sensors deployed at 1m, 3m, 6m, 9m, 12m, 14m, 16m, 18m, 20m, 23m, 26m and 29m

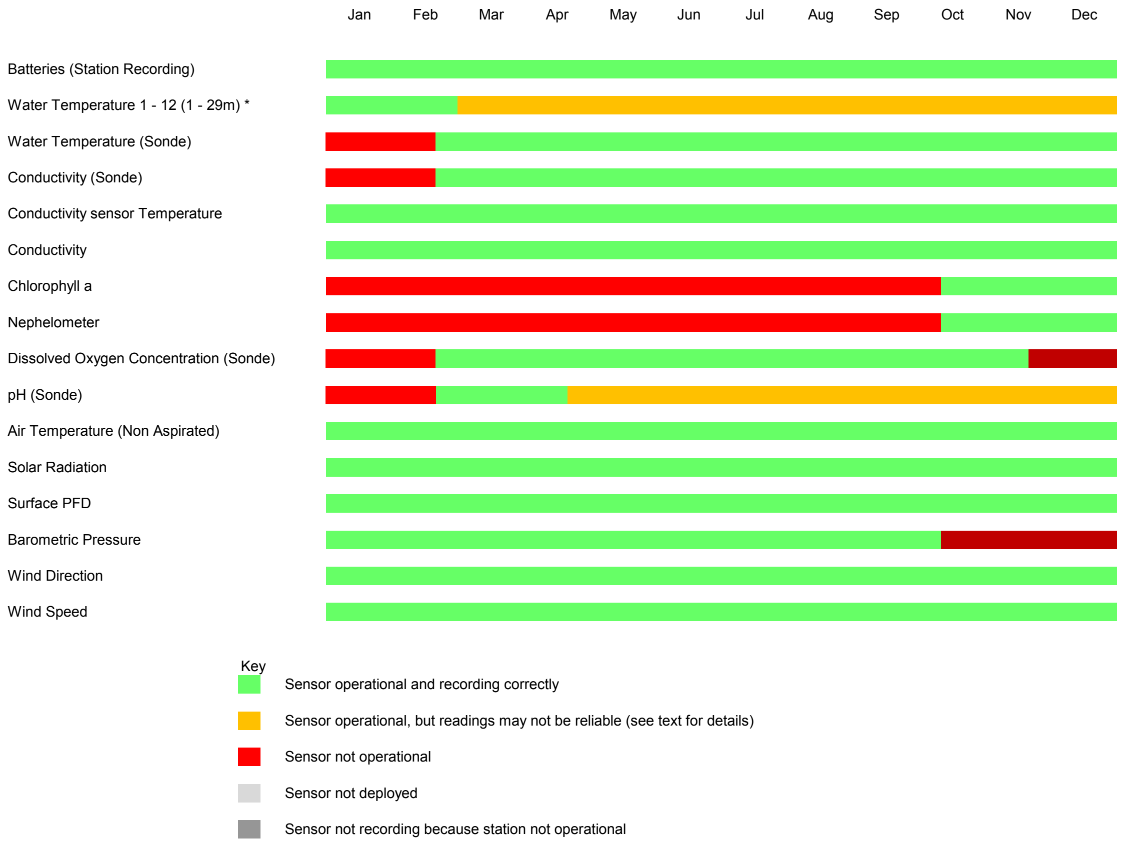
3.3. The technical performance of the system in 2014

The station generally continued to perform well during 2014 (Figure 6), although, as a result of the mooring problem detected in the service visit in February 2014, progressive damage has occurred to the chain of water temperature sensors.

As it was recognised that CEH planned to carry out a major upgrade of the station platform within a matter of months, it was determined that is was not economic to repair these limited failures. Although the upgrade has been a little delayed, it is now expected to be completed in the first half of 2015.

A problem with the software that had inadvertently prevented the Chlorophyll *a* and Nephelometer channels being recorded was corrected remotely via telemetry in late summer.

The planned major upgrade is described in some detail later in this chapter.



* Storm damage to cabling to Water Temperature sensors resulted in progressive failures from mid February. By the end of 2014, five temperature sensors remaind operational.

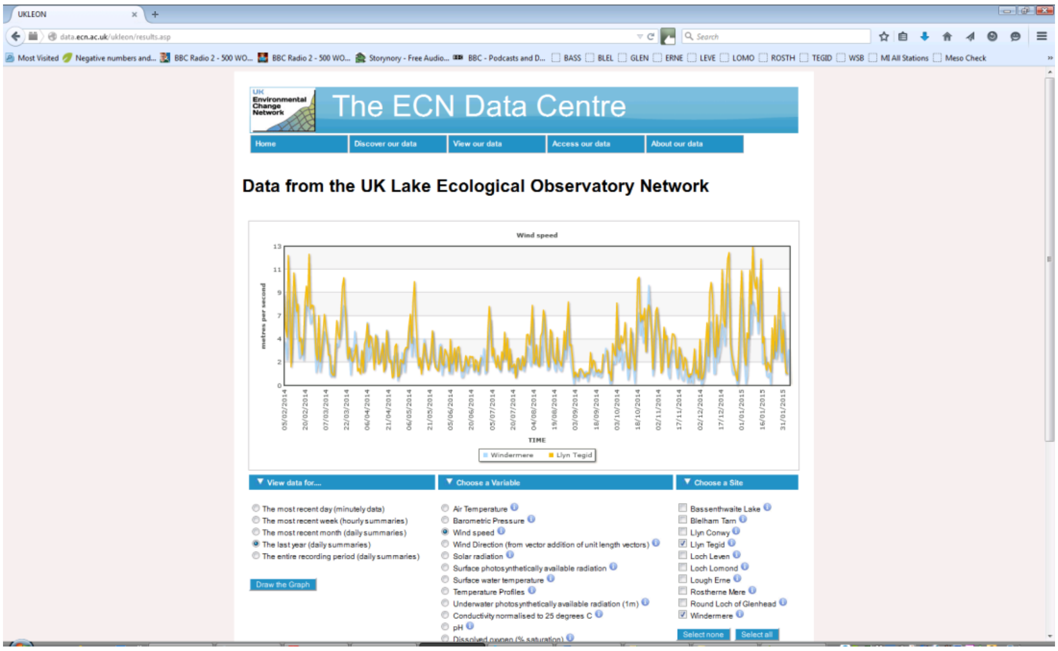
Figure 6 Summary of parameters recorded by the LDMS station on Llyn Tegid between 1 January and 31 December 2014.

In last year’s report we noted the problems with the site originally selected for the planned River Monitoring Station in the Twrch. The SNPA wardens have made progress in identifying alternative sites. There remain a number of issues to be resolved both locally and in adapting the station to operate as a pumped, bankside station. It is expected that this can be advanced when installation work for the upgraded lake station is carried out.

3.4. Data handling

Data from the Llyn Tegid station continues to be downloaded regularly by Lakeland Instrumentation Ltd and the station can be also be downloaded independently by NRW.

In addition data from the Llyn Tegid station along with other UKLEON stations are automatically downloaded by the Centre for Ecology and Hydrology (CEH) regularly and uploaded into an Oracle database hosted by CEH. Summary measurements are made publically available (http://data.ecn.ac.uk/ukleon/) and can be compared graphically with data recorded at other sites. More detailed information can be requested from CEH for scientific analysis.



View data for....

○ The most recent day (minutely data)
○ The most recent week (hourly summaries)
○ The most recent month (daily summaries)
● The last year (daily summaries)
○ The entire recording period (daily summaries)

Choose a Variable

○ Air Temperature
○ Barometric Pressure
● Wind speed
○ Wind Direction (from vector addition of unit length vectors)
○ Solar radiation
○ Surface photosynthetically available radiation
○ Surface water temperature
○ Temperature Profiles
○ Underwater photosynthetically available radiation (1m)
○ Conductivity normalised to 25 degrees C
○ pH
○ Dissolved oxygen (% saturation)

Choose a Site

☐ Bassenthwaite Lake
☐ Blelham Tarn
☐ Llyn Conwy
☑ Llyn Tegid
☐ Loch Leven
☐ Loch Lomond
☐ Lough Erne
☐ Rostherne Mere
☐ Round Loch of Glenhead
☑ Windermere

Figure 7 Screenshot of some sample data publically available from the UKLEON website (http://data.ecn.ac.uk/ukleon/)

Figure 7 shows a screenshot typical of the data presentation available publically from the UKLEON website (in this case a comparison of Wind Speed data from Llyn Tegid and Windermere over the previous year).

3.5. The distribution of data recorded in 2014

The data regularly downloaded from the station by LI Ltd are compiled as hourly summary data for distribution as an Excel Spreadsheet. This is submitted annually to NRW for addition to the NRW data archive, but, with approval of NRW, can be made available directly to project partners by LI Ltd. An additional copy of data from the station in recent years has been maintained by CEH in the UKLEON database.

3.6. Major upgrades planned for 2015

CEH plans to upgrade six of the stations in the UKLEON network in 2015, including the station on Llyn Tegid. Lakeland Instrumentation Ltd in collaboration with Remote Engineering Services Ltd have designed a new modular buoy platform and are currently completing an automatic profiling system. The buoy platforms have already been delivered to CEH and the first has been deployed on Rostherne Mere (Figure 8)

Figure 8 The upgraded buoy station deployed on Rostherne Mere

The profiling systems are due to be delivered shortly, although some trials may be required before they are operationally deployed at all sites.

Figure 9 shows two views of the new elements of the upgrade (the buoy platform and the profiling system winch)

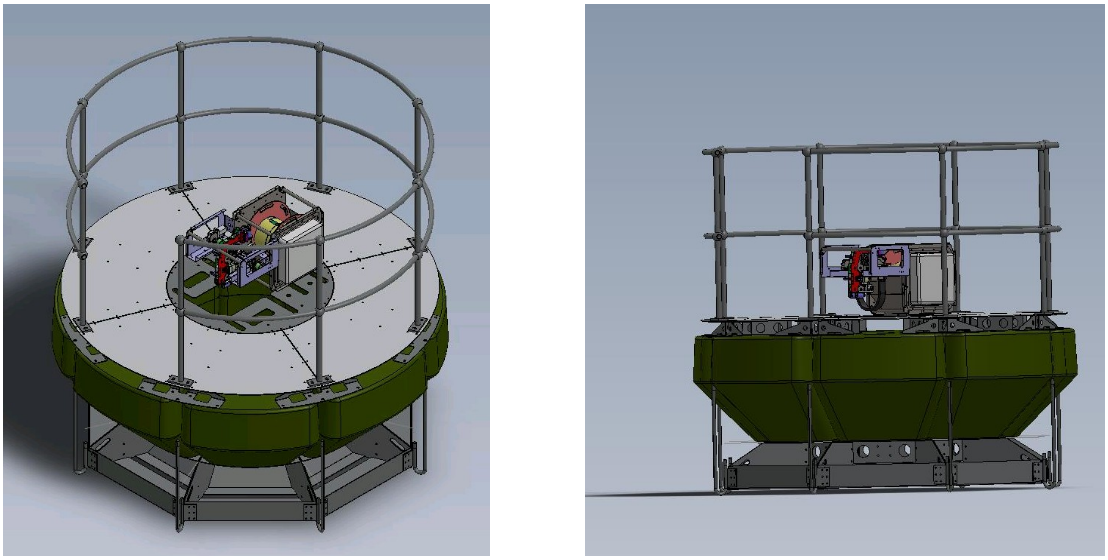


Figure 9 Modelled design drawings of the new buoy platform and winch

3.7. Upgraded Buoy Platform

A modular buoy platform has been designed by Lakeland Instrumentation Limited and Remote Engineering Systems Limited for use on inland, freshwater lakes and reservoirs. The buoy is assembled from a mixture of floatation and base modules to which ballast is added to provide stability in the given environment. The buoy is to be anchored using a 4-point mooring system.

The buoy is fitted with a deck structure to which equipment may be added within the design payload of the buoy. Handrails surround the deck and provision is made for the attachment of fenders and other devices associated with mooring service vessels.

Buoy Operating Parameters – Access

The buoy has been designed to be safe for normal, authorised access and to a limited extent, during unauthorised access.

Total Lift from Floats	1960 Kg
Weight of Sub-structure	360 Kg
Maximum Weight of Added Ballast	400 Kg
Weight of Superstructure	100 Kg
Weight of Deck-Mounted Equipment	200 Kg
Weight of 2 Personnel	200 Kg

Buoy Dimensions

Diameter	2500-mm outside; 1000-mm inside
Overall Height	1100-mm plus handrails
Module Weight	generally 40 Kg
Draft	Approximately 600-mm unmanned

Buoy Materials

Base	Mild Steel; Hot Dip Galvanised
Floats	Rotationally Moulded Polyethylene
Deck	Aluminium Alloy
Handrails	Aluminium Alloy
Fasteners	Zinc Plated Carbon Steel/Stainless Steel

Buoy Design Features

Floatation Modules

The buoyancy for the buoy is provided by eight Floatation Modules that, when they are assembled on the buoy base form a ring 2500-mm outside diameter and 1000-mm inside diameter.

The Floatation Modules are purpose made components constructed from rotationally moulded polythene shell with inhibitors to reduce the effects of exposure to ultra-violet light. The shells have a nominal skin thickness of 8-mm and they are fitted with moulded in, female threaded inserts on the bottom faces to enable their attachment to the base modules and to enable

attachment of the deck support framing to their upper surfaces. The floatation modules are individually filled with polystyrene that is expanded to form a rigid support for the polythene shell. Thus, while the shell of the float is robust in its own right, the floatation module is designed to maintain buoyancy in the event of damage to the shell.
Each floatation module is bolted to the top of a complementary base module via five M16 fasteners each of which has a ‘pull-out’ resistance greater than the buoyancy force and added mass that act on the floatation module.

Base Modules
The base of the buoy is comprised of eight fabricated steel modules that are bolted together to form an octagonal ring that is 1000-mm across the internal faces and 1700-mm across the external faces. Each module is constructed to enable ballast to be loaded into it from the outside perimeter. The fabrication is hot-dipped galvanised to protect it against corrosion.

Drilled, reinforcing plates are welded to the external corners of each base module and the pair of reinforcing plates at each corner of the octagon provide a suitable mounting for the Mooring Posts that are bolted to the base.

Mooring Posts
The buoy is moored by anchors that are attached by mooring chains to the Mooring Posts. Each mooring post comprises an inverted ‘walking stick’ solid steel bar 20-mm diameter that has a ‘butterfly-shaped plated welded to it. The plate is the interface between the mooring post and the base of the buoy.

While the buoy is only moored at four points around its circumference, the interstitial corners of the base are equipped with similar posts but these are used to enable bags of ‘trimming ballast’ to be slung from each of the ‘spare’ positions.

The upper end of each mooring post is threaded to accommodate a socket whose height can be altered to provide support for the periphery of the buoy’s deck.

Deck and Handrails
Aluminium tread-plate forms the decking. It is mounted on stools that enable a service gap of 100-mm between the top of the floatation modules and the underside of the deck plate. Conventional handrails and handrail standards (made from aluminium alloy) are bolted to the decking.

3.8. New Automatic Profiling system (winch)

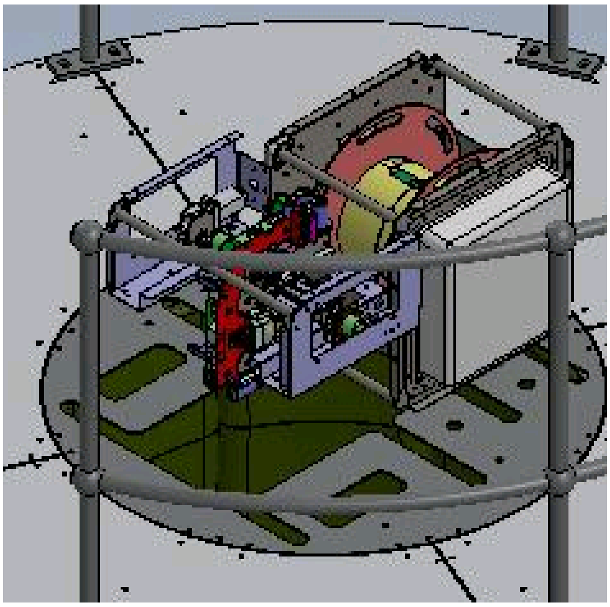


Figure 10 Modelled design drawing of the winch

Winch Deployment Parameters

Line Speed (Variable)	10 metres/minute in either direction
Design Line Tension	10 Kg
Fault Line Tension	20 Kg
Depth Step Accuracy	+/- 1 cm
Winch Dimensions	820 long x 500 high x 485 wide
Weight	40 Kg (approx.)

Construction Materials
The Winch is mainly constructed from Stainless Steel, Hard Anodised Aluminium Alloy and Acetal. Exposed electrical components are fully weatherproof (protected to IP67). The winch is located under a separate, hinged cover when it is mounted on a buoy to offer extra environmental protection and to protect it from theft or vandalism.

Winch Design Features
The winch incorporates a number of features that have been developed to provide flexibility of use to the end user. Principally, the winch drum has been designed so that different diameter cables may be used on the same drum. This has been achieved through the elimination of the normal, mechanically synchronised lay-gear and through use of variably positioned winch drum flanges. Also, it is possible to exchange winch cables without re-wiring their connections within the winch drum. The winch cable is simply ‘plugged into the drum’.

The winch cable passes through a lay-gear guide downstream from the winch drum. The purpose of this is to ensure that the cable is laid neatly on the winch drum so that there is no tendency for the cable to build up locally on itself. The lay-gear also provides support for a travelling cable cleaning brush assembly that removes organic solids from the cable surface.

The operation of the automatic profiling system requires accurate measurement of the cable as it passes through the lay-gear. This is achieved by a multi-turn absolute rotary encoder whose drive is provided by the winch cable running over a specially modified guide roller that 'engages' the cable and prevents slippage of one relative to the other.

The winch drum drive is also equipped with a similar encoder and this works in conjunction with the lay-gear encoder to monitor the cable as it is paid out. The consequence of this is a continuous control of cable 'tension' that prevents slack or excess tension occurring in the winch cable.

The lay-gear is equipped with a number of proximity sensors and a lay-gear travel monitoring encoder that provides inputs to the lay-gear control system and ensures its correct performance particularly when the cable is required to change direction as it comes into contact with the winch drum flanges.

The winch drum is equipped with a proximity switch that penetrates the wall of the winch drum and detects whether the winch cable is present or not. If the latter condition is reached, the winch stops paying out cable since the signal indicates that there are only three 'dead' turns of cable left on the winch drum. The winch uses IP67 rated proximity switches throughout rather than mechanically -operated limit switches. This, expedient avoids the risk of corrosion-induced failure of a switch to operate.

Winch Operation and Maintenance

The umbilical cable from the winch feeds through a moon-pool at the centre of a permanently moored buoy. It is also covered by a hinged. The winch may be hinged back from its normal, horizontal position to a vertical. This repositioning enables access to the sensors suspended from the umbilical cable for maintenance and also enables access to be gained to the side enclosures that house the electronic controls.

4. The Seasonal Variations in the Weather

In 2014, the winter weather in North Wales was mild and very wet but the summer was warm and there was more sun than average in June and July. Figure 11 shows the seasonal variation in the air temperature, the number of hours of bright sunshine and the rainfall reported for the area by the UK Meteorological Office. The bars show the monthly averages and the lines the long-term averages for their observatory in Colwyn Bay.

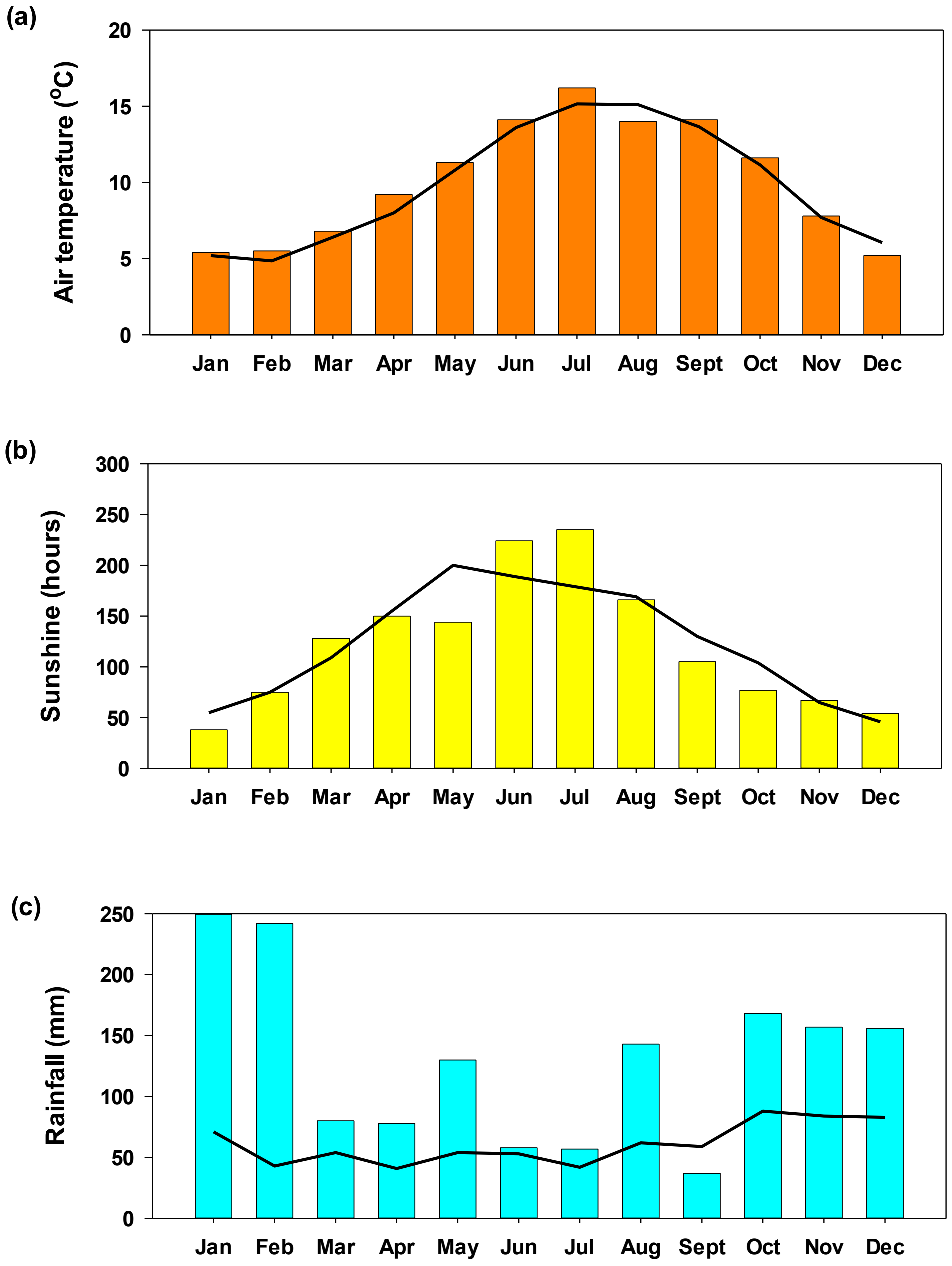


Figure 11 The seasonal variation in (a) the air temperature (b) the hours of bright sunshine and (c) the rainfall recorded for the area in 2014. The bars show the monthly averages and the lines the long-term (1971-2000) averages for a monitoring station near Colwyn Bay (data from the UK Meteorological Office).

In 2014, the air temperatures recorded in North Wales (Figure 5a) were above the long-term average but August was a little cooler due to a major of storm that crossed the UK early in the month. The sunshine hours record (Figure 5b) showed that March and April were sunny months but the May values were very much lower. In contrast, the sunshine totals for June and July were exceptionally high but the August values were depressed by the very stormy weather experienced at the beginning of the month. From a meteorological point of view, the most striking feature of the year was the severe storms experienced in January and February. These storms were associated with periods of exceptionally heavy rain (Figure 5c) and statistics confirm that the winter of 2014 was the wettest experienced in Wales since 1910. The strong winds associated with these storms were responsible for the damage to the buoy but the consequences of the damage did not become evident until later in the year. The LDMS on Llyn Tegid has survived a number of very severe winter storms but the winds recorded in January and February were quite exceptional. Hourly average wind speeds in excess of 10m s^{-1} were recorded for much of January whilst the highest hourly wind speed recorded in February was close to 20m s^{-1}. An analysis of surface pressure measurements by the University of East Anglia showed that the UK had experienced more severe gales during the winter of 2014 than in any other year since 1871. From a limnological point of view, the most influential weather event was the storm that passed over the UK on the 10th August. This produced an exceptionally intense mixing event that mixed the water column to a depth of 12m and had a prolonged effect on the temperature of the lake. This storm was the remnant of hurricane Bertha, which even damaged some buildings in the north-west of Scotland.

5. The Seasonal Dynamics of Llyn Tegid in 2014

Long-term studies in the English Lake District (e.g. George *et al*., 2000) have shown that the dynamics of the lakes can best be described by dividing the year into a series of ten week periods or quintiles. Thus the first quintile (weeks 1-10), covers the 'winter' period when the temperature of the lakes is close to the seasonal minimum. The second quintile (weeks 11-20) covers the 'spring' period of progressive warming and the appearance of the first algal maximum. The third quintile (weeks 21-30) covers the onset of thermal stratification and the appearance of smaller, rapidly growing species of phytoplankton. The fourth quintile (weeks 31-40) covers the period of stable stratification when the lake is usually dominated by slow growing, 'climax' species of phytoplankton. The fifth quintile (weeks 41-50) includes the autumn overturn when the phytoplankton community is dominated by species that grow well under isothermal conditions. In this report, we use the same approach to describe the changes observed in Llyn Tegid but confine our remarks to the 'winter', 'spring' , 'early summer' and 'late summer' periods. In 2014, the damage sustained by the temperature sensors meant that some information was lost. Fortunately, enough survived to provide a record of the seasonal dynamics of the lake and the erosion of the thermocline in late summer.

The periods used for these seasonal summaries were:

Winter: 1st January to 11th March 2014.

Spring: 12th March to 20th May 2014.

Early summer: 21st May to 29th July 2014.

Late summer: 30th July to 7th September 2014.

5.1. The winter measurements (1st January to 11th March 2014)

The air temperature recorded in the first ten weeks of 2014 (Figure 12a) were high compared to recent years and there were very few occasions when the hourly values either approached or reached zero. The surface and bottom temperatures recorded in the first weeks of the year were also high (Figure 12b) and were still above 4°C when the output from the top and bottom sensors became unusable on 18th February. The wind speed at the time of failure was not particularly high so the failure may have been the result of damage sustained several weeks earlier. The relatively high temperatures recorded at the start of 2014 are very different to the conditions experienced in the previous decade. For example, in 2009 the water temperatures remained below 4°C for much of February whilst in 2010 the cold spell continued until the last week in March.

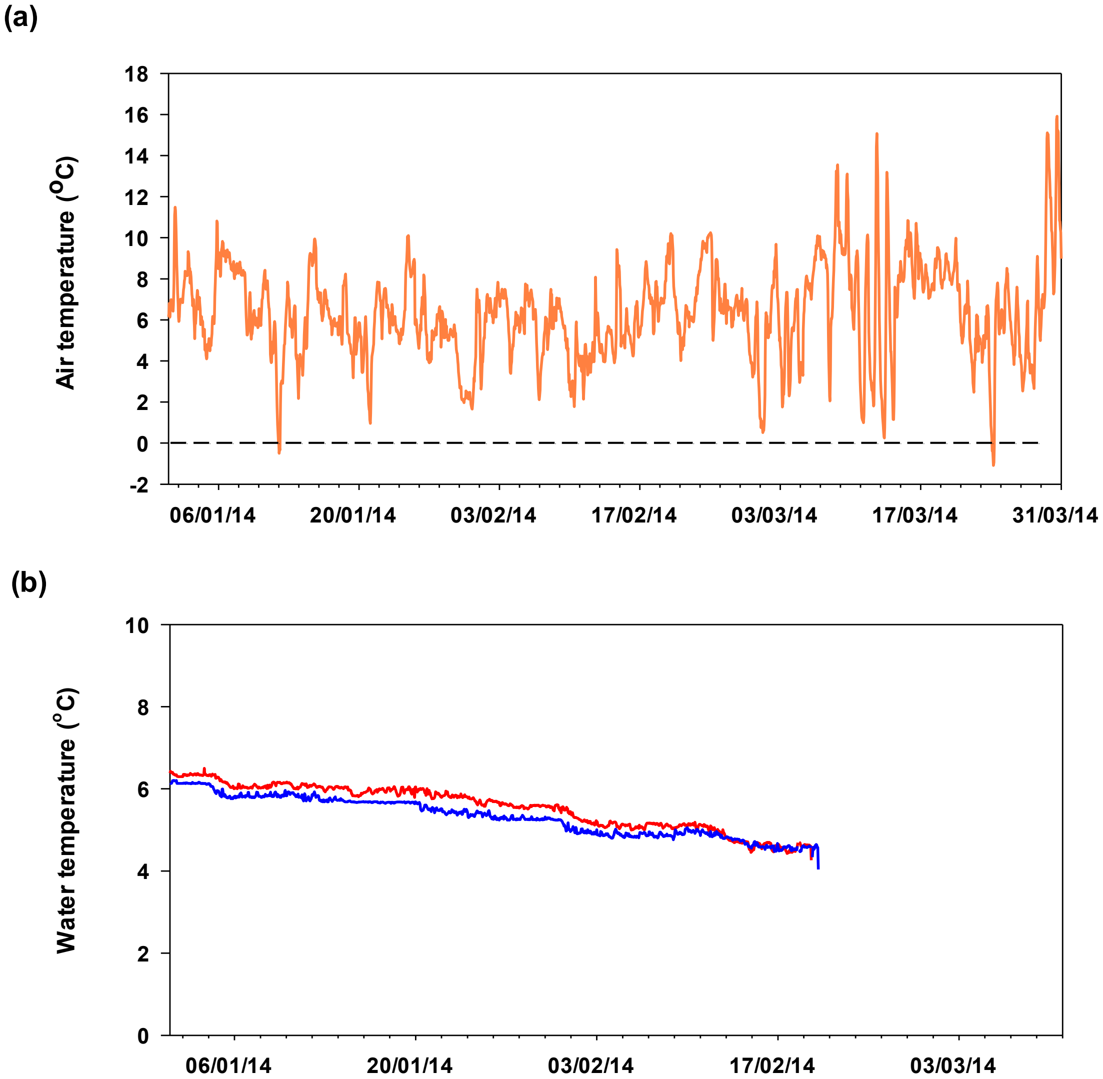


Figure 12 The winter weather and its effect on the lake. a) air temperature, b) the top and bottom water temperatures (the red line shows the near-surface measurements).

5.2. The spring measurements (12th March to 20th May 2014)

Historical measurements of the vertical variations in the water temperature demonstrate that Llyn Tegid usually only became thermally stratified at the end of May. The date of thermal stratification in 2014 was very much earlier since the first signs of structure were already present at the end of April. The air temperatures in Figure 13a show that April was, in fact, a very warm month with day-time temperatures periodically approaching 15°C. The diel variation in the air temperature is always higher when there is no cloud so there were also occasions when the night-time temperatures fell below 5°C. Figure 13b shows the resulting variations in the temperature of the water column. The first signs of thermal stratification appeared in early April and were followed by period of more intense heating at the end of the month.

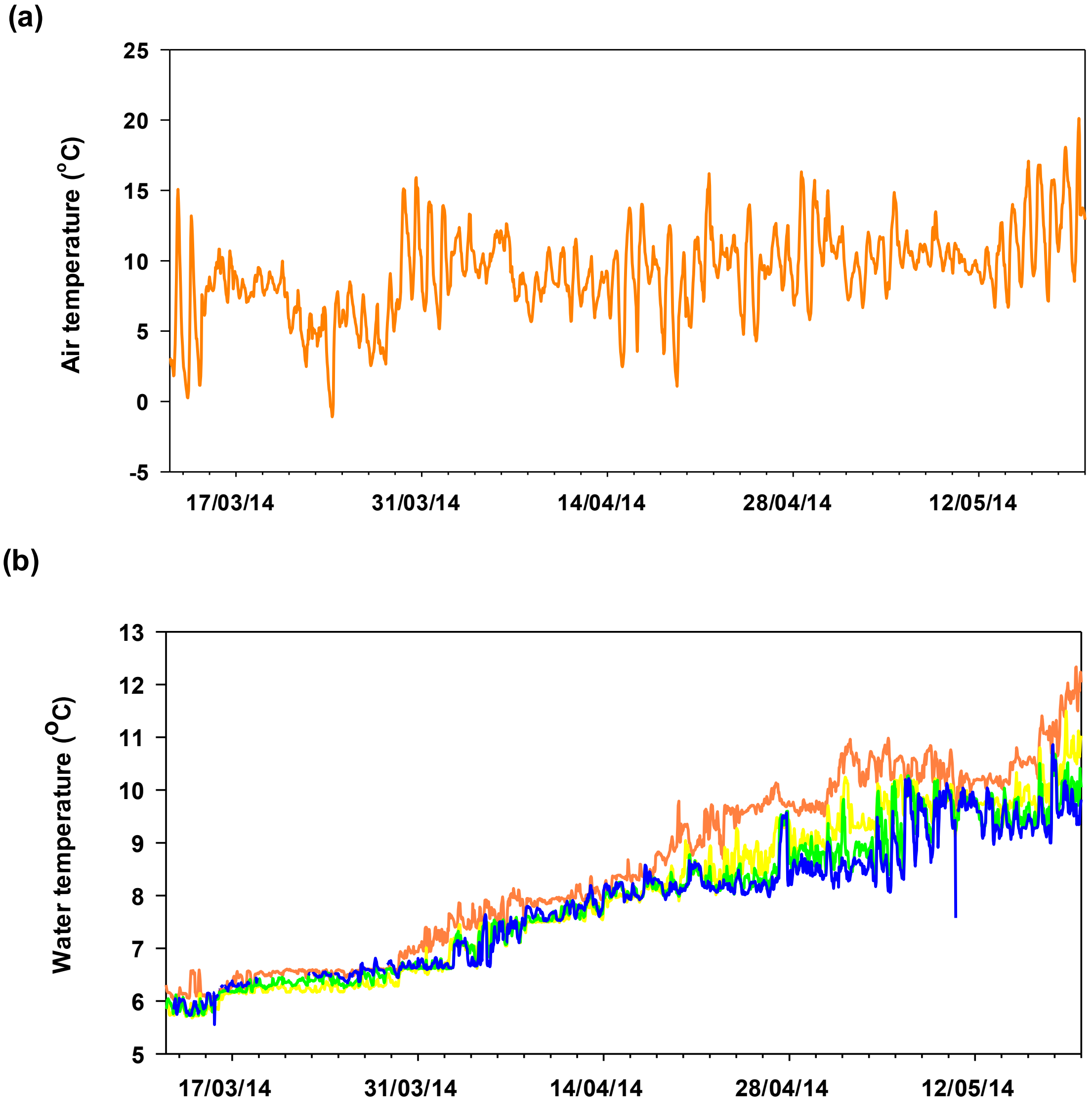


Figure 13 The spring weather and its effect on the lake. a) air temperature, b) the vertical variations in the water temperature. In the temperature record the colour of the lines show the depth of measurement: the orange shows temperature recorded at a depth of 3m, the yellow at a depth of 6m. the green at a depth of 9m and the blue at a depth of 12m.

5.3. The early summer measurements (21st May to 29th July)

June and July were very sunny months so daytime air temperatures were high but there were also periods when the night-time temperature fell below 10°C (Figure 14a). This extended period of warming had the expected effect on the thermal structure of the lake (Figure 14b) with the temperatures at all depths increasing progressively. A short period of more intense surface heating was recorded at the end of June but much of the heat absorbed was soon dissipated in the water column. By the end of the first week of July there were signs of heating in deeper water but the only sustained increase was that recorded at a depth of 9m.

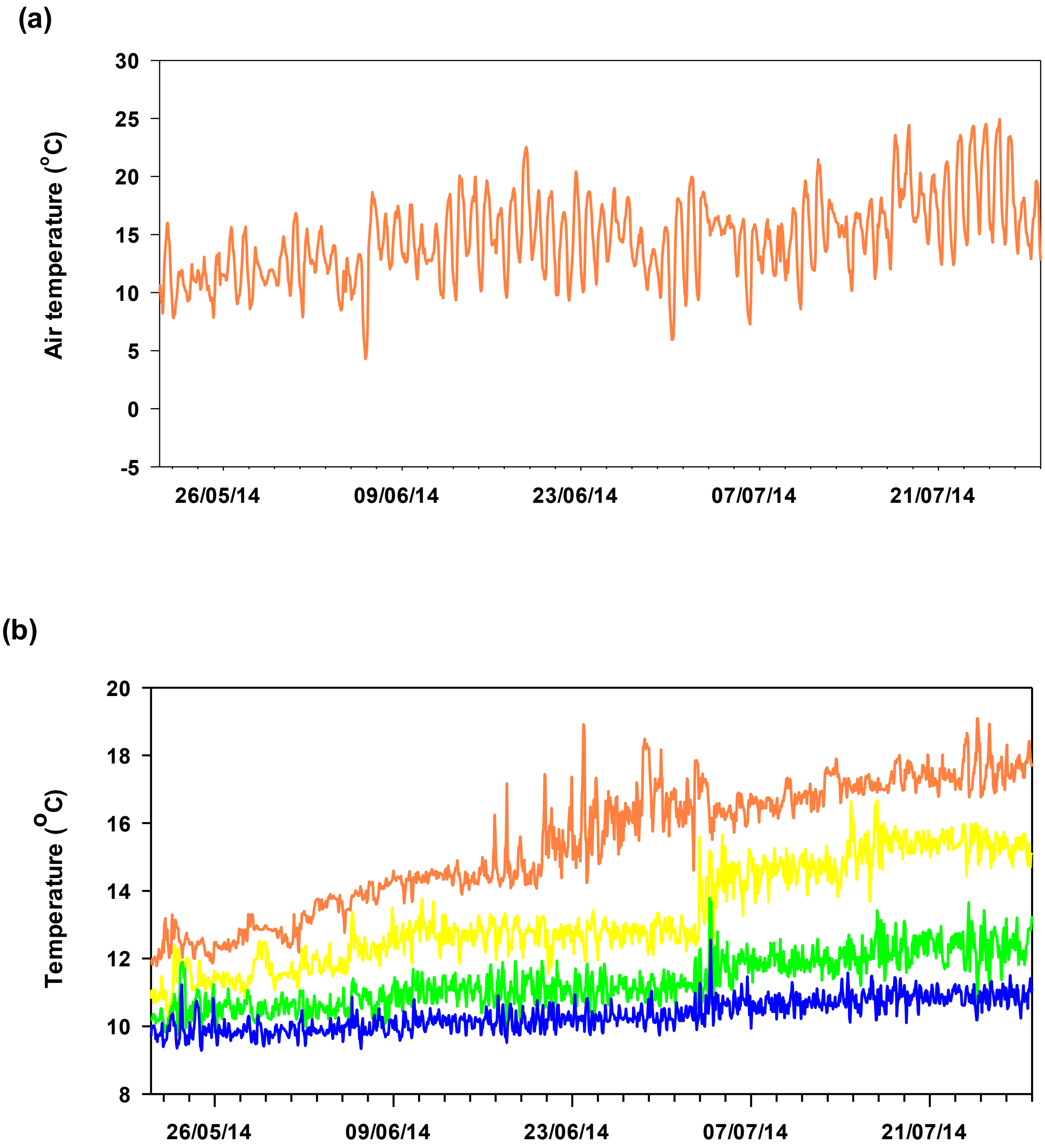


Figure 14 The early summer weather and its effect on the lake. a) The air temperature. b) The vertical variations in the water temperature. The line colours are the same as in Figure 13.

5.4. The late summer measurements (30th July to 7th September)

The extended period of warming came to an end abruptly in early August when a major storm passed over the UK. The air temperatures recorded at Llyn Tegid (Figure 15a) declined sharply as the storm approached the land on 10th August and remained low until the end of the month. The water temperature measurements (Figure 15b) showed that, by the end of the event, the lake had mixed to a depth of 9m by 17th August and by the end of the month there was very little thermal structure left in the top 12m.

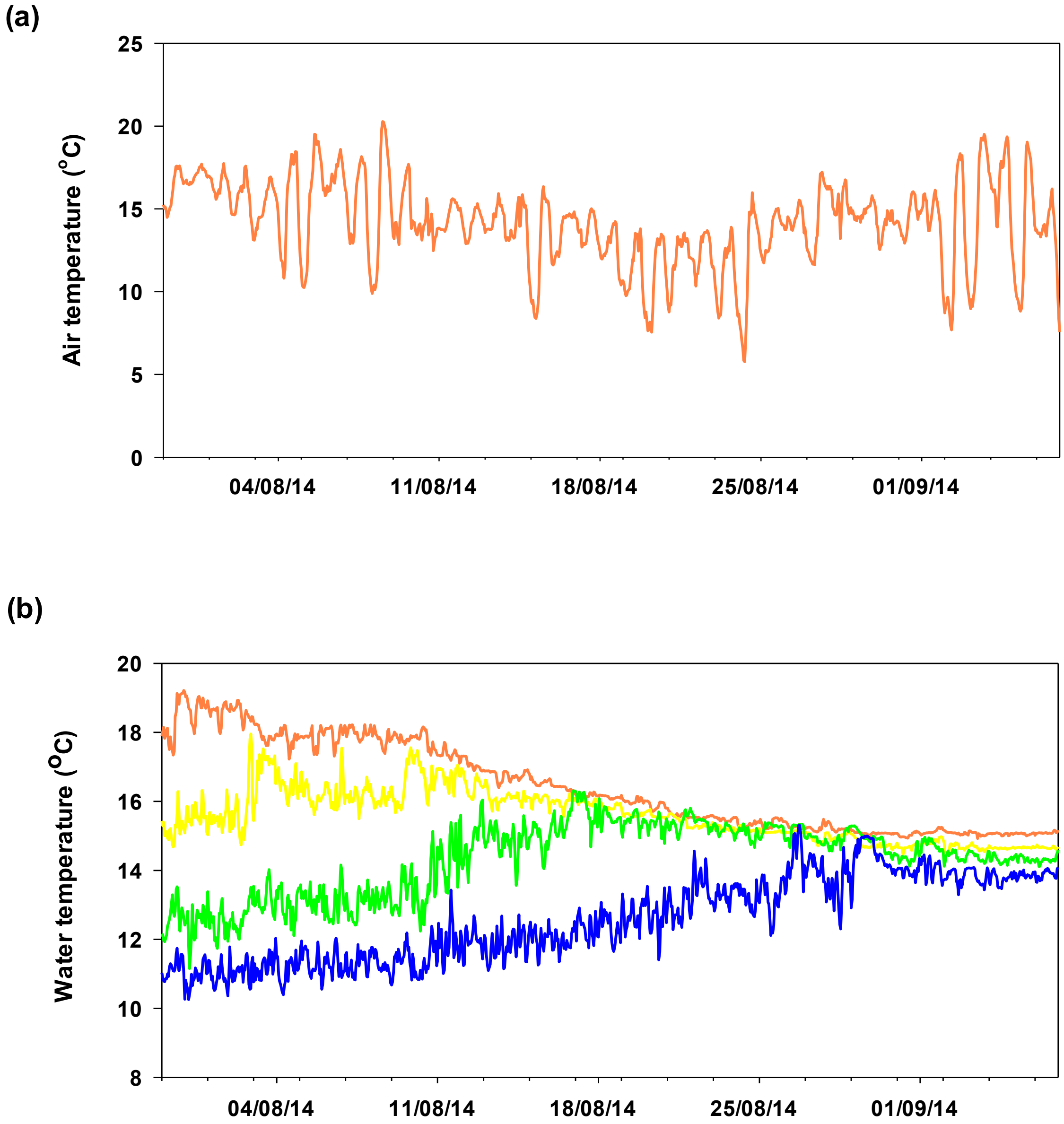


Figure 15 The late summer weather and its effect on the lake. a) The air temperature. b) The vertical variations in the water temperature. The line colours are the same as in Figure 13.

6. The mixing event recorded in August 2014

In previous reports we have presented several examples to show that short-term, extreme variations in the weather can have a major effect on the seasonal dynamics of lakes. In a thermally stratified lake like Llyn Tegid gales that last for just a few hours can fundamentally alter the physical structure of the lake and its seasonal dynamics. Storms of the magnitude of the one that moved in from the Atlantic on 10th August 2014 are, fortunately, very rare in the UK. Its effect on the lake was not only pronounced but very prolonged. In early August, the lake was in the right physical condition to sustain a significant algal bloom; a week later this risk had been removed for the foreseeable future. No prolonged cyanobacterial blooms have been recorded in Llyn Tegid since the LDMS was installed in 2006 but there have been years when local accumulations have appeared in September and even early October. If it were not for the storm that hit the UK on 10th August there was a very real risk of a bloom before the end of the month. The disruptive effects of the storm can only be fully appreciated when the thermal structure of the lake is related to the meteorological data recorded by the buoy. Figure 16a shows the changes in atmospheric pressure that preceded this event and Figure 16b the observed variations in the hourly wind speeds. The results suggest that it was the sustained nature of the storm that had the most effect. Wind speeds were already high on 10th August but increased again on the 11th and 12th August and did not abate until the morning of the 13th August. The vertical variations in the water temperature (Figure 16b) suggest that much of the entrainment was due to the internal waves that followed the storm. The 6m and 9m temperatures had converged by the 16th of August but it took another week for 12m sensor to reach the same temperature.

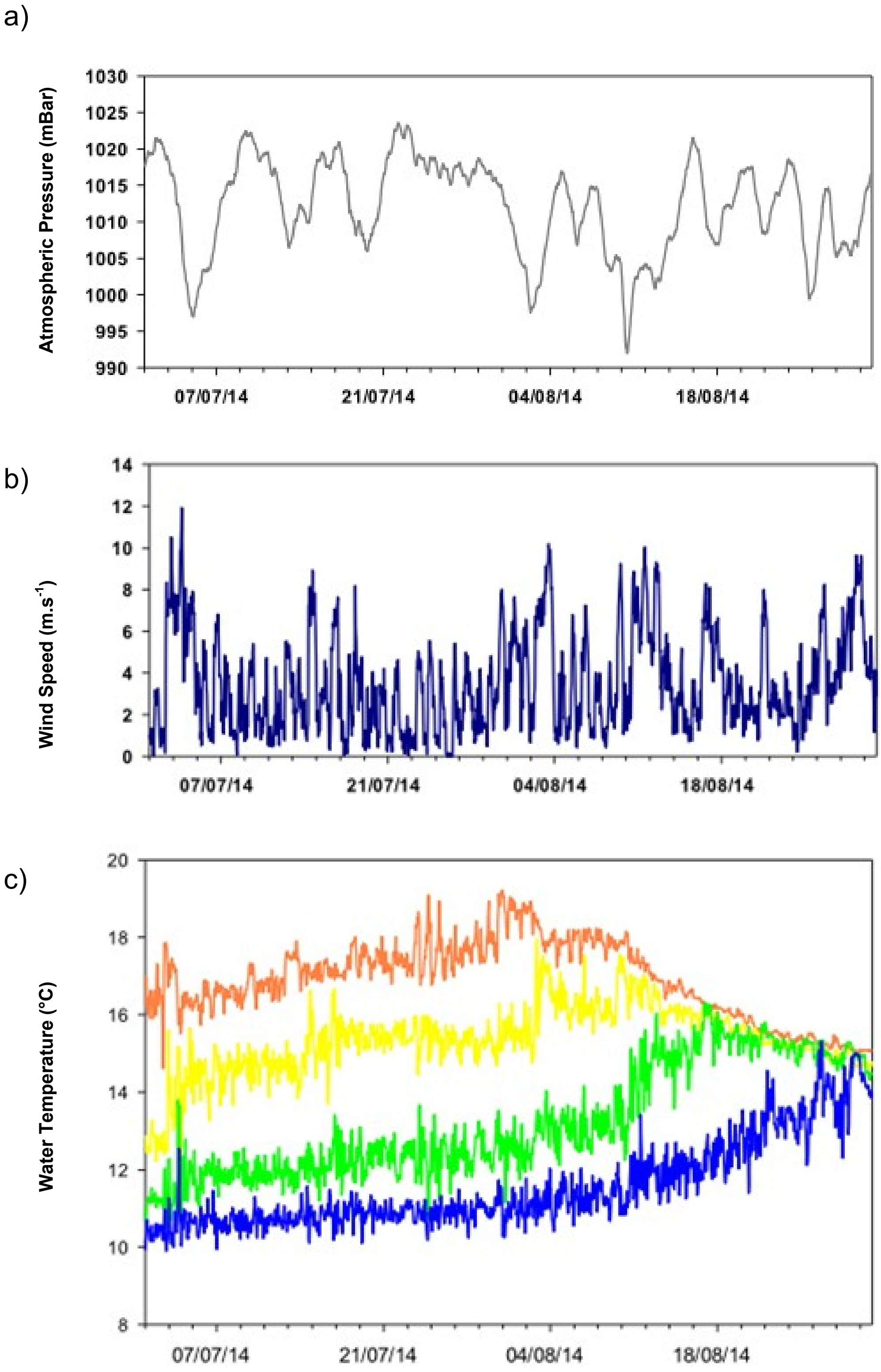


Figure 16 The late summer weather and its effect on the lake. a) The variations in the atmospheric pressure. b) The variations in the wind speed. c) The vertical variations in the water temperature. The line colours are the same as in Figure 13.

7. Discussion

The data acquired by the LDMS deployed on Llyn Tegid has, over the past eight years, allowed us to explore a number of weather related factors that have an effect on the dynamics of the lake.These include:

- The episodic transport of sediment from the surrounding catchment when heavy rains follow an extended period of dry weather.
- The associated increase in the loading of phosphorus adsorbed on to some of the fine particles washed into the lake.
- The episodic entrainment of phosphorus from deep water when strong winds follow a period of stable stratification.
- The periodic appearance of surface ‘blooms’ of cyanobacteria in when water temperatures are high and the wind-speed falls below a critical value of 4 m.s^{-1}.

The profiling system currently being assembled will enable us to explore these episodic events in greater detail and quantify their impact on the transfer of oxygen into deep water. An early version of the winch has been used on an Irish Lough for more than 6 years and a new prototype version was successfully tested in Cumbria in 2013. In the first instance, the system deployed on Llyn Tegid will be programmed to record data that will address two specific issues:

- The early detection of the cyanaobacterial blooms that commonly appear in late summer before they have time to accumulate downwind. form ability to detect potentially dangerous blooms of cyanobacteria at an early stage in their development.
- The extent to which the proportion of the open water habitat available to the gwyniad can be constrained by the combined effect of surface warming and the enhanced consumption of oxygen in deep water

The following examples show how the high-resolution data produced by the new profiling system can help to address these issues and provide the information required to support process-driven models of this sensitive system.

The first is based on data recorded in a large Irish lough. Since this Lough is connected to the sea it frequently develops some very fine structures with steep salinity gradient and layers of migrating phytoplankton. The second is based on some high-resolution profiles acquired in a small Cumbrian lake where upper layers are rapidly warmed by the sun and where the concentration of oxygen found in the hypolimnion is very low at the height of summer.

7.1. Example 1: Detecting the first stages of an incipient algal bloom.

The LDMS deployed on Llyn Tegid was equipped with a simple single band fluorimeter to estimate the biomass of phytoplankton present in the near-surface water. An instrument of this kind provides no information on the kind of algae present but the presence of bloom forming cyanobacteria can sometimes be inferred from the variability of the measurements acquired. Most species of algae behave as passive particles in the physical flow and do not form layers in the water column or patches in sheltered bays. The biomass measured by a fluorimeter may change slowly but will not exhibit the short-term variability commonly associated with drifting patches of cyanobacteria.

In 2008, we used the hourly variation in the chlorophyll concentrations measured at the buoy as a measure of the spatial heterogeneity of the phytoplankton in Llyn Tegid. Figure 17 shows how the 'patchiness' detected in the lake between 1st and 31st July in relation to the wind speed measured in the open water. The 'patchiness' index is based on the variance to mean ratio, where positive values imply more spatial structure. The results show that there was a marked increase in the variance of the hourly values measured at the buoy as soon as the wind speed fell below a daily average of 4m.s^{-1}. Notes prepared by the lake wardens confirmed that sparse patches of cyanobacteria were present at the time but were soon disrupted by the strong winds recorded later in the month.

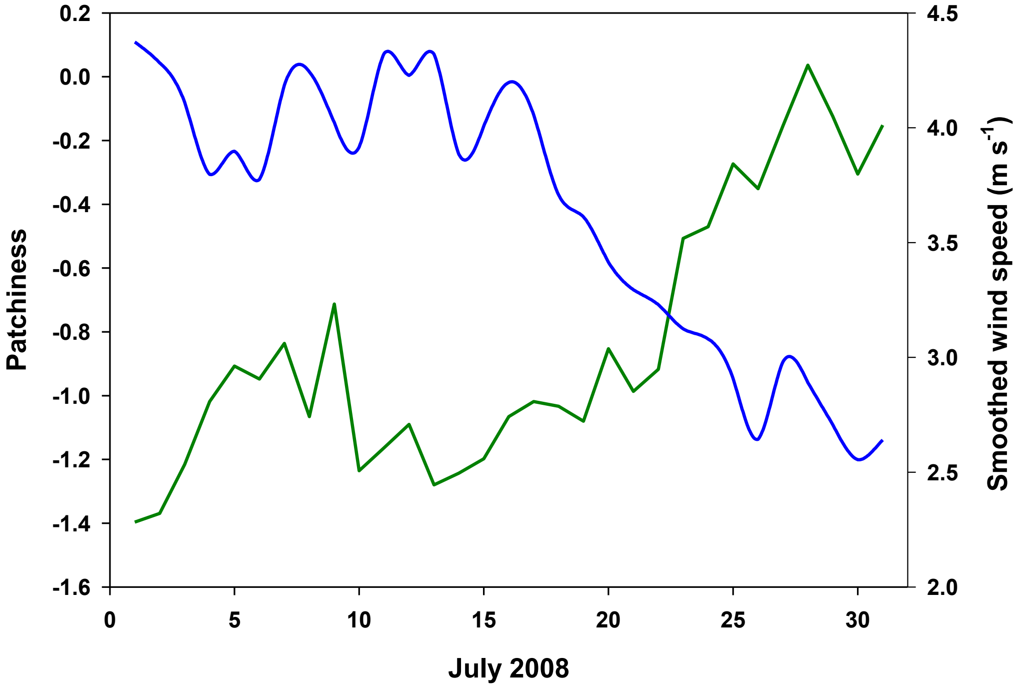
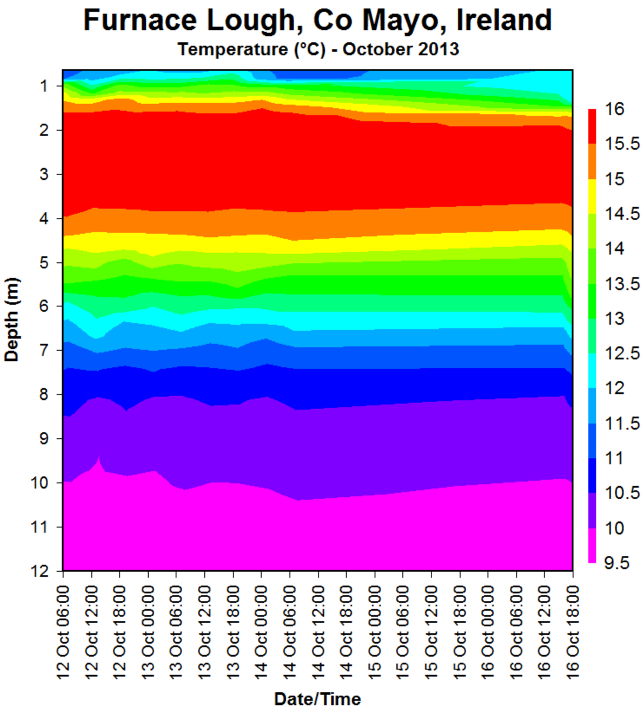


Figure 17 Using a 'time-for-space' approach to detect the early stages of a cyanobacterial bloom in Llyn Tegid. The green line shows the change in the 'patchiness' index and the blue line a smoothed version of the daily wind speed.

The new profiling system will resolve the fine structure of these patches in much greater detail and will also be fitted with a multi-band fluorimeter designed to detect the photosynthetic pigment found in cyanobacteria.

Some indication of the improved resolution can be gained by examining a segment of the temperature and chlorophyll records acquired in Lough Furnace, Ireland, in 2013.

a)



b)

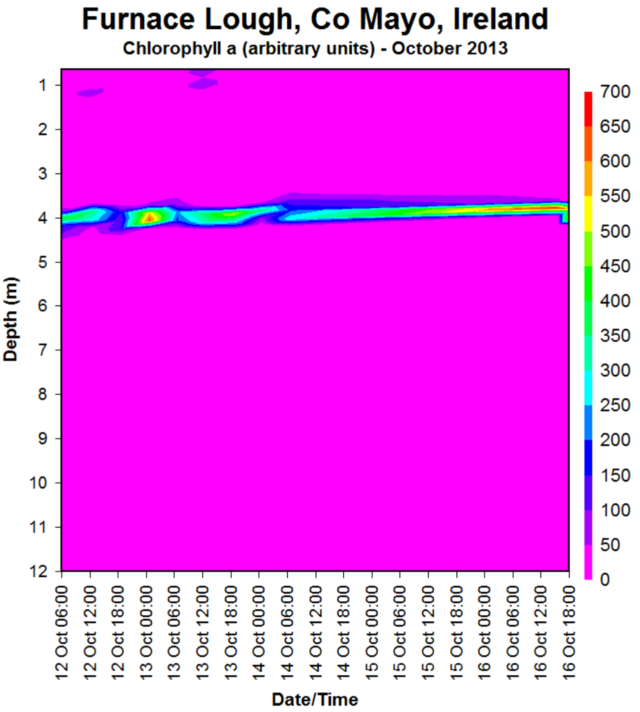


Figure 18 Profiles of a) Water Temperature and b) Chlorophyll *a* fluorescence recorded in Furnace Lough, Co Mayo Ireland in October 2013

7.2. Example 2: Quantifying the potential impact of surface warming and deep water anoxia on the gwyniad.

Llyn Tegid is the only lake in Wales to support a population of the rare fish known as the gwyniad (*Coregonus lavaretus*). The gwyniad is a glacial relict that is closely related to the vendace (*Coregonus alba*) found in the English Lake District. Both species need cool, well oxygenated water to survive and are currently threatened by the combined effects of eutrophication and global warming. In 2007, some fertilised gwyniad eggs from Llyn Tegid were deposited in Llyn Arenig Fawr in the hope that a 'refuge' population could be established in this mountain lake. A report by Winfield *et al*. (2010) suggests that the translocation has shown some initial success and their acoustic survey suggests that the lake now contains small numbers of young fish. The recent cool, wet summers have been kind to the Llyn Tegid gwyniad, but their survival would again be threated if we experience a succession of warm summers.

In the 1990's a detailed study of the factors responsible for the rapid decline in the numbers of vendace present in Bassenthwaite Lake (Cumbria) was undertaken by CEH Windermere. A simple automatic monitoring system was deployed on the lake and the temperature and oxygen data acquired used to support the development of a 1-D model of the water column (Bell *et al*., 2006). The validated model was then used to 'hind cast' the proportion of the habitat available to the vendace at the height of summer during the period when fish numbers had declined. Figure 19 shows the minimum values calculated for each year between 1990 and 2000 which range from 0% in 1995 and 1997 to a 100% in the year 2000. In warm summers, the fish were unable to occupy the warm surface layers but were also unable to retreat into deep water because the oxygen content was low. The projections of the model are a 'worst case' scenario but they suggest that the fish would have struggled to find a refuge in the water column in three out of the ten years studied. Gill net sampling at the end of this period confirmed that the population of vendace in Bassenthwaite is now close to extinction since no young fish are present in the lake. A number of remedial measures were implemented on the lake and its catchment but the introduction of the Eurasian ruffe (*Gymnocephalus cernua*) into the system is now an added threat. This fish is known to be a voracious feeder on vendace eggs and some of their known spawning grounds are also contaminated by silt deposits.

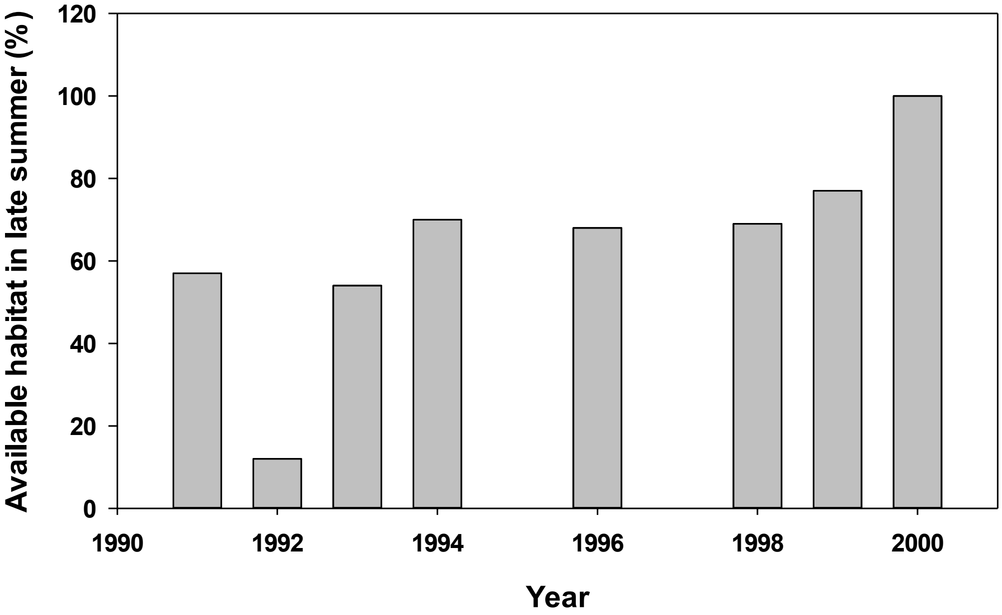


Figure 19 The estimated proportion of the open water habitat available to the vendace in Bassenthwaite Lake at the end of summer (1991-2000).

The temperature and oxygen sensors fitted to the new profiling system will allow us to produce comparable estimates of the habitat available to the gwyniad in Llyn Tegid. Figure 20 shows examples of the high-resolution temperature and oxygen profiles recorded by the systems when it was being tested on Esthwaite Water in September 2013. Esthwaite Water is one of the most productive lakes in the English Lake District and is also sheltered by surrounding hills.

Although Esthwaite Water does not host a population of fish with similar habitat requirements to the gwyniad in Llyn Tegid or vendace in Bassenthwaite Lake, the sample data in Figure 20 clearly illustrates the issue of depleted oxygen levels at depths where cooler waters are available. If similar profiles were present in Llyn Tegid or Bassenthwaite, there would be significant pressure on the gwyniad/vendace populations. Only following the progressive mixing of the water column in mid-September do dissolved oxygen concentrations in the cooler water recover to a level that could sustain a fish population. It is anticipated that similar profile data acquired from Llyn Tegid would greatly assist in improving our insight into the fate of the gwyniad.

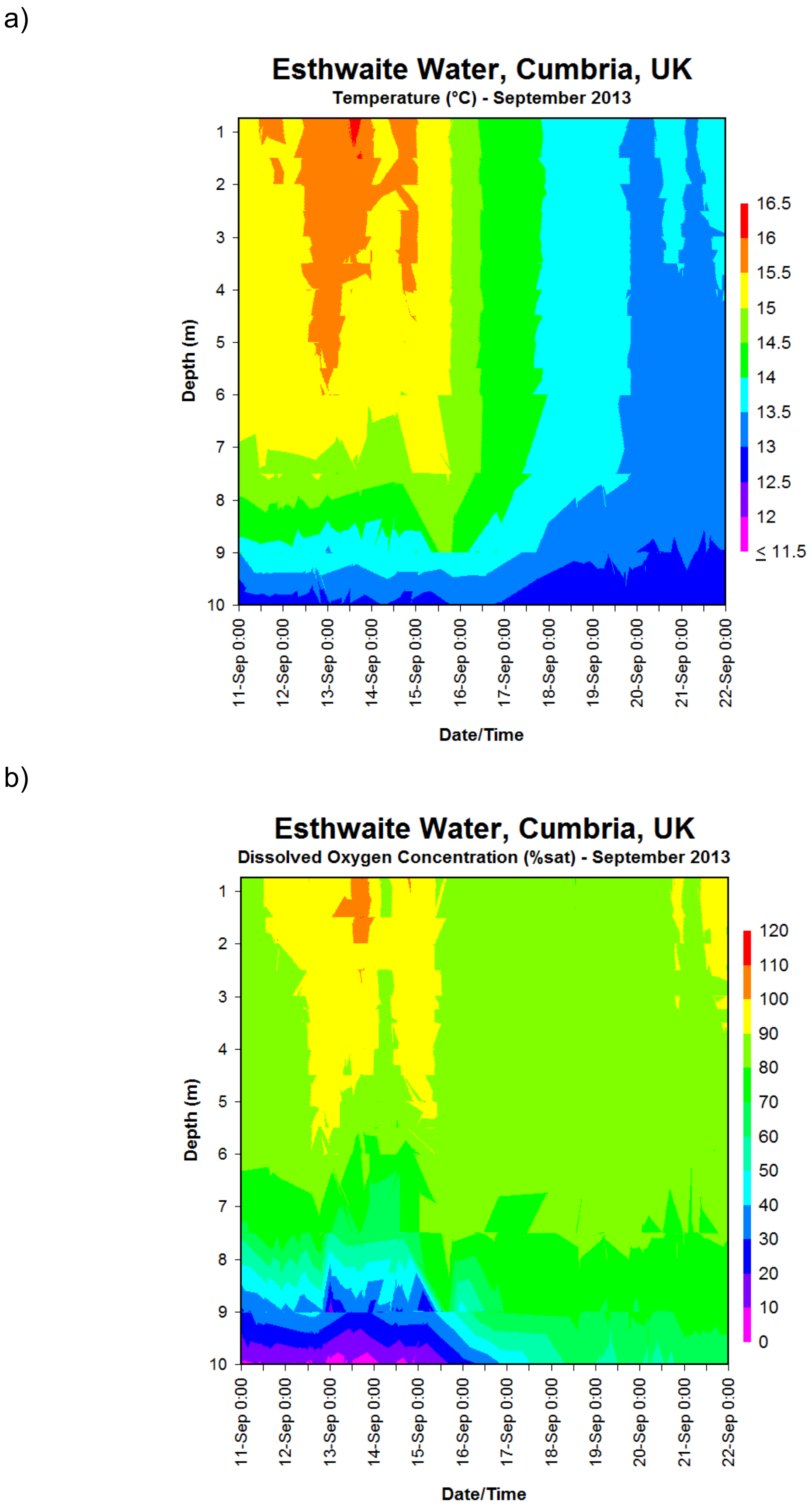


Figure 20 Profiles of a) Water Temperature and b) Dissolved Oxygen Concentration recorded in Esthwaite Water, September 2013

8. Conclusions

The LDMS deployed on Llyn Tegid has now been in operation for more than eight years and has provided us with new insights into the climatic sensitivities of the lake and its catchment. In contrast to what we assumed some years ago, most of the ‘weather related’ impacts observed were connected with an unexpected the change to much wetter and windier summers. This pattern is known to be related to a southerly shift in the position of the Atlantic Jet Stream but the global factors responsible for this shift are poorly understood. The weather patterns experienced in 2014 suggest that this period may be coming to an end and, were it not for the storm that hit the UK in early August, Llyn Tegid could well have experienced some water quality problems.

The replacement of the existing LDMS with a more sophisticated ‘profiling’ system therefore comes at an opportune moment. Once this system has been deployed and associated river monitoring system installed, Llyn Tegid will be one of the most intensively monitored lakes in the UK. The investment made by the Natural Environment Council in these lake monitoring systems provides NRW with an opportunity to participate in an innovative programme at very little cost. For the next two years, Llyn Tegid will also form part of the EU funded NETLAKE project which includes partners from more than twenty European countries. Professor George is a co-coordinator of the Working Group ‘Informing policy and management using lake sensor data’ and has recently provided some ‘Case Studies’ based on previous work in the UK. NRW is one of the ‘end-user’ groups linked to the project.

9. References

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10. Data Archive Appendix

Data outputs associated with this project are archived at 462, media 1523 on server–based storage at Natural Resources Wales.

The data archive contains:

A. This report in Microsoft Word 2003 (.doc) format and Adobe portable document format (pdf) file.
B. Raw data as a Microsoft Excel 2003 (.xls) file containing the following parameters recorded at hourly intervals:
   Mean Water Temperature at depths of 1, 3, 6, 9, 12, 14, 16, 18, 20, 23, 26, and 29 metres
   Mean Air Temperature
   Mean Conductivity Temperature (measured adjacent to conductivity sensor)
   Specific Conductivity (i.e. conductivity temperature corrected to 25°C)
   Conductivity (not temperature corrected)
   Mean Solar Radiation
   Mean Surface PFD
   Barometric Pressure
   Mean Uncorrected Wind Direction
   Mean Wind Speed
   Mean Squared Wind Speed
   Mean Cubed Wind Speed
   Resultant Wind Speed
   Resultant Uncorrected Wind Direction
   Standard Deviation of Resultant Uncorrected Wind Direction
   Underwater PFD (at 1m depth)

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