Cyfoeth Naturiol Cymru
Natural Resources Wales

Llyn Tegid Monitoring Station 2013

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NRW Evidence Report No. 2

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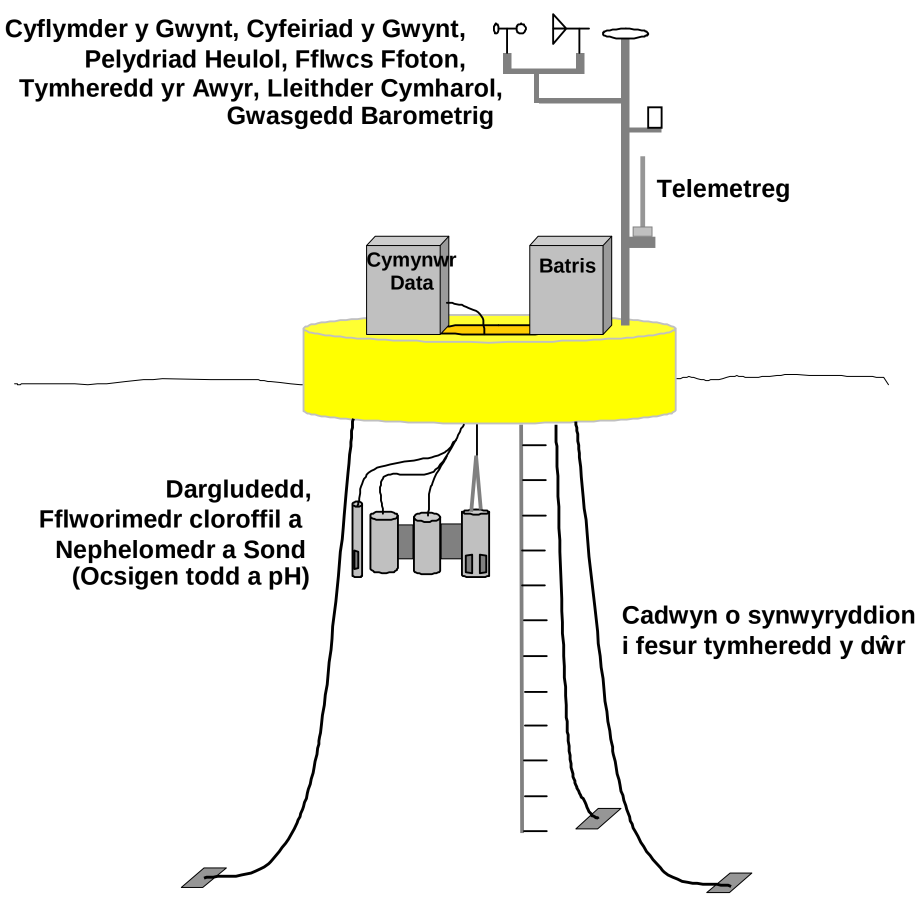
Contents

List of Figures

List of Tables

1. Crynodeb Gweithredol

Y mae'r 'Lake Dynamics Monitoring Station' (LDMS) a osodwyd ar Lyn Tegid bellach wedi bod yn ei lle ers 2006 ac yn dal i ddarparu cofnod manwl o ymatebion y llyn i newidiadau yn y tywydd. Yn 2011 yr oedd y llyn yn un o'r safleoedd a gynhwyswyd yn UKLEON ('UK Lake Ecological Observation Network'), prosiect i sefydlu rhwydwaith o lynnoedd lle gellir defnyddio mesuriadau dwys i hybu tri pwnc ymchwil arddangosiadol: rhagolygon amserol o ymddygiad llyn, effaith y tywydd ar y fflwcs carbon a'r ymateb cydlynol llynnoedd i newidiadau byrhoedlog yn y tywydd. Yn fwy diweddar cynhwyswyd Llyn Tegid yn y rhwydwaith o safleoedd a ariannwyd yn rhannol gan yr Undeb Ewropeaidd yn y prosiect a enwid NETLAKE. Prif bwrpas NETLAKE yw cynnig fforwm trafod i wyddonwyr a rheolwyr ond y mae hefyd yn trefnu gweithdai ac yn cefnogi rhai ymchwiliadau maes. Un pwnc o ddiddordeb cynyddol i ymchwilwyr yw effaith newidiadau eithafol yn y tywydd ar ddeinameg tymhorol llynnoedd. Y mae Llyn Tegid wedi dioddef o sawl digwyddiad o'r fath ers i'r LDMS gael ei gosod ac y mae'r data a gasglwyd wedi newid ein hamgyffred o'r newidiadau a welir yn y dyfodol. Yn yr adroddiad hwn cynigiwn arolwg o'r newidiadau a welwyd yn 2013, gwnawn gymariaethau gyda'r blynyddoedd blaenorol ac esboniwn sut y gellir cysylltu rhai o'r newidiadau gyda ffactorau rhanbarthol a byd-eang yn yr hinsawdd.



Ffigwr 1 Prif nodweddion yr LDMS

Dengys y diagram sgematig yn Ffigwr 1 nodweddion sylfaenol yr LDMS a osodwyd ar Lyn Tegid. Er bod yr orsaf wedi gweithio yn bur dda yn 2013 yr oedd yna rhai problemau technegol a ddisgrifir yn yr adroddiad. O dan nawdd UKLEON, datblygwyd ffordd newydd o grynhoi a chymharu'r data a gesglir gan y rhwydwaith ac fe gychwynnwyd rhai treialon 'byw' yn 2013.

Yr amcanion yn ystod y cyfnod dan sylw oedd:

- Cynnal yr LDMS a osodwyd ar Llyn Tegid trwy gyfuniad pwrpasol o ymweliadau ac arolygu tros y we.
- Arolygu perfformiad technegol yr LDMS a nodi unrhyw newidiadau a wnaed yn 2013.
- Lawr lwytho'r data a gasglwyd gan yr LDMS a'u dosbarthu i CNC a'u partneriaid yn y prosiect.
- Disgrifio patrwm y tywydd a welwyd yn yr ardal yn 2013 a chymharu'r mesuriadau gyda'r cyfartaledd hirdymor.
- Disgrifio effaith y newidiadau a welwyd yn y tywydd ar ddeinameg y llyn yn y gaeaf, y gwanwyn, yr haf cynnar a'r haf hwyr.
- Dangos sut y gellir defnyddio'r data manwl a gesglir gan yr LDMS i fesur effaith newidiadau yng nghyflymder dros gyfnodau sy'n llawer llai nag awr.
- Dangos sut y gellir defnyddio amcangyfrif o sadrwydd y golofn ddŵr, o fesuriadau o'i thymheredd, i gymharu deinameg y llyn dros gyfnod yr haf mewn dwy flwyddyn wahanol.
- Cyflwyno crynodeb o'r gwaith a drefnir gan brosiect NETLAKE ac i gynnig enghreifftiau o'r ffordd y gellir defnyddio y data a gesglir gan y rhwydwaith i ehangu ein dealltwriaeth o effeithiau limnolegol newidiadau byr-hoedlog yn y tywydd.
- Trafod y canlyniadau a gasglwyd gan yr LDMS dros yr wyth mlynedd diwethaf o safbwynt yr hwn a wyddys am newidiadau rhanbarthol a byd-eang yn y tywydd.

Cyflawnwyd yr holl amcanion a nodwyd ar gyfer y flwyddyn ac fe geir disgrifiad llawn o'r canlyniadau yng nghorff yr adroddiad.

Yn 2014, bydd chwech o orsafoedd UKLEON, yn cynnwys Llyn Tegid, yn cael eu huwchraddio trwy osod bwy mwy sefydlog ar y llyn i gynnal system awtomatig i broffilio'r golofn ddŵr. Bydd y proffiliau a recordir gyda'r system yn fodd i ddilyn tyfiant a gwasgariad 'blwms' o algâu a mesur y cyflenwad o ocsigen yn y dŵr dwfn. Fe fydd yr uwchraddio yn gam allweddol i wella sawl agwedd ar allu'r orsaf.

2. Executive Summary

The Lake Dynamics Monitoring Station (LDMS) deployed on Llyn Tegid has been in operation since 2006 and continues to provide a high-resolution record of the lakes response to changes in the weather. In 2011 the lake was one of the sites selected for inclusion in UKLEON (UK Lake Ecological Observation Network), a project designed to establish to establish a network of lake monitoring sites that could be used to support three research topics: real-time forecasting of lake behaviour, the effect of the weather on the flux of carbon and the coherent response of lakes to short-term changes in the weather. More recently Llyn Tegid has been included in a network of sites part-funded by the European Union NETLAKE project. NETLAKE is primarily forum for scientists and managers to exchange information but it also arranges workshops and funds some field investigations. One topic of increasing interest to researchers is the impact of extreme weather events on the seasonal dynamics of lakes. Llyn Tegid has experienced a number of such events since the LDMS has been in operation and the data acquired has changed our perspective on future drivers of change. In this report, we provide an overview of the changes observed in Llyn Tegid in 2013, draw comparisons with previous years and explain how some of these changes are related to climatic features that operate on a regional and global scale.

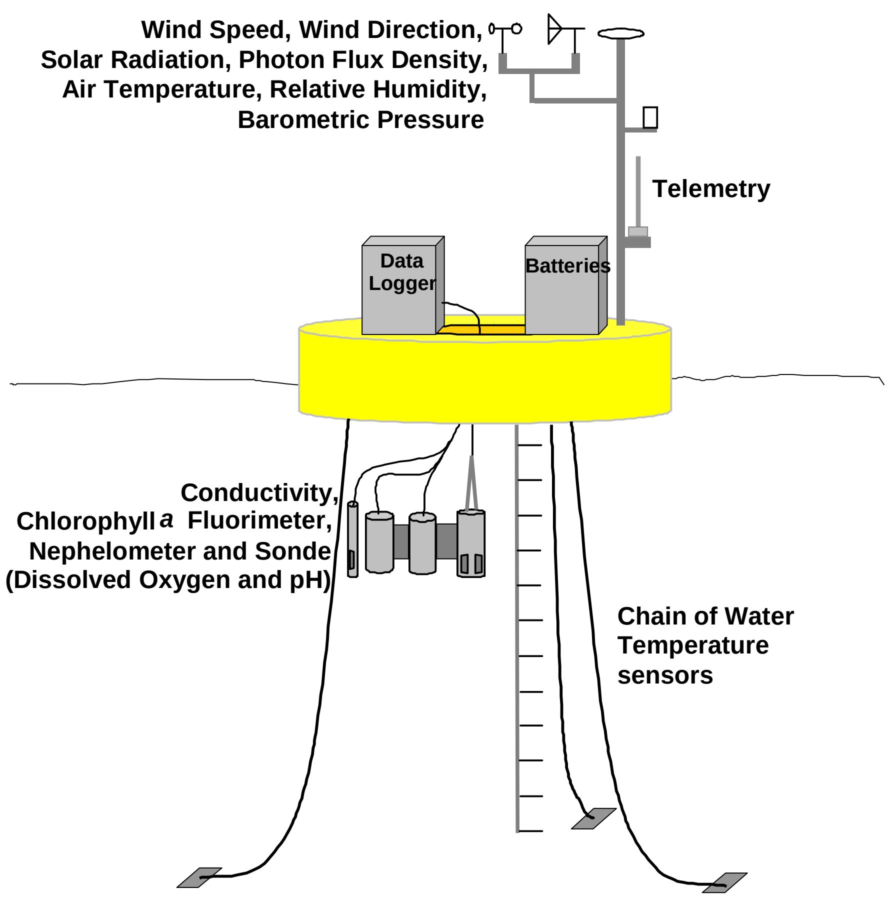


Figure 2 The basic features of the LDMS

The schematic diagram in Figure 2 shows the basic features of the LDMS deployed on Llyn Tegid. Although the station generally performed well in 2013, there were some technical problems which are described in this report. Under the UKLEON project, a means of accessing summary historical data from the station via the web and comparing these with other stations in the UKLEON network has been developed and became 'live' in 2013.

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 2013.
- 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 the area in 2013 and compare these with some long-term averages.
- To describe the impact of the observed changes in the weather on the dynamics of the lake in winter, spring, early summer and late summer.
- To show how the high-resolution data acquired by the LDMS can be used to quantify the impact of sub-hourly variations in the wind-speed.
- To show how estimates of the stability of the water column, based on the acquired temperature measurements, can be used to characterise the summer dynamics of the lake in two contrasting years.
- To provide an update on the work planned by the NETLAKE project and to provide an example of how the data acquired by a network of instruments can be used to enhance our understanding of the limnological effects of short-term variations in the weather.
- To discuss the results acquired by the LDMS over the last eight years in the light of what is known about regional and global-scale changes in the weather.

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

In 2014, six UKLEON stations including the Llyn Tegid system are scheduled to be upgraded with a new slightly larger, more stable buoy fitted with a newly developed automatic profiling system. Profiles taken with this system will allow us to monitor the formation and dissolution of algal blooms and acquire detailed measurement of the concentration of oxygen in deep water. This upgrade will represent a major enhancement in the capability of the station.

3. The Maintenance and Servicing of the LDMS in 2013

3.1. The configuration of the LDMS in 2013

Figure 3 Photograph of the LDMS fitted on Llyn Tegid (December 2012)

Lakeland Instrumentation Ltd (LI Ltd) monitored the performance of the station (pictured in Figure 3) regularly in 2013. Following the December 2012 service visit, the next service visit was planned towards the end of 2013. For logistical (availability of LI Ltd and SNPA staff) and safety reasons (the sustained period of stormy weather towards the end of 2013), the planned visit was delayed until February 2014.

The December 2012 visit was described in last year's report and included the addition of an underwater light (Photon Flux Density, PFD) sensor and a carbon dioxide sensor. The suite of sensors fitted to the station during 2013 is listed in Tables 1 and 2.

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 $50 m.s^{-1}$	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 deploymen. 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 $\mu mol.m^{-2}.s^{-1}$	Military-grade connector fitted	
Underwater Photon Flux Density	Photodiode Quantum Sensor	LI-190S	Licor	0 to 3000 $\mu mol.m^{-2}.s^{-1}$	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	

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

<table>
<tr><th>PARAMETER</th><th>SENSOR TYPE</th><th>MODEL</th><th>MANUFACTURER</th><th>RANGE</th><th>ADAPTATION</th><th>NOTES</th></tr>
<tr><td>Chlorophyll a</td><td>Fluorimeter</td><td>Minitracka (C)</td><td>Chelsea Instruments</td><td>0 to 100µg/L (in acetone)</td><td>Military-grade connector fitted</td><td>12V supply controlled by data logger</td></tr>
<tr><td>Suspended solids</td><td>Nephelometer</td><td>Minitracka (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>Water Temperature (for temperature compensation of Conductivity sensor)</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>pH</td><td>pH</td><td rowspan="2">DataSonde 5x</td><td rowspan="2">Hydrolab</td><td>pH 1 to 14</td><td rowspan="2">Military-grade connector fitted</td><td rowspan="2">Station can operate with alternative models of Sonde</td></tr>
<tr><td>Dissolved Oxygen Sensor</td><td>Luminescent Dissolved Oxygen</td><td>0 to 500%</td></tr>
<tr><td>Water Temperature structure</td><td>‘Chain’ of 12 Platinum Resistance sensors</td><td></td><td>Labfacility</td><td>-5 to +40°C</td><td>Special termination module supplied</td><td>12 sensors deployed at 1m, 3m, 6m, 9m, 12m, 14m, 16m, 18m, 20m, 23m, 26m and 29m</td></tr>
</table>

3.2. The upgrades completed in 2013

Although there were no service visits by LI Ltd to the station in the calendar year 2013, there were important upgrades to the dissemination of data under the UKLEON project. Data retrieved from the Llyn Tegid station along with other UKLEON stations are now automatically loaded into an Oracle database hosted by the Centre for Ecology and Hydrology (CEH). Summary measurements are 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 the CEH for scientific analysis.

3.3. The technical performance of the system in 2013

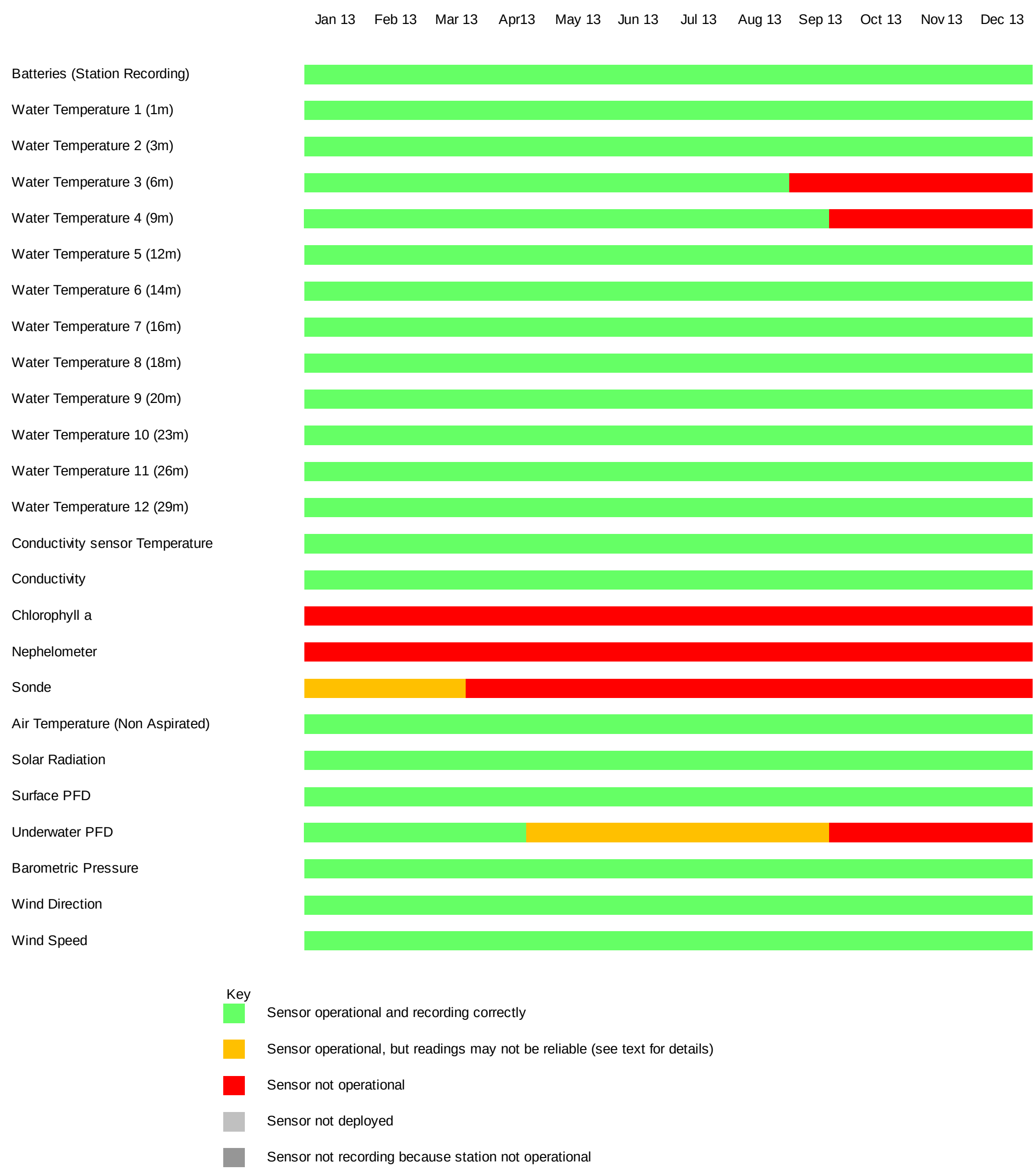


Figure 4 Summary of parameters recorded by the LDMS station on Llyn Tegid between 1 January and 31 December 2013.

The station generally continued to perform well during 2013 (Figure 4). The service visit planned for late 2013 took place in February 2014 and was undertaken by Martin Rouen (LI Ltd) with assistance from Arwel Morris (SNPA warden). It was arranged to address several issues, which had become apparent from reviewing the acquired data:

- To check why the sonde measurements were not being recorded
- To check the underwater light (PFD) measurements
- To retrieve the CO_2 probe for modification
- To check the prt chain
- To visit the site previously identified for the river monitoring station to confirm practical installation details

A surprising finding from the service visit was that the buoy had rotated by about 45° and was easier to rotate manually than should have been the case. This indicated that at least one of the moorings has moved or failed. Neither LI Ltd nor the SNPA warden, Arwel Morris, had been aware of the mooring issue prior to the service visit on site and as a result, were not carrying a bathyscope or underwater video camera to carry out more detailed examination of the mooring system. The problem was almost certainly a very recent development as Arwel Morris noticed it immediately as we approached the station, but it was aligned normally when he last changed the batteries at the station (on 26th December 2013). In early 2014 some of the deeper water temperature sensors (prts) have begun to fail and it was clear on inspection that the prt chain has got caught up in the mooring line (the prt chain could not be lifted, which meant that it must be snagged somewhere). The problems with the mooring and prt chain will be addressed in 2014.

There has been a longstanding fault where the sonde measurements have not recorded correctly at the Llyn Tegid station. This could have been due to a variety of causes, but it was discovered during the February 2014 service visit that the station has a slightly different arrangement with the wiring to the sonde compared to the other sites (for historical reasons). This was found to be wired incorrectly for the sonde. The wiring was corrected in the field and the sonde is now being recorded both by the logger and internally by the sonde itself. Some sonde data to mid-March 2013 is available as the sonde had previously been set to record internally as a precaution against such a problem.

The underwater light (PFD) measurements show a sudden attenuation in spring 2013 and a further marked reduction later in the year. During the site visit, it became apparent that the boom holding the underwater light cell in position had 'disappeared' completely (presumably, to the lake bed). The underwater light cell was still attached by its electrical cable and the wiper assembly was attached to the light cell even though its own cable had been severed. The sensor and wiper were retrieved and removed for repair.

The carbon dioxide probe (an upgrade carried out under UKLEON in December 2012) had not been deployed in the water (due to water leakage issues observed at other sites). The sensor has been recording atmospheric

CO_2 concentration during 2013. It was removed during the February 2014 service visit, ready to be redeployed once adapted to resolve the potential water leakage issue. A new system for attaching the gas permeable membrane (used to make these atmospheric sensors suitable for submersion) has been developed and is currently under test at CEH Lancaster.

A software error introduced during the service visit in December 2012 unfortunately resulted in the 'Minitracka' sensors being measured by the station but not recorded. Unfortunately, this was not noticed by LI Ltd while periodically checking the station remotely during in 2013. The sensors were being read and displaying valid readings in real-time (the problem being that the readings from these two sensors were not being recorded). This will be corrected by a further software upgrade in early 2014.

The site identified by D Glen George and Hywel Griffiths (Aberystwyth University) as suitable for the new River Monitoring Station was visited by Martin Rouen (Lakeland Instrumentation Ltd) and Arwel Morris (SNPA) with the intention of determining final practical arrangements to enable the system to be fully described to obtain necessary permissions. The river level and flow rate were much higher than when the site was initially identified and it was soon apparent that although the river flow was significantly below its peak, the water current was too strong for the safe installation of the river monitoring station. It is now proposed that an alternative configuration of station is fitted slightly higher up the Twrch river probably in the nearby village. Subject to the availability of suitable site, a station which pumps water from the river to a bankside flow cell containing the sensors will be fitted. By keeping the relatively expensive sensors above the river level, the risk of significant damage to the station during flood events is greatly diminished. The SNPA wardens have very good local knowledge and will identify potential sites for the station. It is expected that this delayed deployment can be completed in 2014.

Notwithstanding these particular issues, the station otherwise performed reliably during the calendar year 2013 with no significant breaks in the data record and most sensors performing correctly all year.

3.4. The distribution of data recorded in 2013

LI Ltd has regularly downloaded the station and has compiled the hourly summary data for distribution as an Excel Spreadsheet to the following partners:

- Arthur Arrowsmith, Natural Resources Wales
- Dafydd Edwards, Snowdonia National Park Authority
- Glen George, Aberystwyth University (Honorary Professor)
- Henry Lamb, Aberystwyth University
- Helen Millband, Natural Resources Wales
- Arwel Morris, Snowdonia National Park Authority
- Richard Pritchard, Natural Resources Wales
- Rhian Thomas, Natural Resources Wales

4. The Seasonal Variations in the Weather

In 2013, North Wales experienced an unusually cold spring and a wet autumn but summer conditions were much closer to the historical average. Figure 5 shows the 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.

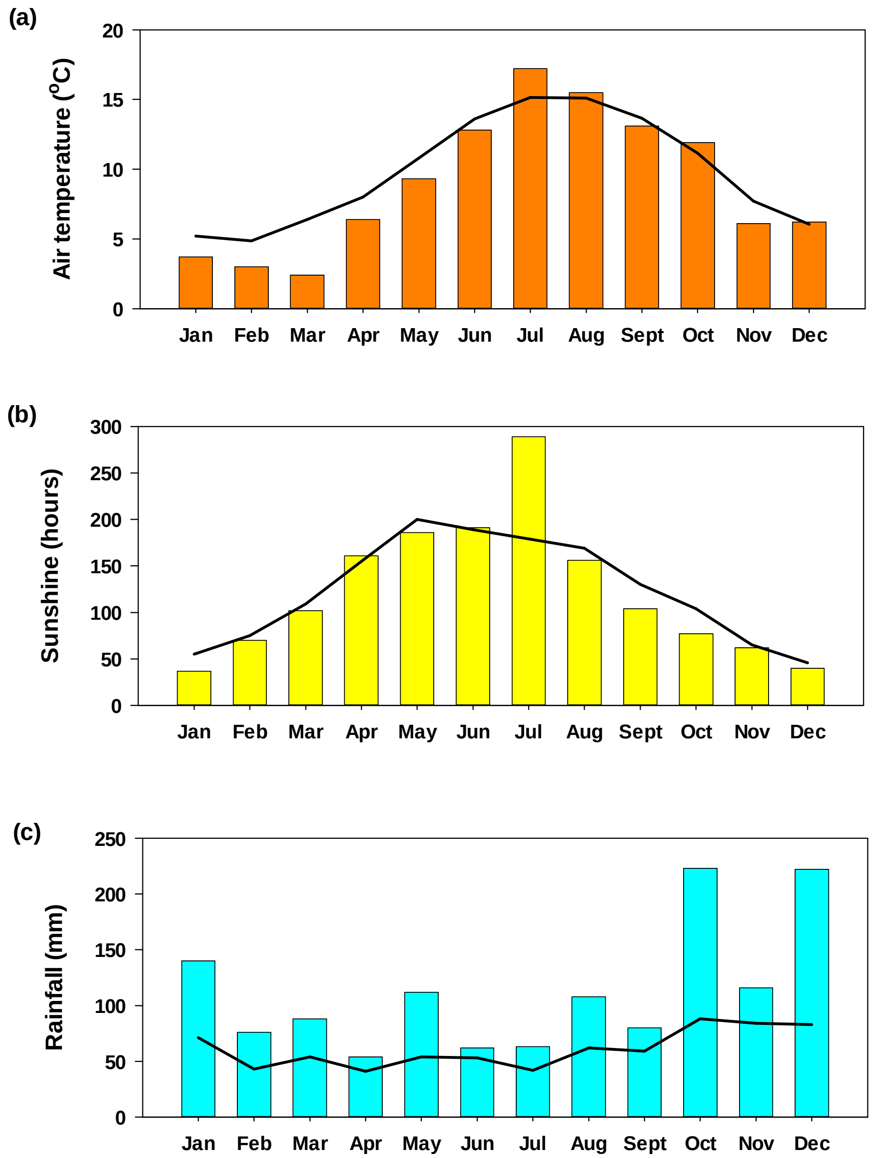


Figure 5 The seasonal variation in (a) the air temperature (b) the hours of bright sunshine and (c) the rainfall recorded for the area in 2013. The bars show the monthly averages and the lines the long-term (1971-2000) averages for a monitoring station near Colwyn Bay (data from the UK Meteorological Office).

The mild weather experienced at the beginning of 2013 was followed by an extended period of very cold weather (Figure 5a). In the UK, the air temperatures in March were amongst the lowest ever recorded and, at the several locations in Wales, the average temperature was 4°C below the historical average. These cold conditions persisted into May and June before a high-pressure system from the Atlantic produced a sudden change in early July. July proved to be an exceptionally warm month and, in some parts of Wales, maximum temperatures reached 30°C, a level not observed since 2006. The number of hours of bright sunshine recorded in July were 40 % above the historical average but the number reported in August were below the historical average (Figure 5b). In contrast to previous years, the summer was relatively dry but the rainfall totals recorded in October and December were *c*. 150% higher than average (Figure 5c). Statistically, the summer of 2013 was the warmest recorded since the LDMS was installed in 2006 but the weather patterns recorded were very different to those observed in previous warm summers.

5. The Seasonal Dynamics of Llyn Tegid in 2013

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 each case, the key measurements acquired by the LDMS are presented and related to the hourly variations in the local weather. The periods used for these seasonal summaries were:

Winter: 1st January to 11th March 2013.

Spring: 12th March to 20th May 2013.

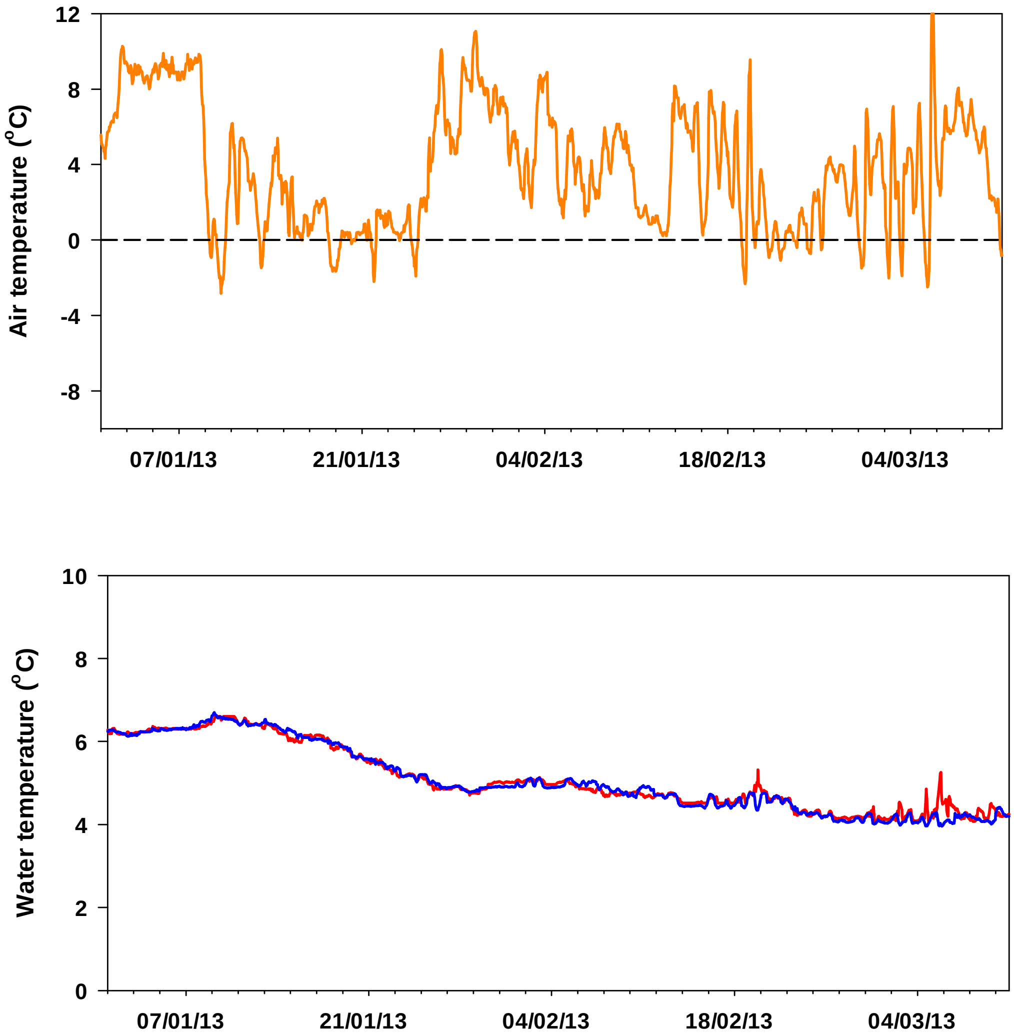
Early summer: 21st May to 29th July 2013.

Late summer: 30th July to 7th September 2013.

5.1. The winter measurements (1st January to 11th March 2013)

The air temperature measurements in Figure 6a show that winter of 2013 was cold with temperatures falling below zero on 10 days in January, 6 days in February and 4 days in March. The main period of cooling was recorded between the 17th and 28th January when the water temperature fell from a maximum of 6.2°C to a low of 4.7°C (Figure 6b). The cooling period recorded in early March was unusual for the time of year and produced the lowest water temperatures in the time-series. At times, these temperatures were very close to 4°C, the temperature of maximum density, but no reverse stratification was detected.

(a)



(b)

Figure 6 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 2013)

In recent years, cold winters have been followed by unusually warm springs but this was not the case in 2013. The air temperatures recorded in the spring (Figure 7a) were very low for the time of year. On several occasions the night-time temperatures were below freezing and the day-time maxima only reached 10°C on 13th April. The water temperatures recorded during the period were, consequently, very low (Figure 7b). The first signs of warming appeared in early May but the daily average of the recorded near-surface temperature only reached 10°C on 20th May.

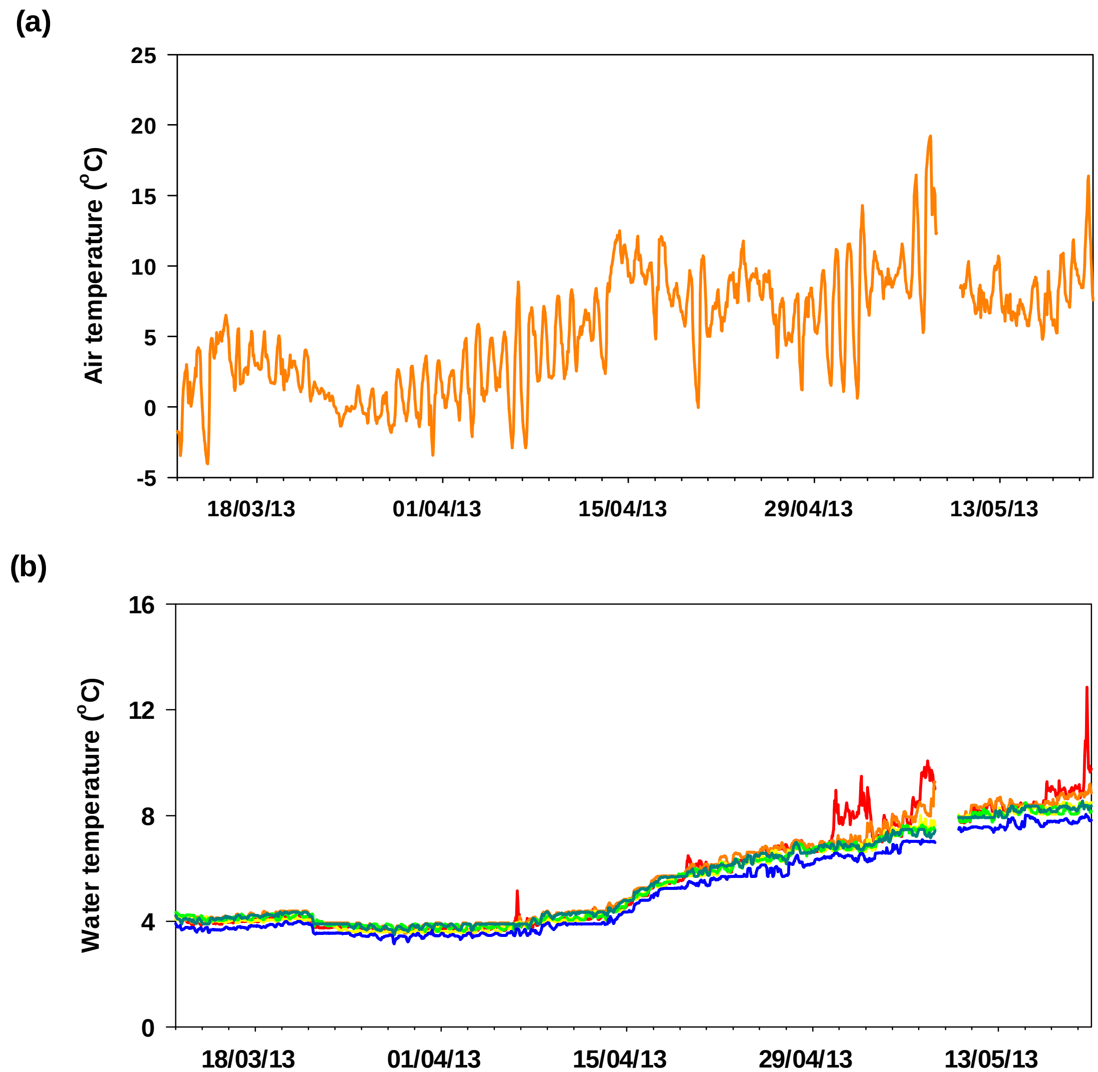
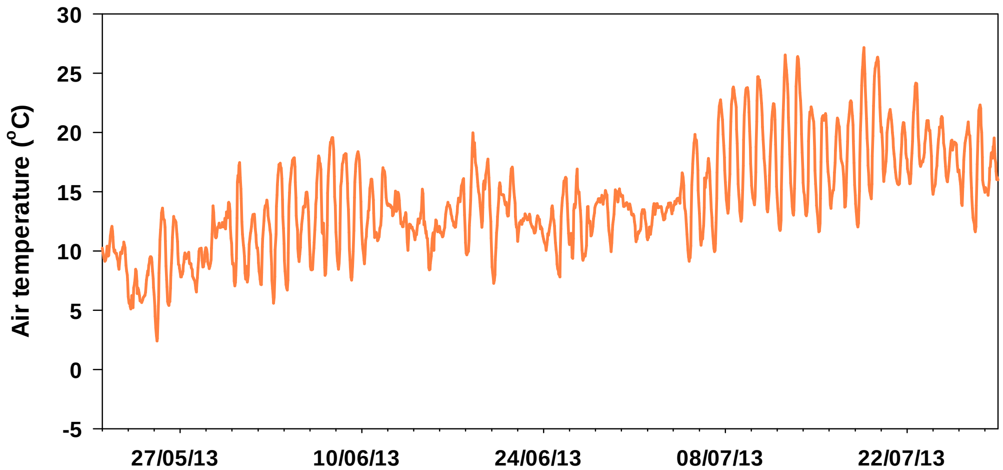


Figure 7 The spring weather and its effect on the lake. a) air temperature, b) the vertical variations in the water temperature. In the temperature record the colour of the lines show the depth of measurement i.e. the red shows the surface temperature and the blue the bottom temperature.

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

After a brief period of warmth in late May the air temperatures remained low throughout June and early July (Figure 8a). Since there were periods of turbulent mixing associated with the frequent showers stratification was weak and the near surface temperatures remained below 15°C for much of the period (Figure 8b). The fine weather experienced in July resulted in some very pronounced surface warming. The recorded air temperatures were not particularly and the key driving variable was the long period of very clear sunny days.

(a)



(b)

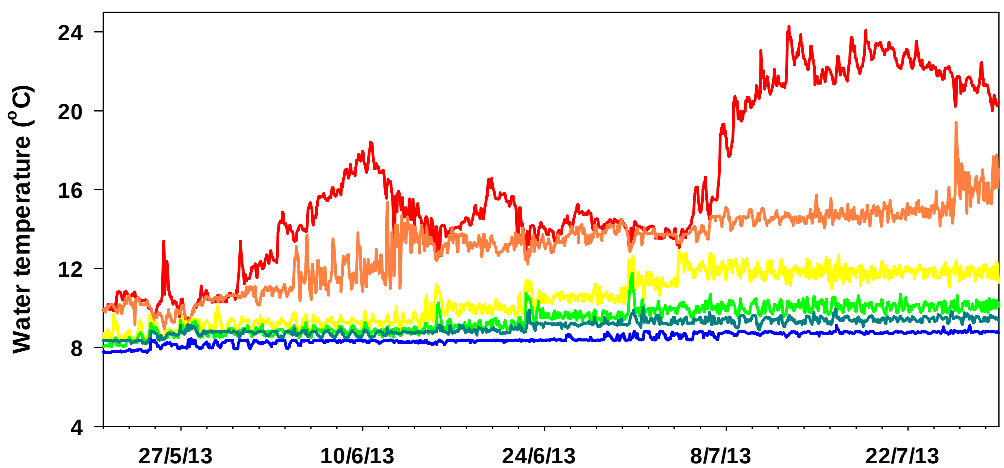


Figure 8 The early summer weather and its effect on the lake. a) The air temperature. b) The vertical variations in the water temperature. In the temperature record the colour of the lines show the depth of measurement i.e. the red shows the near surface temperature and the blue the bottom temperature.

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

The air temperatures recorded in late summer (Figure 9a) were again low for the time of year with several night time temperatures falling below 10°C. The surface water temperature (Figure 9b) declined throughout the period as a series of mixing events dispersed the surface heat gained in July deeper into the water column. By the middle of August, the effects of the unusually sunny July had disappeared as a sequence of low pressure systems once again dominated the weather. Since the air temperatures were low and the wind speeds high throughout the period the late summer blooms of cyanobacteria that have often appeared at the end of the growing season did not materialise.

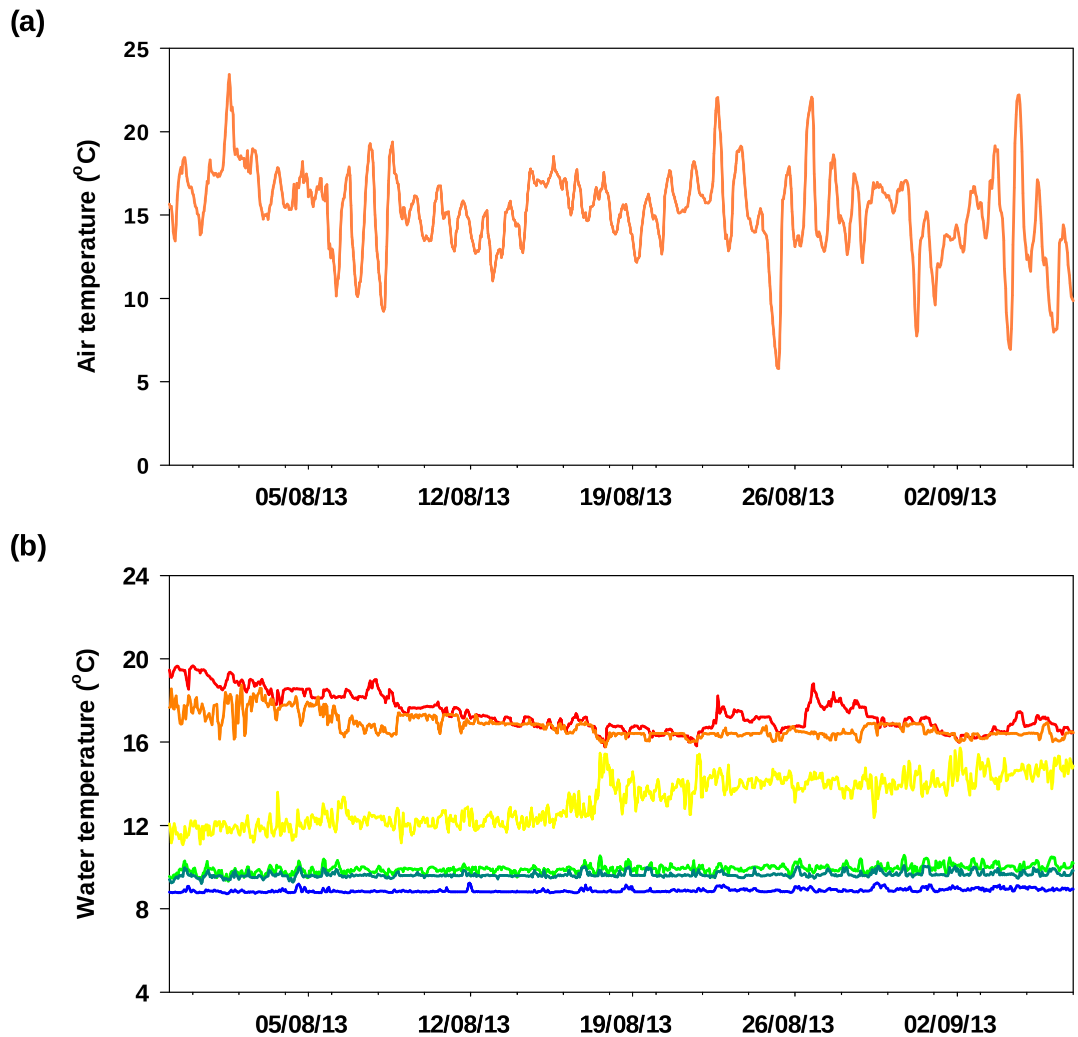


Figure 9 The late summer weather and its effect on the lake. a) The air temperature. b) The vertical variations in the water temperature. In the temperature record the colour of the lines show the depth of measurement i.e. the red shows the surface temperature and the blue the bottom temperature.

6. Using the LDMS to monitor the impact of an extreme event

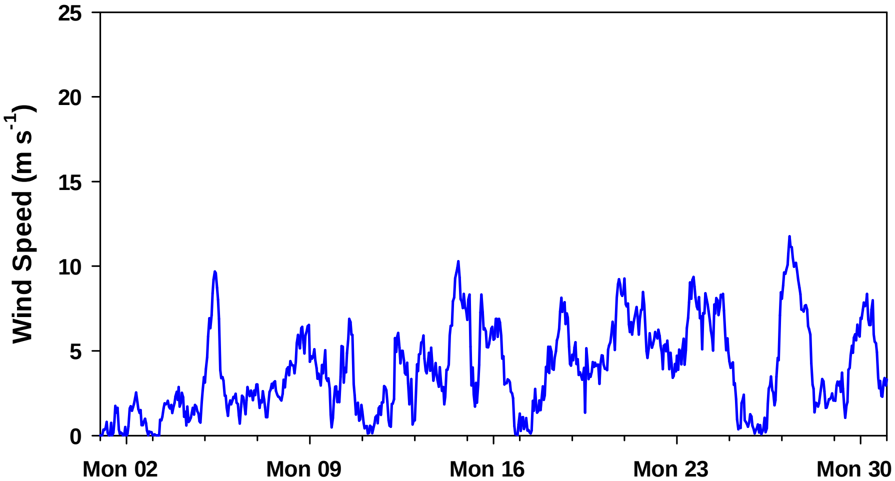
In recent years, it has become clear that extreme weather events are becoming increasingly common as the temperature and the moisture content of the atmosphere increases. For lakes, the most important extreme events are those connected with short-term increases in the wind speed. Gales that last for just a few hours can have a major effect on the physical, chemical and biological characteristics of a thermally stratified lake by entraining nutrients from deep water and 're-setting' the natural succession of the different functional groups that dominate the phytoplankton.

In previous reports, we have used hourly averages of the wind speeds recorded by the LDMS to support our seasonal analyses but the system also stores the values acquired at 4 minute intervals. Figures 10 a and b show the extent to which the commonly reported hourly average underestimate the mixing action of the wind. We have selected some measurements from in December 2013 since these wind speeds were relatively high. To set these measurements in a broader context both values have been corrected for the non-standard height of the anemometer. Wind speeds are conventionally reported for a standard height of 10m but measurements acquired at other heights can be adjusted by applying an empirical correction. The correction factor is based on the assumption that the wind blowing over a flat surface has a stable profile has a predictable profile where the frictional effect decrease with distance from the ground. In these circumstances, the speed of the wind at the 'standard' height can be estimated by:

$$U_x = U_r \, (Z_x/Z_r)^{\alpha}$$

Where U_x is the wind speed at the standard height (Z_x), U_r the wind speed at the height of measurement (Z_r) and α is an empirical coefficient. For the neutral conditions expected over the smooth surface of a lake this factor must be close to the commonly quoted value of 1/7 (0.143). Figure 10a shows the time-series of hourly averages stored by the LDMS logger between 1st December and 31st December 2013. Most values are below 8 m s^{-1} and there was only one occasion when the average exceeded 10 m s^{-1}. Figure 10b shows the time-series of 4 minute measurements stored by the LDMS logger between 1st December and 31st December 2013. Speeds in excess of 15 m s^{-1} are now common and there was one occasion when the speed reached 25 m s^{-1}. It is important to note that these are not maximum gust speeds but integrations over a 4 minute period. High resolution measurements of this kind are particularly important for modelling studies since the wind stress at the water surface is a squared function of the measured wind speed.

(a)



(b)

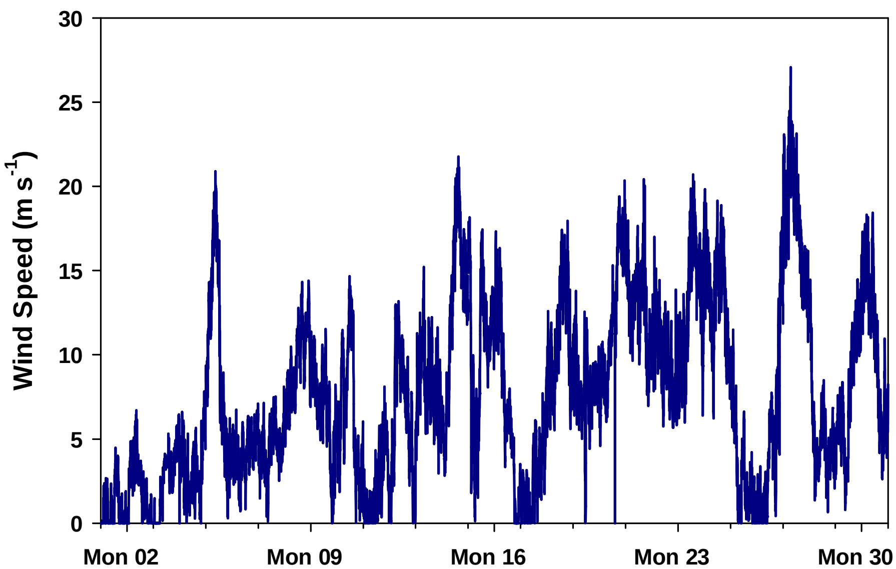


Figure 10 A comparison of the average hourly wind speeds and the high resolution measurements acquired by the LDMS in December 2013. Both values have been adjusted to match those expected at the standard measurement height of 10m.

7. Using the temperature measurements acquired by LDMS to compare the stability of the water column in 2012 and 2013.

The most serious weather-related problems encountered in Llyn Tegid are those connected with warm summers and prolonged periods of calm. These are the conditions that typically lead to the enhanced growth of cyanobacteria and the increased consumption of oxygenation in deep water. In recent years, the summers experienced in North Wales have been cold and wet so any blooms that develop have appeared very late in the year. In 2013, we detected the first signs that the lake is returning to a more ‘normal’ state where summer stratification is more intense but this boost to the temperature of the water was still relatively short-lived.

Figure 11 compares the seasonal variation in the stability of the lake in 2013 with that observed in 2012. In 2012, the summer was so cold and wet that the lake was only weakly stratified in July and August. The highest stabilities were recorded in early September but by then the summer growth of phytoplankton was coming to an end. In 2013, the seasonal variation the stability of the water column was much closer to those expected in a ‘normal’ year. The intense stratification that characterises the lake in summer was, however, delayed by the cold spring and the improved growing conditions in July did not continue into August.

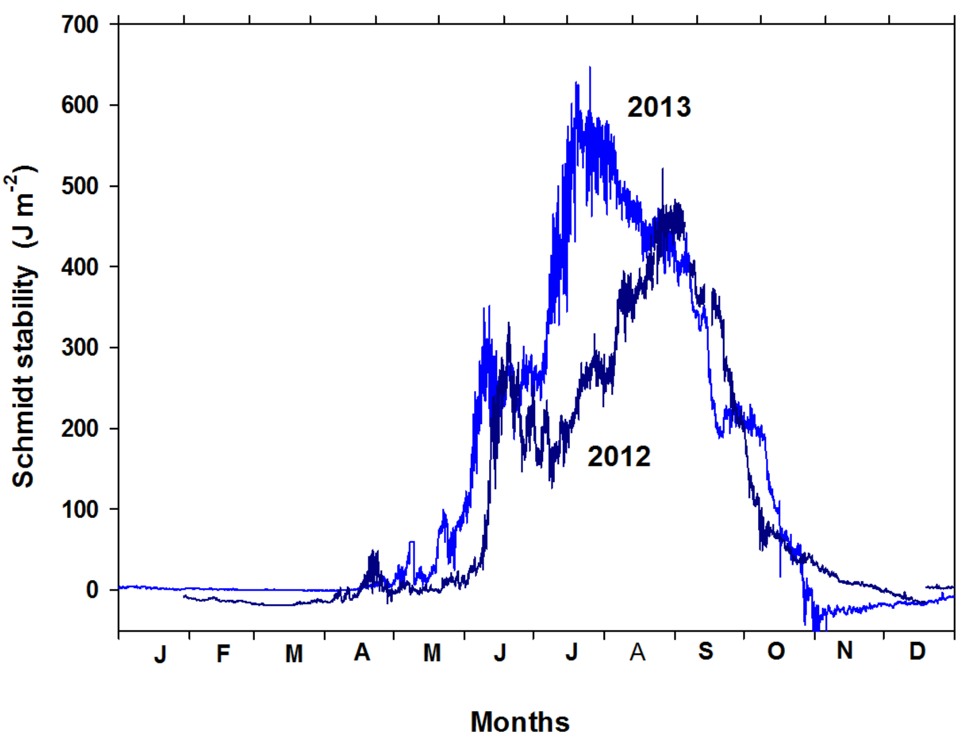


Figure 1 A comparison of the seasonal variation in physical stability of Llyn Tegid in 2012 and 2013.

8. Llyn Tegid and the NETLAKE project

NETLAKE is a four-year project funded by the EU to promote the wider use of automatic monitoring systems in lakes. The project includes partners from more than twenty European countries and will use a combination of field studies, workshops and web-based tools to meet its objectives. Professor George is member of the Management Committee and also serve as the co-coordinator of the Working Group on 'Informing policy and management using lake sensor data'. Llyn Tegid is the only Welsh site included in the network and Dr Rhian Thomas from Natural Resources Wales has been appointed as the *rapporteur* for the site. In February 2013, Professor George attended the inaugural meeting of NETLAKE at the Dundalk Institute of Technology in Ireland and also helped organise the first Workshop of the 'Policy and Management' Working Group in the Netherlands. Unfortunately, no representatives from Natural Resources Wales were able to attend the meeting but opportunities to attend the workshops and meetings organised by the project are sure to arise in the future. Data acquired by the LDMS on Llyn Tegid has already been used to support a 'Case Study' on algal blooms and we may also include some information on the bloom observed in Llyn Padarn in 2009.

One of the issues addressed by the NETLAKE project is the extent to which lakes located in different parts of Europe respond to short-term variations in the weather. Lakes are known to act as integrators of the local climate but their response typically varies with the size and physical characteristics of the lake. In the past four years, the UKLEON project managed by the Centre for Ecology and Hydrology at Lancaster has built up a network monitoring stations in the UK. Some of these stations have now been included in NETLAKE so the analyses can be broadened to include some comparisons with sites in mainland Europe. Comparative studies of this kind can produce very useful information on the 'coherent' responses of lakes to sudden or extreme variations in the weather.

In the UK, the most influential extreme events are often connected with the movement of low-pressure systems across the Atlantic. Figure 12a shows the extent to which the low pressure systems that dominated the UK in June 2013 disrupted the expected summer increase in the temperature of Llyn Tegid in Snowdonia and the South Basin of Windermere in the English Lake District. The atmospheric pressure variations measured at the two sites followed much the same pattern and there was a high-level of temporal coherence in the surface temperature of the two lakes. The cross-plot in Figure 12b shows the relationship between the two sets of atmospheric pressure measurements. The systematic disposition of the points reflects the geographic evolution of the low pressure area as it moved from east to west. The cross-plot in Figure 12c shows the relationship between the two sets of surface temperature measurements. These values are inherently more 'noisy' since local variations in the wind-speed and cloud cover also have an effect on the individual measurements.

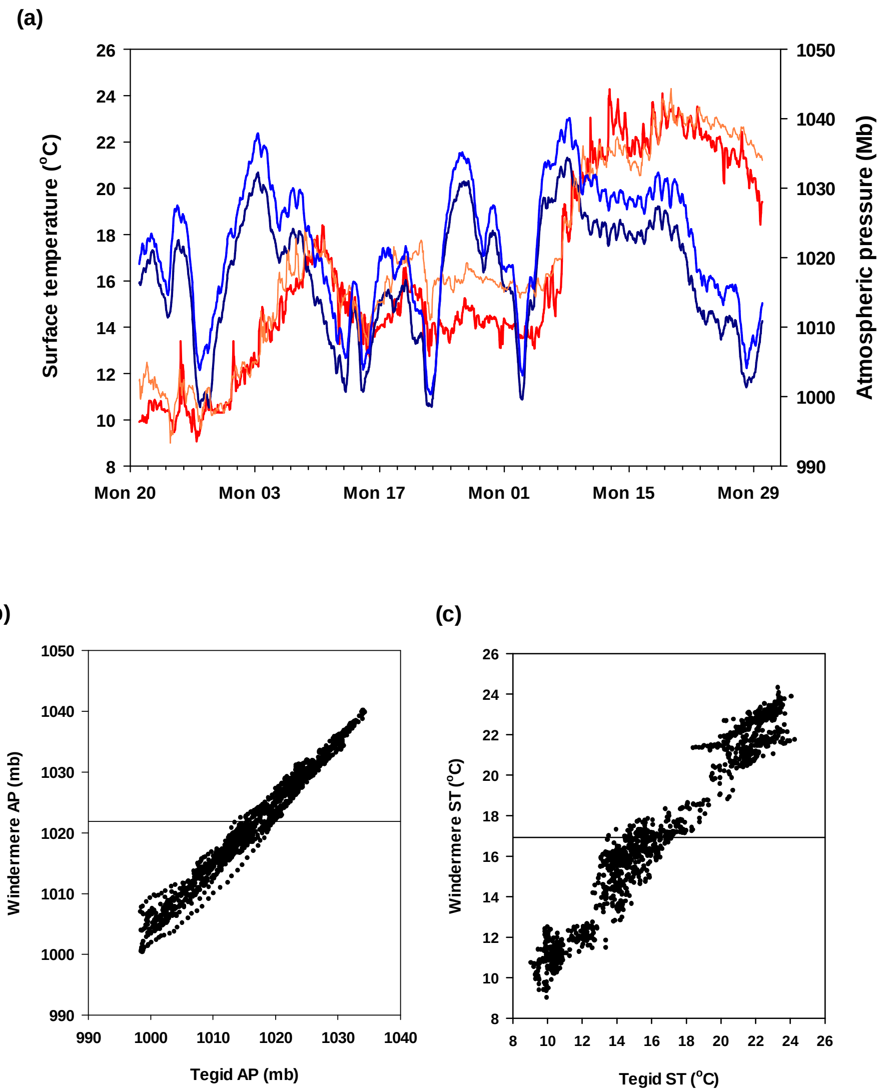


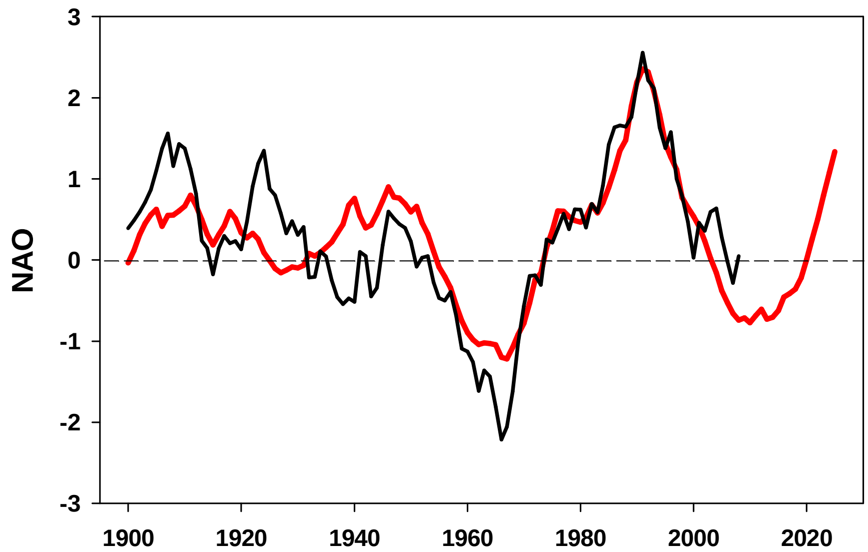
Figure 2 (a) A comparison of the seasonal variation in the atmospheric pressure and surface temperature of Llyn Tegid (Snowdonia) and the South Basin of Windermere (English Lake District) in June and July 2013. The darker colours show the measurements from Llyn Tegid. (b) The relationship between the two sets of atmospheric pressure measurements. (c) The relationship between the two sets of surface temperature measurements.

9. Discussion

When the LDMS was deployed on Llyn Tegid in 2006 the most pressing weather-related issues were expected to be the periodic appearance of cyanobacterial blooms and the increased consumption of oxygen in deep water. In the event, this did not turn out to be the case since there was a sustained change in both the winter and summer weather. To date these changes have placed a severe constraint on the summer growth of phytoplankton but they have increased the nutrient loads and the amount of sediment carried into the lake by heavy rain. A paper on impact of these extreme events is in preparation and will be completed when the analyses of the 2013 data is complete. In this discussion, we will explain the reasons for the recent change in the weather and speculate how these might change in the near future. The weather patterns experienced in recent years are known to be driven to two poorly understood features of the global climate. The first is the year-to-year variation in the North Atlantic Oscillation (NAO) and the second is the anomalous behaviour of the Jet Stream over the Atlantic.

The NAO index is a measure of the pressure gradient that develops during the winter between a selected station near Iceland and another in the Azores. When the index is positive, the mass flow of air is across the Atlantic and winters in the UK are relatively mild and wet. When the index is negative, the mass flow of air is from the continent and winters in the UK are cold and we generally have more snow. Throughout 1980s and 1990s this index was in its positive ‘mild winter’ phase but over the last few years it entered a negative phase and produced some very cold winters. The factors regulating the strength and form of this pressure gradient are known to be complex and cannot yet be simulated with the available climate models. In 2005, Dr Arnold Taylor from the Plymouth Marine Laboratory developed a simple empirical model to simulate both the observed and predicted fluctuations in the NAO. Details of the model need not concern us here but it was based on the coupling of atmospheric ‘signals’ in the Atlantic with ocean processes in the Pacific. The projections assume that global temperatures would continue to rise and that there would be no major change in the sea-surface temperatures associated with *El Niño*. The outputs of the model are, however, of considerable interest since they predicted the recent sequence of cold winters well before the event. Figure 13a compares the predictions made by the model with the historical variations recorded in the NAO. The historical time-series has been updated but the predictions are those produced in the early 2000s. Since the predictions of the model produce a regular wave pattern and the observations are very noisy, the raw values for the NAO have been smoothed with a moving average. If these projections are to be believed, the recent run of cold winters will end within the next few years. We will then return to a situation where the seasonal growth of phytoplankton will start earlier in the year and we can expect more nutrients to reach the lake during the winter (George *et al*., 2004). It is too early to say if the mild winter of 2013-2014 is a for-taste of this climatic shift but it is consistent with the findings of the model.

(a)



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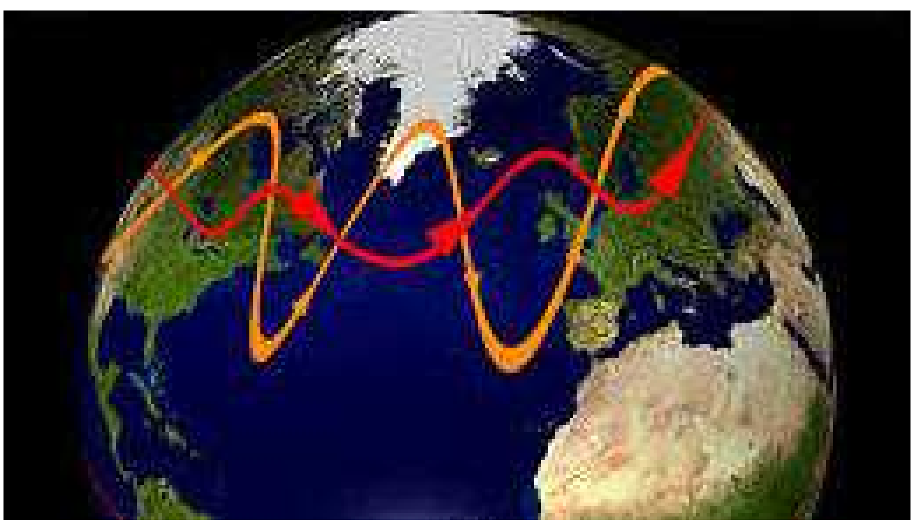

Figure 3 (a) The historical variations in the NAO index (black) and the fluctuations predicted by the Taylor model. The historical sequence has been smoothed to simplify the comparison with the simulated fluctuations. (b) Schematic to show the typical position and amplitude of the Jet Stream (red) and the perturbations observed in recent years (orange).

The second climatic feature of interest is the anomalous position of the Jet Stream. The Jet Stream is the fast flowing jet of air that circles the pole at altitudes between 9 and 16 km. This flow has a major effect on the weather experienced at ground level since it controls the trajectory of the low pressure systems that bring the wind and rain. The red line in Figure 13b shows the form of the Jet Stream in a 'normal' summer when it is positioned to the north of the UK and its meanders are of a modest size. The orange line shows the situation that has become increasingly common where the Jet Stream is located further to the south and towards the south and its meanders have increased in size. When the Jet Stream follows this southerly path, the waves that propagate from west to east also slow down and give rise to periods of bad weather that may persist for weeks rather than days. A report recently released by the Meteorological Office and the Centre for Ecology and Hydrology (2014) suggests that this shift is, almost certainly, caused by global warming. It is thought to be driven by a comparable shift in the Pacific Jet Stream which is, in turn, driven by an increase in the temperature of the ocean. At present, we cannot connect a particular period of storminess to these global-scale processes but most experts agree that their frequency and intensity has increased.

The influence of ocean temperatures on the dynamics of the atmosphere is known to follow a quasi-cyclical pattern. In the next few years, we can expect a return to warmer summers with more intense and extended and periods of thermal stratification. In 2013, CEH were fortunate to secure some additional funding which will allow a number of UKLEON lake sites to be fitted with advanced automatic profiling systems. Llyn Tegid has been selected as one of the 'profiling' sites and plans are in hand to deploy one of these systems on a re-designed buoy. Profiles taken with this system will allow us to monitor the formation and dissolution of algal blooms and acquire detailed measurement of the concentration of oxygen in deep water. This upgrade will represent a major enhancement in the capability of the station.

10. Conclusions

The LDMS deployed on Llyn Tegid has now been in operation for more than six years and has provided us with new insights into the climatic sensitivities of the lake. In 2006, we assumed that the most pressing weather-related problems would be those connected with the periodic appearance of algal blooms and the increased consumption of oxygen in deep water. The changing weather patterns experienced in recent years have, however, given rise to a range of problems that can best be explained by an increase in the frequency and severity of extreme events. The 'extreme events' noted have included: unusually cold winters, periods of intense mixing in mid-summer and the increased transport of sediment from the catchment during periods of heavy rain. The unusually cold winters experienced between since 2010 can be explained by the current state of the atmospheric pressure gradient known as the NAO (North Atlantic Oscillation). Evidence is presented to suggest that this period is coming to an end and that we will soon return to the situation where the lake stratifies earlier in the year. The unusually wet and windy summers experienced during the same period are known to be connected with the southerly position of the Atlantic Jet Stream but it is too early to decide if the warm conditions experienced in July 2013 are an indicator of forthcoming change. Once the Jet Stream returns to its more typical 'northerly' position we can expect the ecological problems associated with warm, calm summers to increase. These could include the earlier onset of algal blooms and a marked reduction in the oxygen content of the deep water which would, in turn, threaten the survival of the lake's unique gwyniad population. The new sensors and profiling system due to be installed in 2014 will greatly enhance our monitoring capabilities on the lake and provide the high-resolution data required to compare the changes reported in Llyn Tegid with those observed in other European lakes.

11. References

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12. Data Archive Appendix

Data outputs associated with this project are archived as project 446, media 1487 on server–based storage at Natural Resources Wales.

The data archive contains:

A. This report in Microsoft Word 2003 (.doc) format an 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 dep)th

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