Scottish Natural Heritage
Commissioned Report No. 469

The Round Loch of Glenhead: Recovery from acidification, climate change monitoring and future threats

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COMMISSIONED REPORT

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The Round Loch of Glenhead: Recovery from acidification, climate change monitoring and future threats

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COMMISSIONED REPORT

Summary

The Round Loch of Glenhead: Recovery from acidification, climate change monitoring and future threats

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Background

The Round Loch of Glenhead supports the qualifying habitat “Oligotrophic to mesotrophic standing waters with vegetation of the *Littorelletea uniflorae* and/or of the *Isoëto-Nanojunceteai*” in the Merrick Kells Special Area of Conservation. It is also a flagship site in the UK’s Acid Waters Monitoring Network. It is now recovering from acidification, although the degree of recovery is as yet limited. Continued recovery is threatened by the prospect of climate change, especially from an increase in winter precipitation and sea-salt laden Atlantic storms

In this report we summarise the long-term data currently available for the Round Loch of Glenhead, describe the installation of equipment funded by SNH, assess the current status of the loch and describe concerns for the future.

Main findings

- Evidence from 20 years of water chemistry monitoring shows that The Round Loch of Glenhead is showing significant improvement but remains chronically acidified. Increasing nitrate concentrations are offsetting the recovery and sulphate concentrations still remain above those expected under reference conditions.

- Trends in biology are consistent with the improvements in chemistry with significant changes occurring in the populations of epilithic diatoms, aquatic macrophytes and macroinvertebrates. There have also been increases in the density of trout fry found in the loch outflow.

- Despite the improvements the data show that the loch’s current acid neutralising capacity of 14 µeq/l is still significantly below the value of 20 µeq/l needed to meet the critical loads exceedance target under UNECE protocols and the ca. 30 µeq/l value estimated as the pre-acidification reference value.

- The limited scale of chemical recovery is corroborated by diatom data that show no re-appearance yet of the dominant pre-acidification taxa that occurred in the loch in the early 19th century and before.

- Future concerns include the threat of eutrophication, if nitrate concentrations continue to rise, and climate change, principally through the projected increase in winter precipitation and the frequency and intensity of sea-salt laden storms. Increased storminess might also lead to the remobilisation of toxic substances stored in catchment peats.

- To cater for these threats at the Round Loch and other upland waters the Acid Waters Monitoring Network will be re-branded in the forthcoming contract period (2011-2014) as the "Upland Waters Monitoring Network" and modified, as and when funds become available, to extend its capability in monitoring nutrient trends, changes in temperature and flow, and changes in toxic substance loads.

- In the case of the Round Loch the installation of water-level and outflow loggers funded by SNH complements instrumentation for monitoring water column temperature already deployed and completes the climate proofing of the loch for monitoring purposes. The loch is now the most fully equipped site for monitoring upland water quality and freshwater biodiversity in the UK.

- The Round Loch has recently been included in a new national network of lakes, funded by NERC, where water quality and climate are being monitoring by telemetered buoys in order to understand better the effects of future environmental change on the hydrochemistry and biology of the loch.

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Acknowledgements

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The installation of water-level and stream-flow loggers described in this report was funded by SNH. We thank Iain Sime and SNH for their support.

1 INTRODUCTION

The Round Loch of Glenhead is an acidified upland lake in Galloway and one of the flagship sites in the Acid Waters Monitoring Network (AWMN), a Defra-funded programme set up in 1988 to monitor the response of acidified lakes and streams in the UK to planned reductions in the emissions of sulphur and nitrogen gases from fossil-fuel combustion sources.

Here we report on a project to install instruments at the Round Loch site to measure and monitor lake-level and outflow stream discharge, designed to complement the long-term chemical and biological monitoring that has been undertaken at the site since 1988. The work at the Round Loch is part of a wider objective to instrument all sites in the AWMN with flow loggers and thermistors over the next few years to enhance the Network's capacity with respect to its value in detecting future effects of climate change on upland waters.

The Round Loch is a priority site for climate monitoring as it supports the qualifying habitat "Oligotrophic to mesotrophic standing waters with vegetation of the *Littorelletea uniflorae* and/or of the *Isoëto-Nanojunceteai*" in the Merrick Kells Special Area of Conservation (SAC). It is the most intensively studied upland lake in the UK and currently one of the sites included in a new NERC-funded project on lake water quality and climate change (see 4.2).

In this report we summarise the long-term data currently available for the Round Loch of Glenhead, describe the installation of equipment funded by SNH, assess the current status of the loch and describe concerns for the future.

2 SITE DETAILS

The Round Loch of Glenhead lies at 298 m altitude in the Galloway region of south-west Scotland. The loch is 12.7 ha in area and receives drainage from minor streams and by seepage and pipe-flow from catchment blanket peats. The outflow drains to the south-west into the Glenhead Burn and Loch Trool. The loch has a single deep basin (maximum depth 13.5 m) offset to the south with slopes rising gently away from the southern shore. An island is located just off the western shore some 250 m from the outflow.

The loch drains a catchment of 90 ha, which to the north and north-east rises to the steep cliffs of Craiglee at an altitude of 531 m. The catchment lies on the Loch Doon granite intrusion and the rocks include tonalite and those of a tonalite/granite transition. The catchment soils are dominated by deep peat and peaty podsols, with skeletal soils and bare rock characterising the steepest slopes.

The catchment is unafforested and the moorland vegetation is dominated by *Molinia*, *Erica*, *Pteridium* and *Trichophorum* and includes other species commonly associated with upland blanket mires such as *Calluna*, *Nardus* and *Potentilla*. This community was maintained by low-density sheep grazing and periodic burning (Jones et al. 1989) until 2001 when Forest Enterprise in conjunction with Scottish Natural Heritage replaced the sheep with low numbers of cattle, grazing from May to September. Both the loch and catchment fall within the Merrick Kells Site of Special Scientific Interest (SSSI), SAC and UNESCO biosphere reserve.

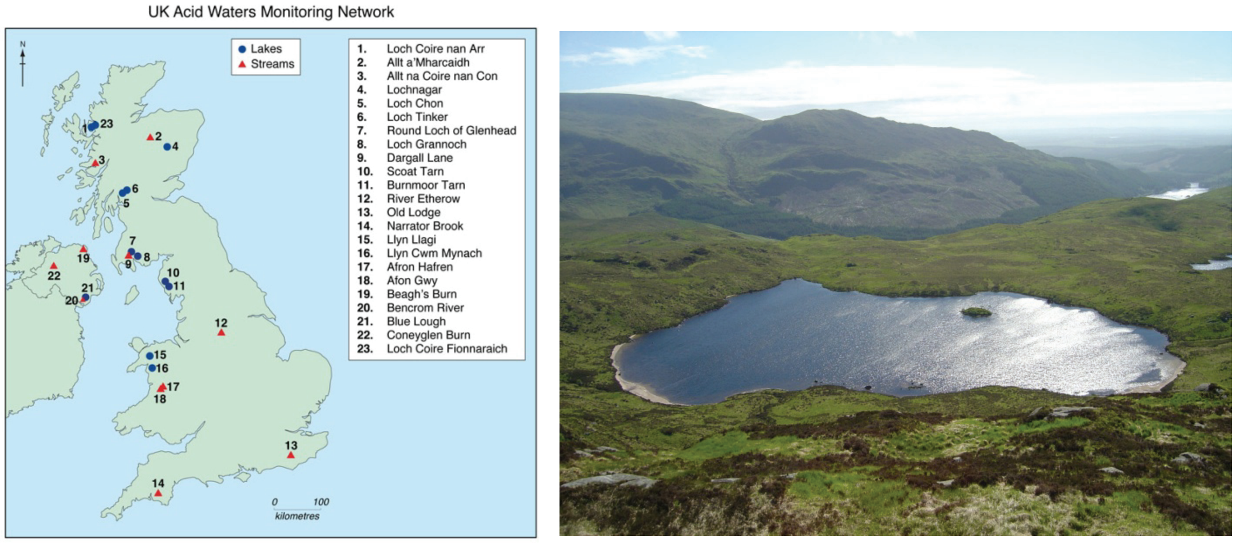

Figure 1. Map of UK Acid Waters Monitoring Network sites and photo of the loch from Craiglee looking southwest (Photo: Ewan Shilland).

The loch and its catchment (Figure 1, site 7) have been the object of research since the late 1970s and was a key site in the debate over the causes of surface water acidification in the early 1980s. Its acidification status was first recognised as a result of palaeoecological studies, conducted by University College London (Flower & Battarbee 1983, Jones et al. 1989) that showed acid-sensitive diatom taxa decreasing in relative abundance and being replaced by acid-tolerant diatoms from the mid-19th century onwards indicating a decline in pH of about 0.8 units between 1850 and 1980 (Figure 2).

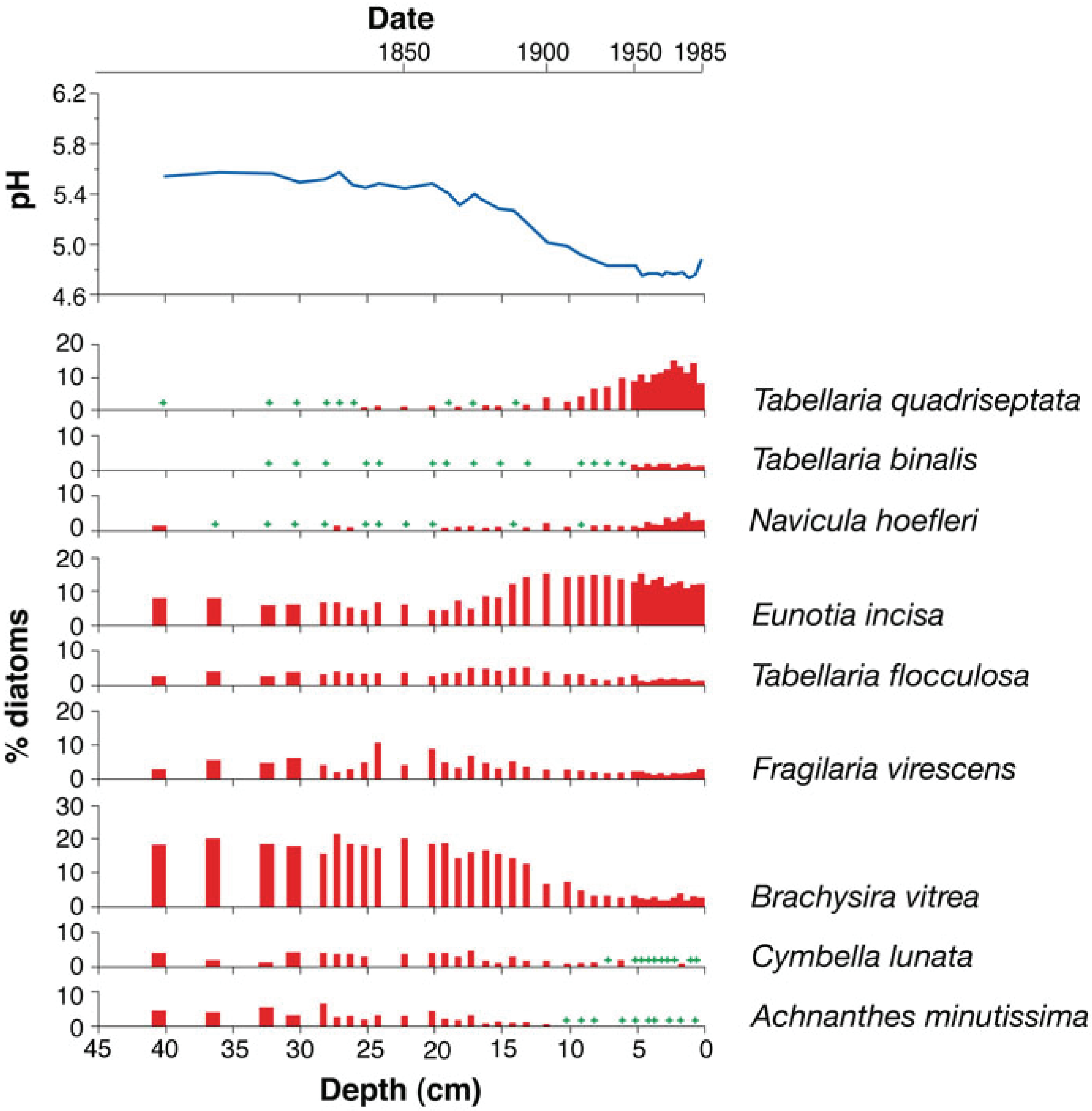

Figure 2. Diatom diagram and diatom-inferred pH from the Round Loch of Glenhead (redrawn from Jones et al. 1989).

3 TRENDS IN WATER CHEMISTRY AND BIOLOGY 1988-2009

Chemical and biological monitoring of the Round Loch has been maintained continuously from 1988 through to the present day. The data for the site along with data from all other sites in the AWMN are reported annually. Every five years an interpretative exercise is conducted, the most recent covering 20 years from 1988-2008 (Kernan et al. 2010). All reports are available from the AWMN website (http://awmn.defra.gov.uk). The data presented here for the Round Loch of Glenhead are drawn from both the latest annual report and the 20 year interpretative report as well as a range of other published and unpublished sources.

3.1 Water chemistry

Time-series graphs of key spot-sampled chemical determinands for individual samples for the Round Loch of Glenhead are shown in Figure 3.

The results show that the concentration of non-marine sulphate (xSO_4^{2-}) representing the chief acidifying anion in most sensitive UK fresh waters, has fallen substantially over the 20 year period, in line with reductions observed in bulk deposition concentrations at the nearby Acid Deposition Monitoring Network (ADMN) site of Loch Dee. However, the reductions in xSO_4^{2-} are not monotonic. There is a period of increasing concentration from 1988 to 1997 followed by a marked decrease thereafter. The present day (2009) concentration of ca. 20 µeq/l is still considerably higher than the concentration expected in comparison with reference sites in the north-west of Scotland.

Trends in the concentration of nitrate (NO_3^-), the secondary acidifying anion, are upwards at the Round Loch of Glenhead. This is similar to Loch Chon in the AWMN but dissimilar from most sites that show evidence of a long-term decline in NO_3^- concentrations. The increase at the Round Loch of Glenhead indicates that NO_3^- is making a significant and rising contribution to the “total acidity” (i.e., xSO_4^{2-} + NO_3^-) at the site. Concentrations in the reference sites in the north-west of Scotland show values close to the limit of detection. Taken together the higher than background sulphate and nitrate concentrations at the Round Loch help to explain the limited nature of recovery from acidification at this site (see 5.3 below).

Chloride values are high and variable. There is a close relationship between chloride (Cl^-) concentrations and the Arctic Oscillation (AO) Index at the Round Loch (Kernan et al. 2010). The AO Index has increased gradually since the 1950s, reflecting a change in climate towards conditions likely to generate more frequent and more intense sea-salt events in western Europe. The data show that the intense sea-salt events observed during the early years of AWMN monitoring at the Round Loch were unprecedented in the last 60 years and that the loch has experienced a combined acid stress from sea-salt related acid episodes and from acid (S and N) deposition over those years. If the increase in the AO is caused by anthropogenic impacts on climate (i.e. as a result of increased greenhouse gas emissions), as has been suggested elsewhere, sea-salt events in future may become more frequent and intense and delay or prevent the full recovery of surface waters from the effects of acidification (see 6.3.1 below).

Although there is some way yet to go there has been a significant improvement in the acidity status of the loch driven mainly by the decline in sulphate concentration. This is clear from the statistically significant increase in water pH over the last 20 years that shows in particular a jump in values in 2001 from a summer maximum of 5.2 to 5.4. However, there has been a slight reverse trend in pH since 2005. This decline cannot be explained by corresponding declines in bulk acid deposition and may instead be related to a recent return to higher levels of sea-salt deposition, and possibly rainfall, during 2007 and 2008.

Concomitant with the pH increase has been a significant decline in biologically available, or labile, inorganic aluminium (labile Al) concentrations. Labile Al is toxic for aquatic biota, especially fish and benthic invertebrates, even at very low concentrations. However, despite this marked decline, concentrations at the present day of ca. 20 µg L^{-1} remain significantly above those found in non-acidified but geologically sensitive surface waters characteristic of northwest Scotland (e.g. Loch Coire nan Arr). According to our wider data holdings of water chemistry in this region, labile Al concentration rarely rises above 10 µg L^{-1}. Labile aluminium therefore at the Round Loch remains at levels that are still probably toxic.

Other signs of recovery at the Round Loch include the decrease in the concentration of the base cation, calcium (Ca^{2+}) driven mainly by the corresponding decreases in the dominant anions SO_4^{2-} and to some extent Cl^-, and increases in dissolved organic carbon (DOC), concentrations. The DOC increase is one of the most consistent features of the chemical data across the AWMN and is attributed to a combination of falling sea-salt deposition in the early years of monitoring followed by more recent reductions in SO_4^{2-} (Monteith et al. 2007), indicating a gradual return to higher DOC concentrations that is thought thereby to have occurred naturally in the past. This trend at the Round Loch has significant implications for the loch's recovery both chemically and biologically as DOC is an organic acid, a substance that complexes toxic aluminium and decreases incident light penetration in lakes.

Figure 3 also shows trends in Acid Neutralising Capacity (ANC). ANC is a measure used to summarise the overall acid-base status of low alkalinity lakes and streams. Unsurprisingly, given the significant trends in the dominant ions described above, there have been significant increases in ANC at the Round Loch. This trend has major significance for the management of the loch as attaining an ANC of 20 µeq L^{-1} is required under UNECE protocols to prevent exceedance of critical loads (see 5.1 below). For the Round Loch ANC has increased from negative values at the beginning of the monitoring period to a current value of ca. 14 µeq L^{-1} indicating that there is still some way to go. Recovery could also be threatened by episodic depressions of pH and elevations of Al^{3+} if sea-salt deposition were to increase in future (see 6.3.1).

In conclusion the chemical evidence shows that the Round Loch is showing significant improvement but the site remains chronically acidified. Increasing nitrate concentrations are offsetting the recovery and the site is threatened by an increase in sea-salt deposition that might occur in future under current climate projections for Scotland.

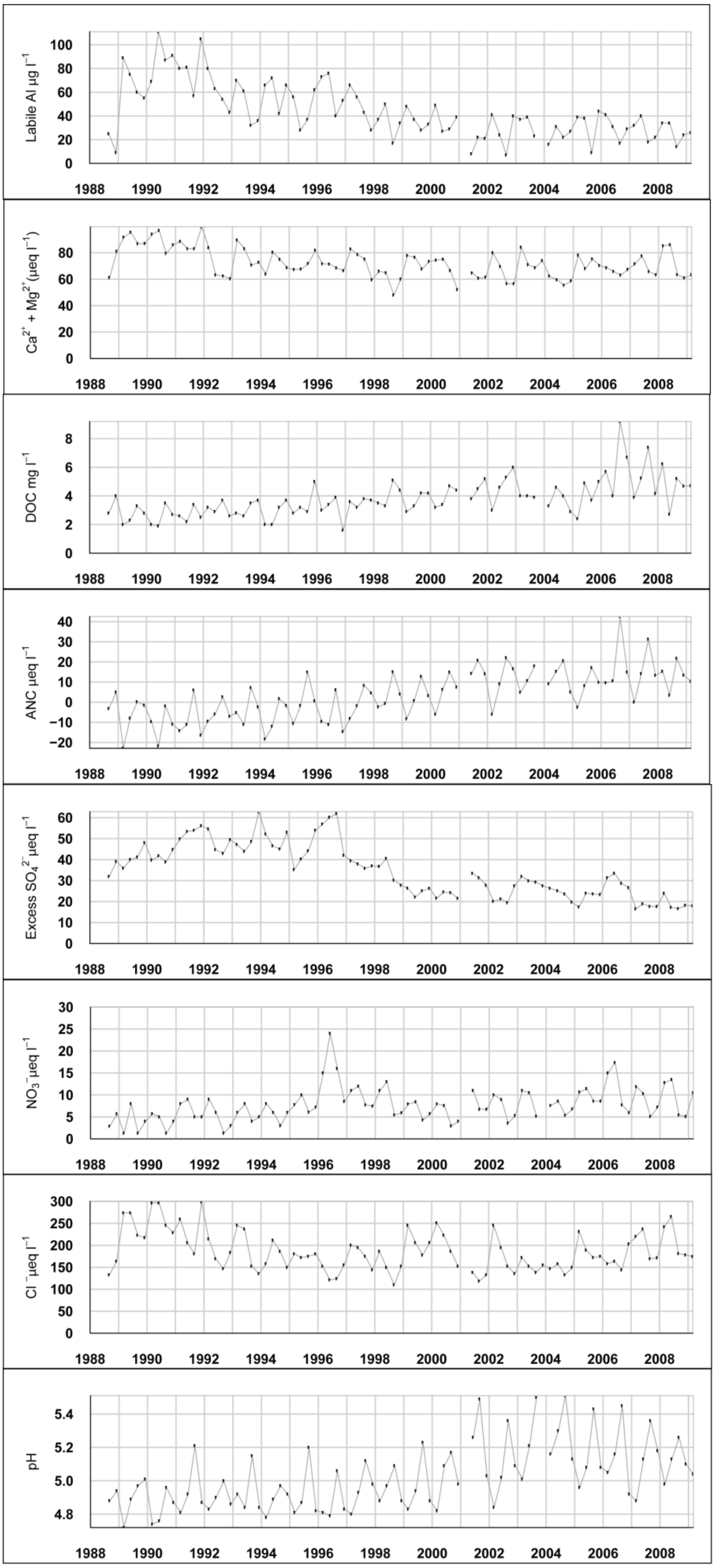

Figure 3. Spot sampled chemistry data for the Round Loch of Glenhead (1988-2008)

3.2 Epilithic Diatoms

Epilithic diatoms have been sampled from the Round Loch annually since 1988 from the inception of the AWMN. The methods used for collection and analysis follow standard protocols (http://awmn.defra.co.uk). Time series of the annual mean percentage frequency (from 3-4 replicate samples) of taxa occurring at greater than 2 % abundance in any one sample is shown in Figure 4.

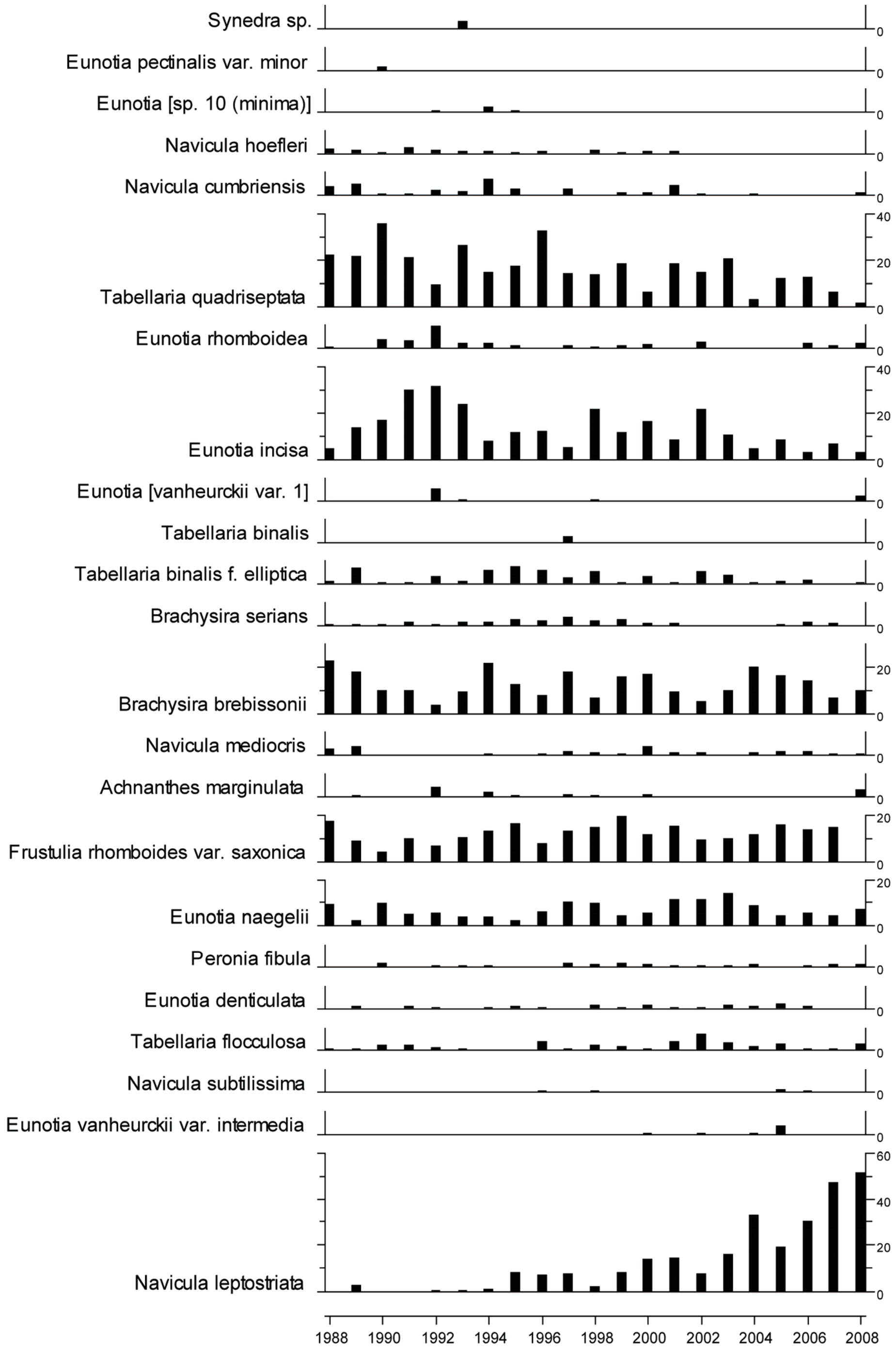

Figure 4. Epilithic diatom percentage abundance summary for the Round Loch of Glenhead, 1988-2008

The epilithic community of the Round Loch has undergone substantial change during the monitoring period with species shifting from an assemblage dominated by the acidobiontic species *Tabellaria quadriseptata* (SWAP pH optimum = 4.9), and to a lesser extent *Eunotia incisa* (SWAP pH optimum = 5.1), to one increasingly dominated by *Navicula leptostriat*a (SWAP pH optimum = 5.1) since 1994. *N. leptostriata* was not recorded in 1988 and 1990 in the epilithon, although it was present in the loch, but by 2008 this species comprised ca. 50% of the entire epilithic assemblage. Trends in the epilithon can be compared with trends in the sediment trap assemblages (see below) and with the long-term record of diatom assemblages preserved in sediment cores from the loch (see Figure 2).

Overall the diatom data follow the chemical data providing evidence of a shift away from acid tolerant taxa to those with somewhat higher pH optima. The flora, nevertheless, is still one characteristic of very acidic conditions and there are no signs so far of a return of taxa such as *Brachysira vitrea* that would have dominated the epilithon in the pre-acidification period (see Figure 2).

3.3 Diatom assemblages collected from sediment traps, 1991 - 2008

The diatom data from sediment traps from the Round Loch are somewhat different from the data shown above from the epilithon as the trap material represents diatoms derived from epiphytic, epipelic and epipsammic sources as well as from the epilithon. The assemblages therefore provide an integrated sample of all diatoms in the loch and are directly analogous to assemblages preserved in sediment cores allowing the recent changes indicated by the trap data to be placed in the context of the longer time record provided by sediment cores. The trends in trap diatoms at the Round Loch are nevertheless very similar to those for the epilithon, showing a more muted but still significant shift away from the most acid tolerant taxa (e.g. *Tabellaria quadriseptata*, *T. binalis* f. *elliptica*, *Navicula hoefleri*) taking place in the late 1990s towards co-dominance by *Navicula leptostriata and Frustulia rhomboides* var. *saxonica.*

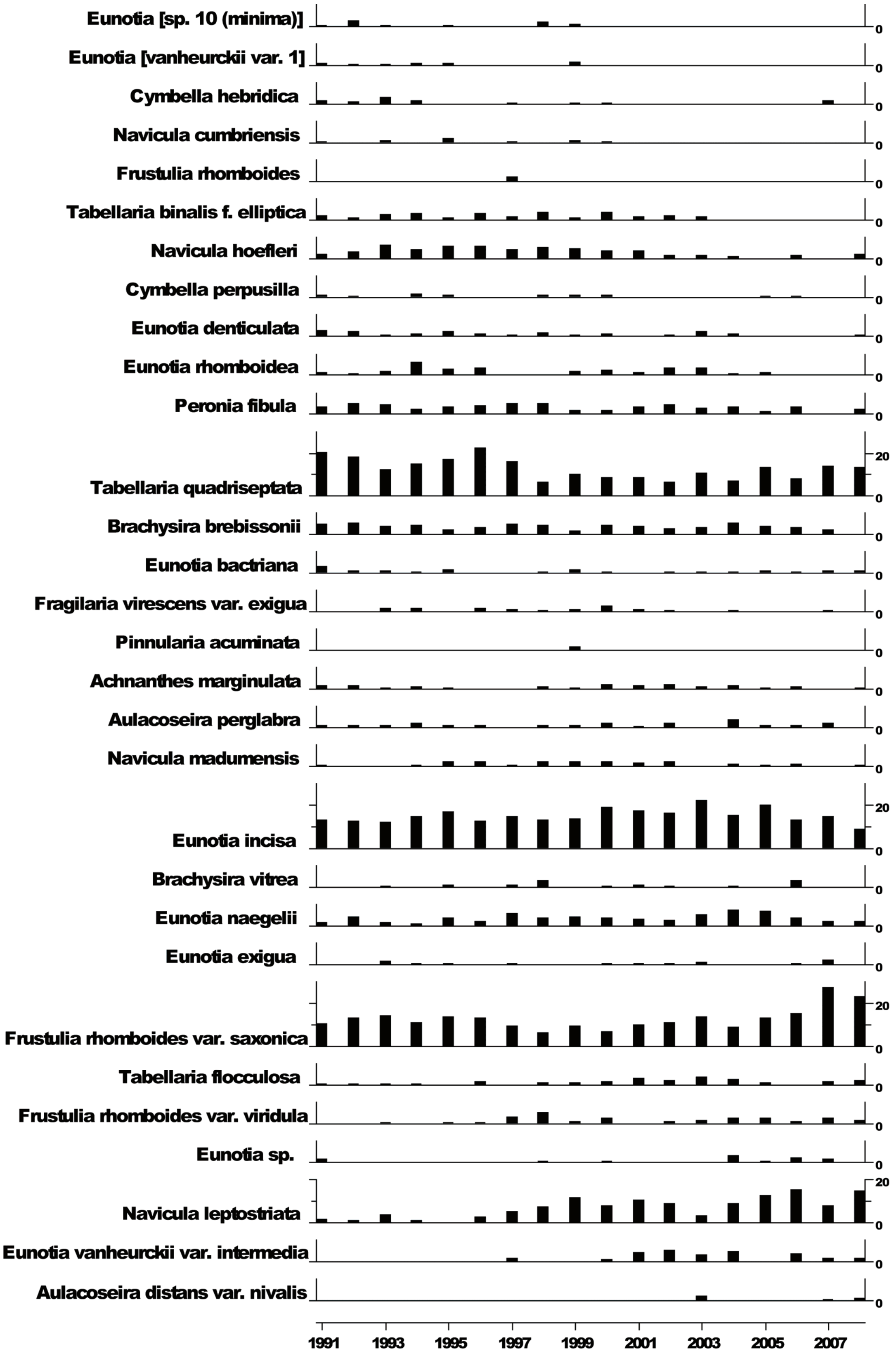

Figure 5. Sediment trap diatom data for the Round Loch of Glenhead, 1991-2008. Species occurring at less than 1% abundance in all years are omitted.

3.4 Aquatic Macrophytes

Aquatic macrophyte populations in the Round Loch have been monitored since 1988 initially on an annual basis then, after 1993, biannually. The methods used follow AWMN protocols (http://awmn.defra.gov.uk). Relative species abundance is determined on a five point scale (comparable to the DAFOR scoring system (Palmer et al. 1992) using shoreline survey, shore transects and deep-water grapnel trawls, as follows:

1. rare/infrequent
2. occasional but not abundant
3. widespread but not abundant
4. locally abundant
5. widespread and abundant

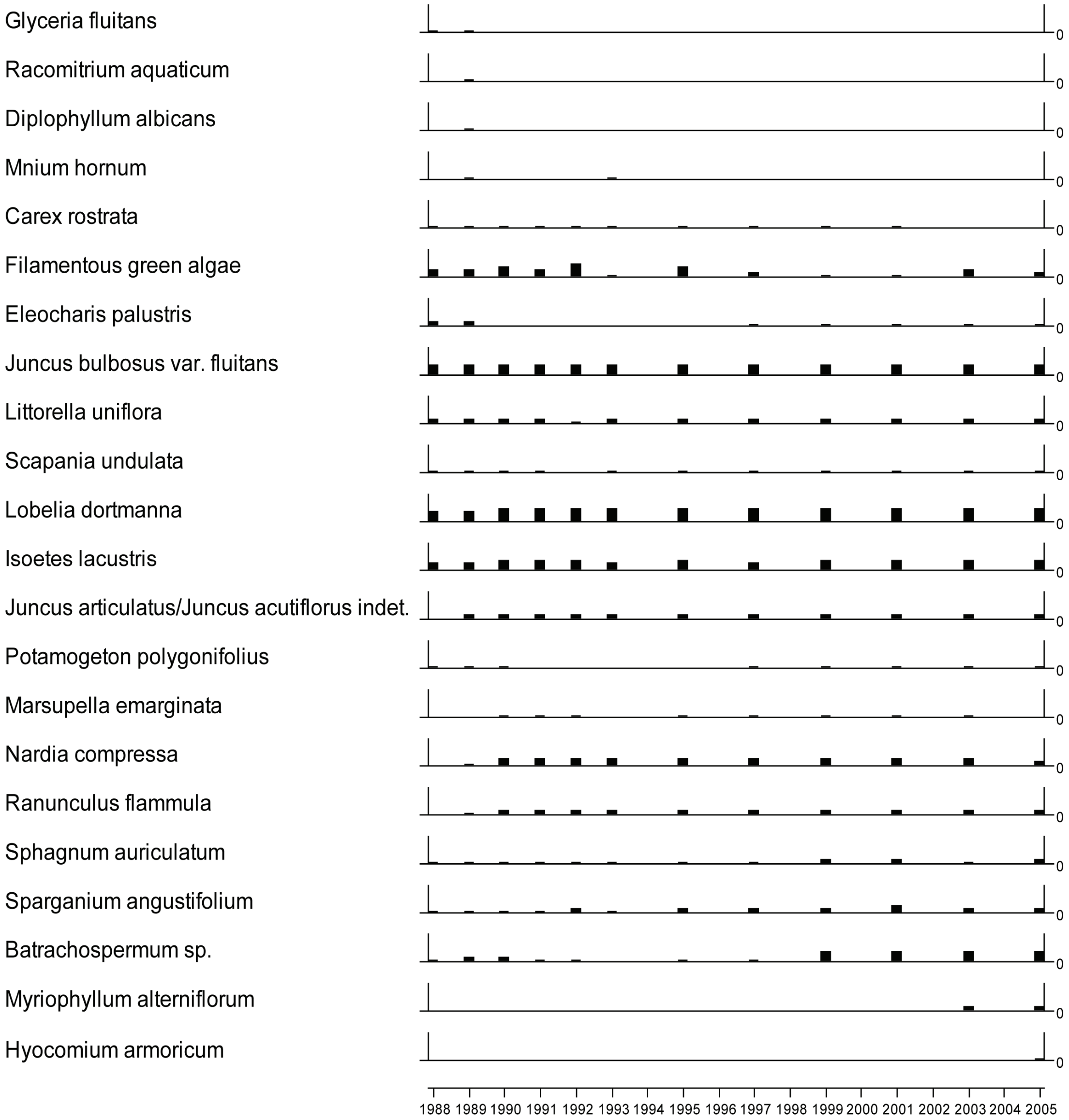

Figure 6. Aquatic macrophyte data for the Round Loch of Glenhead, 1988-2008

The macrophyte flora of the Round Loch (Figure 6) is species-poor, and characteristic of an upland oligotrophic loch with the dominant taxa being the acid-tolerant isoetid species *Littorella uniflora*, *Lobelia dortmanna*, *Isoetes lacustris* and the acidophilous rush *Juncus bulbosus* var. *fluitans*. Liverworts, especially *Nardia compressa*, are locally abundant on rocks in shallow water but mosses, represented by *Sphagnum* sp., are less common. The scarce emergent vegetation consists of small patches of *Carex rostrata*, *Eleocharis palustris*, *Juncus acutifloris/articulatus* and some *Ranunculus flammula*.

During the period of monitoring the assemblage has remained relatively stable, with the significant exception of the detection in 2003 of the acid-sensitive elodeid species *Myriophyllum alterniflorum*. This species was detected at a single open water location that year but has since spread around much of the lake perimeter. The establishment of this species, one of few oligotrophic macrophytes that form open-water stands, is likely to have a wider influence on the ecology of the loch, by providing an additional substrate for epiphytic algae and a source of food and shelter from predation for aquatic invertebrates.

The recent appearance of *M. alterniflorum* could be indicative of decreasing acidity and the presence now of some bicarbonate alkalinity in the loch but further work will be necessary to verify this. We also assume that this taxon occurred in the loch prior to acidification, an assumption we are currently attempting to assess using palaeoecological techniques.

3.5 Macroinvertebrates

Macroinvertebrate samples have been collected from the Round Loch of Glenhead since 1988 using standard sampling protocols. The data (Figure 7) are shown as % abundance of the annual aggregated sample of five kick samples from the lake littoral zone. Figure 7 also shows the annual total number of individual animals.

The time trend is statistically significant, the change being particularly marked late in the record. Of particular note is that the snail, *Radix balthica*, was found for the first time in 1996. It first occurred only sporadically but has been present every year from 2002. Such taxa are associated with water plants, and its appearance (or re-appearance?) may be related to the presence of the aquatic macrophyte *Myriophyllum alterniflorum* that has established itself strongly from 2003 (see 3.4). Macroinvertebrate recovery at this site is consistent with the chemical trends described above, where pH and acid-neutralising capacity have risen, while labile Al concentration has fallen during the period.

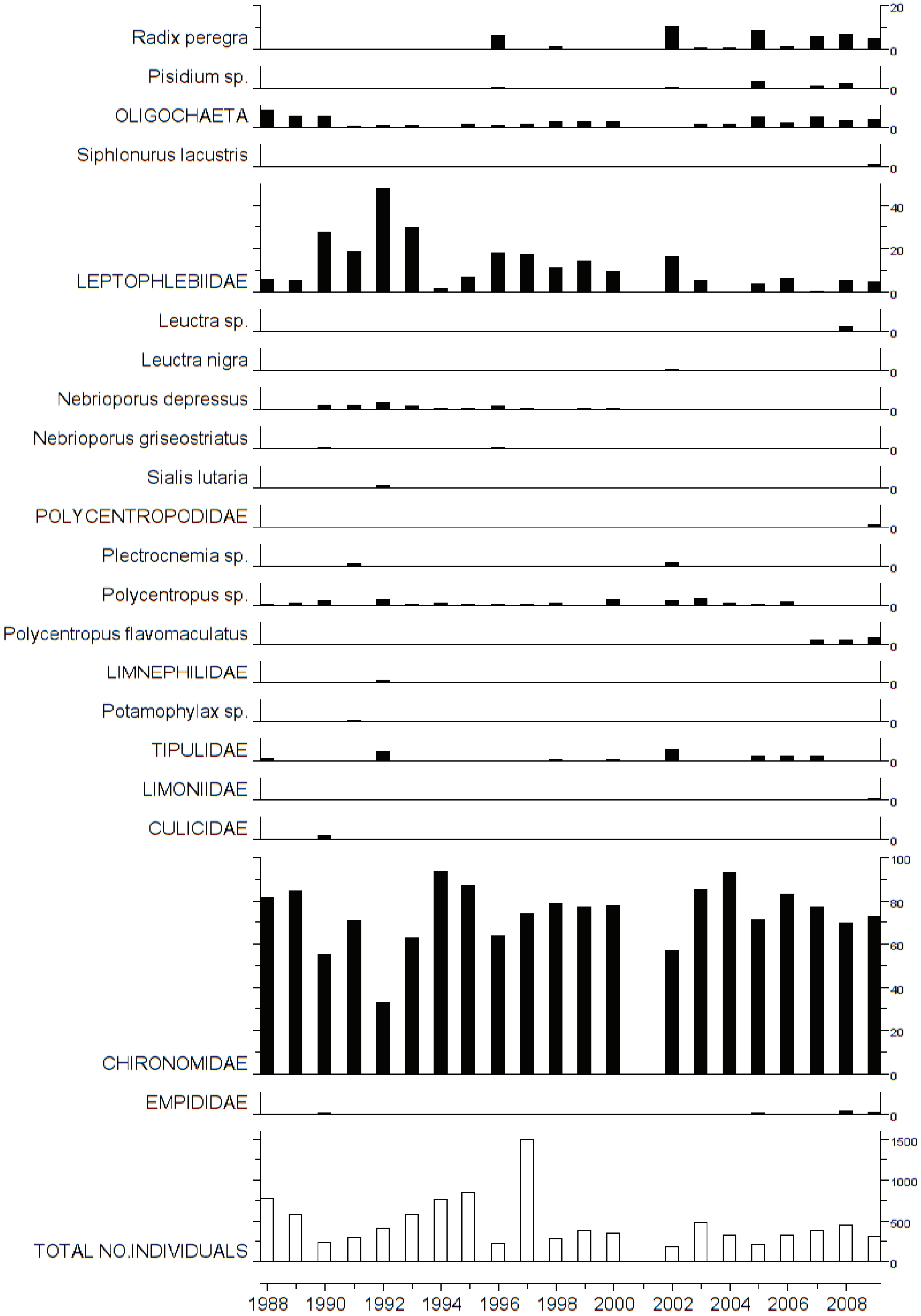

Figure 7. Macroinvertebrate percentage abundance summary for the Round Loch of Glenhead (1988-2009). No sampling took place in 2001 due to Foot and Mouth restrictions.

3.6 Fish

Salmonid populations have been monitored at the outflow of the Round Loch since 1988 on an annual basis using electrofishing techniques carried out along three replicate reaches. A minimum of three passes was performed at each site. The populations were divided between species and age classes (0+ (fry) and >0+ (parr)) on the principle that different species and age classes have differing chemical requirements and that 0+ fish are better indicators of local conditions than older fish.

Although populations were very low at the start of monitoring we believe, unlike some sites in the AWMN, that the Round Loch never completely lost its brown trout population. Figure 8 shows changes in the density of trout fry at the Round Loch by reach. They show an increasing trend between 1997 and 2006. However, parr densities (Figure 9) appeared to increase until ca. 1995 after which numbers have declined, with reaches sometimes recording no parr.

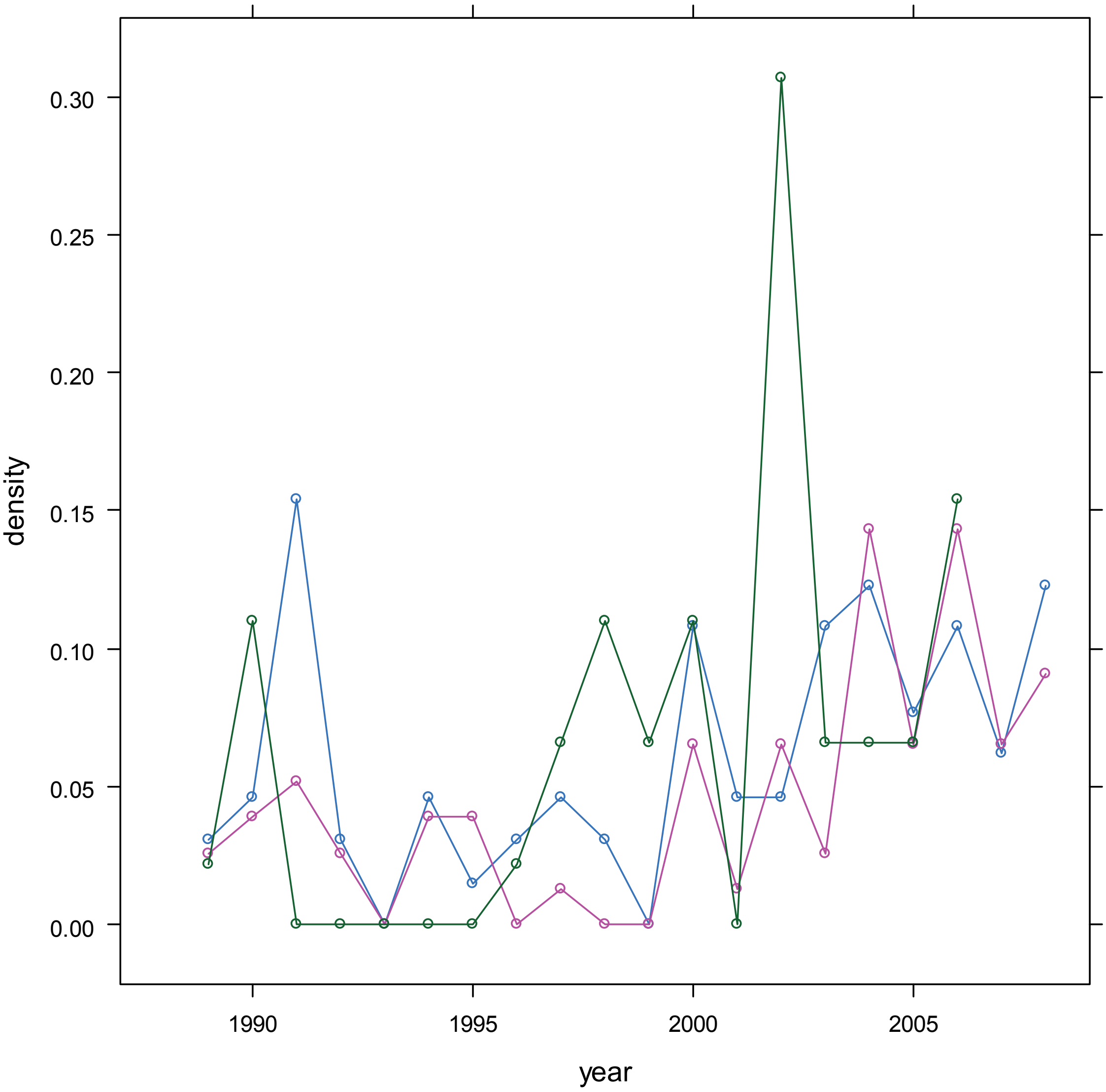

Figure 8. Summary of trout fry density (numbers m^{-2}) for the Round Loch of Glenhead outflow stream (1988-2008). Blue series = Reach 1, Pink series = Reach 2, Green series = Reach 3.

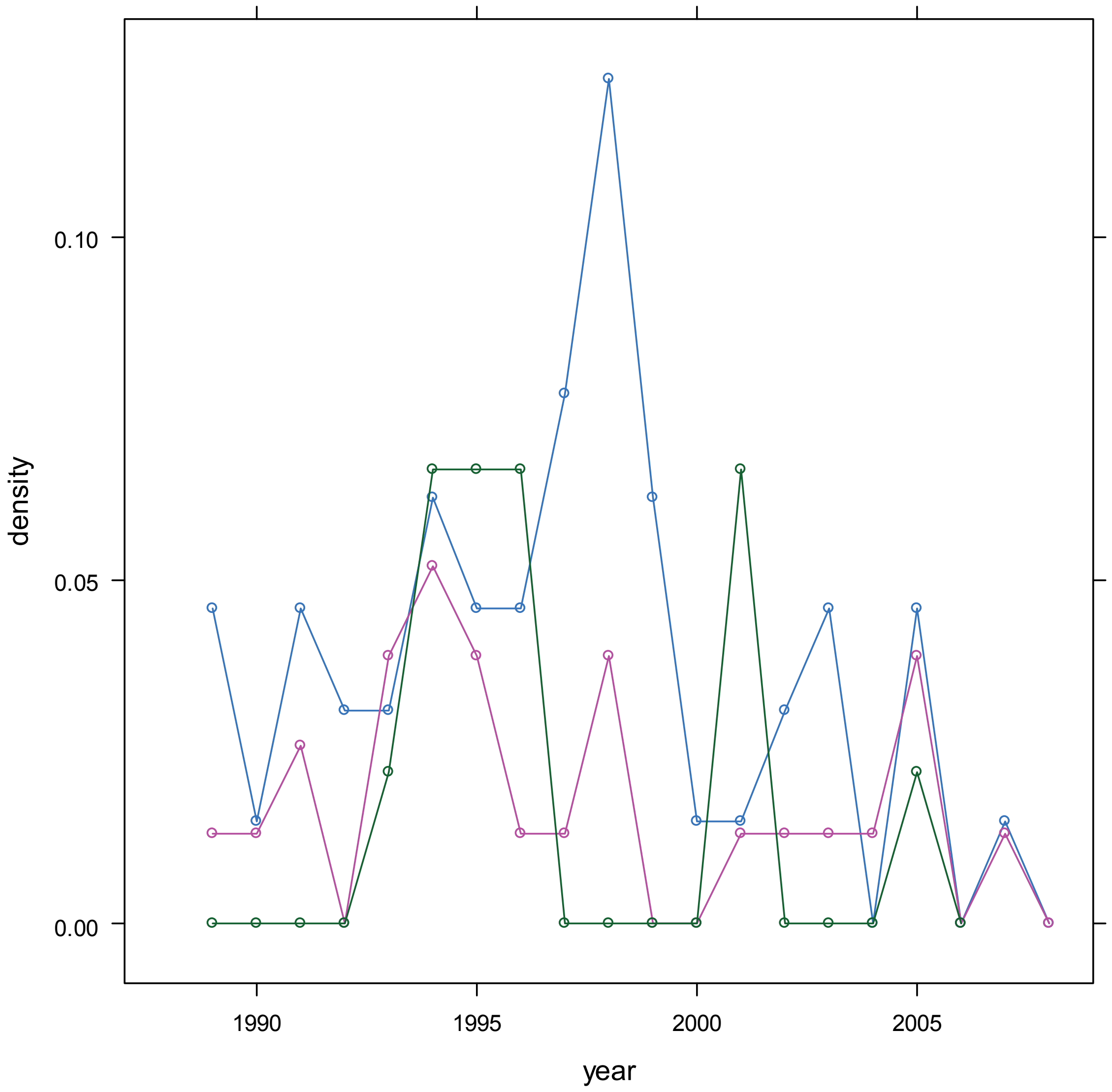

Figure 9. Summary of trout parr density (numbers m^{-2}) for the Round Loch of Glenhead outflow stream (1988-2008). Blue series = Reach 1, Pink series = Reach 2, Green series = Reach 3.

4 CLIMATE CHANGE MONITORING

Although the AWMN was designed primarily to monitor the recovery of upland waters from the effects of acidification, protocols over the years have been added or extended to address the potential influence of other pressures, especially climate change.

For the Round Loch of Glenhead, this has involved the installation of water column thermistors (in 2004), and an automatic water quality monitoring system supporting a weather station (in 2005) anchored in the centre of the loch. The installation of flow and water-level loggers (in 2011, funded by SNH, see section 4.3) completes the climate-proofing of the site. Together data from these instruments should enable an assessment of the direct and indirect effects of future climate change on the ecological status of the loch to be made.

These systems that comprise the climate change monitoring capability at the Round Loch, together with examples of data currently available, are described below.

4.1 Water column thermistors

A pair of thermistors attached to the sediment trap array were installed in the Round Loch of Glenhead in 1999. The top thermistor is positioned at 1 m below the water surface and the bottom one at 1.5 m above the lake bed.

Data from 2004 to 2008 (Figure 10) show the expected regular seasonal temperature cycle in the loch with surface waters varying from summer maxima of 18 – 21 °C and winter minima of 2 - 3 °C. Data for the last two winters (2009-2010, 2010-2011), when the loch was ice-covered for short periods, are not shown.

Comparison between the top and bottom water column temperatures shows that the loch is isothermal (i.e. continuously mixed resulting in constant temperature at all depths) for most of the year, reflecting the windiness of the local climate, but each summer there are short periods of stratification. The loch can therefore be described as "polymictic". An important question in the future is the extent to which increased warming in summer might lead to longer and more stable periods of stratification and thereby alter the chemical and biological dynamics of the loch.

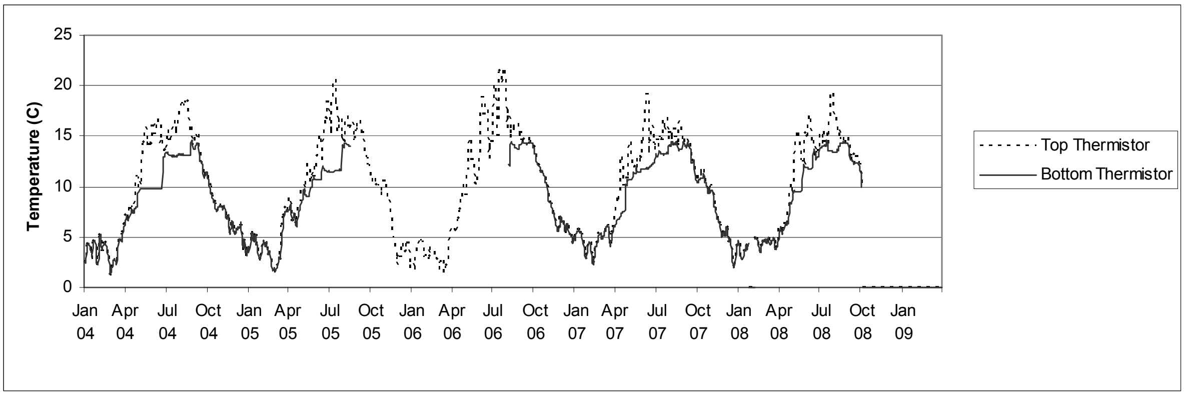

Figure 10. Thermistor data for the Round Loch of Glenhead, 2004-2008.

4.2 Automatic Water Quality Monitoring Station (AWQMS)

In 2005 an automatic water quality monitoring station was installed at the Round Loch of Glenhead as part of a network of automatic sensors deployed in a range of UK lakes by CEH Windermere. The station (Figure 11) comprises a toroidal buoy secured to the lake bed using a three point mooring and stainless steel housings mounted on the buoy containing rechargeable sealed lead-acid batteries used to power the station. The mast supports meteorological sensors and an antenna allows stored and real-time data to be telemetered to the laboratory via the cellphone network.

Figure 11. a) The deployment of the AWQMS at the Round Loch of Glenhead by helicopter and b) the installed station once the sensors had been fitted on-site. (pictures by Don Monteith).

The temperature profile of the water column is recorded using a chain of temperature sensors spaced to capture detailed changes in the thermal structure of the lake, enabling water column temperature data to be compared directly with incident meteorological conditions. Figure 12 shows sample data for 2006 and indicates how the high winds on 18 May, 22 June, 9 July and 2 August suddenly break down the thermal stratification of the loch.

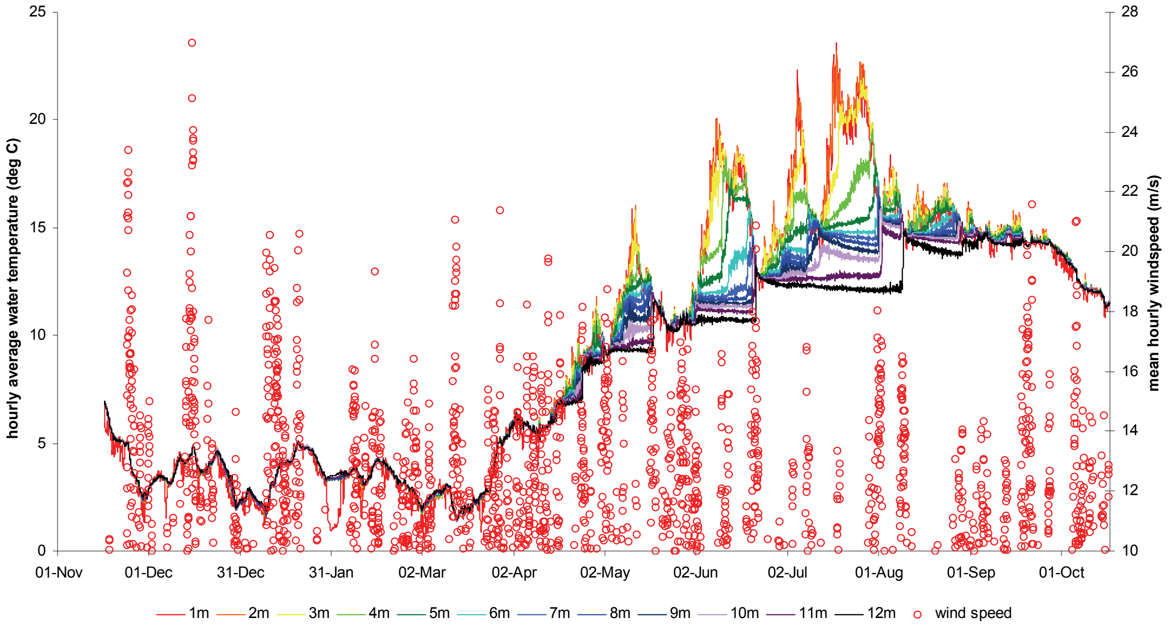

Figure 12. Hourly average water temperature data at different depths in the water column and mean wind speed for 2005-2006 (from Monteith, unpublished).

From January 2011 the AWQMS on the Round Loch will begin contributing to the NERC-funded "United Kingdom Lake Ecological Observatory Network" a new initiative headed by CEH Lancaster. The system will be equipped with new self-cleaning sondes at the surface to measure temperature, oxygen, conductivity, pH, phytoplankton chlorophyll a and the concentration of CO_2.

4.3 Installation of streamflow, water-level and conductivity loggers

Funding required to finalise the climate proofing of the Round Loch of Glenhead by adding a flow and water-level monitoring capability to the temperature monitoring described above was provided by SNH in December 2010. For lake-level (and surface-water temperature) logging an In-Situ Level Troll 500 was purchased and this was supplemented by an In-Situ Aqua Troll 200 logger positioned in the lake outflow to measure flow and water conductivity. The purpose of the outflow conductivity measurements is to provide data on episodic sea-salt inputs during storms which should result in short-term increases in conductivity and may result in episodic depression of pH as sea-salt base cations displace acidity from soils. Flow monitoring is also important in order to monitor outflow fluxes from the loch, including carbon and nitrogen.

The site visit to the Round Loch of Glenhead for installation of loggers and stage boards took place over 19-20th January 2011. On 19th January the outflow logger was installed on the site of previous instrumentation used for the PhD Thesis studies of Hong Yang at UCL (Yang, 2009). A new stage board was installed, plus stilling pipe with locking cap to hold the Aqua troll 200 (Figure 13). The location of the outflow logger is some 100m downstream of the loch itself due to the need to find a suitable site for secure attachment of the stilling pipe and a suitable stream section for a flow rating curve (Table 1). The logger was programmed to commence at 1700 and dilution gauging was carried out in conjunction with a stage board reading at 1555.

Figure 13. Installation of stilling pipe, 19th January 2011 at the Round Loch of Glenhead ouftlow (Photo Chris Curtis).

The lake level logger (Level Troll 500) was installed through the ice on 20th January. The stilling pipe was attached to a vertical rock slab in c. 30cm of water (Table 1). A lake-level stage board was attached to a more accessible boulder a few metres away (Fig. 14a). It is anticipated that the stage board and level logger should operate over the full range of lake-level variations.

Table 1: Location and dates of logger installation at Round Loch of Glenhead

	Outflow	**In-lake**
Logger type	In-Situ Aqua Troll 200	In-Situ Level Troll 500
Measurements	Temperature,level conductivity	Temperature, level
Logging interval	15 minutes	15 minutes
Logger location (GPS)	NX 44822, 90148	NX 44840, 80469
Stage board location	As above	NX 44831, 80465
Installation date	19/01/11	20/01/11
Stage	213mm (1555, 19/01/11) 202mm (1531, 20/01/11)	328mm (1330, 20/01/11)
Commenced logging:	**See text**	**1330, 20/01/11**

Figure 14. a) Lake level stage board at Round Loch of Glenhead, and b) Checking the outflow level logger on 20th January and standard solutions for dilution gauging (flow calibration) (Photos Chris Curtis).

The lake-level logger was programmed to commence the previous day, hence it was already logging when installed. Logging of the first data points following installation commenced at 1330 on 20th January 2011 and data were checked in real time with a laptop computer connection to verify that logging was taking place. A stage board reading was also taken at the same time to provide a calibration point linking logger level to an arbitrary but fixed lake stage. It may be possible to link the stage to a previous record of lake-level recording carried out by Hong Yang during his PhD studies.

The outflow logger had been pre-programmed to start logging at 1700 on 19th January and was installed before logging commenced. On returning to the site the following day the logger was downloaded to check that it was operating correctly (Fig. 14b). It was noted that the level (depth from stream water surface to logger) reading was wildly inaccurate (reading some 5m depth, when actual depth was around 20cm). The In-Situ technical help was contacted by telephone from the site and we were advised that the readings suggested a faulty instrument, with a recommendation to remove the logger and email the datafile to In-Situ.

Despite the faulty logger, it was noted that the stream stage had decreased overnight so we took the opportunity to carry out a second flow dilution gauging and hence obtained a second point for a flow-stage calibration curve at 1531 on 20th January (Table 1).

The faulty logger was subsequently returned to UCL and the datafile emailed to In-Situ on 21st January, who suggested a factory reset of the instrument. The reset failed to rectify the problem according to analysis of a second datafile by In-Situ so the instrument was returned to In-Situ on 1st February. Following testing at the manufacturers in the USA, In-Situ finally agreed to replace the instrument under warranty on 16th March. The replacement logger has now been installed (at c. 1400 on 2nd May) and checked in real time. Logging is now occurring. Dilution gauging was also carried out. As the flows were very low we have a further point for the stage-flow calibration curve.

5 ECOLOGICAL STATUS

Legislation governing the restoration of acidified surface waters in the UK is set out by a number of different protocols and directives, principally:

- United Nations Economic Commission for Europe (UNECE) Oslo Protocol on Further Reduction of Sulphur Emissions (Second Sulphur Protocol) 1994;
- UNECE Gothenburg Protocol to Abate Acidification, Eutrophication and Ground-level Ozone, 1999;
- EU Proposal for a National Emission Ceilings Directive (NECD) (1999);
- EU Water Framework Directive (WFD) (2000).

The first three of these are concerned with the reduction of emissions of acidic gases in member states to decrease levels of acid deposition (S and N) to levels below the “critical load” and the last, the Water Framework Directive, is concerned with maintaining aquatic ecosystems in, or restoring them to, ‘good’ ecological status or better.

The target status using the critical loads approach is an acid neuturalising capacity (ANC) of 20 µeq L^{-1} which corresponds to a probability of damaged brown trout populations of 10%. The target under the WFD is a restoration to good ecological status defined by the extent to which a water body deviates from the reference condition. Here we describe the current status of the Round Loch of Glenhead according to these criteria.

5.1 Critical load exceedance

Critical loads and critical load exceedances can be calculated in different ways depending on the models used and the assumptions in the models used. These are fully explained in the AWMN 20 year interpretative report (Kernan et al. 2010). The principal models used are the Steady State Water Chemistry (SSWC) model and the First-order Acidity Balance (FAB) model. Exceedances have been calculated for three different deposition periods, 1986-88, 1996-98 and 2004-06. Both models use ANC to define critical threshold values. In the case of the Round Loch recent measured ANC values are around 10 µeq L^{-1}, i.e. still below the critical threshold of 20 µeq L^{-1} used for critical loads modelling although considerably higher than the average measured ANC of -9 µeq L^{-1} at the start of monitoring in 1988-91.

5.1.1 SSWC Model

Critical load exceedance calculations with the SSWC model use S deposition and nitrate flux based on measured concentrations of S and N in surface waters. At the start of monitoring in the late 1980s, the Round Loch showed the second greatest exceedance of Scottish AWMN sites with only Loch Grannoch, also in Galloway, having a higher exceedance. By 1996-98, both these Galloway sites remained the most exceeded in Scotland but the gap between them was reduced. By 2004-06, the Round Loch had overtaken Loch Grannoch as the most exceeded of Scottish AWMN sites and showed the second highest exceedance in the whole AWMN, with only Scoat Tarn in the English Lake District having a greater value (Figure 15). As the exceedance of SSWC critical loads is driven by measured nitrate as well as sulphate concentrations the increasing trend in nitrate at Round Loch is the reason it has overtaken Loch Grannoch as the most exceeded of the Scottish sites. Nitrate levels at Loch Grannoch have declined since peaking in the late 1990s.

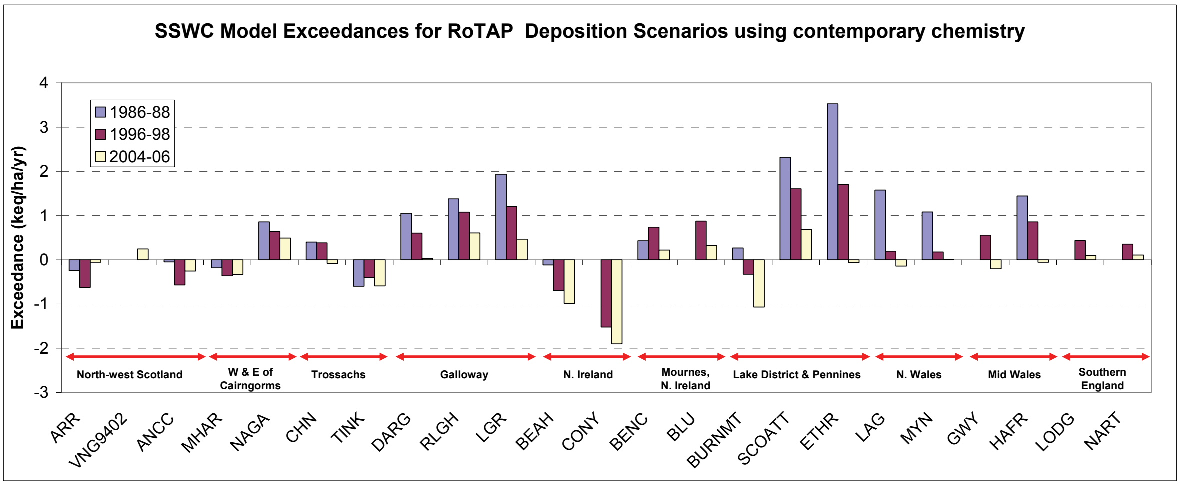

Figure 15. SSWC Model critical load exceedances for AWMN sites based on three deposition scenarios, 1986-1988, 1996-1998 and 2004-2006. RLGH = Round Loch of Glenhead (from Kernan et al. 2010).

5.1.2 FAB Model

Unlike the SSWC model the FAB model uses total N deposition instead of nitrate concentrations to determine the contribution of N to exceedance. It uses a theoretical mass balance for S and N on long-term sinks for acid anions. This allows for nitrate leaching to increase in future as soil sinks become saturated. As such it represents worst-case exceedances whereas the SSWC output can be considered to represent the best case.

With the FAB model, the Round Loch shows the greatest exceedance of all Scottish AWMN sites under all three deposition loads (Figure 16) and, as with the SSWC model, most recent deposition data show Round Loch to be second only to Scoat Tarn in England within the AWMN, in terms of exceedance.

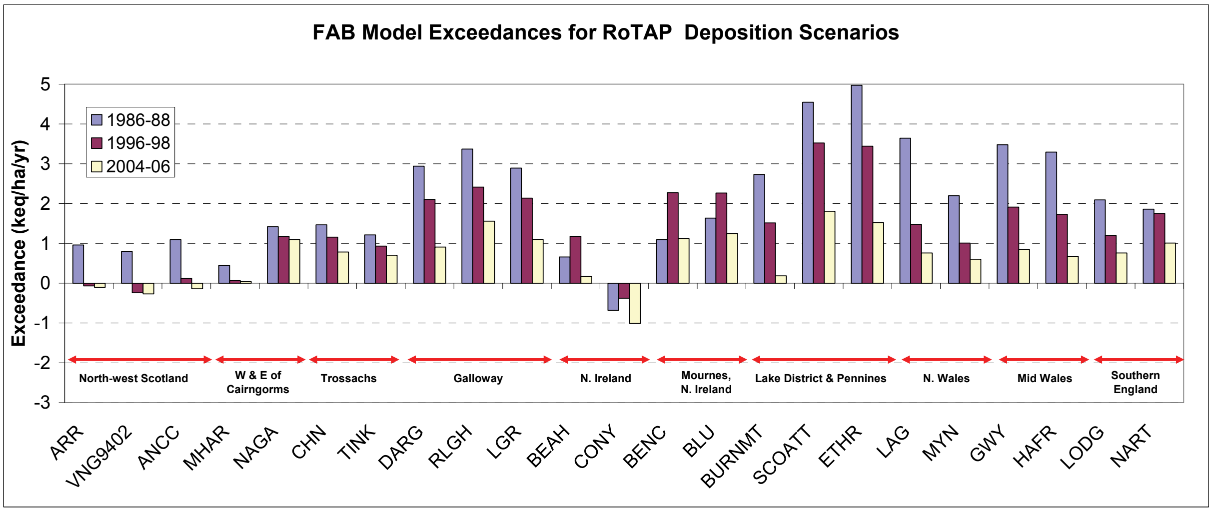

Figure 16. FAB Model critical load exceedances for AWMN sites based on three deposition scenarios, 1986-1988, 1996-1998 and 2004-2006. RLGH = Round Loch of Glenhead (from Kernan et al. 2010).

The continued exceedance of critical loads at Round Loch suggest that ANC cannot recover to the critical value of 20 µeq/l without further reductions in deposition. The consequences of future deposition scenarios for critical load exceedance are discussed below (6.1).

5.2 Progress towards reference conditions

The 20 µeq/l target for ANC is the target needed in theory to eliminate critical load exceedance for acidified waters in the UK under UNECE protocols and the EU NECD Directive. Achieving this target, however, does not necessarily mean for any specific surface water that "good ecological status" as defined by the EU WFD has been or will have been reached. In most cases the "good ecological status" target is a more demanding one.

To assess progress towards that target it is necessary to define reference conditions. In the case of the Round Loch of Glenhead this has been attempted in three different ways, by biogeochemical modelling to hindcast water chemistry using the MAGIC model, by using diatom analysis of lake sediment cores to reconstruct pre-acidification pH and by direct comparison of diatom assemblages from sediment cores and sediment traps to assess the dissimilarity between pre-acidification and present-day diatom floras.

5.2.1 Reference ANC using MAGIC model hindcasts

Although the MAGIC model is primarily used to simulate future changes in surface water chemistry according to specified acid deposition scenarios it can also be used to hindcast past water chemistry based on assumptions of past acid deposition. This exercise has been carried out for all AWMN sites (Kernan et al. 2010) using deposition estimates back to 1860, a date that is close in time, according to palaeoecological evidence (Flower & Battarbee 1983) to the date when the loch started to become more acidic. For the Round Loch MAGIC hindcasts an ANC value of ca. 31 µeq/l for 1860. Using the value of ca. 14 µeq/l for present day ANC the progress towards achieving the critical threshold of 20 µeq/l used for critical loads modelling can be estimated at 80% relative to measured ANC at the start of monitoring in the late 1980s. On the same basis, recovery towards the reference value is only 58%. Moreover, further increases in ANC values may be limited if nitrate concentrations continue to increase, offsetting any further recovery that could be achieved with further reductions in S deposition.

5.2.2 Reference pH using diatom analysis from sediment cores

Diatom analysis of lake sediment cores can be used to reconstruct the pH history of lakes (Battarbee et al. 1988). The approach is based on the use of contemporary diatom and water chemistry data from lakes along a pH gradient that enable the pH optimum of individual taxa to be estimated. Such training-set data can then be used to create a transfer function in which the diatom pH optima are used to infer past water column pH based on the taxonomic composition of the fossil diatom assemblages in sediment cores (Birks et al. 1990). The results can vary slightly depending on the training set used. We have assessed the accuracy of the method by comparing pH inferences from an analysis of sediment trap diatom samples collected from the loch between 1991 and 2007 with annual mean measured pH from the UK AWMN using three different training sets (Battarbee et al. 2008). Whilst the trends in pH inferred from the trap diatoms followed closely the trends in mean measured pH, there was a tendency for the diatom-inferred values to under-estimate the measured values although all inference models provided estimates of the measured values within the standard error of the method (cf Battarbee et al. 2005) of +/- ~0.3 pH units.

We then applied the different transfer functions to three different dated cores taken from the loch. The results (Figure 17) show that the pre-acidification, or reference pH, for the loch is likely to have been between 5.5. and 5.7. This compares with a mean annual pH of ca. 5.2 at the present day.

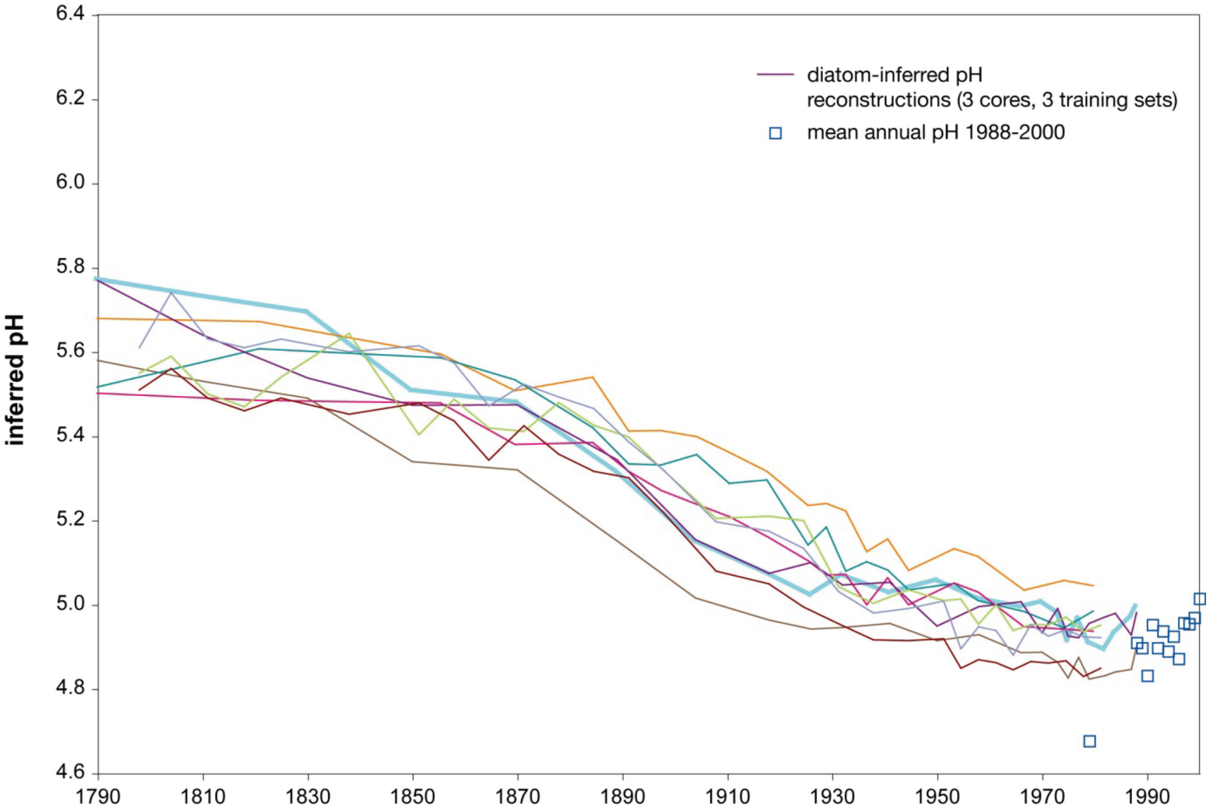

Figure 17. Diatom inferred pH for three sediment cores from the Round Loch of Glenhead (1790-1990) using three different training sets and measured pH from the AWMN (1988-2000) (redrawn from Battarbee et al. 2005).

5.2.3 Reference diatom populations

The most direct method of assessing the ecological status of the Round Loch of Glenhead and other AWMN lake sites is by comparing pre-acidification and contemporary diatom assemblages. This can be done by combining the data from the sediment traps (that provide annual data from 1991 to the present day) with sediment core data that extend back with an approximately sub-decadal resolution to 1800 AD and before.

The changes that have taken place can be visualised best by entering the Round Loch core and trap data into a Principal Components Analysis (PCA) of diatom assemblage data from a large dataset of 121 low alkalinity lakes from across the UK (Figure 18). The sites represent the full range of low alkalinity lake types found in the UK (Battarbee et al. 2011) varying in degree of acidification, base cation status, DOC, altitude and distance from the coast. Each of the 121 sites is represented by two samples, one from the ca 1800 AD level in a core from that site and one from the surface sediment sample (= present day at the time of sampling). These are not differentiated in Figure 18. The Round Loch data are thereby constrained by the range of variability in the overall dataset. The time trajectory for the loch shows the post-1800 changes in diatom assemblages caused by acidification and the post-1990 changes that represent the response to emission reduction. By comparison with the basal or pre-acidification reference sample it graphically illustrates the degree of recovery that has taken place. The gap between present day and reference assemblage composition is considerable. The flora is still dominated by taxa such as *Tabellaria quadriseptata* that was very rare in the past, and *Brachysira vitrea,* the dominant taxon of the pre-acidification flora (Figure 2) has yet to reappear in any abundance.

Of special interest is the evidence provided by the analysis of the direction of the recovery arrow. The data show that the diatoms are tracking back broadly in the direction of the reference assemblage, but the reverse-trajectory is beginning to be deflected away from the reference direction, indicating that the current diatom assemblage in the Round Loch has a different composition to that at any time during the acidifying stage. Inspection of the diatom data indeed show that for the Round Loch of Glenhead, *Navicula leptostriata* is increasing strongly (cf Figure 4) but was relatively rare in the past (Figure 2). The significance of this difference is not yet fully understood. It may simply be related to stochastic factors, to in-lake population dynamics or to the influence of external factors, such as climate change or nutrient enrichment from N deposition, or indeed a combination of factors (see section 6).

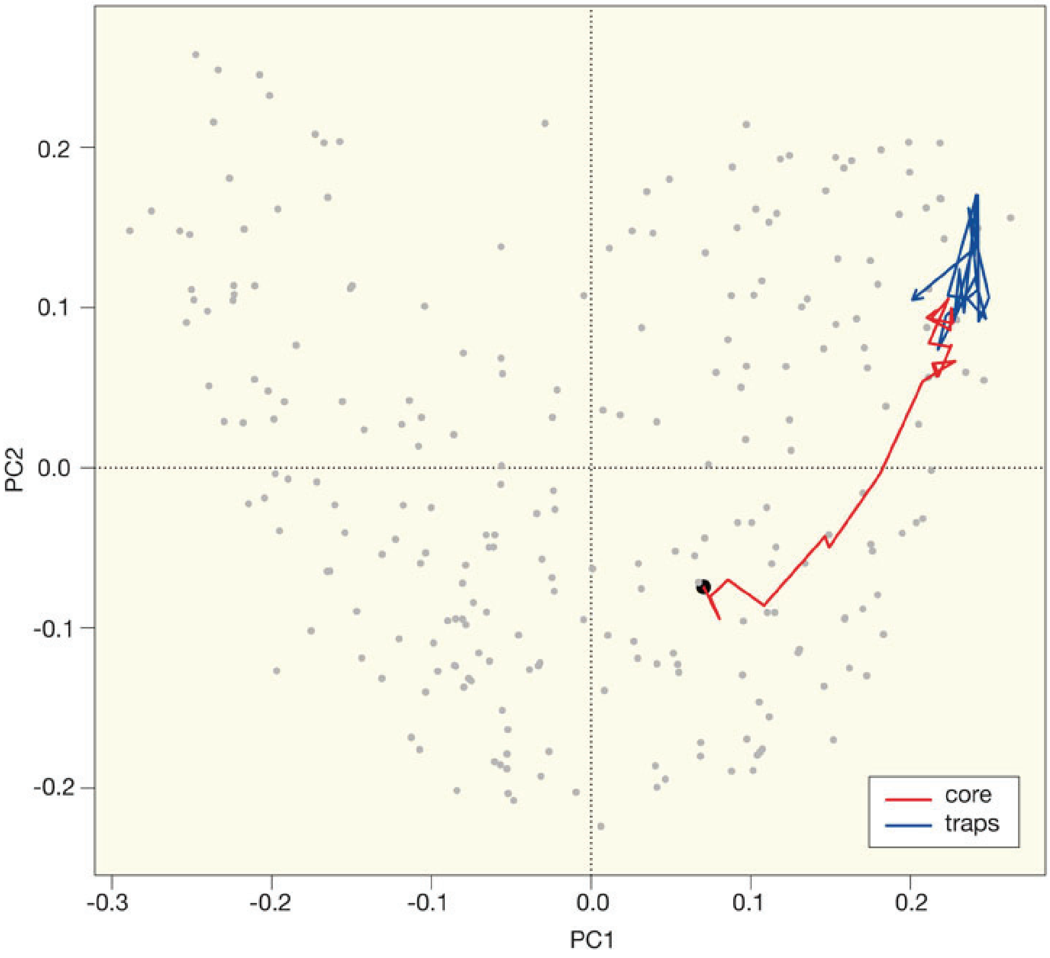

Figure 18. Principal Components Analysis (PCA) of diatom assemblages from 121 UK low alkalinity lakes with the diatom assemblages for the Round Loch of Glenhead core and sediment trap samples from ca. 1800 AD (black circle) to 2008 (blue arrow) inserted passively.

5.3 Reasons for limited recovery from acidification

After 20 years of monitoring, the chemical and biological data from the Round Loch of Glenhead are consistent in showing an improvement in water quality at the site since the successful introduction of measures to reduce acid emissions in the UK in the 1980s. However, when judged against the target ANC of 20 µeq L^{-1} required for the site to comply with the critical value for UNECE protocols or, more significantly against the pre-acidification reference conditions of ca. ANC 30 µeq L^{-1}, pH 5.5-5.7 and a diatom flora dominated by taxa such as *Brachysira vitrea,* the recovery to date both chemically and biologically can be seen to be quite limited.

The Round Loch is no different from other acidified sites in the AWMN in this regard. There are many possible reasons for the limited scale of recovery across the network. The precise mixture of factors will vary on a site by site basis but for the Round Loch it is apparent that both sulphate and nitrate concentrations are still significantly above background levels.

For SO_4^{2-} this may be due to continued release from catchment soils. Although many studies have shown that S acts conservatively in catchment soils and that reductions in deposition are rapidly followed by concomitant reductions in sulphate flux to surface waters there is also evidence that stored ‘legacy’ S may continue to be released through time even after deposition is reduced to negligible levels, especially at sites with organic soils, through both oxidation and erosion processes.

For nitrate, the Round Loch is one of only two sites in the network where nitrate has increased over the last 20 years. Present levels (ca. 10 µeq L^{-1}) remain much higher than the expected background values of 0-5 µeq L^{-1} found in reference sites indicating that the Round Loch soils have become saturated by N as a result of sustained N deposition over many decades leading to seasonal (winter) leaching (Curtis et al. 2005). Direct deposition of nitrate and ammonium to the loch surface is also an important factor.

Other factors such as long-term base cation depletion of catchment soils or changes in sea-salt deposition may also be involved but, assuming that the relatively high sulphate concentration will decline as S is gradually lost from catchment soils, the primary concern is the need for a further and more pronounced reduction in N deposition.

6 FUTURE ISSUES

Although the Round Loch is recovering from the effects of acidification there is uncertainty about how far the recovery will proceed and the extent to which future pressures will influence the direction of ecosystem change that is taking place. The main concerns are future changes in acid deposition, the behaviour of nitrogen and its potential for causing eutrophication and the role of climate change both through the direct impact of changing temperature, precipitation and windiness and indirectly through its impact on catchment biogeochemistry. Future land-use change may also influence water quality but, in the absence of plans to afforest the Round Loch catchment, this is a minor issue as long as the catchment is managed as at present for low intensity rough grazing by cattle.

6.1 Future acid deposition scenarios

According to the official modelled deposition scenarios for 2020 used in the forthcoming RoTAP Report (in review), substantial reduction in acid deposition from 2004-06 levels will occur at the Round Loch. Excess S deposition will decline from 0.58 keq ha^{-1} yr^{-1} to 0.30 keq ha^{-1} yr^{-1}, a reduction of almost 50%. NO_x will show a lesser decline from 0.58 to 0.41 keq ha^{-1} yr^{-1} (29%) while NH_y shows the smallest proportional reduction from 0.84 to 0.65 keq ha^{-1} yr^{-1} (23%). However, critical load models for the Round Loch indicate that exceedance of critical loads continues beyond 2020.

For future N deposition scenarios the SSWC model is ill-equipped to predict the fate of nitrate leaching, as it contains no mass-balance for N. However it can be used by making assumptions that either nitrate concentrations remain constant, or that they decrease in proportion to reductions in total N deposition (best case). FAB is designed specifically to deal with just such future scenarios and so can provide estimates of nitrate leaching and critical load exceedance under a notional steady-state with any future N deposition scenario. Hence critical load exceedance may be estimated in three ways for 2020 deposition levels (Fig. 19).

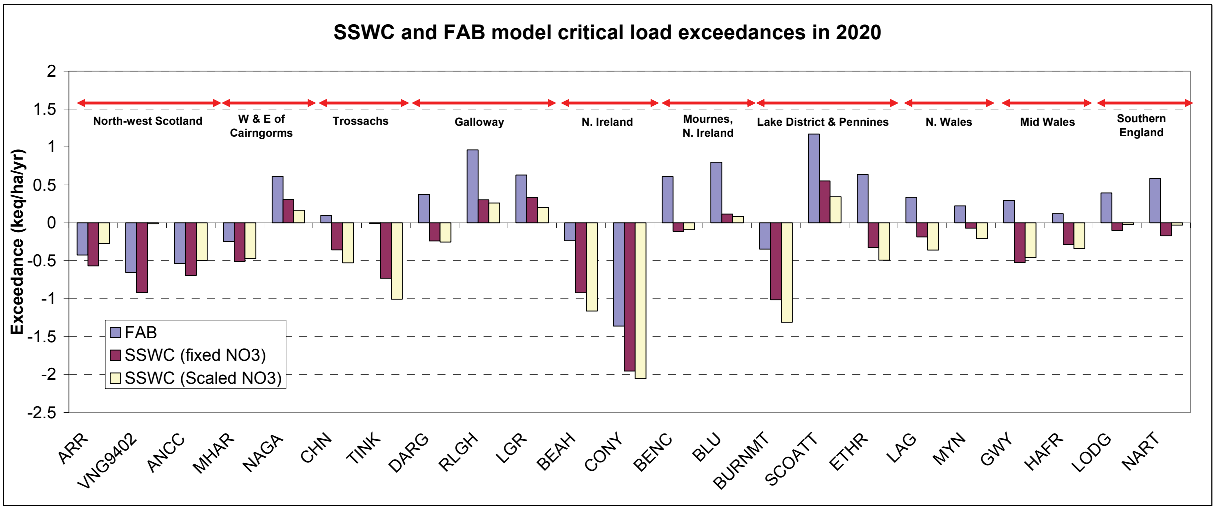

Figure 19. Projected critical load exceedances for AWMN sites in 2020 according to SSWC and FAB models. RLGH = Round Loch of Glenhead (from Kernan et al. 2010)

After 2020, none of the sites in north-west Scotland shows exceedance under any model, while exceedances persist at Lochnagar (all scenarios) and Loch Chon under the worst-case FAB model. However, the two loch sites in Galloway (Round Loch of Glenhead and Loch Grannoch) are exceeded under all scenarios, while the stream site, Dargall Lane, is exceeded only under the worst-case FAB scenario. Hence Round Loch is one of only three Scottish AWMN sites, all of which are lochs, expected to exceed critical loads under even best-case scenarios beyond 2020. While it has to be acknowledged that the worst-case nitrate leaching scenarios predicted by the FAB model may never be realised, best-case exceedances predicted using the SSWC model and nitrate scaled to reductions in N deposition do indicate that the acidification problem at Round Loch, as well as Loch Grannoch and Lochnagar, will persist for some time into the future. Furthermore, without further planned reductions in acid deposition, it is possible that complete chemical recovery to either the critical value of 20 µeq L^{-1} or the reference value of c. 31 µeq L^{-1} will never be achieved. Without chemical recovery, the re-establishment of biological reference communities cannot be achieved.

In addition to the three Scottish lochs continuing to exceed critical loads under best-case scenarios, only two other AWMN sites fall into this category, Blue Lough in Northern Ireland and Scoat Tarn in the English Lake District. Another ten sites exceed critical loads under the worst-case FAB model but the Scottish lochs dominate the core of most impacted sites in the AWMN into the future.

6.2 Nitrogen deposition and eutrophication

In contrast to SO_4^{2-}, NO_3^- acts not only as an acid anion but also as a nutrient. It is consequently a potential cause of eutrophication in upland waters as well as a cause of acidification. So far there is little evidence to show that the Round Loch has become more productive over the last 20 years, although the monitoring data indicate that nitrate levels have increased over that time.

Table 2. Nutrient limitation status of phytoplankton and periphyton yield at AWMN sites in early, mid or late summer bioassays (NO: nutrients not limiting, N = nitrogen; P = phosphorus; CO: co-limitation by both N and P). Sites ordered by increasing mean NO_3^- concentration (µeq L^{-1}); N deposition (Ndep) in kgN ha^{-1} yr^{-1} (from Kernan et al. 2010).

	2004-06 mean		**Bromley**		**Curtis & Simpson 07**		**Periphyton**	
Site Name	Ndep	NO_3^-	2009	Early	Mid	Late	Early	Late
Loch Coire Fionnaraich	9.8	1.9	Co	Co	N	Co		
Loch Coire nan Arr	8.7	2.3		Co	Co	Co	P	Co
Loch Tinker	23.6	2.5	Co					
Burnmoor Tarn	17.3	5.3	Co	Co	N	Co		
Llyn Llagi	16.2	6.1	Co	P	Co	Co	NO	NO
Round Loch of Glenhead	24.7	9.5	NO	Co	Co	Co	P	NO
Loch Grannoch	16.6	11.7	Co					
Scoat Tarn	23.9	13.9	Co	P	P	P		
Lochnagar	19.1	16	Co	Co	P	P		
Loch Chon	23.6	16.7	Co					
Blue Lough	23.5	20.2	NO	Co	P	P	Co	P

However, the AWMN is not yet ideally designed to detect the impact of eutrophication and the main effects may lie ahead if NO_3^- concentrations continue to increase and if future climate change accelerates N leaching from catchment soils (Curtis et al. 2005). What has been demonstrated, both in the UK and in other countries, is that the productivity of some upland waters is indeed either N-limited or co-limited by N and P (Maberly et al. 2002, Curtis & Simpson 2007, Bromley 2009). The Round Loch itself (Table 2) is co-limited.

Eutrophication or exceedance of nutrient-N critical loads is of relevance to the Gothenburg Protocol under the Convention on Long-range Transboundary Air Pollution. Furthermore, nutrient-poor lakes in the UK uplands designated under the EU Habitats Directive for their oligotrophic character may be undergoing enrichment. This change may also contribute to their deviation from the good ecological status required under the EU Water Framework Directive. It is therefore important to understand the likely (and in many cases ongoing) changes in the structure and function of oligotrophic lake ecosystems caused by the deposition of nitrogen as a nutrient and to modify AWMN protocols to track changes in the productivity of upland lakes. This is especially relevant for the Round Loch of Glenhead.

6.3 Potential threats from climate change

In the UK threats to the recovery of acidified upland waters from climate change are likely to be more related to changes in the seasonality, intensity and frequency of precipitation and sea-salt deposition events, than to temperature. Any increase in rainfall is expected to generate runoff with lower base cation concentration, lower pH and ANC, and higher aluminium and DOC concentrations, while increased storminess may lead to an increase in episodic sea-salt deposition, increasing the frequency and intensity of a process by which marine cations temporarily displace acid cations from the exchange sites of acid soils, causing pulses of highly acidic runoff. Increased winter precipitation and greater storminess may also cause accelerated soil erosion leading not only to an increase in sediment loads but also to the remobilisation of toxic substances stored in the soils following decades of air pollutant deposition.

6.3.1 Sea-salt deposition and ANC

Analysis of AWMN data shows that the temporal pattern of sea-salt deposition across the Network can be linked to the state of the North Atlantic Oscillation (NAO) and, even more strongly, to the Arctic Oscillation (AO). This observation explains the higher than expected acidity that occurred at sites across the Network in the early period of monitoring when the AO index was at its highest for 60 years. It also indicates the possible future threat of sea-salt deposition if the AO continues to become more intense as recent trends indicate.

Monteith (in Kernan et al. 2010) has examined the possible impact of a return to the 1989-1991 level of sea-salt deposition on the ANC of AWMN sites statistically by using linear models to predict the combined effect of anthropogenically derived acids (i.e. sum of xSO_4^{2-} and NO_3^- concentration) and sea-salt (Cl^- concentration) on ANC for 11 AWMN sites, including the Round Loch, that are both geographically vulnerable to sea-salt deposition and are particularly acid-sensitive systems. The results showed that the two variables explained between 22.6 and 67.9 % of the variance in ANC in individual water samples at the 11 sites indicating for chloride that on average a 50 µeq L^{-1} increase in Cl^- concentration would be expected to depress ANC by almost 10 µeq L^{-1}.

Monteith consequently used the model coefficients to predict the future effect of a hypothetical return to the sea-salt concentrations experienced at individual sites over the first five years of monitoring on ANC while fixing xSO_4^{2-} and NO_3^- concentrations at recent (2003-2008) levels. The results suggest that, were the 1989-1991 levels of sea-salt inputs to recur, mean ANC levels of all sites would be depressed significantly. In the case of the Round Loch of Glenhead this reduction would on average amount to ca. 12 µeq L^{-1}, countering much of the improvement that has been observed at this site over the last 15 years and possibly leading to an increase in the concentrations of H^+ and Al^{3+} ions above toxic levels for some acid-sensitive biota resulting in the loss of recently re-established taxa at the site.

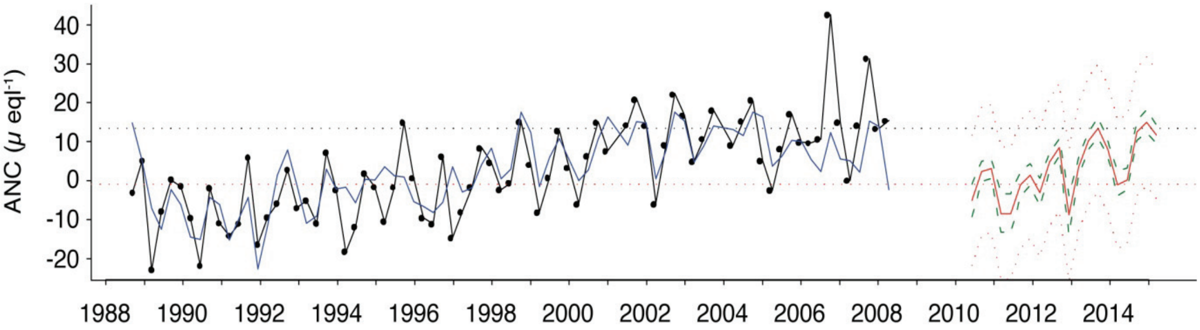

Figure 20. Acid neutralising capacity, modelled ANC, projected ANC for 2010 to 2015 assuming 1988-1991 chloride concentrations for the Round Loch of Glenhead (from Monteith in Kernan et al. 2010).

Targets for recovery, fixed by existing legislation, may need to be revised to allow for the effects of future climate change. In particular it may be difficult or impossible to achieve the "good ecological status" objective of the Water Framework Directive for the Round Loch if future changes in precipitation and sea-salt deposition reduce its potential for a full recovery.

6.3.2 Trace metals and persistent organic pollutants (POPs)

Since 1970, emissions of trace metals to the atmosphere in the UK have declined dramatically, principally as a result of declining coal use, reduction in iron and steel production, better controls on incinerators and, for Pb, the introduction of unleaded petrol. These declines have reduced trace metal emissions to low levels such that possibilities for continuing reductions into the future are limited. Nevertheless trace metals and POPs may increasingly contaminate upland waters if they are remobilised from catchment soils during storm events and transported to aquatic ecosystems where they may accumulate in food chains.

Although no studies of this kind have yet been carried out at the Round Loch there is good evidence of the threat from studies on Lochnagar by Yang et al. (2002) who showed that the effects of the rapid decline in metal emissions and deposition that has occurred since 1970 is not reflected by concomitant declines in the sediment record. As there are no direct sources of contamination to account for this observation Yang et al. maintain that the lack of response to depositional changes can only be the result of metals previously deposited onto the catchment now being transferred to the loch. More recent research by Rose et al. (2011) supports this conclusion.

As the Round Loch of Glenhead catchment has experienced higher air pollutant loads in the past than Lochnagar and has easily eroded organic soils it is highly probable that the same processes are operating at this site and might be expected to accelerate under a future climate with higher precipitation and increased storminess.

Previous work has shown clearly how toxic substance concentrations can contaminate and bio-accumulate within the food chain and reach high levels in fish tissue (Rognerud et al. 2002) such that physiological functioning may be impaired. However, it is still unclear whether the concentrations in fish exceed human consumption guidelines.

These observations are of particular importance to the Water Framework 'Daughter' Directive (2008/105/EC) that affirms the aim of the WFD to ensure that "existing levels of contamination in biota and sediments will not significantly increase". Of the trace metals, this Directive considers Hg to be of particular concern although Pb and Cd remain priority substances.

All metals monitoring under the auspices of the AWMN has ceased as a result of funding reductions from Defra over the last few years. A priority for the future is to re-instate the trace metals monitoring programme at Lochnagar and extend the protocols to other key sites in the Network, especially the Round Loch.

7 PLANS FOR THE FUTURE

The concerns described above highlight the importance of continued monitoring at the Round Loch and other sites in the AWMN not only to track responses to changes in acid deposition but also to take account of other known current and future pressures, especially from climate change. Consequently, over the next 12 months the Acid Waters Monitoring Network will be re-branded as the “Upland Waters Monitoring Network” and the network will be progressively expanded as funds become available to include additional sites and protocols designed to address these wider concerns.

Plans include:

- adding sites in more alkaline upland areas vulnerable to the effects of N deposition and climate change;
- expanding the scope of monitoring to include regular surveys of catchment soils, vegetation and land-cover;
- co-locating automatic weather stations and bulk deposition collectors at all sites;
- installing temperature and flow and water-level loggers to all sites; and
- modifying protocols for chemical and biological monitoring at all sites to enable the potential impact of N deposition, remobilised toxic substances and climate extremes to be identified.

The Round Loch of Glenhead is now one of the best equipped sites in the Network. The investment in flow and water-level loggers funded by SNH completes the climate-proofing of the site. Priorities for the Round Loch now are to:

- introduce new protocols needed to assess the risk of eutrophication by adding chl a measurements and routine algal bioassays;
- introduce measures for monitoring the potential re-mobilisation of toxic substances from catchment soils based on the protocols used at Lochnagar;
- design and introduce methods for recording changes in catchment land-use and land cover.

Implementation of these new measures will depend on the availability of new funding, and new funding will be needed from 2014 onwards to maintain the automatic station in the loch, once the current NERC project comes to an end.

In addition to extending our monitoring capability as described above there is also need for continued research to understand better how climate change will modify biogeochemical processes in the catchment and in the loch and how climate change will modify the physical and chemical dynamics of the water column. Understanding better how the structure and functioning of the loch will respond to the combined impact of changing acidity, nutrient concentrations and climate is also a priority relevant to the legislative requirements of both the Habitats Directive and the Water Framework Directive. An urgent issue in this context is the need to improve our understanding of reference conditions at the site using both palaeoecological and spatial analogues to develop improved methods of defining favourable condition for the SAC habitat type and the “good/moderate” boundary used by national agencies in their implementation of the WFD.

8 CONCLUSIONS

Evidence from 20 years of water chemistry monitoring shows that the Round Loch of Glenhead is showing significant improvement but remains chronically acidified. Increasing nitrate concentrations are offsetting the recovery and sulphate concentrations still remain above those expected under reference conditions.

Trends in biology are consistent with the improvements in chemistry with significant changes occurring in the populations of epilithic diatoms, aquatic macrophytes and macroinvertebrates. There have also been increases in the density of trout fry found in the loch outflow.

Despite the improvements the data show that the loch's current acid neutralising capacity of 14 µeq L^{-1} is still significantly below the value of 20 µeq L^{-1} needed to meet the critical loads exceedance target under UNECE protocols and the ca. 30 µeq L^{-1} value estimated as the pre-acidification reference value.

The limited scale of chemical recovery is corroborated by diatom data that show no re-appearance yet of the dominant pre-acidification taxa that occurred in the loch in the early 19th century and before.

Future concerns include the threat of eutrophication, if nitrate concentrations continue to rise and climate change, principally through the projected increase in winter precipitation and the frequency and intensity of sea-salt laden storms. Increased storminess might also lead to the remobilisation of toxic substances stored in catchment peats.

To cater for these threats at the Round Loch and other upland waters the Acid Waters Monitoring Network will be re-branded as the "Upland Waters Monitoring Network" and modified, as and when funds become available, to extend its capability in monitoring nutrient trends, changes in temperature and flow and changes in toxic substance loads.

In the case of the Round Loch the installation of water-level and outflow loggers funded by SNH complements instrumentation for monitoring water column temperature already deployed and completes the climate proofing of the loch. The loch is now the most fully equipped site for monitoring upland water quality and freshwater biodiversity in the UK.

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