ECRC RESEARCH AT LOCHNAGAR: 1997/8

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Executive Summary

This report describes the ongoing programme of research undertaken by the Environmental Change Research Centre at Lochnagar. Over the last decade the loch has become an important part of both national and international monitoring networks and research projects. For example, the UK Acid Waters Monitoring Network (UKAWMN), the UK Environmental Change Network (ECN) and the UNECE International Co-operative Programme for Assessment and Monitoring of Acidification of Rivers and Lakes.

Lochnagar has been part of the UKAWMN since its inception in 1988. Dip samples for water chemistry are taken from the outflow every three months. Macroinvertebrates, epilithic diatoms and the trout population of the outflow are sampled annually and the aquatic macrophytes every two years.

Water chemistry data for 1988 - 1997 show the loch to be acidic with low ionic concentrations. The latter half of the data series shows substantially increased concentrations of total oxidised nitrogen, accompanied by depressed pH and elevated levels of soluble aluminium. Statistical trend analysis of the 1988 - 1996 epilithic diatom data-set indicates a significant linear trend consistent with recent evidence for a small decline in pH.

The macroinvebrate fauna is low in diversity but typical for a moderately acid, high altitude lake. The density of annually sampled brown trout demonstrates that the population of the outflow has been relatively constant over the past 9 years with no evidence of improvement or decline.

Sediment core data demonstrate that Lochnagar has been impacted by atmospherically deposited pollutants since the mid-nineteenth century. Concentrations of lead and zinc increase from this time to 1910 and 1970 respectively, since when they have declined significantly. Concentrations of carbonaceous particles (indicators of high temperature fossil-fuel combustion) also peak in the 1970s. Diatom reconstructed lake water pH indicates a gradual decrease from pH 5.6 in the mid-19th century to around pH 5.0 by the 1940s, since when the pH has remained relatively constant.

Since 1991, Lochnagar has been the UK site in three EU funded European mountain lake research programmes, AL:PE (1991-1993), AL:PE II (1993-1995) and MOLAR (1996-1999). This work has shown the importance of these remote and sensitive ecosystems as sensors of long-range transported pollutants and as providers of early warning signals for more widespread environmental change. Additionally, these studies highlight the importance and urgency of understanding the present and future impacts of pollutants, both singly and in combination, on aquatic ecosytems.

Current work (MOLAR) addresses the question of relating atmospheric deposition of pollutants (in particular trace metals and fly-ash particles) to the sediment record thereby providing a more quantitative estimate of atmospheric deposition through time and hence, the possibility of defining a sediment based critical load for metals. This work involves a detailed study of metal cycling and metal storage in all compartments of the lake and its catchment.

Monitoring of trace metal deposition has been ongoing since 1996 and provides a unique dataset for upland UK. In addition, the regular sampling allows some idea of episodicity to be determined. A small automatic weather station deployed in the catchment provides meteorological data to better interpret pollutant deposition data, and by back trajectory work, possibly source regions.

1. Introduction

Lochnagar experiences some of the harshest environmental conditions in the British Isles. In addition, because of its altitude and underlying geology it is particularly sensitive to atmospherically deposited pollutants. Over the last decade it has therefore become an important part of both national and international monitoring networks and research projects. Lochnagar is a key site in the UK Acid Waters Monitoring Network (UKAWMN) and data collected at the site contribute to the UK Environmental Change Network (ECN) and the UNECE International Co-operative Programme for Assessment and Monitoring of Acidification of Rivers and Lakes.

This document aims to describe and summarise the ongoing research activities of the Environmental Change Research Centre (ECRC) on and around the lake and catchment of Lochnagar. These studies take a number of forms from long-term monitoring of lake water chemistry and biology to shorter term studies such as the EU funded AL:PE and MOLAR research programmes and PhD studies linked to these. Some summary data are included but no interpretation of these data is included in this report.

1.1. The loch and its catchment

Lochnagar (National Grid Reference NO 252 859) lies at an altitude of 785m in the centre of the granitic massif which comprises much of the Balmoral Forest in Aberdeenshire. Lochnagar is a corrie loch and lies below a north-east facing steep backwall which rises to the summit of the same name. No distinguishable inflow feeds the loch and drainage is primarily from small seepage channels. The outflow stream drains to the north-east through a series of small pools to the Lochnagar Burn which in turn feeds the Gelder Burn a south-bank tributary of the River Dee. Snow generally occupies the catchment to a varying extent between November and May and a significant snow field accumulates most years over the main winter period. Snow-melt therefore comprises a major input to the loch. Lochnagar freezes each winter and partial ice cover may last from November to May with complete cover between January and April in most years. The loch has a surface area of 9.8 ha and the bathymetric map (Figure 1.1) shows that the loch floor slopes sharply to a deep basin. The loch is deep for its size and the deepest point, with a maximum depth of 24m is offset towards the backwall. The mean depth is 8.4m.

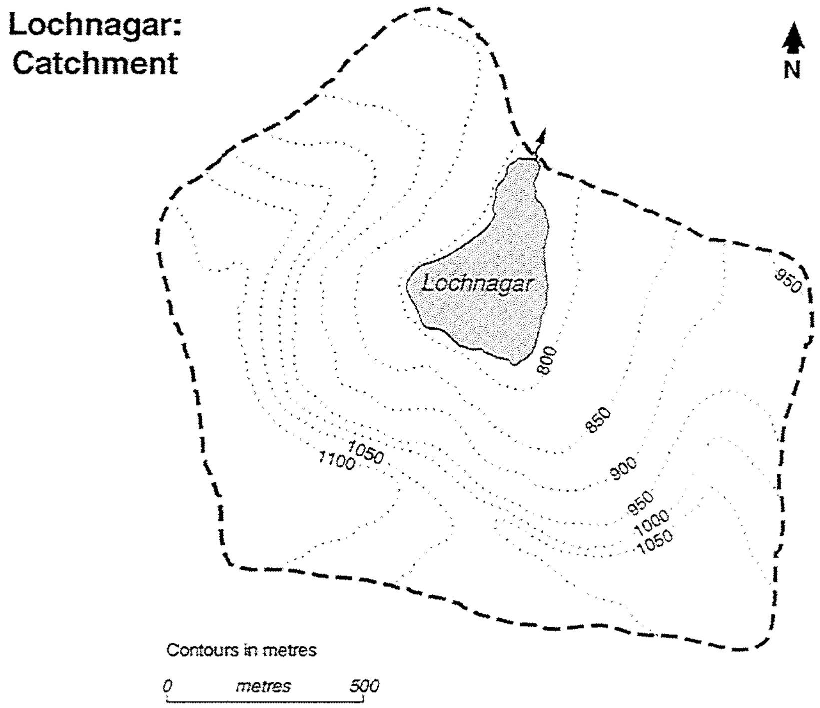
The loch drains a precipitous catchment of 91.9 ha (Figure 1.1) which reaches a maximum altitude of 1155m at the summit of Lochnagar to the west of the loch. The geology is composed of biotite granite overlain in places by blanket peat. The catchment is dominated by bare rock both on the steep backwall and the extensive fields of large boulders and coarse screes that have developed between the corrie ridge and the loch. The catchment is unafforrested and the sparse vegetation is dominated by a community of stunted *Calluna* and *Vaccinium*, interspersed in places with *Scirpus*, whilst lichens and mosses are abundant on the boulders and screes. Of the localised areas of peat in the catchment, certain areas, notably along the eastern shore, are severely eroded. Pine stumps are revealed in peat exposures adjacent to the outflow and further down the Lochnagar Burn. The catchment lies above the limit of summer sheep grazing in the region and there is no evidence for, nor any expectation of, any land-use change or active land-management within the catchment. Red deer range across the catchment but stalking in the area, once popular, is now strictly controlled.

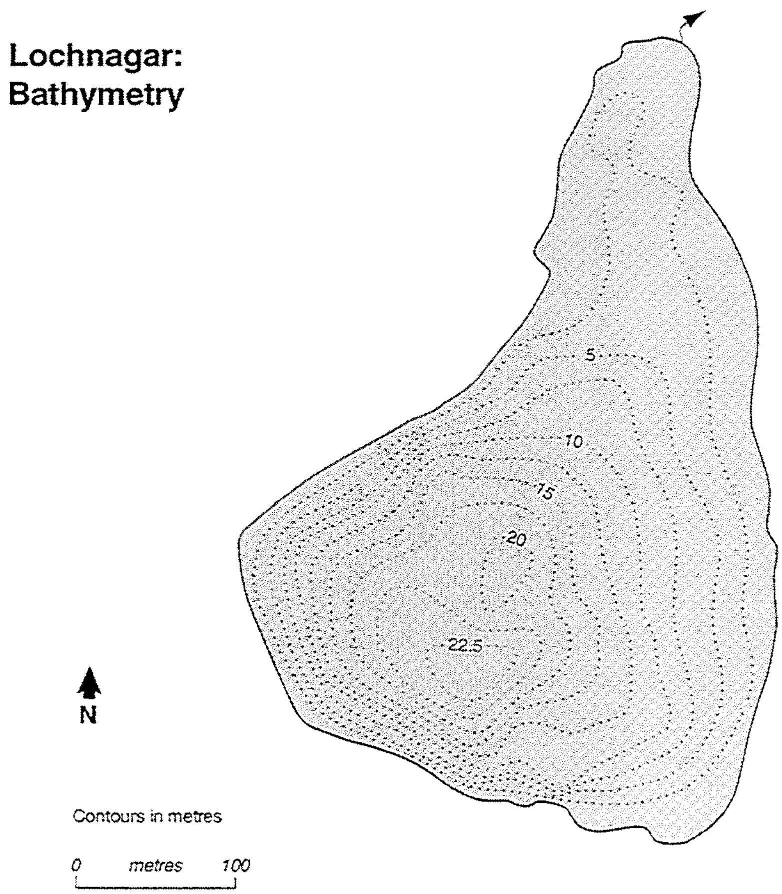
The loch and its catchment receive an annual rainfall of 1400 mm (interpolated data from 1988 - Institute of Hydrology) to c.1600 mm (measured 1996/97 - see below) with wet deposited acidity of 0.48 kg H^+ ha^{-1} yr^{-1} and wet deposited non-marine sulphate of 7.33 kg S ha^{-1} yr^{-1} (1988-89) (Juggins *et al.*, 1989).

1.2. Previous studies

Prior to the initiation of the UKAWMN in 1988 the Palaeoecology Research Unit (PRU), later the ECRC, undertook a palaeoecological evaluation of the acidification of Lochnagar as part of a study funded by the Department of the Environment on the causes of surface water acidification in the UK.

Figure 1.1. Catchment and bathymetric map of Lochnagar.





A sediment core was taken in June 1986 and ^{210}Pb, ^{137}Cs and ^{241}Am analyses were utilised to provide a chronology. Historical pH was reconstructed using the preserved remains of diatom frustules in the sediment and lithostratigraphic, geochemical, magnetic, fly-ash and palynological analyses undertaken. This work has been published in the scientific literature (Jones *et al.*, 1993; Battarbee *et al.*, 1995) and the main conclusions were as follows:

- Diatom analysis showed a clear acidification sequence. Although the first signs of acidification occurred in the mid-nineteenth century a more pronounced change occurred c.1880 as several circumneutral species decline and acidophilous and acidobiontic diatom species increase.
- The reconstructed pH history shows that prior to acidification the pH of the loch was c.5.7. Recent pH is reconstructed to 4.8 compared to measured values of c.5.0.
- Geochemical analyses indicated a progressive contamination of the upper sediments by trace metals, notably zinc and lead. Zinc contamination commenced in the early/mid-nineteenth century whilst lead contamination occurred earlier. Enrichments of trace metals over background is due to atmospheric deposition.
- Magnetic accumulation in the sediment record increased only slowly between 1900 and the 1940s since when a steady increase is apparent to the core top suggesting contamination by fly-ash deposition.
- Concentrations of spheroidal carbonaceous particles (SCP), unambiguous indicators of industrial fossil-fuel combustion, progressively increased in the sediments from the 1890s with a major increase occurring between 1950 and 1973.
- The recent pollen record is dominated by a trend from *Calluna* to *Gramineae* over the last 200 years.
- The conclusion of this work was that the evidence for acidification at Lochnagar was consistent with the acid deposition hypothesis and that the pattern and timing of this acidification could not be accounted for by alternative hypotheses.

1.3. The Hull Acid Rain Model (HARM)

The Hull Acid Rain Model (HARM) (Metcalfe & Whyatt, 1995) is used to predict the proportion of sulphur deposition from identified point sources to any site in the UK. This model has been applied to all the UKAWMN sites and the output for Lochnagar (1995) is shown in Table 1.1. This suggests that the major deposition sources for the site are large coal-fired power stations in the English Midlands (e.g. Drax, Ferrybridge, Eggborough) with other source areas being power stations near Glasgow (Longannet) and to a lesser extent Northern Ireland (Ballylumford) (Metcalfe, pers. comm.). This information does emphasise the broad geographical range of sources that are likely to have an impact on Lochnagar and the long-range transport to the site of gaseous pollutants in particular. Whilst it is generally accepted that the UK itself is the main recipient of UK atmospheric emissions, the table ignores possible contributions from depositing pollutants with sources outside of the UK. This has been suggested by previous workers (e.g. Davies *et al.*, 1984) where 'black snow' events have been traced, using back-trajectory models to industrial centres in central and eastern Europe, and also from particle characterisation studies (Rose & Harlock, in press).

Table 1.1. Sulphur deposition (kg S $ha^{-1}yr^{-1}$) at Lochnagar from named point sources. Distance from the source to Lochnagar is also given.

	Source	Type	Distance (km)	S dep.		Source	Type	Distance (km)	S dep.
1	Drax	Coal P.Stn	385	0.391	25	Grangemouth	Oil refinery	112	0.045
2	Longannet	Coal P.Stn	102	0.377	26	Littlebrook	Coal P.Stn	652	0.039
3	Ferrybridge	Coal P.Stn	381	0.296	27	West Thurrock	Coal P.Stn	652	0.035
4	West Burton	Coal P.Stn	429	0.271	28	Aberthaw	Coal P.Stn	620	0.033
5	Eggborough	Coal P.Stn	385	0.238	29	Coolkeeragh	Oil P.Stn	331	0.027
6	Cottam	Coal P.Stn	436	0.220	30	Staythorpe	Coal P.Stn	457	0.025
7	Ratcliffe	Coal P.Stn	473	0.212	31	Fawley	Oil refinery	695	0.025
8	Blyth	Coal P.Stn	228	0.199	32	S. Killingholme	Oil refinery	419	0.019
9	Rugeley	Coal P.Stn	475	0.185	33	Grain	Oil P.Stn	665	0.019
10	Ballylumford	Oil P.Stn	289	0.183	34	Uskmouth	Coal P.Stn	602	0.017
11	Cockenzie	Coal P.Stn	112	0.172	35	Fawley	Oil P.Stn	694	0.016
12	Thorpe Marsh	Coal P.Stn	400	0.145	36	C. Donnington	Coal P.Stn	472	0.016
13	Didcot	Coal P.Stn	608	0.144	37	Killingholme	Oil refinery	423	0.014
14	Peterhead	Oil P.Stn	105	0.120	38	Stanlow	Oil refinery	416	0.014
15	Fiddlers Ferry	Coal P.Stn	401	0.118	39	Richborough	Oil P.Stn	695	0.013
16	Ironbridge	Coal P.Stn	483	0.082	40	Agecroft	Coal P.Stn	388	0.012
17	Willington	Coal P.Stn	469	0.073	41	Ferrybridge	Coal P.Stn	381	0.012
18	High Marnham	Coal P.Stn	443	0.069	42	Drakelow	Coal P.Stn	476	0.011
19	Methil	Coal P.Stn	87	0.061	43	Coryton	Oil refinery	654	0.011
20	Skelton Grange	Coal P.Stn	371	0.060	44	North Tees	Oil refinery	294	0.011
21	Kilroot	Coal/Oil P.Stn	298	0.059	45	Padiham	Coal P.Stn	357	0.011
22	Kingsnorth	Coal/Oil P.Stn	665	0.057	46	Pembroke	Oil P.Stn	598	0.010
23	Drakelow	Coal P.Stn	476	0.051	47	Belfast West	Oil P.Stn	312	0.010
24	Tilbury	Coal/Oil P.Stn	656	0.048	48	Ince	Oil P.Stn	502	0.006

2. The UK Acid Waters Monitoring Network.

The United Kingdom Acid Waters Monitoring Network (UKAWMN) funded by the Department of the Environment, Transport and the Regions, was established in 1988 in order to monitor the ecological response of acid sensitive freshwaters to the changing nature of acid deposition in the UK. The Network consists of 22 sites, 11 lakes and 11 streams all situated on acid sensitive lithologies, and (reflecting the geographical distribution of these geological types) mostly in the north and west of the country.

Lochnagar is of particular importance to the UKAWMN, as the sole lacustrine representative for the Grampian mountains, and as the only example of a arctic-alpine environment. It is the highest UKAWMN lake site (altitude of 785 m), and the only one to consistently freeze (often for a duration of over 4 months) each winter.

The loch is subject to standard UKAWMN sampling protocols for water chemistry and biology. Dip samples for water chemistry are taken from the outflow every three months. Macroinvertebrate kick samples are taken annually from shallow water (littoral) locations in the spring, epilithic diatoms (unicellular algae which grow on submerged mineral substrates) are sampled annually during the summer, aquatic macrophytes (higher plants, usually identifiable with the naked eye) are sampled every two years during the summer and the trout population of the outflow is determined by electrofishing, each autumn. Two submerged sediment traps are emptied annually and the contents analysed to determine the species composition of diatom remains and the annual atmospheric flux of carbonaceous particles. The acidification history of the loch has been studied for the UKAWMN using a finely sectioned and radiometrically (^{210}Pb) dated sediment core taken in 1991. Lake water pH has been reconstructed using a diatom - pH weighted averaging approach, whilst the concentration of certain metals and carbonaceous particles have been determined to provide a more direct assessment of the atmospheric pollutant loading on the site.

The sediment core data demonstrate that Lochnagar has been impacted by atmospherically deposited pollutants throughout the duration represented by the core (i.e. since the mid-nineteenth century)(Figure 2.1). Concentrations of lead and zinc increase from the base of the core to 10 cm (1910) and 5 cm (1970) respectively, since when they have declined significantly. Carbonaceous particle concentrations also peak in the 1970s. Figure 2.2 presents the species composition of diatom remains in contiguous slices of the dated 1991 sediment core and the (diatom inferred) reconstructed lake water pH. The diatoms indicate a gradual decrease in lake water pH from about pH 5.6 in the mid-nineteenth century to around pH 5.0 by the 1940s, since when the pH has remained relatively constant with no significant post-1970 changes in the diatom assemblages. A similar trend was found in a core taken in 1986 (Patrick *et al.* 1989) Figure 2.3 summarises the species composition of diatom remains and the estimated flux of carbonaceous particles to sediment traps since their installation in 1990. The limited duration of sediment trap data is currently too short for the assessment of trends.

Table 2.1 provides a summary of mean, maximum and minimum values for a number of key water chemistry parameters from 1988 - 1997, while the temporal variation of seven of these is provided in Figure 2.4. The data show the loch to be an acidic site with low ionic concentrations. The latter half of the data series differs from the earlier 5 years due to substantially increased concentrations of total oxidised nitrogen, accompanied by depressed pH and elevated levels of soluble aluminium. More recent data (MOLAR; Section 3) suggest a decline in nitrate, but comparable UKAWMN data for this period are currently unavailable. It is interesting that the lake has become more acidic at a time when non-marine sulphate concentration (which, with nitrate, is normally a major source of atmospherically deposited acidity) appears to be in decline. The mechanism responsible for the elevated nitrogen levels is unclear, but could be related to particular climatic conditions, such as a number of relatively warm summers experienced since 1990.

Temporal variation of epilithic diatom and macroinvertebrate species are provided in Figure 2.5 and 2.6 respectively. The diatom epilithon are dominated by species characteristic of acid lakes, such as *Achnanthes marginulata*, *Eunotia incisa* and *Tabellaria quadriseptata*. High abundance of *A.marginulata* is typical for high mountain, ultra-oligotrophic lakes. Statistical trend analysis of the 1988 - 1996 data-set has indicated a significant linear trend in species composition which is consistent with the recent evidence for a small decline in pH. The macroinvebrate fauna is low in diversity but typical for a moderately acid, high altitude lake, with relatively poor representation of stoneflies (with the exception of *Capnia* sp.), and a relatively abundant Chironomid population which shows large variation in size between years.

The density of annually sampled brown trout is provided in Figure 2.7 and demonstrates that the population of the outflow has been relatively constant over the past 9 years with no evidence of improvement or decline.

Table 2.2 describes the current aquatic macrophyte assemblage of the loch. The loch is characterised by plants which are adapted to acid and low nutrient conditions. The Quillwort, *Isoetes lacustris* and the aquatic rush *Juncus bulbosus* var. *fluitans* are the only vascular plants present; winter ice cover and low temperatures probably prevent the establishment of other acid tolerant vascular species. All other species listed are bryophytes (mosses and liverworts) the most common of which are the moss *Sphagnum auriculatum* and the liverwort *Nardia compressa*.

Table 2.1 Summary of Lochnagar water chemistry (1988 - 1996)

Determinand	Mean	Max	Min
pH	5.36	5.81	4.95
Alkalinity ($CaCO_3$)	0.07	0.60	-0.50
Conductivity	21.5	35.0	4.0
Ca (mg l^{-1})	0.57	1.00	0.43
Mg (mg l^{-1})	0.39	0.70	0.30
Na (mg l^{-1})	2.16	1.00	1.60
K (mg l^{-1})	0.30	0.50	0.10
Fe (mg l^{-1})	0.01	0.05	0.01
Mn (mg l^{-1})	0.01	0.01	0.00
Soluble Al (μg l^{-1})	39.9	147.0	4.0
Soluble labile Al (μg l^{-1})	23.5	137.5	2.5
Cl (mg l^{-1})	3.17	5.90	1.80
SO_4 (mg l^{-1})	2.80	4.10	2.20
Total Oxidised N (mg l^{-1})	0.20	0.39	0.02
PO_4 (mg l^{-1})	0.00	0.03	0.00
Si (mg l^{-1})	1.03	1.50	0.30
Dissolved Organic Carbon (mg l^{-1})	0.99	3.40	0.62

Table 2.2 Species list for aquatic macrophytes occurring in Lochnagar (1996)

Species	Abundance
Mosses	
Fontinalis antipyretica	rare
Sphagnum auriculatum	frequent
Racomitrium aquaticum	rare
Liverworts	
Nardia compressa	occasional
Scapania undulata	frequent
Pteridophytes	
Isoetes lacustris	occasional
Flowering plants	
Juncus bulbosus var. fluitans	occasional

Figure 2.1 Sediment concentration depth/age profiles of lead, zinc and carbonaceous particles

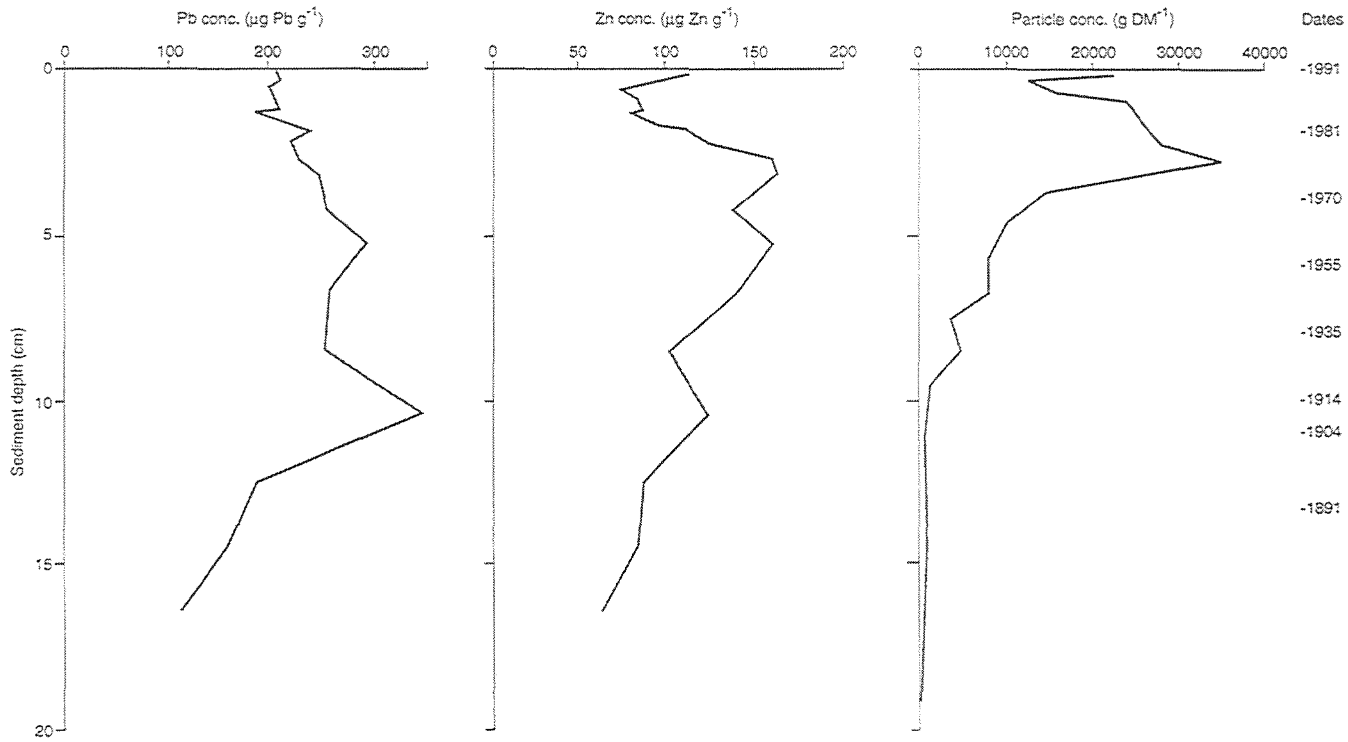


Figure 2.2. Sediment core diatom summary diagram (including all species occurring at >2% abundance in any one sample) and weighted average pH reconstruction

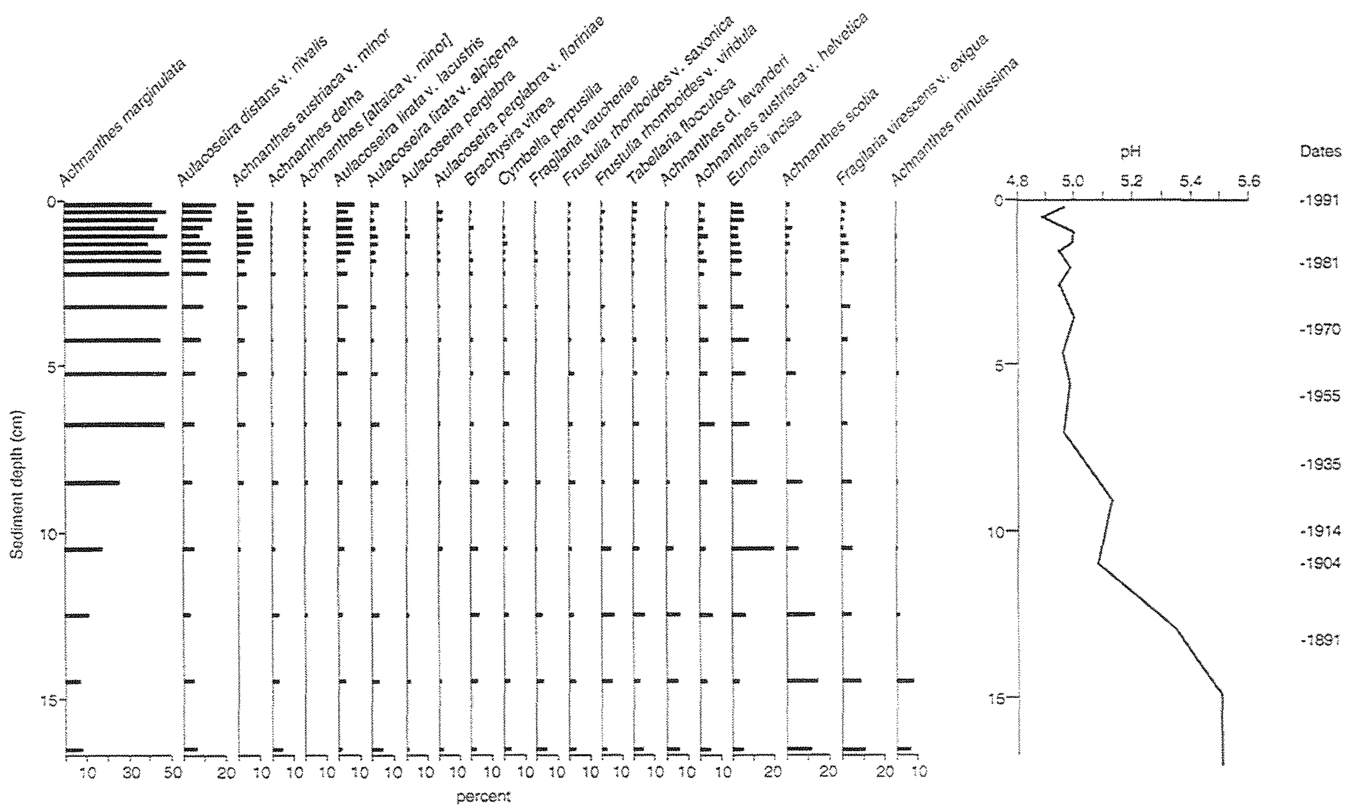


Figure 2.3. Sediment trap diatom and carbonaceous particle diagram. Includes all diatom species occurring at >1% abundance in any one sample). Carbonaceous particle flux (no. trap^{-1} day^{-1}) for preceding year.

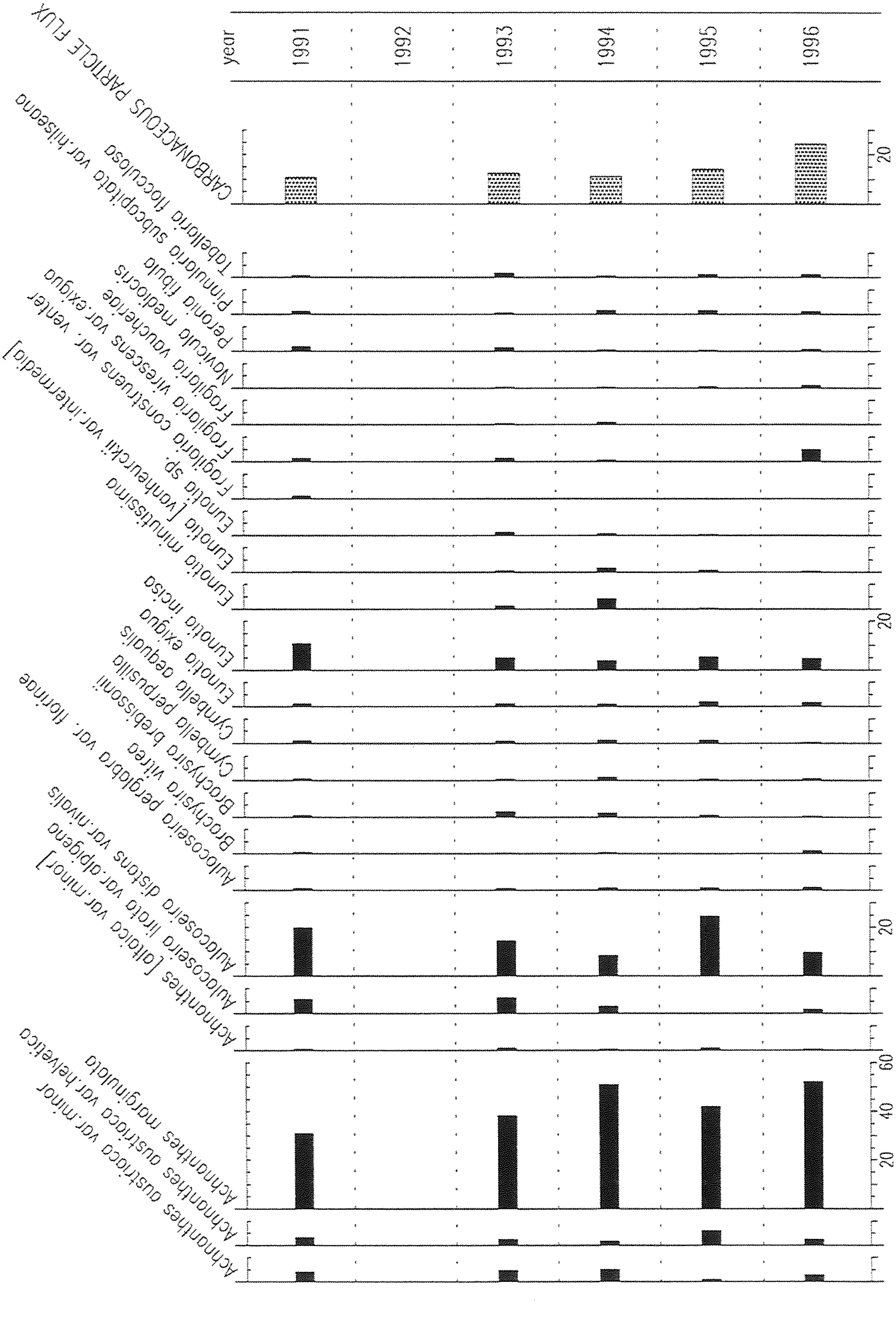


Figure 2.4. Summary of UKAWMN water chemistry for 7 key determinands 1988 - 1996

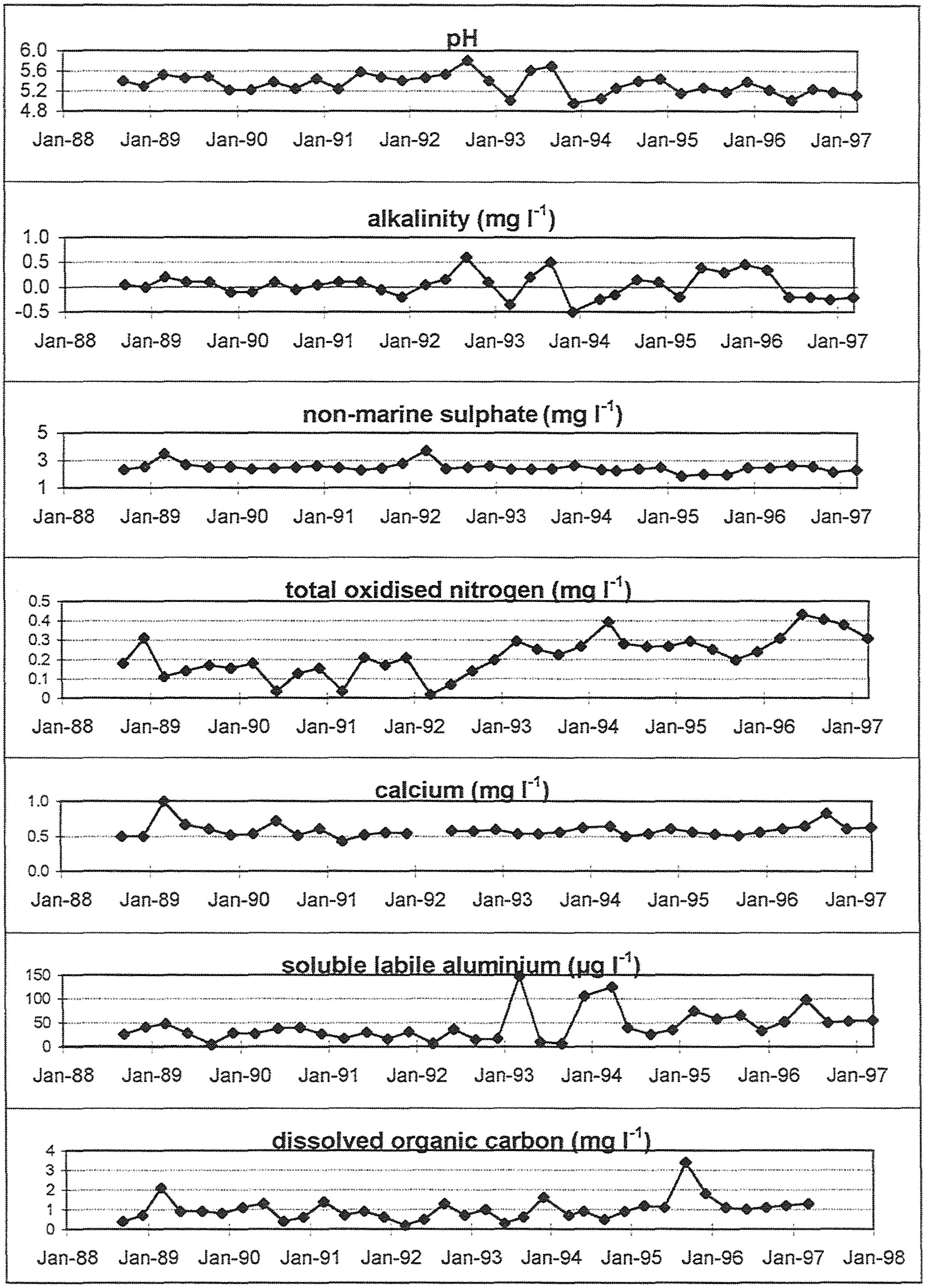


Figure 2.5. UKAWMN summary of epilithic diatom % relative frequency 1988 -1996

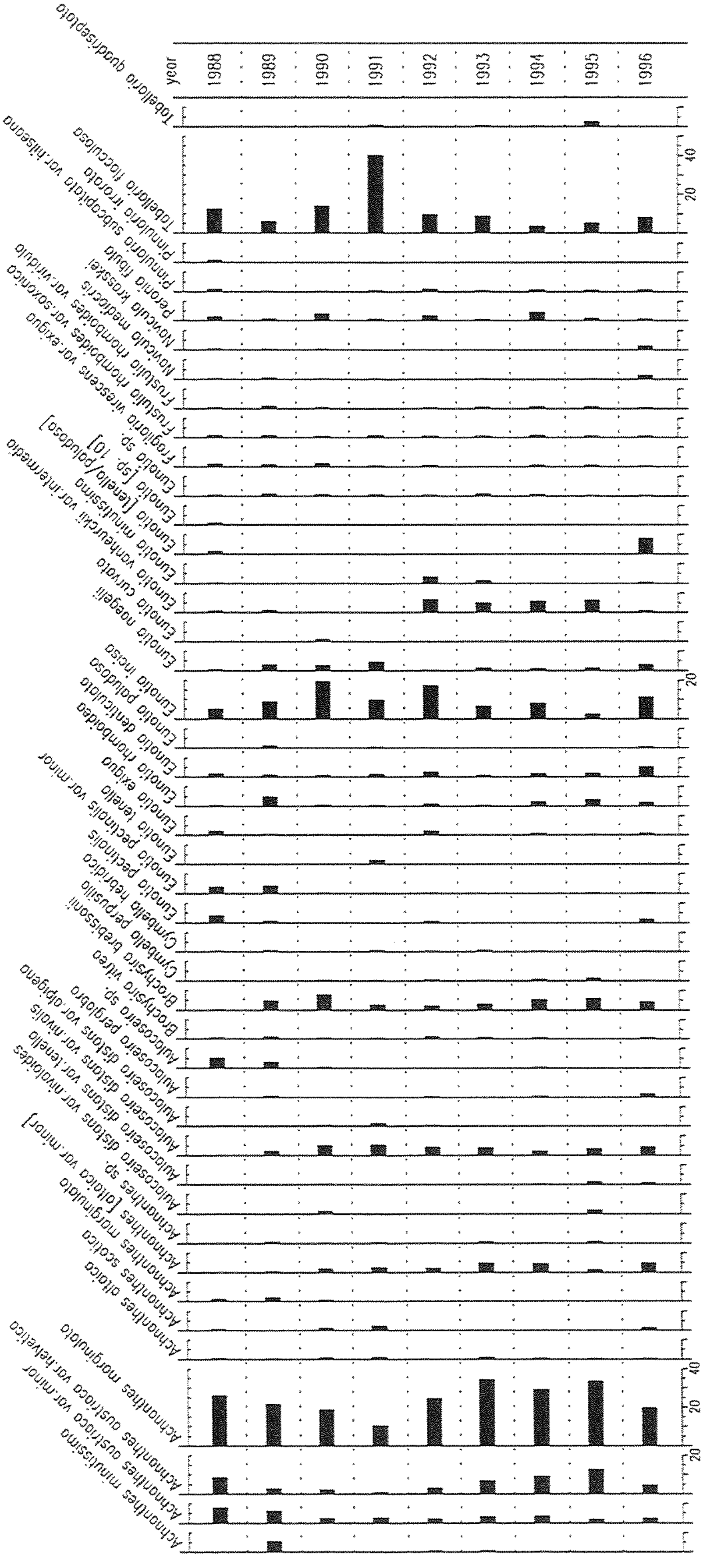


Figure 2.6. UKAWMN summary of littoral macroinvertebrate abundance (% data) 1988 - 1996

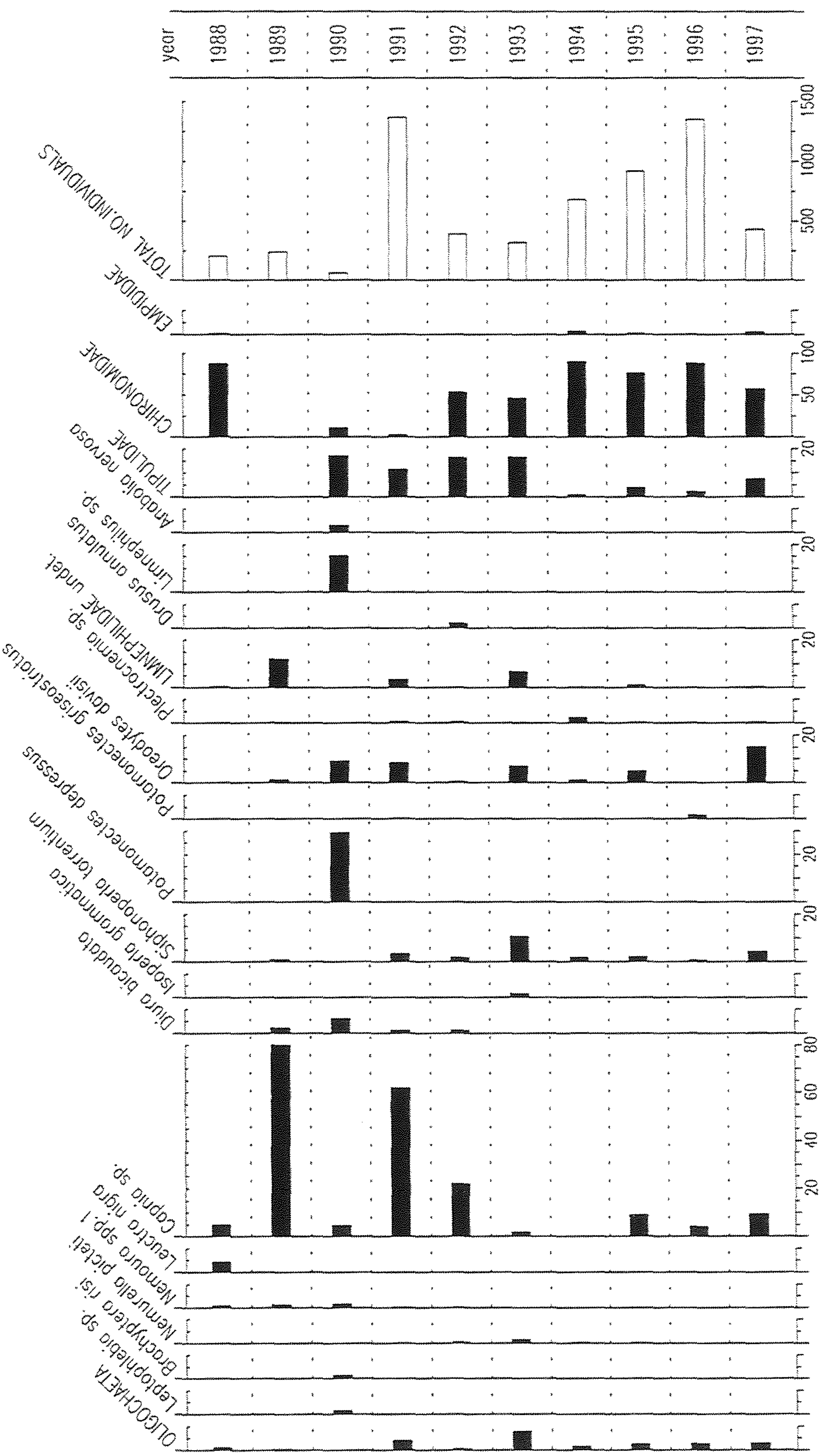
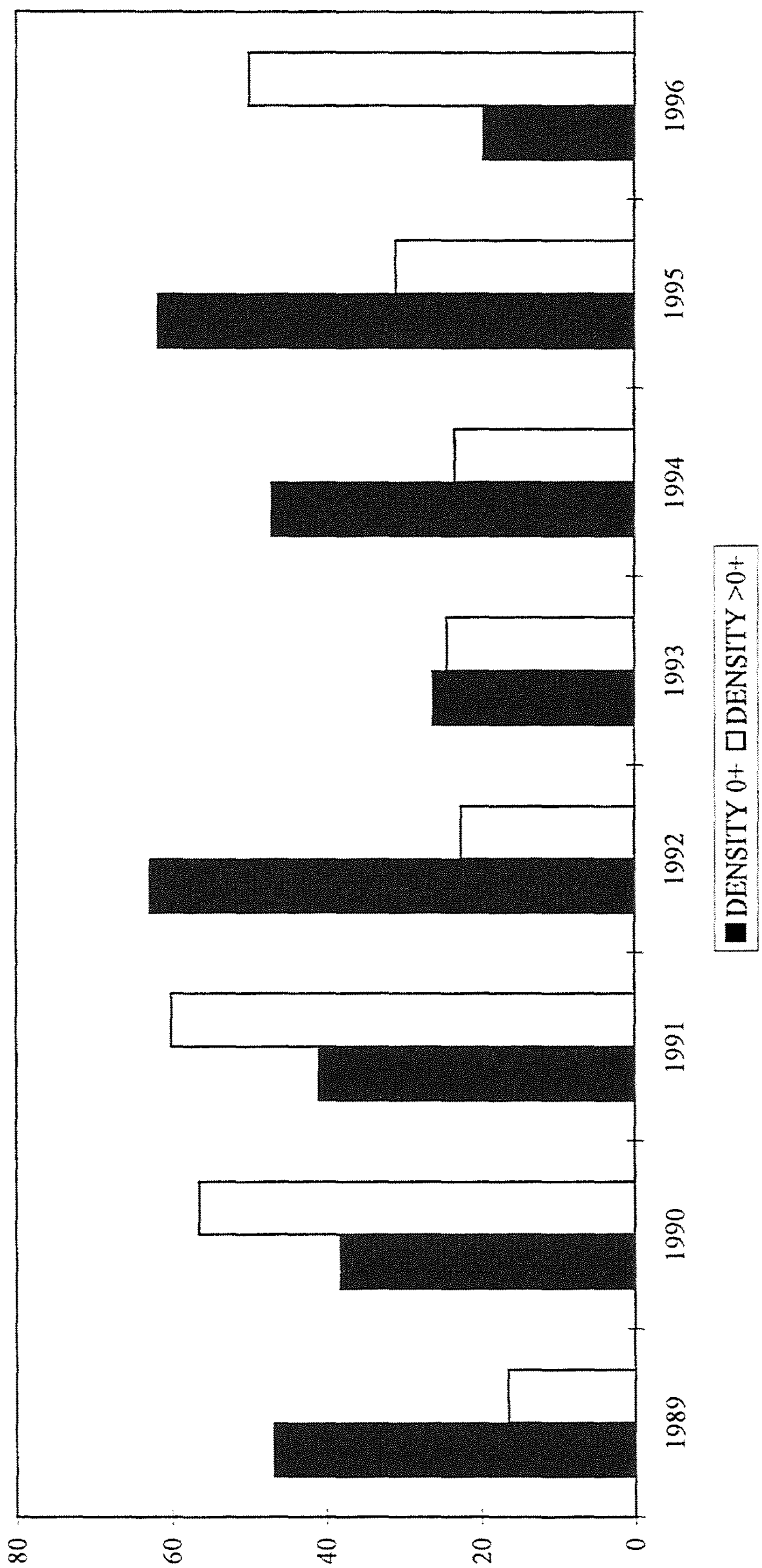


Figure 2.7. UKAWMN summary of mean trout density in the Lochnagar outflow burn 1989 -1996. (Units are numbers 100 m^{-2}). (0+ = New recruits; >0+ = trout > 1 year old).



3. EU funded mountain lakes research programmes

The AL:PE (Acidification of Mountain Lakes: Palaeolimnology and Ecology) projects (Parts I & II), funded by the EU, ran from 1991 - 1993 and 1993 - 1995 respectively and represented the first comprehensive study of remote mountain lakes at a European scale. The AL:PE projects emphasised that remote mountain lake ecosystems throughout the arctic and alpine regions of Europe, despite their remoteness, are threatened by acid deposition, toxic air pollutants and climate change. Whilst these studies were concerned primarily with the lakes themselves, the results of the study have much greater significance as these lake ecosystems, together with their sediment records act as environmental sensors for the wider environment. The AL:PE results illustrate two main issues: (i) the importance of these remote and sensitive ecosystems as sensors of long-range transported pollutants and as providers of early warning signals for more widespread environmental change; and (ii) the importance and urgency of understanding the present and future impacts of pollutants, both singly and in combination, on aquatic ecosytems.

Although acid deposition is currently thought to be the most potent threat, disentangling the interactions between the effects of changing deposition patterns of acids, nutrients, trace metals and trace organics in the context of global climate change presents an immense scientific challenge. The AL:PE programme began to address this challenge and its successor, the current MOLAR project (Measuring and modelling the dynamic response of remote mountain lake ecosystems to environmental change: A programme of **MO**untain **LA**ke **R**esearch), is designed to tackle these issues more specifically by focusing on in-depth studies of key sites. Lochnagar has been a site in both the AL:PE and MOLAR research programmes. The data presented below aim to summarise some of the results generated from the earlier work and the ongoing monitoring activities at the loch as part of MOLAR and a linked project on metal deposition and cycling (Section 5.1).

The aims of the current MOLAR study at Lochnagar are twofold. First, to learn more about the levels of deposition of atmospheric pollutants at a remote upland area of the UK and second, to relate contemporary atmospheric depositions to pollutant sinks such as aquatic and catchment biota, lake sediments and catchment soils. In this way the relationship between atmospheric pollutant flux, lake water concentrations and biological levels can be determined and in addition, by relating contemporary atmospheric deposition to contemporary sediment levels we can learn more about past deposition of pollutants from the full sediment record.

3.1. Automatic Weather Station (AWS).

A small AWS (Delta-T Devices - WS01) was installed at Lochnagar at the end of August 1996. Air temperature, wind speed and direction, air pressure and humidity are recorded every half an hour. Rainfall is recorded every 24 hours. The AWS has been very successful with only short periods of data loss (e.g. loss of wind data due to icing of the vanes). Summary data for the first full year are presented in Table 3.1 and Figures 3.1 - 3.5. Data available from the AWS now covers the period August 1996 to March 1998.

Table 3.1. Monthly meteorological summaries for Lochnagar September 1996 - August 1997.

	Wind speed (ms^{-1})			Air Temp (°C)			Relative Humidity (%)	Air Pressure (Pa)		Rainfall	
	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	No. days	Total (mm)
Sep 96	3.28	0.01	8.76	8.29	2.12	19.15	80.95	898.6	940.8	16	89.4
Oct 96	4.60	0.30	11.49	5.65	-0.84	12.98	85.69	894.7	929.3	29	274.0
Nov 96	3.90	0.00	12.64	0.06	-5.72	11.29	82.57	871.0	929.3	12	97.0
Dec 96	3.08	0.00	10.82	-0.88	-6.58	10.81	83.87	885.0	937.0	9	36.0
Jan 97	2.34	0.00	10.21	0.07	-9.39	10.18	80.69	905.0	946.0	11	46.6
Feb 97	5.63	0.00	13.60	-0.02	-4.40	5.77	83.07	866.5	937.0	15	227.6
Mar 97	4.88	0.00	11.41	2.60	-3.49	10.02	78.80	894.7	939.5	20	166.0
Apr 97	3.45	0.00	11.09	3.22	-4.61	11.83	79.20	901.1	938.9	12	38.4
May 97	2.72	0.00	8.18	5.20	-6.49	19.60	81.10	895.4	938.2	16	196.6
Jun 97	3.10	0.06	8.95	7.03	1.22	16.17	83.07	902.4	939.5	23	213.0
Jul 97	2.84	0.08	7.80	11.53	2.42	19.44	78.04	909.4	936.3	17	123.0
Aug 97	2.77	0.04	7.19	12.67	6.59	22.29	79.48	903.7	934.4	14	91.6

Figure 3.1. Daily Rainfall for Lochnagar August 1996 - September 1997

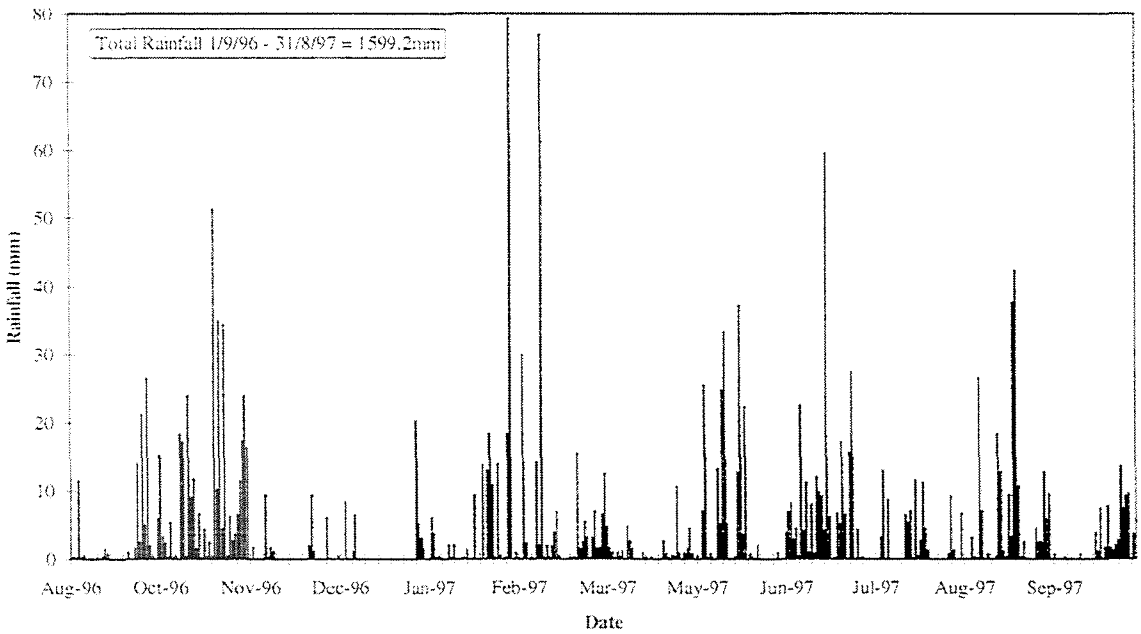


Figure 3.2. Daily mean air temperature for Lochnagar August 1996 - September 1997

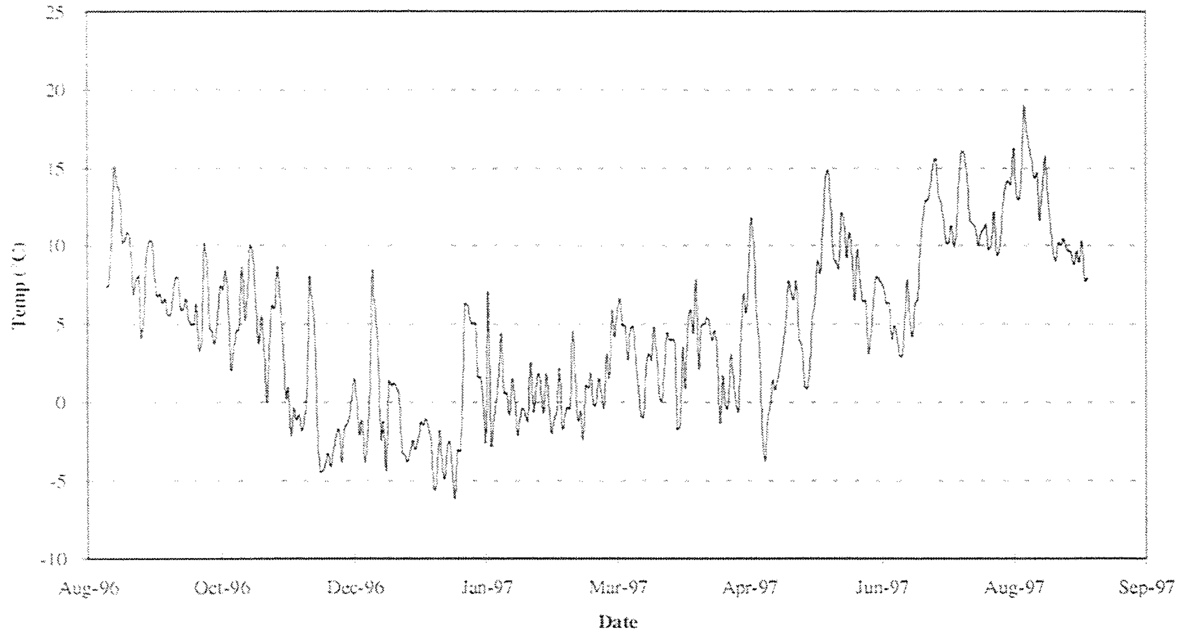


Figure 3.3. Maximum and minimum daily air temperature for Lochnagar August 1996 - September 1997

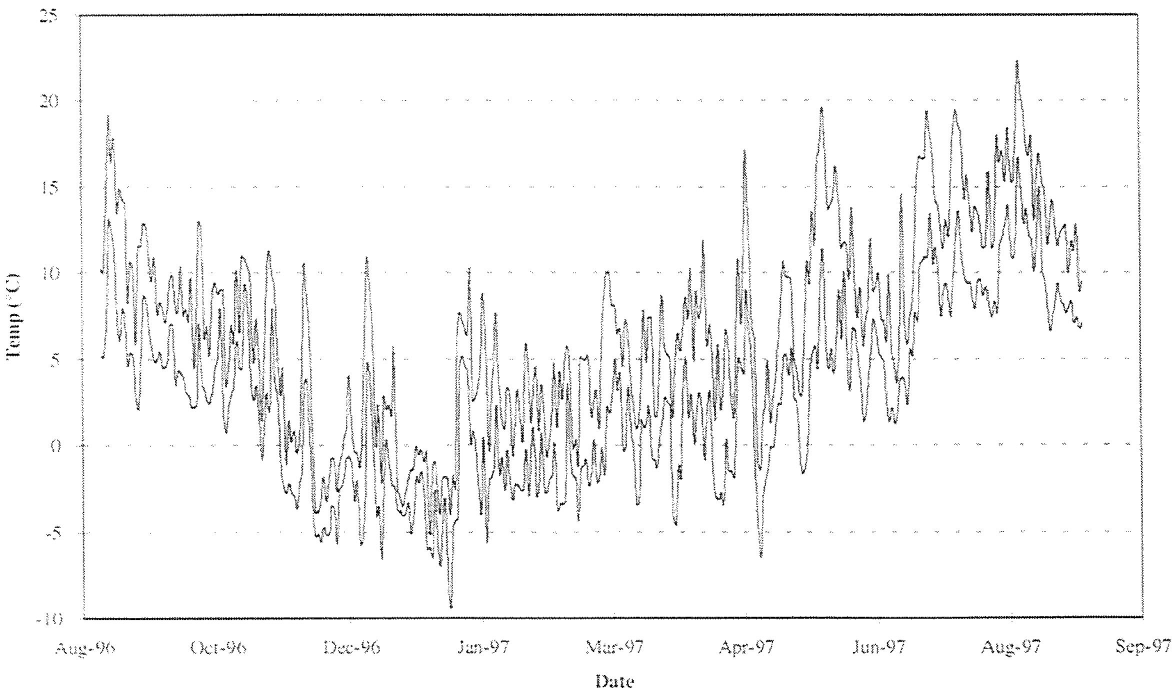


Figure 3.4. Monthly wind directions for Lochnagar September 1996 - August 1997

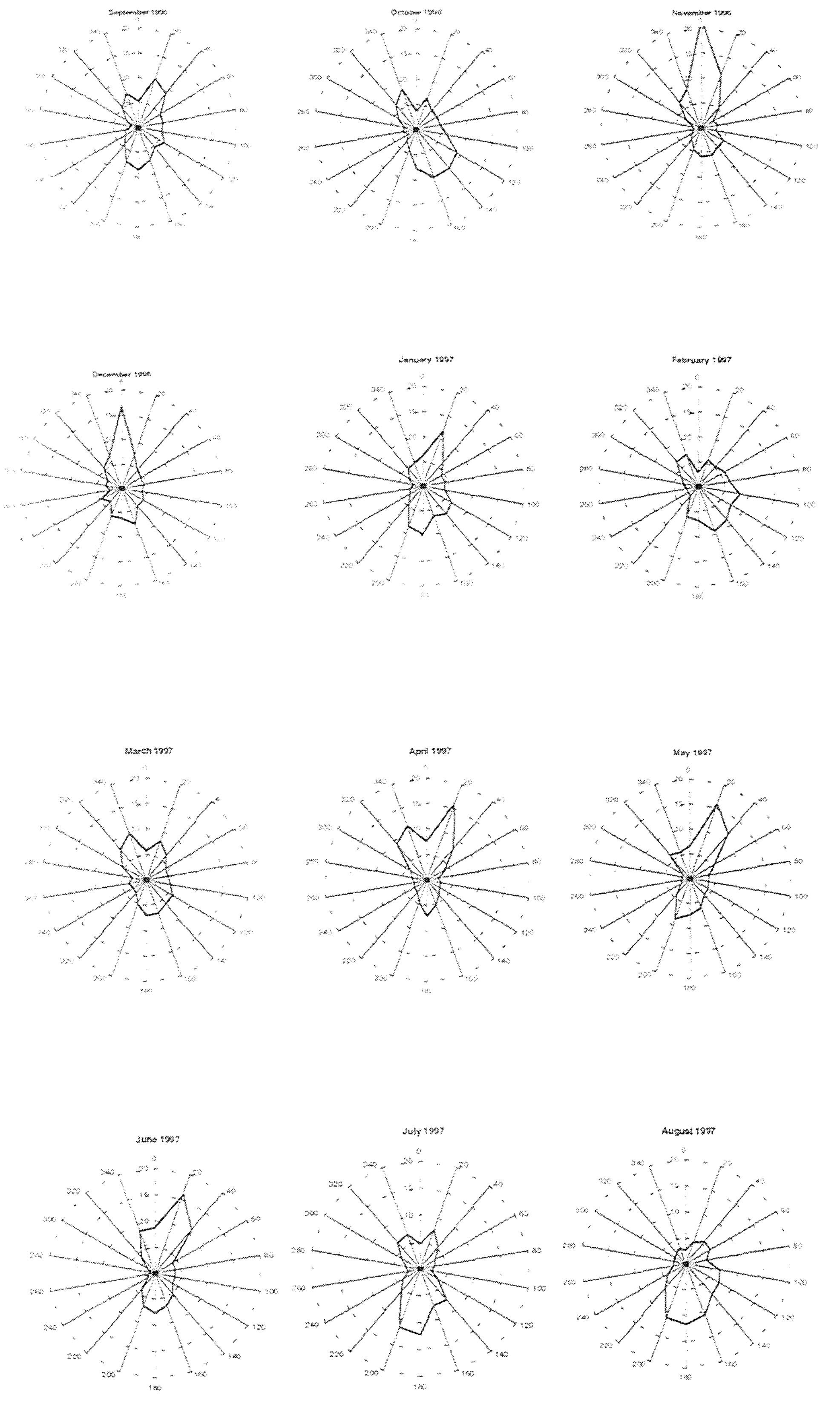
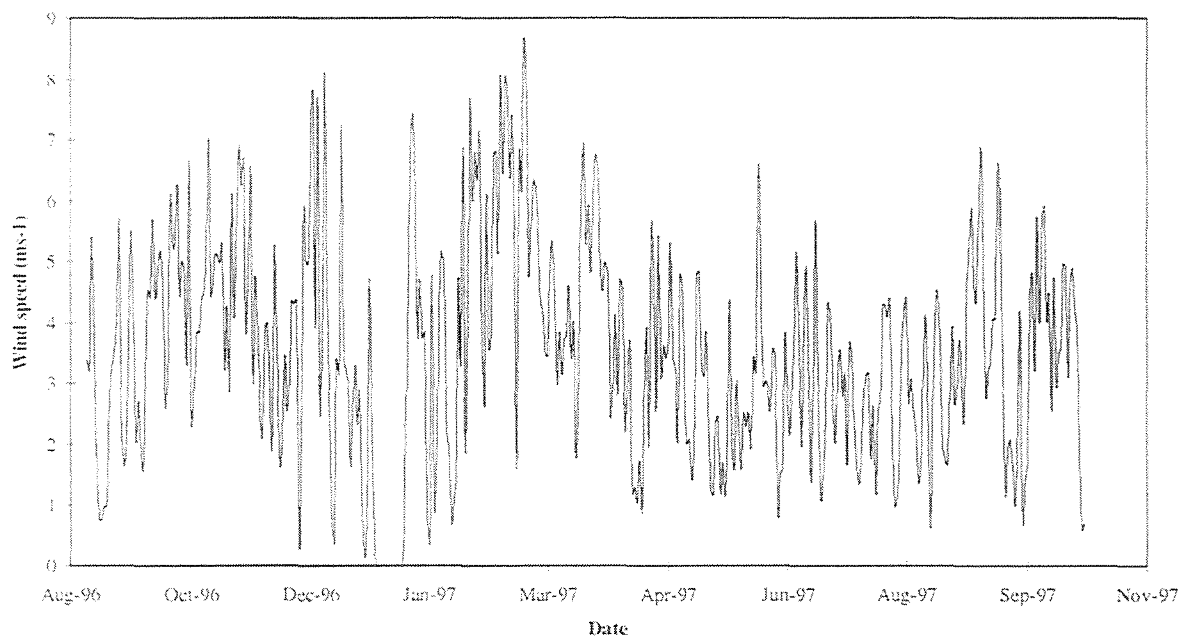


Figure 3.5. Mean daily wind speed for Lochnagar August 1996 - September 1997



3.2. Lake water temperature loggers.

Temperature loggers have been deployed at four depths in the loch (2m, 3m, 5m and 7m) since October 1996. Data retrieval has been reliable and trends show good agreement with air temperature measurements made by the AWS. Water temperatures are generally seen to change in a series of small steps following periods of significant increase or decrease in air temperature. For example, the increase in temperature shown for Spring 1997 in Figure 3.6. The loggers demonstrate the thermal inertia of the water body with all depths showing attenuated responses to changes in air temperature whilst the deeper loggers are both slower to increase in temperature after the winter and slower to cool at the end of the summer (Figure 3.7).

3.3. Bulk Deposition

Two bulk deposition collectors have been installed at Lochnagar, close to the AWS, since August 1996 and are emptied weekly in the summer and fortnightly in the winter. Samples from one collector are analysed for major ion chemistry (pH, conductivity, NH_4^+, Ca^{2+}, Mg^{2+}, Na^+, K^+, SO_4^{2-}, NO_3^- and Cl^-) at the SOAFD Freshwaters Laboratory in Pitlochry whilst further sub-samples are filtered and sent to the ECRC for SCP analyses. The second collector is sampled and analysed for trace metals (including: Cu, Ni, Zn, Pb, Hg, As, Cd, V and Co) by ICP-MS (Inductively Coupled Plasma-Mass Spectroscopy) at UCL. Despite detection limits being low for ICP-MS, trace metal concentrations in bulk deposition are often below them. However, the results of the other analyses emphasise the episodicity of deposition at the site and examples are given in Figure 3.8 and 3.9.

Figure 3.6. Daily mean air and surface water temperature at Lochnagar, Spring 1997.

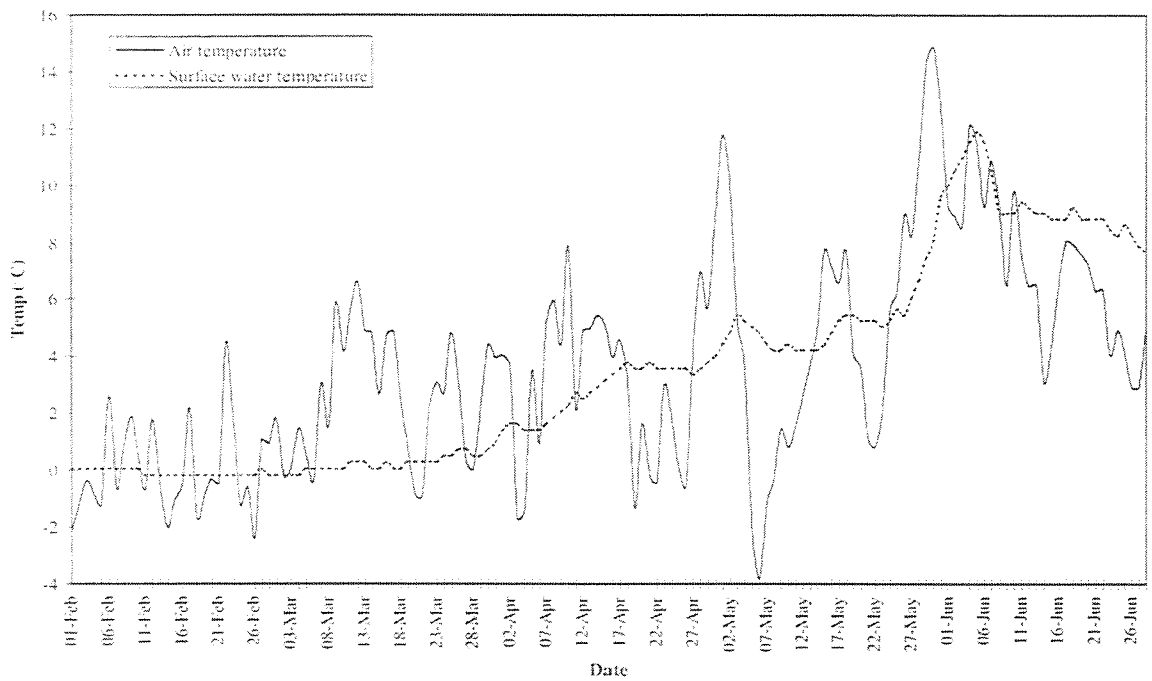
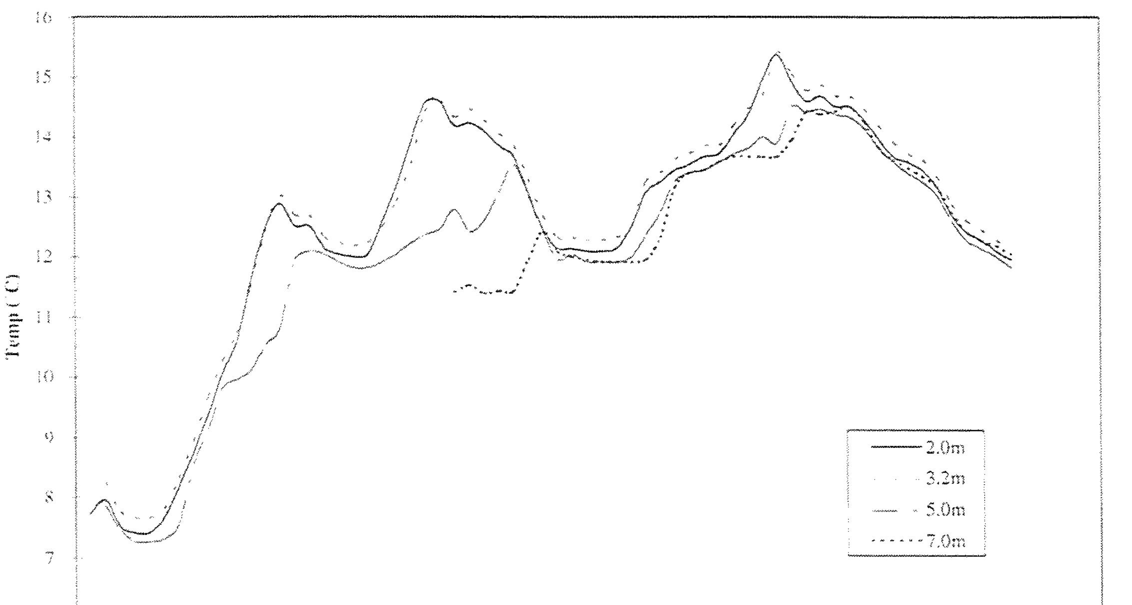


Figure 3.7. Water temperature at 2m 3.2m, 5m and 7m for Lochnagar 29th June - 31st August 1997.



3.3.1. Mercury deposition

In addition, since September 1997, a separate Hg deposition collector has been installed at the site. These samples are analysed by cold vapour-atomic fluorescence spectroscopy (CV-AFS) which has a lower detection limit than ICP-MS. This is done at the Norwegian Institute for Air Research (NILU). The first data are now available and show levels of Hg in deposition in the order of 20 - 40 ng l^{-1}. Very little Hg deposition data are available for the UK and so these data are especially valuable.

3.4. Lake water chemistry

Lake water major ion chemistry has been undertaken quarterly since 1988 as part of the UKAWMN (see Section 2). However, since August 1996 water samples have been taken more regularly as part of the MOLAR programme, weekly during the summer and fortnightly during the winter. These samples have been analysed for many of the same ions as the bulk deposition, for example, pH, conductivity, NH_4^+, Ca^{2+}, Mg^{2+}, Na^+, K^+, SO_4^{2-}, NO_3^- and Cl^-. In addition, the water samples are analysed for alkalinity, total nitrogen, total phosphorus, total organic carbon, various aluminium species (total monomeric, non-labile and labile) and silica. These analyses are undertaken at SOAFD in Pitlochry. Data from some of the analyses are available over longer time periods than others, but selected species are shown in Figure 3.10. In addition, the regular lake water samples are analysed for a range of trace metals including Cd, Pb, Cu, Co, Zn, Cr, Ni, Mn, V, As and Hg. These data are summarised in Table 3.2.

Lake water is also filtered in order to determine the level of suspended solids and to determine the concentration of fly-ash particles in the water column.

Table 3.2. Trace metals in lake waters at Lochnagar.

Date	Cd µg l^{-1}	Pb µg l^{-1}	Cu µg l^{-1}	Co µg l^{-1}	Zn µg l^{-1}	Cr µg l^{-1}	Ni µg l^{-1}	Mn µg l^{-1}	V µg l^{-1}	As µg l^{-1}	Hg ng l^{-1}
7/11/96	0.071	0.65	<0.1	0.11	5.6	<0.5	<0.2	11.3	<0.2	<0.1	1.4
30/11/96	<0.04	0.62	0.20	0.08	2.4	<0.15	0.21	*	<0.2	*	*
11/12/96	<0.04	1.08	0.46	0.07	2.3	11.74	0.21	*	2.95	*	*
28/12/96	<0.04	0.68	0.20	0.07	2.3	<0.15	0.20	*	<0.2	*	*
5/2/97	<0.04	0.74	0.27	0.07	2.4	<0.15	0.19	*	<0.2	*	*
26/2/97	<0.04	0.83	0.18	0.06	2.6	<0.15	0.22	*	<0.2	*	*
9/3/97	0.033	0.47	<0.1	0.08	4.6	<0.5	0.20	7.6	<0.2	0.1	<1.0
19/3/97	<0.04	1.19	1.40	0.06	2.6	<0.15	0.21	*	<0.2	*	*
2/4/97	<0.04	0.51	<0.02	0.05	1.9	<0.15	0.14	*	<0.2	*	*
16/4/97	<0.04	1.18	2.02	0.11	3.6	2.73	0.30	*	<0.2	*	*
30/4/97	0.047	0.44	<0.1	0.07	3.2	<0.5	<0.2	6.4	<0.2	0.1	<1.0
5/9/97					data not yet available						1.6
21/10/97					data not yet available						12.5
19/11/97					data not yet available						16.3

* parameter not measured.

Figure 3.8. pH, conductivity, NH_4^+, Ca^{2+}, Mg^{2+}, Na^+, K^+, SO_4^{2-}, NO_3^- and Cl^- concentrations of bulk deposition samples collected at Lochnagar between August 1996 and January 1998.

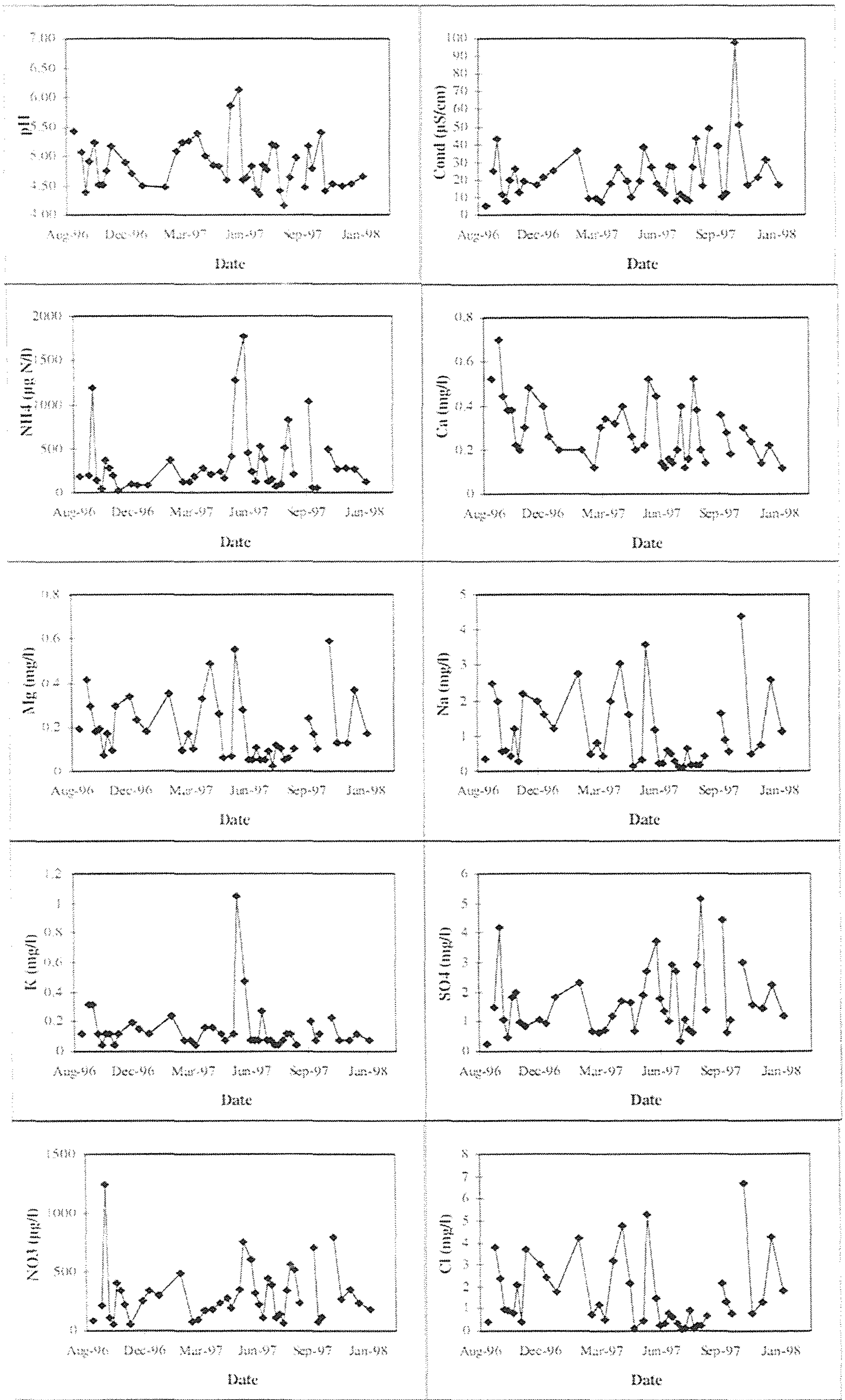


Figure 3.9. SCP, Zn, Cu and Pb concentrations in bulk deposition samples from Lochnagar. * denotes below detection limit. Metals data after April 1997 currently unavailable.

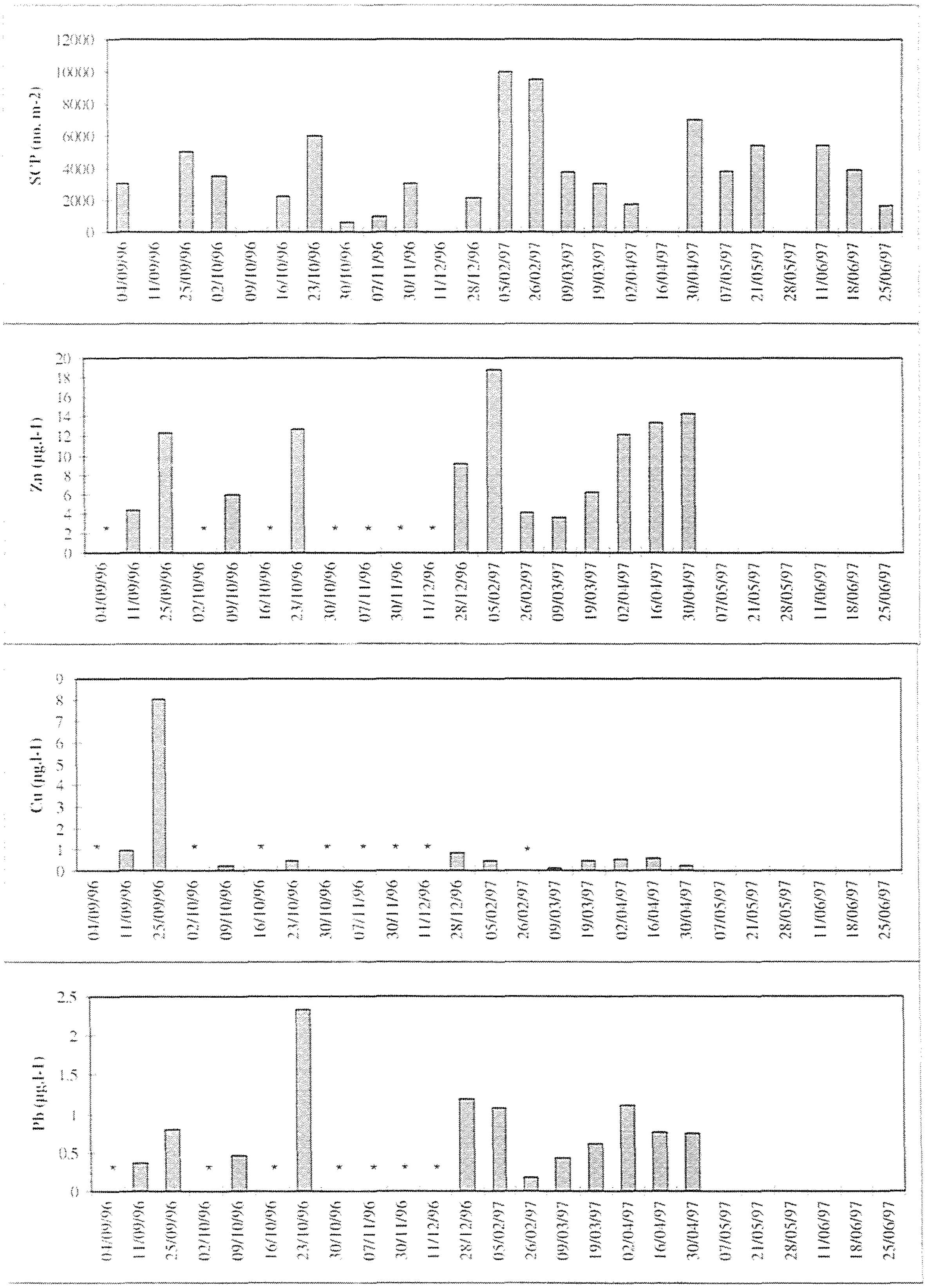
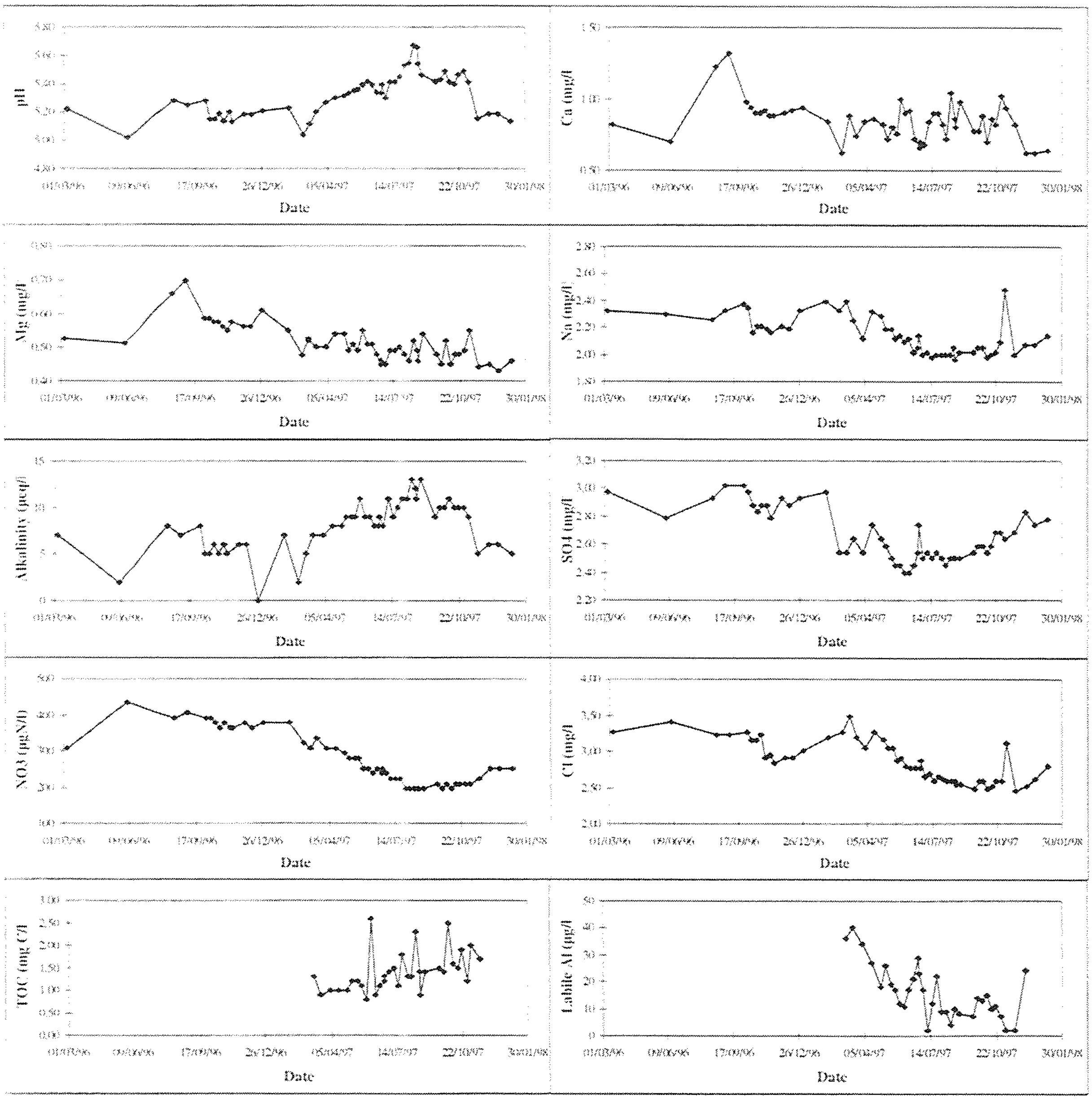


Figure 3.10. Selected water chemistry data for Lochnagar. March 1996 - January 1998



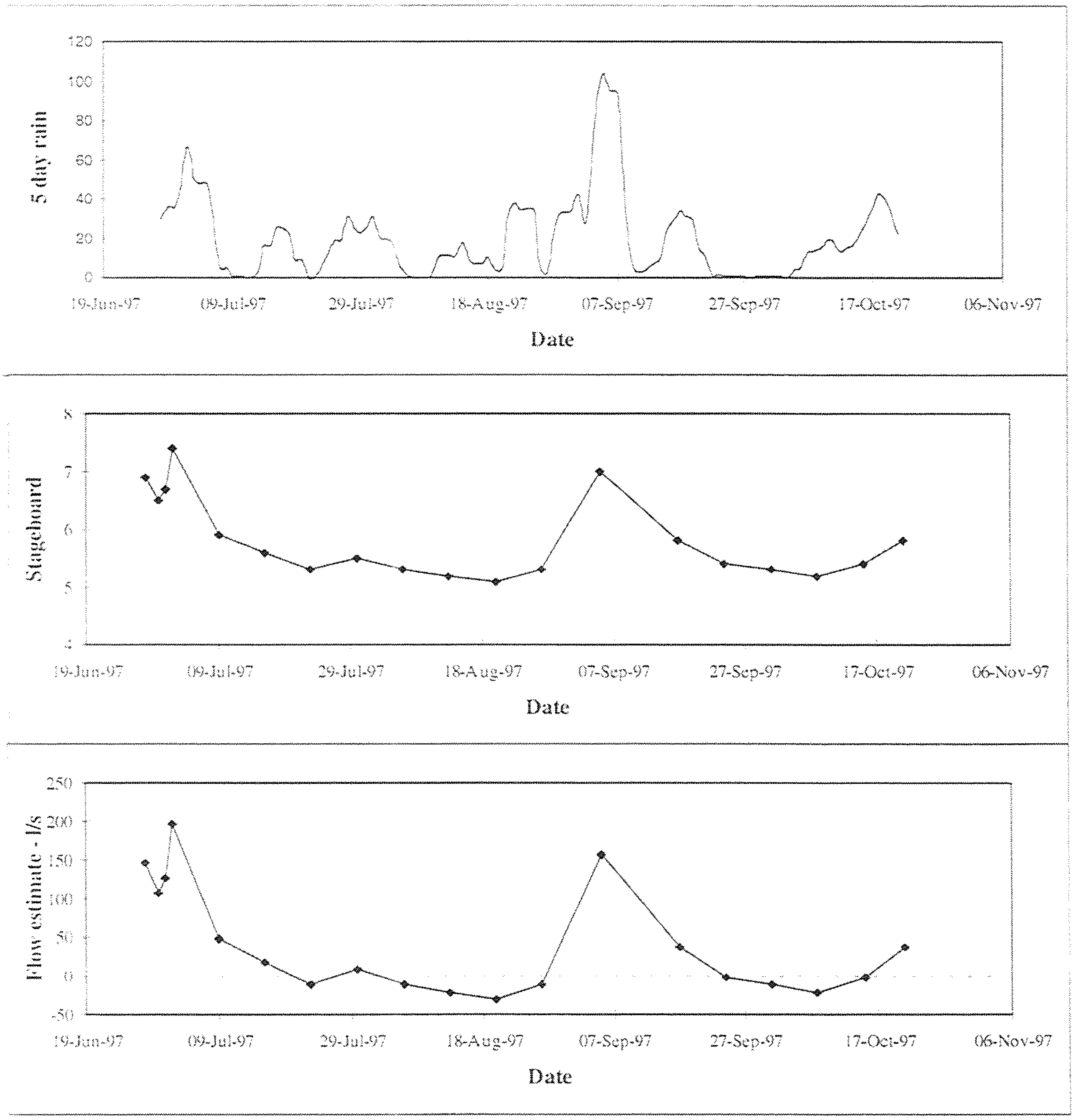
3.5. *Outflow measurements*

For pollutant budget studies like these being undertaken at Lochnagar it is important that the quantities of pollutants leaving the system are recorded. In order to do this, two measurements are required. Concentrations of the pollutants in the outflow and an estimate of outflow stream volume.

The first of these has been covered in Section 3.4, as the lake water samples are taken from the lake area adjacent to the outflow. The second is more difficult. Ideally, a calibrated V-notch weir is constructed in order to measure flow accurately but this is neither practical or desirable at Lochnagar. Instead, a stageboard has been installed at the outflow near to the lake and readings are taken upon every site visit. As flow, and water height varies, the stageboard is being calibrated using a dilution gauging technique. In this way an estimate can be made of water volume leaving the lake via the outflow stream. This is, of course, only an approximation as flow may vary greatly between readings, but currently it is the best available approach.

Water volume leaving the lake is related to rainfall and stageboard readings converted to flow (in litres per second) can be seen to correlate well with rainfall measurements. The best correlation is seen with the total rainfall from the previous five days ($r^2 = 0.73$, $n = 17$) and it is possible that after further calibration this daily measurement might allow a better estimate of flow. Figure 3.11 shows a comparison between the two approaches illustrating that although there is broad agreement the stageboard readings are comparatively coarse. Figure 3.11 also shows the estimate of flow from the stageboard. Further calibration is required especially at low flows as the current calibration does not yet cover the full range of readings giving negative results at the lower stageboard levels.

Figure 3.11. Comparison between 5 day rainfall and outflow stageboard reading at Lochnagar, and calculated flow from the latter.



3.6. Lake sediments

One of the main aims of these studies on pollutants (see also Section 4) in the various lake and catchment compartments is to gain a better understanding of the relationship between atmospheric deposition and the lake sediment record. In this way, and by using the sediment archive, it is hoped to get a more quantitative insight into historical atmospheric deposition at the site.

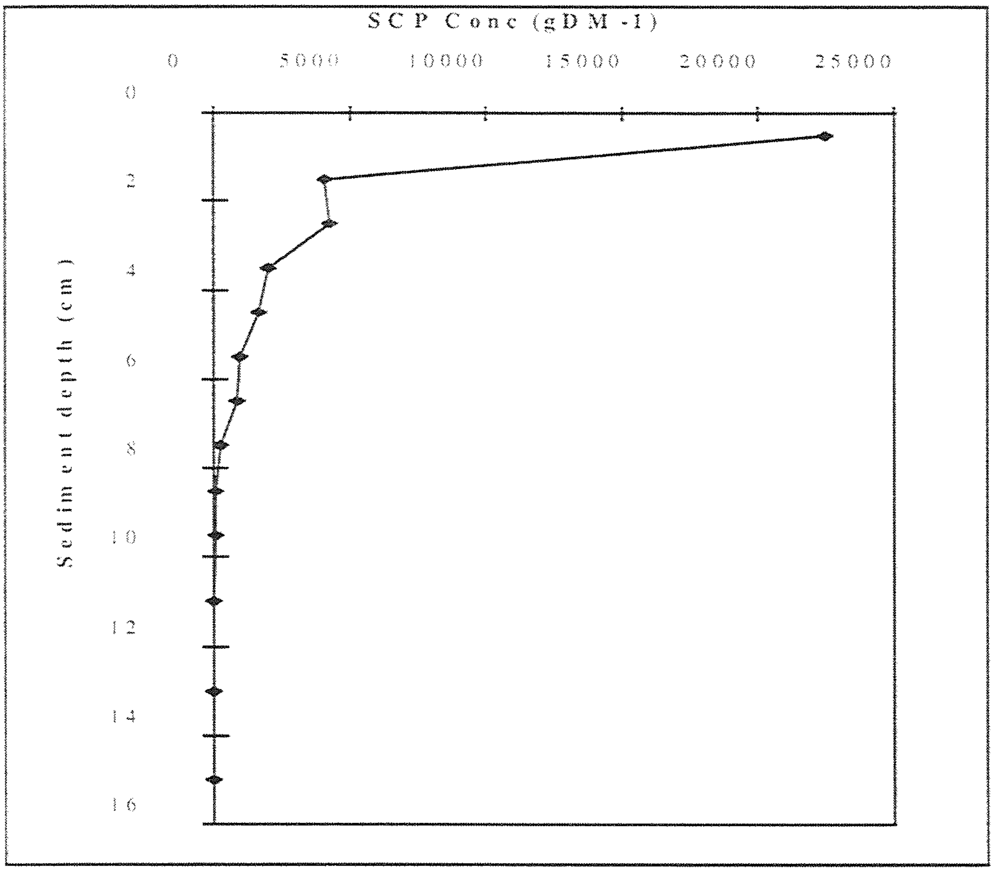
Sediment cores have been taken on several occasions at Lochnagar and a full sediment survey has now been carried out in order to obtain a full basin pollution inventory (see Section 5.1). However, other studies have concentrated on the historical trends in the record using a single core from the deepest water area. The sediment in Lochnagar is interspersed with large boulders towards the lake margins and the littoral area has little sediment accumulation. The estimated sediment area is shown in Figure 5.1. The main deep water area of the lake basin has a good depth of organic sediment covering the full post-Industrial period although the full extent is currently unknown. In this area the sediment record of depositing pollutants (metals, SCP) is seen to be relatively consistent confirming its integrity. As part of the AL:PE and MOLAR projects sediment cores were analysed for SCP and dated using radiometric (^{210}Pb, ^{137}Cs etc.) chronologies. SCPs are only produced by the high temperature combustion of fossil-fuels and the lake sediment provides an unambiguous record of atmospheric deposition from this source. The profile in Figure 2.1. is typical of that found in Scottish lochs (Rose *et al.*, 1995). The record begins in the mid-nineteenth century and concentrations increase slowly up to the 1950s when there is a rapid increase due to the post-War boom in the electricity generating industry. A peak is reached in the late 1970s followed by a decline to the sediment surface. This decrease is due to the introduction and increased use in flue-gas particle arrestor technology and, in Scotland in particular, the decline in heavy industry. As part of earlier projects cores were also analysed for metals (Pb and Zn) and the results of these are given in Jones *et al.* (1993) and Battarbee *et al.* (1995). A more recent sediment metals study is outlined in Section 5.

3.7. Soil cores

Just as it is important for ecosystem studies to determine how much of a deposited pollutant is leaving the system via the outflow (Section 3.5) so it is also important to determine how much is stored in the catchment. This provides a catchment inventory, i.e. that which has been deposited but has not impacted the lake. More importantly perhaps, it also determines the amount of pollutant which, given a change of environmental conditions, is available to be released directly into the lake and could therefore be considered a significant potential source.

An estimated 40% of the Lochnagar catchment has some degree of soil cover although this varies in thickness from very thin to more than a metre of peat nearer the loch shores, particularly on the eastern side where, in places, it is significantly eroded. As part of the MOLAR programme, SCP concentrations were determined in a soil core taken from this eastern area and the concentrations were seen to be reasonably high with a peak at the surface (Figure 3.12). Currently, it is uncertain how this represents a historical record of deposition, although the surface maximum and the shorter profile suggests a slower accumulation than the lake sediment record. A further study, where a small number of soil cores were taken from representative areas of the catchment in order to determine variability in storage and to gain a better estimate of the catchment inventory, is being undertaken at present. This work is mainly concerned with trace metals and is described further in Section 5. SCPs will also be analysed from these cores.

Figure 3.12. SCP profile from Lochnagar soil core



4. Critical loads of acid deposition

Lochnagar is included within the Critical Loads Advisory Group (CLAG) national mapping dataset for critical loads. It was selected to represent the most sensitive lake site to acid deposition in the 10km square of the OS national grid in which it is located. Under the CLAG mapping programme, critical loads of acid deposition are calculated for c. 1500 lake and stream sites on the basis of a one-off water sample from each site, and exceedances are calculated with nationally modelled deposition and runoff data. In the case of Lochnagar, a water sample from March 1994 was used, assuming that it would be representative of volume-weighted annual mean chemistry at the site. Modelled runoff was obtained by using a digitized catchment outline overlain onto the national 1km runoff database at the Institute of Hydrology, Wallingford, to weight by catchment area. Runoff data are based on annual mean values over the period 1992-1994. National total nitrogen and non-marine sulphur deposition data were obtained for the same period from the 20km grid dataset modelled by the Institute of Terrestrial Ecology, Penicuik.

Critical loads and exceedances were calculated using two steady-state models used in national mapping programmes throughout Europe, the steady-state water chemistry (SSWC) model and the first-order acidity balance (FAB) model. The SSWC and FAB models employ certain assumptions and empirical relationships to determine the pre-industrial weathering supply of base cations to a water body providing buffering against acidification. The models calculate the load of acid deposition which will result in some pre-defined chemical condition in the water over the long term. Acid neutralizing capacity (ANC) is selected as the critical chemical parameter, and a critical ANC concentration of 0 $\mu eq l^{-1}$ is used, corresponding with a 50% probability of damage to brown trout populations according to studies in Norway. If the deposition load exceeds the critical load, this means that the buffering against acidification provided by weathering cannot maintain ANC concentrations above the selected critical value.

The steep, rocky nature of the Lochnagar catchment, along with sensitive geology and sparsity of soils, make it a vulnerable site to the adverse effects of acid deposition. This sensitivity to acidification is reflected in low critical loads. According to the SSWC model, the critical load for total acidity was just exceeded in 1994 by 0.02 keq ha^{-1} yr^{-1}, and this was borne out by the water chemistry, indicating an ANC value close to zero. The process-based FAB model, which can predict the likely impact of nitrogen deposition in the future, indicates a slightly greater exceedance than the SSWC model of 0.17 keq ha^{-1} yr^{-1}, due to anticipated increases in nitrate leaching as N saturation occurs within catchment soils. According to FAB, Lochnagar could be protected from acidification by reducing either sulphur or nitrogen deposition, i.e. the critical load is only exceeded by both acid species acting together.

For the national critical loads mapping work, critical load calculations have to be based on a very limited amount of water chemistry data because of the great number of sites studied, and it is assumed that one water sample taken at the appropriate time of year represents mean conditions. The critical load exceedances described above are based on one such sample. however, for Lochnagar much higher quality data are available now due to the long-term monitoring under the UKAWMN and the intensive monitoring under the MOLAR programme. These temporal data will provide much better estimates of the fluxes of acidity from the catchment in the stream outflow from Lochnagar. In addition, bulk deposition chemistry has been measured, which will provide much more reliable estimates of acid input fluxes to the catchment than can be obtained from national datasets modelled at 20km square resolution. It will thus be possible to derive much more reliable critical load values for the site, and also to determine the acidification damage through critical load exceedance with more confidence.

Ongoing work at Lochnagar includes a comparison of steady-state model outputs using the high-quality dataset collected there with much more detailed analysis through the application of the dynamic model MAGIC. While dynamic modelling requires a much greater input of data than the steady-state models, these data will soon be available for Lochnagar and will provide a picture of the response of the lake through time, both past and future, to acid deposition. Such modelling has great relevance in predicting the impact of increasingly important nitrogen deposition on the prospects of acid sensitive sites for chemical and biological recovery as sulphur deposition continues to decline nationally.

5. Trace metals and persistent organic pollutants

5.1. Trace metal budget studies

In the UK there have been few studies on trends in trace metal deposition, notable exceptions being the work of Peter Cawse and Steve Baker (AEA Technology) at a rural / semi-rural network (1970s - present) and a network of three sites on the east coast of the UK to determine atmospheric inputs to the North Sea. Monitoring of trace metal concentrations in freshwaters over a significant period of time is also severely limited. Regular monitoring of trace metal deposition and freshwater concentrations in upland UK is almost non-existent and therefore the monitoring at Lochnagar described in Sections 3.3 and 3.4 assume a much greater importance. This is especially so as the UNECE Convention on Long-Range Transboundary Air Pollution (LRTAP) has recently highlighted the need for better mapping of trace metal concentrations in surface waters and sediments in Europe.

The impact on freshwater and terrestrial ecosystems by trace metals deposited from the atmosphere has recently assumed a much higher political profile as the UNECE LRTAP has started to look into the development of a critical loads and effects based approach for the reduction of these pollutants. At Bad Harzburg in November 1997, it was decided by the '*Workshop on critical limits and effect based approaches for heavy metals and persistent organic pollutants*' that the UNECE would adopt an effects based critical loads approach for the deposition of Pb, Cd, possibly Hg, and other metals proposed for subsequent addition. However, there is currently some debate as to the best way of defining critical loads for metals in freshwater systems.

The idea of developing an effects based approach for the reduction of metal emissions is complicated as it is unlikely that concentrations in natural freshwaters will reach levels likely to impact aquatic organisms although there are published instances of this (e.g. Neal *et al.*, 1996). However, it is currently unclear whether long-term exposure to lower levels of trace metals, with subsequent bioaccumulation, is more or less damaging to populations of aquatic organisms than individual pulses of higher concentrations.

The lake sediment record allows historical trends in trace metal deposition to be identified, and a 'sediment based critical load' might therefore be defined as the point at which sediment metal concentrations first exceed a background metal concentration.

If undisturbed, the sediment record provides a reliable archive of temporal trends in metal deposition, but it is not certain how sediment concentrations quantitatively relate to atmospheric metal deposition and by implication atmospheric emissions. This is fundamental if a sediment based critical load is to be developed. In order that such an approach can be adopted for freshwaters further knowledge is required on how trace metals atmospherically deposited to a lake and its catchment are either stored or move through ecological pathways. Little is known about the quantities of metals atmospherically deposited at remote locations in the UK and how these effect the metal contents of catchment and lake flora and fauna (i.e. whether ecologically important concentrations are attained).

At Lochnagar, a PhD student, Handong Yang is attempting to answer this question by undertaking an intensive study on the movement of trace metals into and out of the catchment. In particular, this study concentrates on the metals Hg, Cd, Pb, Cu and Zn. Understanding in depth the metal cycling at a site where trace metal input is almost exclusively atmospheric, and where there has been no catchment disturbance, is fundamental if a critical loads model for metals is to be developed and applied more broadly across the UK.

In addition to the deposition and water monitoring of trace metals already outlined in Section 3.3 and 3.4, this study involves the determination of the trace metal content of all lake and catchment biological and physical compartments. Therefore, sampling of catchment vegetation, aquatic macrophytes, zooplankton, freshwater algae and sediment trap material have been undertaken in addition to a number of lake sediment (Figure 5.1) and catchment soil cores to estimate total metal storage and retention. In this way it is hoped that trace metals in deposition can be related to sediment levels more quantitatively so that the sediment record can then be interpreted as a record of atmospheric flux. Examples of sediment and soil analyses are given in Figures 5.1 and 5.2.

The regular analysis of trace metals in deposition will also allow episodicity to be determined. This, combined with the automatic weather station data, should allow information to be derived on the major directions of transport for depositing pollutants. Back-trajectory work will enable possible sources to be identified. This work has been ongoing since August 1996 and so the time-series is currently relatively short. However, the dataset is already valuable, not least because of the lack of monitoring at similar locations in the UK, and the longer this work can be maintained the more important it will become.

5.2. Metals and persistent organic pollutants in fish.

Annual monitoring of brown trout (*Salmo trutta*) populations in the Lochnagar outflow stream is undertaken as part of the UKAWMN by scientists at the Scottish Office, Agriculture, Fisheries and Environment Department (SOAFD) laboratory in Pitlochry. These data are presented in Section 2. In July 1993, as part of the AL:PE programme (Section 3) ten fish, were sent for analysis, five for trace metals and five for persistent organics.

In the 2-4 year old fish, weighing from 41 - 296g, the Cd and Pb in liver ranged from 1.33 - 2.58 and 0.52 - 0.77 $\mu g\ g^{-1}$ wet weight respectively. Hg in muscle ranged from 0.04 - 0.08 $\mu g\ g^{-1}$ wet weight. In comparison with brown trout analyses from reference sites in mid-Norway, these concentrations were high. Geographical distributions of metals in fish are quite pronounced in these upland lakes with higher concentrations found in western areas close to the Atlantic Ocean. The trace metal concentrations in brown trout from Lochnagar were higher than expected for its location.

Concentrations of HCB (hexachlorobenzene), HCH (hexachlorocyclohexane), DDT and PCBs (polychlorinated biphenyls) were analysed in fish with weights between 108 and 211g. Concentrations of total PCBs were found to be between 2.01 and 5.77 (mean 3.48 $\pm$ 1.84) $\mu g\ kg^{-1}$ wet weight and between 134.8 and 289 (mean 187 $\pm$ 82) $\mu g\ kg^{-1}$ lipid weight. PCBs represented the most abundant organic compounds and concentrations of total DDTs were low, amongst the lowest of the AL:PE mountain lake dataset (including sites from Norway, the French and Italian Alps, the Polish and Slovakian Tatras, Pyrenees and Sierra Nevada).

5.3. Historical trends in toxaphene.

Toxaphene is a complex mixture of hundreds (and possibly thousands) of polychlorinated compounds and isomers. It is variously reported as having been used as an insecticide, pesticide and piscicide and is semivolatile, hydrophobic and extremely persistent. Although heavily used between the mid-1960s and mid-1970s it is completely banned in certain areas of the world. Because of the complex nature of the compound, toxaphene data are usually reported as total values although some workers have attempted to study major components of the whole.

Although temporal trends in toxaphene from lake sediment core analyses has now been undertaken in a number of locations, including the Canadian Arctic, there are currently no data for the UK. A sediment core taken from Lochnagar in 1997 is being analysed for toxaphene and it is hoped that the results will soon be available. This will provide the first sediment measurements of toxaphene in the UK, the first historical record and will provide valuable information on the distribution of this harmful compound to remote areas.

Figure 5.1 Locations of sediment cores taken from Lochnagar to determine the total sediment storage of metals and SCPs.

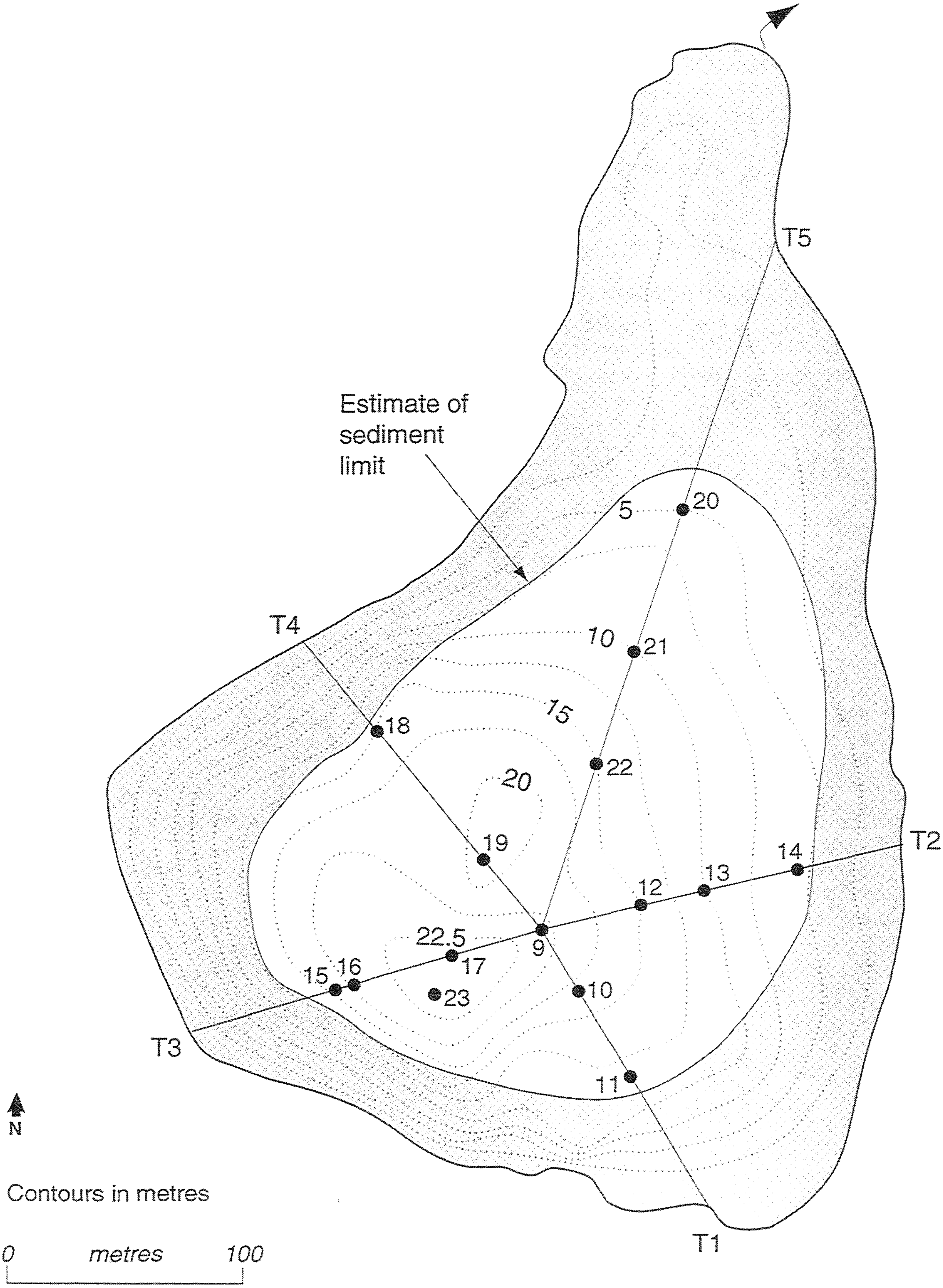


Figure 5.2. XRF analyses of a lake sediment core from Lochnagar.

Units for Si, Al, Ti, Ca, K, Fe, Mn, S, are mg g^{-1}; for Cu, Pb, Zn, Br, Zr, Rb, Sr, and Cl, µg g^{-1}; and for LOI, parts per thousand. The vertical axis is sediment depth in cm.

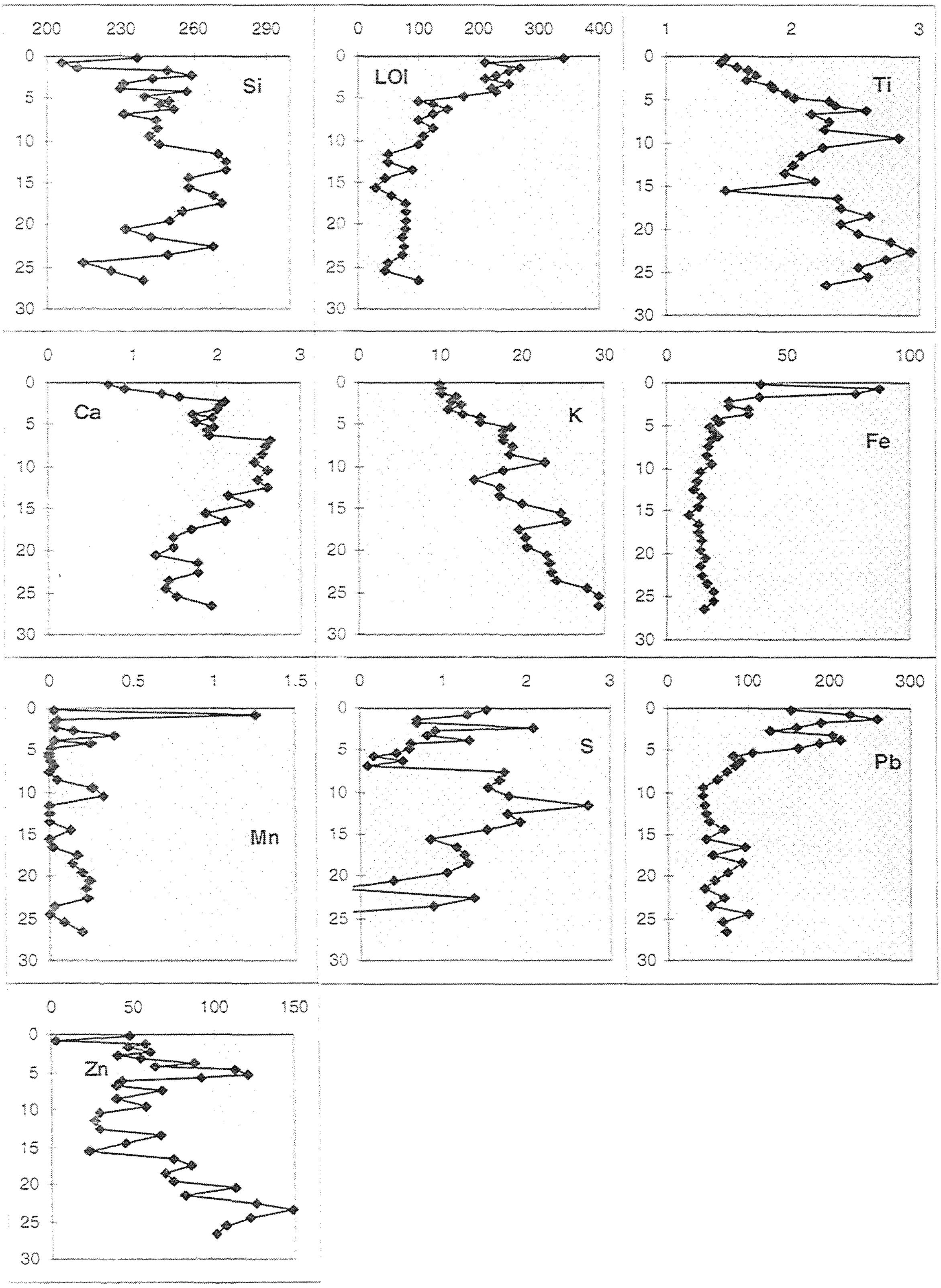
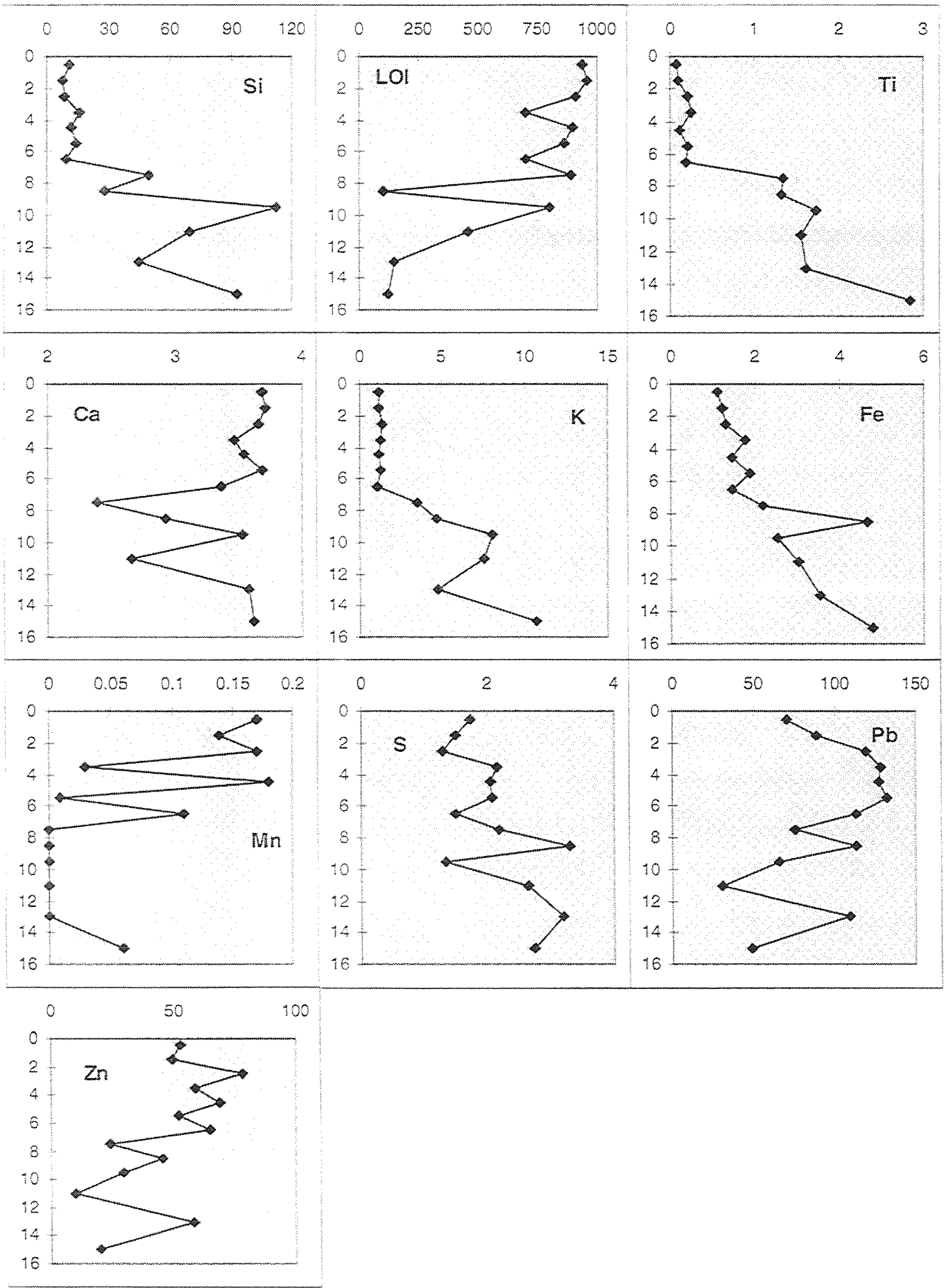


Figure 5.3. XRF analyses of a soil core from the Lochnagar catchment.

Units for Si, Al, Ti, Ca, K, Fe, Mn, S, are mg g^{-1}; for Cu, Pb, Zn, Br, Zr, Rb, Sr, and Cl, µg g^{-1}; and for LOI, parts per thousand. The vertical axis is sediment depth in cm.



6. Future work

6.1. UK Acid Waters Monitoring Network

Lochnagar has been an important site in the UKAWMN since its inception in 1988. Recently, the DETR has agreed to fund the Network until 2000, thus completing Year 12 of monitoring and making this a unique and increasingly valuable dataset. This period will include a detailed analysis of the data from the first ten years of the Network including an assessment of the trends thus far. It is to be hoped that this very important work will be continued well into the next century when the impact of emission reductions in the chemistry and biology at all UKAWMN sites can be observed.

6.2. Trace metal studies

The UNECE have decided that an effects based critical loads approach should be implemented for the deposition of key trace metals including Pb, Cd and Hg (see Section 5.1). In order that such an approach can be adopted for freshwaters further knowledge is required on how trace metals, atmospherically deposited to a lake and its catchment are either stored or move through ecological pathways. Little is known about the quantities of metals atmospherically deposited at remote locations in the UK and how these effect the metal contents of catchment and lake flora and fauna (i.e. whether ecologically important concentrations are attained).

The monitoring at Lochnagar is a first step towards answering some of these questions. Understanding in depth the metal cycling at a site where trace metal input is almost exclusively atmospheric and where there has been no catchment disturbance is fundamental if critical loads models for metals are to be developed and applied more broadly across the UK.

Deposition, catchment and lake compartments are currently well monitored (see above) but longer time-scales are required in order that the full 'source to sink' pathways (atmosphere to sediment, soils, biota, outflow) can be determined and that possible anomalous sampling periods can be placed in their proper context. In particular it is important to determine how atmospheric depositions relate quantitatively to the sediment record so that levels of past atmospheric deposition can be estimated. This can only be done over a period of years. Consequently, the following continued sampling programme is to be undertaken from April 1998 - March 2001, funded by the DETR:

Proposed work programme

- Bulk atmospheric deposition samples and lake water samples will be taken fortnightly throughout the year.
- The AWS and lake water temperature measurements will continue at their present level.
- Suspended solids sampling, catchment vegetation, aquatic macrophytes, epilithic algae and zooplankton sampling will continue at the current frequency.
- Inflow water samples and snow samples will be taken when possible.
- Outflow stream flow measurements will continue at their current level.
- Lake sediment and catchment soil surveys have been completed and will not be repeated.

Samples will be analysed for Hg, Cd, Pb, Zn and Cu.

6.3. Climate studies

A project titled "Climate History as recorded by ecologically sensitive Arctic & Alpine Lakes in Europe during the last 10 000 years: A multi-proxy approach" (CHILL-10 000) has recently been funded by the EC Environment and Climate Programme (Area 1.1.2) with participants from Austria, Denmark, Finland, Norway, Spain, Sweden, Switzerland and the UK.

The aim of this research is to investigate quantitatively past climate changes as recorded in the sediments of ecologically sensitive lakes. Lochnagar is one UK site under consideration for inclusion in this project. This is because it fulfils the criteria of being relatively undisturbed by human activity and lies in a high altitude situation where it is susceptible to the effects of climate change. Further, high quality monitoring data are already available.

If selected, the aim would be to retrieve a single core containing the full length of the sediment record (c.10 000 years). It is anticipated that the maximum depth of sediment accumulation, representing this period of time, would be contained within 2.0-2.5 m of sediment. A corer, designed specifically for operation at remote lakes and which causes no disturbance to surrounding sediments, would be used for this purpose.

Acknowledgements

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