4 Site Summaries

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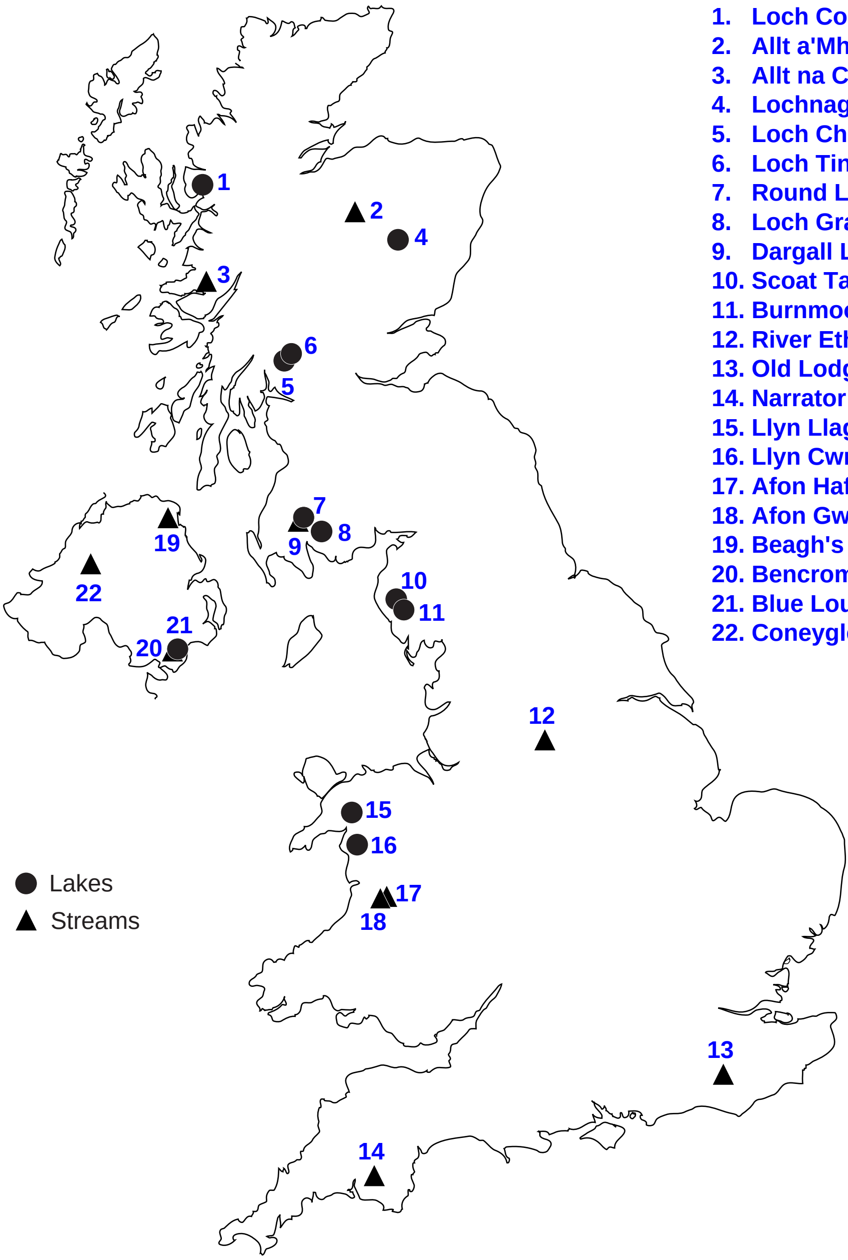
Figure 4.1.1

Location of UKAWMN sites



1. Loch Coire nan Arr
2. Allt a'Mharcaidh
3. Allt na Coire nan Con
4. Lochnagar
5. Loch Chon
6. Loch Tinker
7. Round Loch of Glenhead
8. Loch Grannoch
9. Dargall Lane
10. Scoat Tarn
11. Burnmoor Tarn
12. River Etherow
13. Old Lodge
14. Narrator Brook
15. Llyn Llagi
16. Llyn Cwm Mynach
17. Afon Hafren
18. Afon Gwy
19. Beagh's Burn
20. Bencrom River
21. Blue Lough
22. Coneyglen Burn

4.1 Loch Coire nan Arr

Site Review

Loch Coire nan Arr is the most northerly of all UKAWMN sites. As atmospheric pollution loads at the site were known to be low and the water chemistry relatively well buffered, the site was initially considered as a potential control for the other more impacted regions to the south. However, palaeoecological studies have since suggested that the loch has undergone very slight acidification in recent years (Patrick *et al.*, 1995). In 1991 a temporary dam was placed on the loch outflow as a means of conserving the water supply to a fish farm located beneath the site. More recently a permanent structure with sluice, has replaced this. The dam has raised mean water level at the site by at least 0.5 m loch shoreline. The water level change has clearly reduced the extent of emergent macrophyte stands at the site (see below).

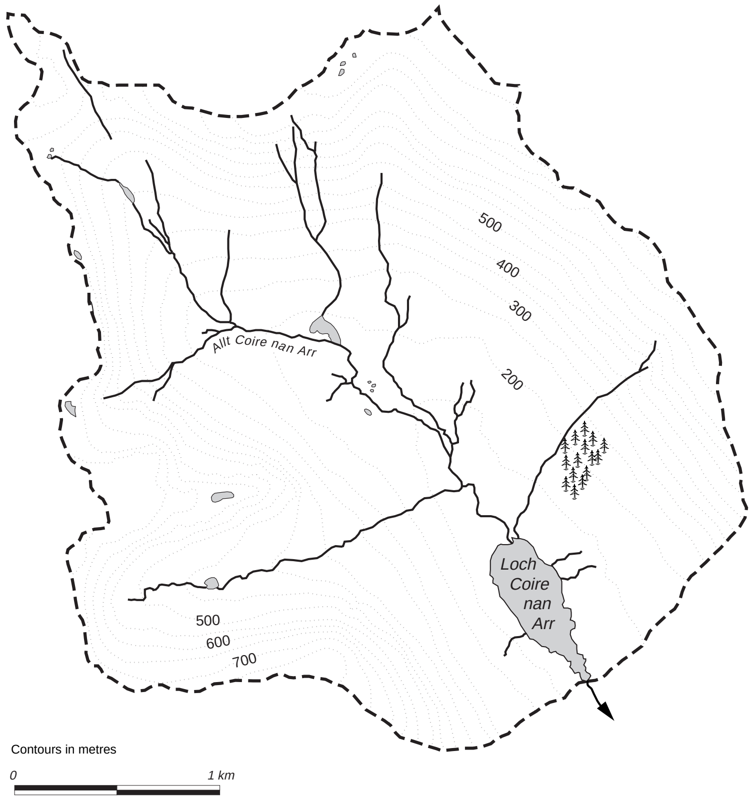


Figure 4.1.1

Loch Coire nan Arr: catchment

Table 4.1.1

Loch Coire nan Arr: site characteristics

Grid reference	*NG 808422*
Lake altitude	*125 m*
Maximum depth	*12.0 m*
Mean depth	*4.8 m*
Volume	*5.6×10^5 m^3*
Lake area	*11.6 ha*
Catchment area (excl. lake)	*897 ha*
Catchment: Lake area ratio	*77.3*
Catchment Geology	*Torridonian Sandstone*
Catchment Soils	*peat*
Catchment vegetation	*moorland 99%*
	conifers <1%
Net relief	*771 m*
Mean annual rainfall	*3311 mm*
1996 deposition	
Total S	*14 kg ha^{-1} yr^{-1}*
non-marine S	*8 kg ha^{-1} yr^{-1}*
Oxidised N	*3 kg ha^{-1} yr^{-1}*
Reduced N	*3 kg ha^{-1} yr^{-1}*

Table 4.1.2

Loch Coire nan Arr: summary of chemical determinands, July 1988 - March 1998

Determinand		Mean	Max	Min
pH		*6.39*	*6.95*	*5.75*
Alkalinity	µeq l^{-1}	*37.8*	*89.0*	*4.0*
Ca	µeq l^{-1}	*42.5*	*70.0*	*17.5*
Mg	µeq l^{-1}	*60.8*	*158.3*	*25.0*
Na	µeq l^{-1}	*232.2*	*495.7*	*130.4*
K	µeq l^{-1}	*8.5*	*15.4*	*2.6*
SO_4	µeq l^{-1}	*40.8*	*56.3*	*27.1*
xSO_4	µeq l^{-1}	*13.8*	*23.1*	*-15.6*
NO_3	µeq l^{-1}	*2.9*	*7.9*	*< 1.4*
Cl	µeq l^{-1}	*257.7*	*664.8*	*123.9*
Soluble Al	µg l^{-1}	*15.3*	*40.0*	*< 2.5*
Labile Al	µg l^{-1}	*3.1*	*7.0*	*< 2.5*
Non-labile Al	µg l^{-1}	*13.7*	*33.0*	*< 2.5*
DOC	mg l^{-1}	*2.2*	*5.2*	*< 0.1*
Conductivity	µS cm^{-1}	*39.2*	*85.0*	*21.0*

Water Chemistry

(Figure 4.1.2, Table 4.1.2-3)

Although potentially susceptible to acidification, with a ten-year mean Ca concentration of just 43 μeq l^{-1}, Loch Coire nan Arr receives low levels of anthropogenic S and N deposition and is not acidic. Mean pH is 6.39 and mean alkalinity 38 μeq l^{-1}, with labile Al concentrations at or close to detection limits. Non-marine SO_4 concentrations reflect the low deposition, with a ten year mean of 13.5 μeq l^{-1}. NO_3 concentrations have remained below 10 μeq l^{-1} throughout the monitoring period, although some seasonality is observed with concentrations above detection limits during all winter periods (Figure 4.1.2e).

The proximity of this site to the coast results in large marine ion inputs, and Na and Cl concentrations at the loch are therefore high (10 year means 203 μeq l^{-1} and 258 μeq l^{-1} respectively). Both ions show a pronounced seasonal cycle, with winter peaks resulting from large frontal storms at this time. Marine ion deposition events have been shown to cause episodic acidification through the 'sea-salt effect' (Wright *et al.*, 1988; Langan, 1989) whereby marine cations temporarily displace H^+ from soil exchange sites. This natural process is evident in pH and alkalinity minima that occur concurrently with marine ion maxima (Figure 4.1.2a,b). Some temporary retention of marine SO_4 may also occur (Evans *et al.*, in press; Section 5.3), leading to reduced or even negative xSO_4 concentrations (Figure 4.1.2d).

In accordance with the continuously low pollutant deposition at the site, no significant trends were observed for pH, alkalinity, base cations or mineral acid anions. There are also no identifiable changes in chemistry following the rise in water level in 1991. However, large and highly significant increases were observed over the last decade for both DOC and non-labile Al (Table 4.1.3). LOESS curves suggest that these increases took place fairly steadily between 1988-1996, but may have levelled off in recent years. The SKT estimated total increase over the decade of 2.5 mg l^{-1} represents a major change in water chemistry given a mean concentration in the first year of sampling of just 1.0 mg l^{-1}. Organically complexed non-labile Al shows a clear correlation with DOC, suggesting that concentrations are determined by the availability of complexing ligands (Driscoll *et al.*, 1984). Since almost all Al present is in non-labile form, total soluble Al exhibits similar behaviour (Figures 4.1.2j,k). The issue of DOC trends is discussed in detail in Section 5.2.3.

Epilithic diatoms

(Figure 4.1.3, Table 4.1.4)

The epilithic diatom flora of Loch Coire nan Arr demonstrates marked inter-annual variation over the past decade. Samples are dominated by *Tabellaria flocculosa*, (pH optima 5.4) *Brachysira vitrea* (pH optima 5.9) and *Achnanthes minutissima* (pH optima 6.4), *T. flocculosa* was most abundant between 1989-1991, gradually declined until 1997 and increased again in 1998. These changes have been largely reciprocated by *A. minutissima*. Similar patterns in species variation have

Table 4.1.3

Significant trends in chemical determinands (June 1988 - March 1998)

Determinand	Units	Annual trend (Regression)	Annual trend (Seasonal Kendall)
DOC	*mg l^{-1}*	*+0.21******	*+0.25****
Non-labile Al	*μg l^{-1}*	*+1.13****	*+1.00**

** Trend significant at $p < 0.05$; ** trend significant at $p < 0.01$; *** trend significant at $p < 0.001$*

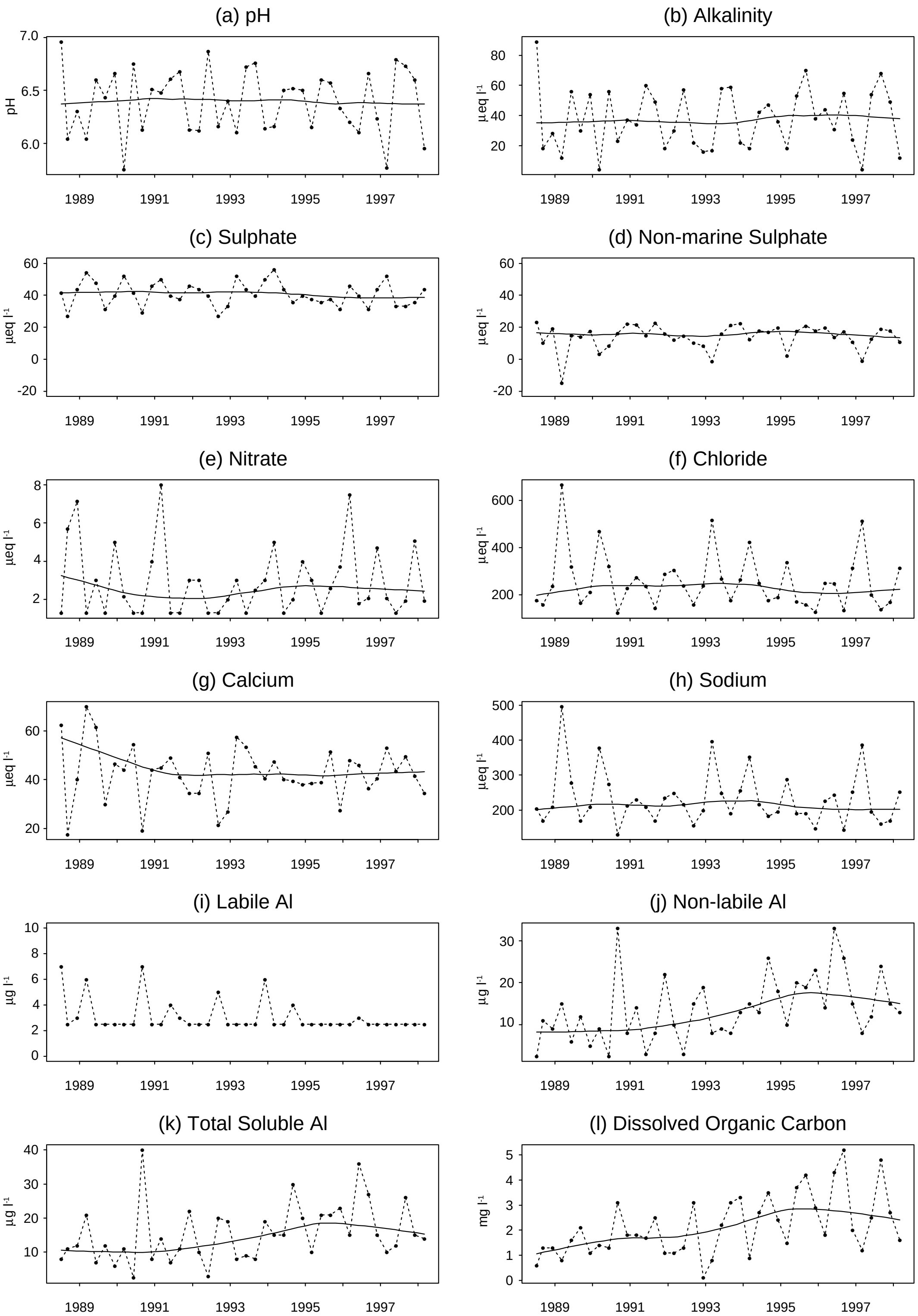


Figure 4.1.2

Loch Coire nan Arr: summary of major chemical determinands (July 1988 - March 1998)

Smoothed line represents LOESS curve (Section 3.1.2)

Table 4.1.4

Loch Coire nan Arr: trend statistics for epilithic diatom, macrophyte and macroinvertebrate summary data (1988 - 1998)

	Total sum of squares	Number of taxa	Mean N_2 diversity	λ_1RDA/λ_2RDA	λ_1RDA/λ_1PCA
Epilithic diatoms	*294*	*150*	*6.2*	*0.42*	*0.39*
Macrophytes	*49*	*20*	*12.6*	*1.19*	*0.73*
Invertebrates	*983*	*48*	*3.0*	*0.78*	*0.52*

Variance explained (%)	within year	between years	linear trend	p unrestricted	p restricted
Epilithic diatoms	*49.9*	*50.1*	*7.0*	*0.01*	*0.24*
Macrophytes	*	*	*30.1*	*<0.01*	*<0.01*
Invertebrates	*42.4*	*7.6*	*15.8*	*0.00*	*0.01*

Table 4.1.5

Loch Coire nan Arr: relative abundance of aquatic macrophyte flora (1988 - 1997) (see Section 3.2.3 for key to indicator values)

Abundance Taxon Year	88	89	90	91	92	93	95	97
INDICATOR SPECIES								
Nitella flexilis[1]	2	3	3	3	3	3	1	1
Myriophyllum alterniflorum[2]	3	3	3	3	3	3	2	2
Utricularia sp.[2]	2	3	3	2	2	0	2	2
Callitriche hamulata[3]	2	3	3	3	3	3	3	3
Sphagnum auriculatum[4]	0	1	1	1	1	1	1	1
Juncus bulbosus var. *fluitans*[4]	5	5	5	5	5	4	4	4
OTHER SUBMERGED OR FLOATING LEAF SPECIES								
Batrachospermum sp.	1	1	0	0	0	0	1	0
Filamentous green algae	1	2	3	1	1	1	1	1
Fontinalis sp.	1	1	1	0	0	0	0	0
Rhytidiadelphus sp.	0	1	1	1	0	1	0	1
Lobelia dortmanna	3	3	4	4	3	3	3	3
Isoetes lacustris	4	4	4	4	4	3	3	3
Littorella uniflora	3	3	4	4	4	3	3	3
Subularia aquatica	0	0	0	0	0	0	0	1
Potamogeton natans	4	4	4	4	4	2	2	4
Potamogeton polygonifolius	0	0	1	1	0	1	1	1
Sparganium angustifolium	1	2	2	2	2	1	2	2
EMERGENT SPECIES								
Equisetum fluviatile	2	2	2	2	2	1	2	0
Ranunculus flammula	2	2	3	3	3	2	3	1
Carex nigra	1	2	2	2	2	1	2	1
Carex rostrata	0	0	1	1	0	0	0	0
Eleocharis multicaulis	2	2	1	1	1	0	0	0
Glyceria fluitans	1	1	1	1	1	0	1	0
Juncus acutifloris/articulatus	1	3	2	2	2	1	0	0
Juncus effusus	1	1	1	1	1	1	1	1
TOTAL NUMBER OF SPECIES	*20*	*22*	*23*	*22*	*19*	*18*	*19*	*18*

occured in sediment trap samples from the loch which have been collected since 1991 (Figure 4.1.6). As the sediment traps should provide an integrated annual sample, it would seem that the epilithon data are generally representative of the diatom crop for the full growing season. The varying proportion of *A. minutissima* and *T. flocculosa* appear to indicate fluctuating levels of acidity and this is also shown by the diatom inferred pH derived from pH weighted averaging applied to the whole assemblage (Figure 7.3a) which suggests a gradual increase in pH between 1990 and 1996. Although these inferences are not strongly supported by changes in water chemistry, low pH was recorded in the spring of 1990, 1997 and 1998, apparently associated with high rainfall and Cl concentrations. The floristic similarity between 1998 samples and those of 1989-1991 appear to rule out any long term trend. RDA shows time to be insignificant as a linear variable at the 0.01 level using the restricted permutation test. The extent to which species variation may be influenced by 'natural' oscillations in acidity will require verification by ongoing monitoring.

Macroinvertebrates

(Figure 4.1.4, Table 4.1.4)

The macroinvertebrate benthic fauna is moderately diverse and dominated by Chironomidae and the acid tolerant mayfly family Leptophlebiidae. Several mayfly species have been recorded throughout the study period. The acid sensitive *Baetis* spp. has appeared intermittently since 1991, *Siphlonurus lacustris* has been recorded in all years except 1990 and in most recent years *Centroptilum luteolum* replaced the acid tolerant Leptophlebiidae as the dominant mayfly. In studies of Finnish freshwaters *C. luteolum* has a pH preference of approximately 6.0 (Hämäläinen & Huttunen, 1996). The acid tolerant caddisflies *Plectrocnemia* spp. and *Polycentropus* spp. were recorded throughout most of the monitoring period, being most abundant in 1995 and 1993 respectively. However, *Plectrocnemia* spp. has been absent since 1996. RDA shows a significant linear trend at the 0.01 level. The shift in species relative abundance, and in particular the decrease in the relative adundance of acid tolerant Leptophlebid mayflies and the appearance of *C. luteolum* since 1996 is indicative of an improvement in conditions.

Fish

(Figure 4.1.5)

The outflow of Loch Coire nan Arr was first fished in 1989. Trout density is intermediate for UKAWMN sites. There are no significant linear trends in density, mean condition factor or coefficient of variance of condition factor for either age group over the last nine years. However, general declines in density of both groups are apparent since 1991, possibly reflecting an influence of the outflow dam on the stream population. In common with many of the other Scottish sites, very high recruitment occured in 1991. Mortality of this cohort however appears to have been high as there is no evidence of higher than average trout densities progressing through the subsequent year groups. Poorest recruitment occurred in 1992 and 1996.

Aquatic macrophytes

(Table 4.1.4-5)

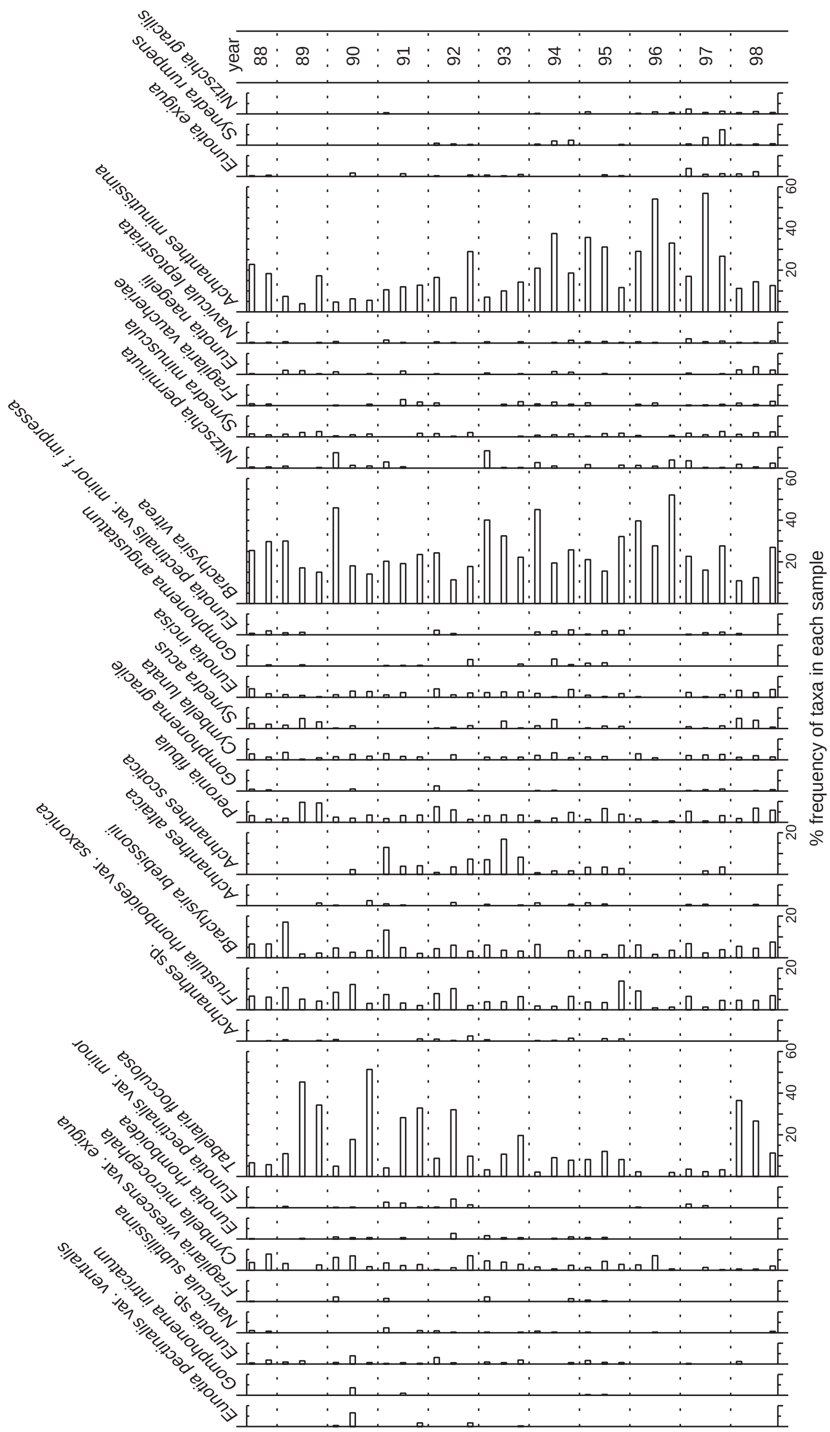
The aquatic macrophyte flora of Loch Coire nan Arr is typical of non-acid oligotrophic lakes. The submerged community is dominated by the isoetids, *Isoetes lacustris*, *Lobelia dortmanna* and *Littorella uniflora*. The acid sensitive charophyte species *Nitella flexilis*, and other species intolerant of acidity levels at the more acid UKAWMN lake sites (i.e. *Myriophyllum alterniflorum* and *Utricularia* sp.) are also present.

The installation of a dam, and the consequent increases in mean water level and level fluctuations, appear to have led to a substantial reduction in the abundance of some submerged species. In particular *N. flexilis*, which was widespread during the first few years of monitoring, is now considered rare. Conversely, *Potamogeton natans*, which forms floating leaved beds in moderately deep water, appears to have increased. Assessment of cover of

Figure 4.1.3

Loch Coire nan Arr: summary of epilithic diatom data (1988 - 1998)

Percentage frequency of all taxa occurring at >2% abundance in any one sample



submerged species has been hampered by the problem of precise re-location of transects now that the characteristics of the lake perimeter have changed. It is highly likely that the water-level change has also been responsible for the loss of emergent stands of *Equisetum fluviatile*, *Carex rostrata* and *Eleocharis multicaulis*. It is unlikely that these species could become re-established at the site unless water level management were to cease for a considerable period. "Sample year" is significant as a linear trend according to RDA and restricted permutation tests but this almost certainly results from the effects of water level change.

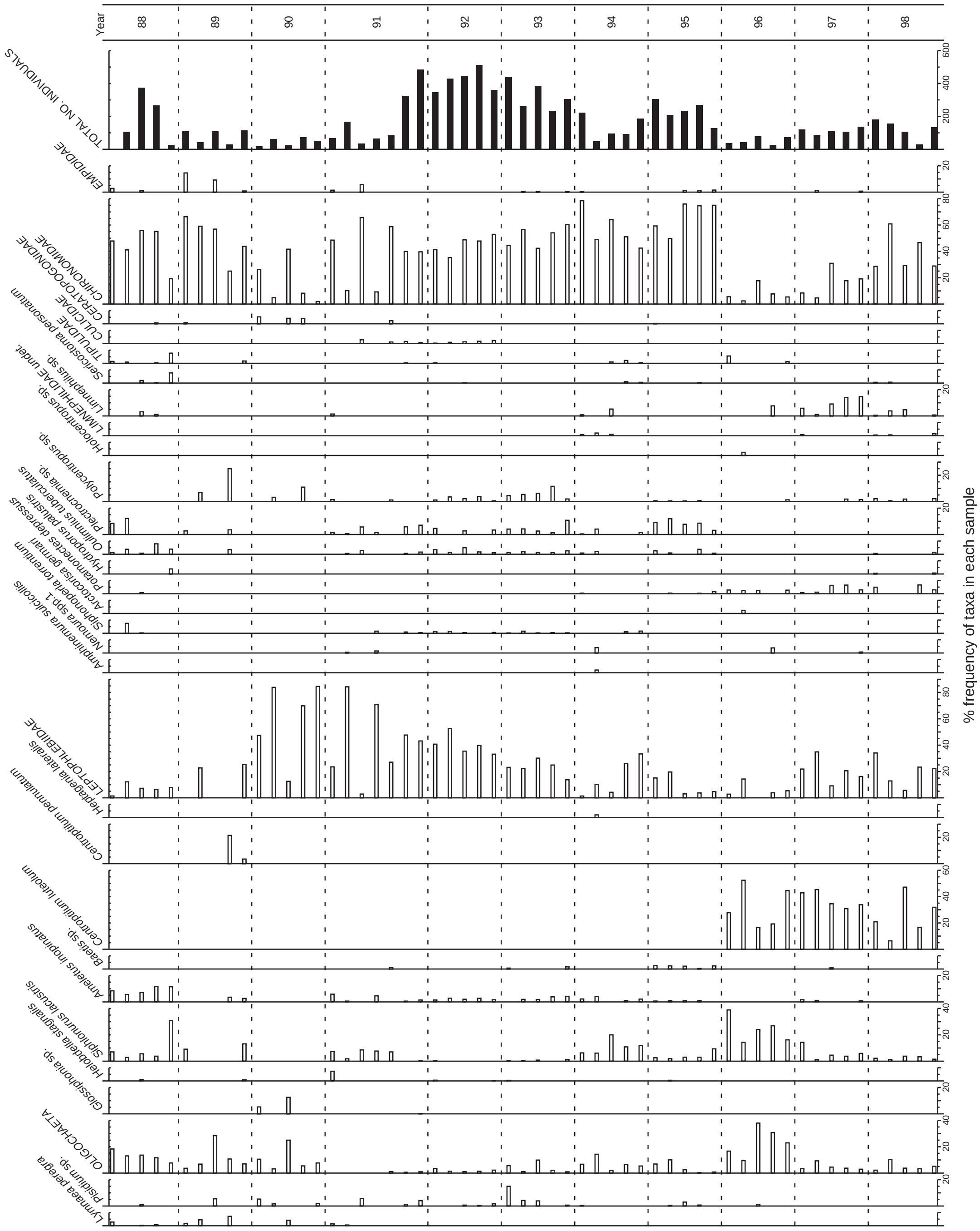
Summary

Despite geological sensitivity, Coire nan Arr receives very low levels of pollutant inputs, and has remained unacidic for most of the monitoring period. Episodic pH and alkalinity reductions are a feature of the site, due to large winter inputs of marine ions and high rainfall, and it is possible that these have influenced the inter-annual differences in species assemblages of diatoms and macroinvertebrates. However, negative alkalinities, have not been recorded at any time during the study period. Given the low levels of pollutant deposition, loch chemistry appears generally stable over the last ten years, but significant increases have been recorded for DOC and non-labile Al. A rise in water level following damming, and subsequent water level management since 1991, has led to considerable inundation of the loch's former shoreline. The increased DOC at this site could therefore result from peat erosion. However, similar trends are observed at many other sites in the Network, suggesting a more general pattern of rising DOC. This issue is discussed in detail in Section 5.2.3. Changes in water level have almost certainly lead to a reduction in the representation of emergent macrophytes (through loss of habitat), while out-flow regulation may have had an impact on the trout density of the outflow burn

Figure 4.1.4

Loch Coire nan Arr: summary of macroinvertebrate data (1988 - 1998)

Percentage frequency of taxa in individual samples



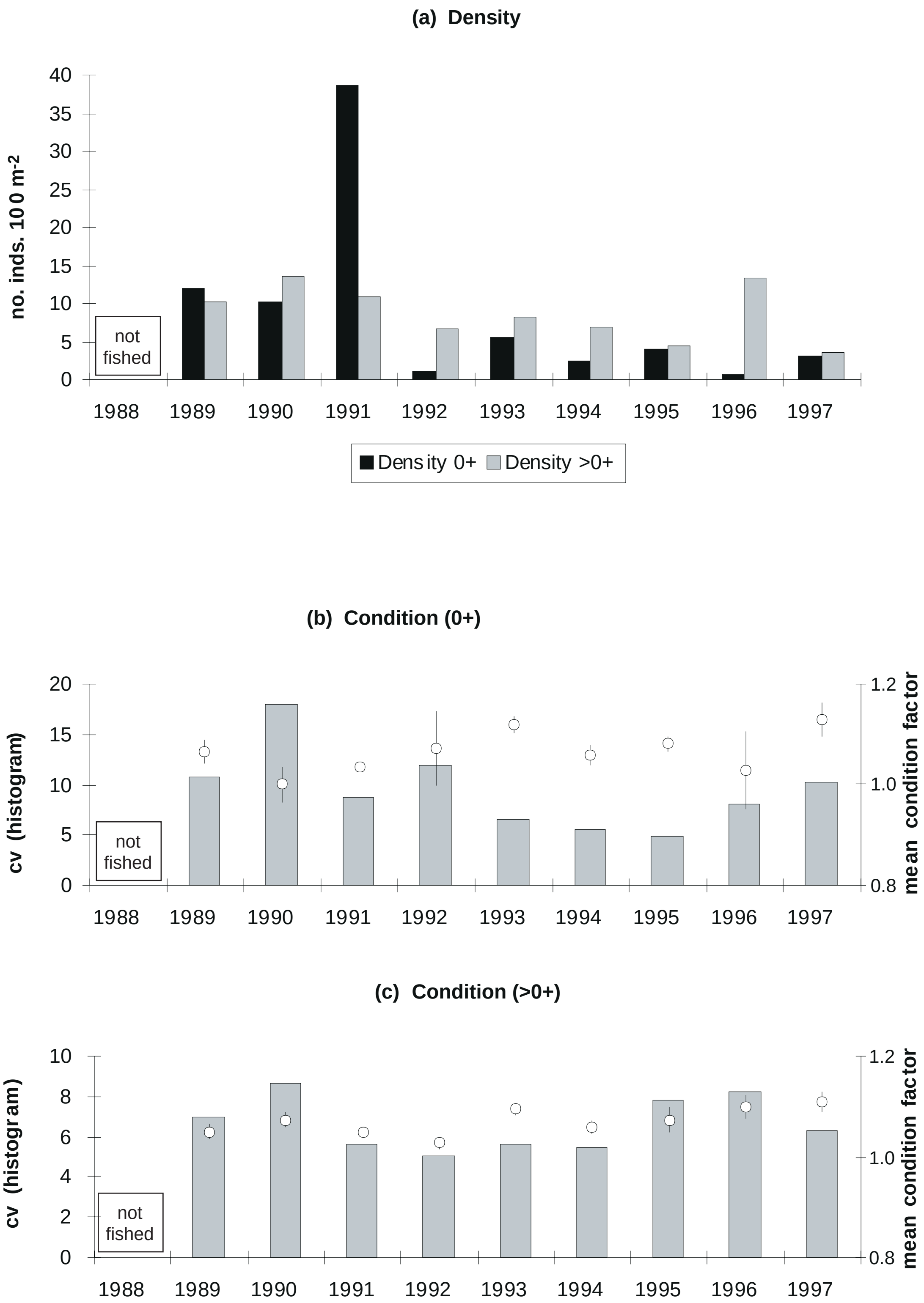


Figure 4.1.5

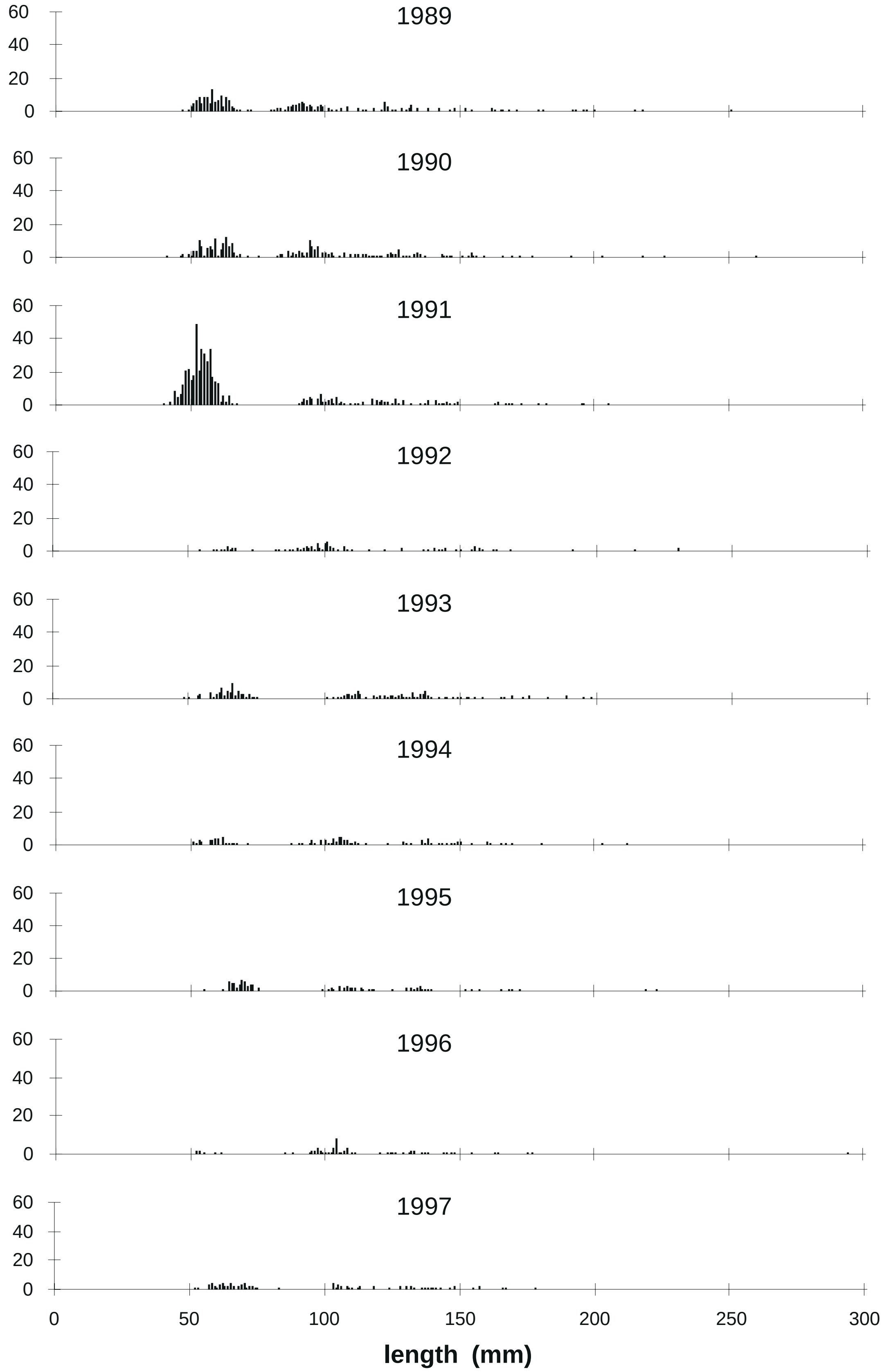
Loch Coire nan Arr: summary of fish data (1988 - 1997)

(a) Trout population density for 0+ and >0+ age classes (individuals 100 m^{-2})

(b) Mean condition factor (with standard deviation) of the trout population and its coefficient of variation (histogram)

Figure 4.1.5

Loch Coire nan Arr: summary of fish data (1989 - 1997)
(c) Trout length frequency summaries (1989 - 1998)



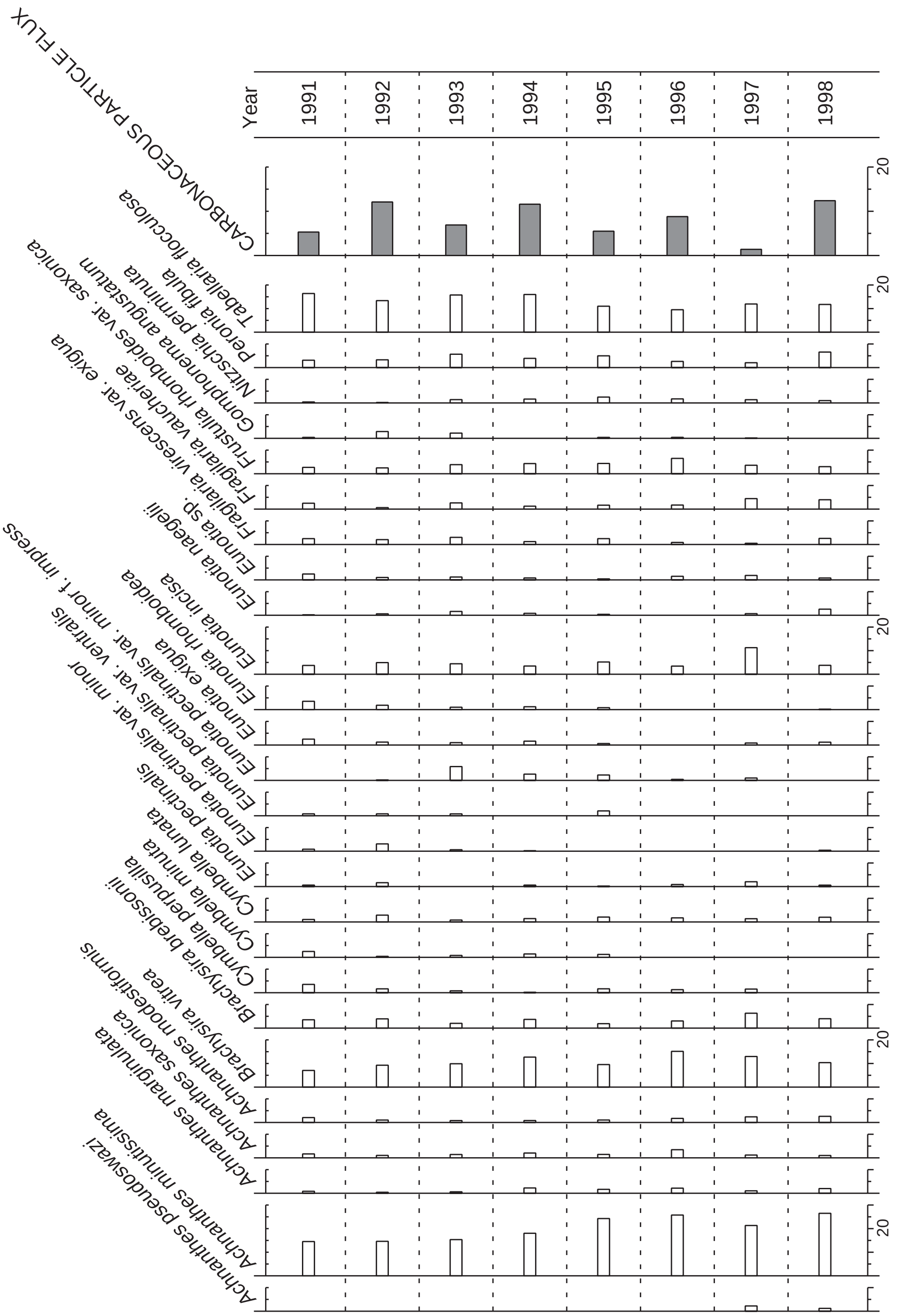


Figure 4.1.6

Loch Coire nan Arr: summary of sediment trap data for diatoms and carbonaceous particles

Relative frequency of diatom taxa (>2% in at least one sample) at time of trap retrieval and estimated carbonaceous particle flux (no. $trap^{-1}$ day^{-1}) for preceding year

4.2 Allt a'Mharcaidh

■ Site Review

The Allt a'Mharcaidh, in the western Cairngorms of northeast Scotland, is a well buffered mountain stream which is subject to occasional acid episodes. No physical changes have been observed in the study catchment since the onset of monitoring in 1988. The Allt a'Mharcaidh was studied as part of the SWAP project (e.g. Ferrier & Harriman, 1990). It is one of the two British sites represented in the UNECE Integrated Monitoring Programme (UNECE - IMP) and is also a freshwater site in the UK Environmental Change Network (ECN).

■ Water Chemistry

(Figure 4.2.2, Table 4.1.2-3)

The Allt a'Mharcaidh has a relatively well buffered chemistry, with a 10 year mean pH of 6.45. Although the site can be considered acid-sensitive, with a mean Ca of 42 μeq l^{-1}, S and N deposition are low. Mean xSO_4 is 33 μeq l^{-1}, whilst virtually all incoming N is retained; NO_3 concentrations in 88% of samples collected were below detection limits, and the maximum recorded was 5 μeq l^{-1}.

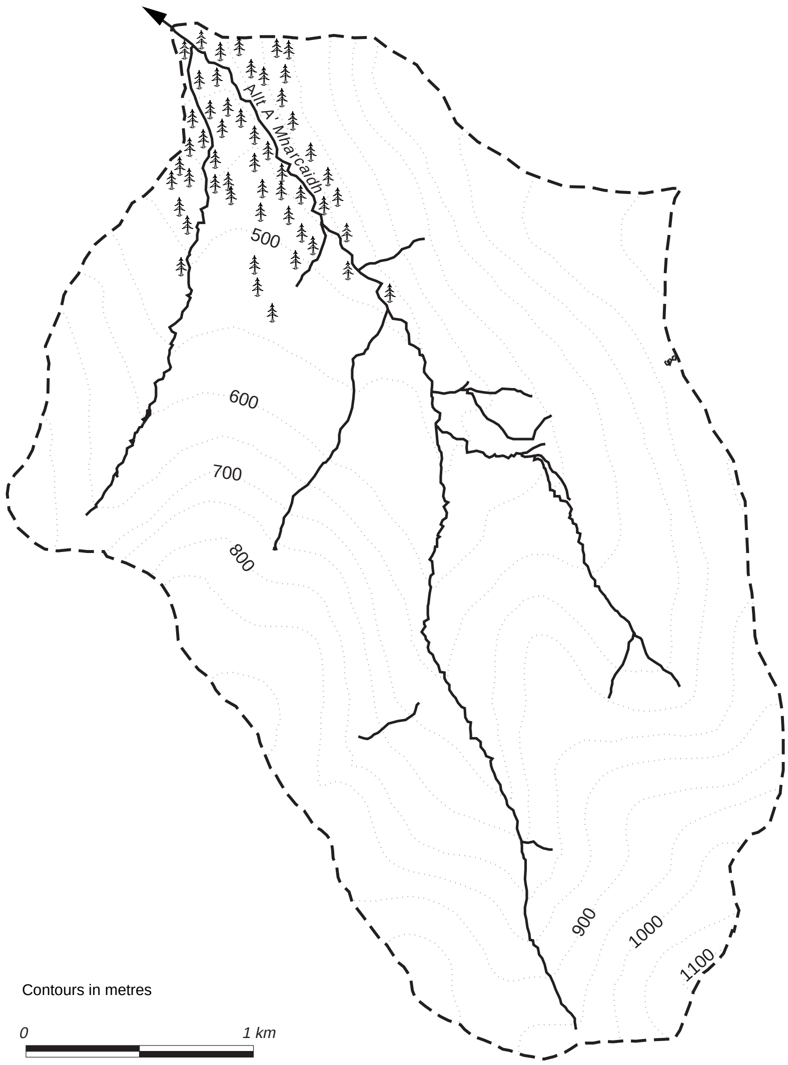


Table 4.2.1

Allt a'Mharcaidh: site characteristics

Grid reference	*NM 881045*
Catchment area	*998 ha*
Minimum catchment altitude	*325 m*
Maximum catchment altitude	*1111m*
Catchment Geology	*granite*
Catchment Soils	*alpine & peaty podsols, blanket peat*
Catchment vegetation	*moorland c. 98% native pine c. 2%*
Mean annual rainfall	*1331 mm*
1996 deposition	
Total S	*12 kg ha^{-1} yr^{-1}*
non-marine S	*8 kg ha^{-1} yr^{-1}*
Oxidised N	*3 kg ha^{-1} yr^{-1}*
Reduced N	*5 kg ha^{-1} yr^{-1}*

The Allt a'Mharcaidh is however subject to acidic episodes, in which alkalinity falls to around zero and pH to <5.5. Previous work by Harriman *et al.* (1990) showed that approximately 75% of pH and alkalinity variation could be explained by flow. The main chemical change generating acidity at high flows appears to be dilution of base cations, although occasional pulses of marine ion deposition, notably in early 1993 (Figure 4.2.2) may have generated acidic episodes through the sea-salt effect. Apart from these infrequent events, sea-salt inputs are generally low, reflecting the inland location of this site.

Trend analyses show little or no chemical change at the Allt a'Mharcaidh over the last decade. The only significant trend identified is for DOC (Table 4.2.3), which is found to be increasing using

Figure 4.2.1

Allt a'Mharcaidh catchment

Table 4.2.2

Allt a'Mharcaidh: summary of chemical determinand, July 1988 - March 1998

Determinand		Mean	Max	Min
pH		*6.45*	*7.08*	*5.12*
Alkalinity	µeq l^{-1}	*44.2*	*91.0*	*-4.0*
Ca	µeq l^{-1}	*42.0*	*60.5*	*4.5*
Mg	µeq l^{-1}	*29.2*	*50.0*	*16.7*
Na	µeq l^{-1}	*135.2*	*213.0*	*91.3*
K	µeq l^{-1}	*7.4*	*12.8*	*2.6*
SO_4	µeq l^{-1}	*44.4*	*72.9*	*29.2*
xSO_4	µeq l^{-1}	*32.9*	*57.9*	*18.3*
NO_3	µeq l^{-1}	*1.4*	*5.0*	*< 1.4*
Cl	µeq l^{-1}	*110.1*	*259.2*	*56.3*
Soluble Al	µg l^{-1}	*35.7*	*166.0*	*< 2.5*
labile Al	µg l^{-1}	*6.7*	*46.0*	*< 2.5*
Non-labile Al	µg l^{-1}	*29.8*	*150.0*	*< 2.5*
DOC	mg l^{-1}	*2.3*	*12.1*	*< 0.1*
Conductivity	µS cm^{-1}	*24.0*	*38.0*	*14.0*

regression analysis. However the same increase is not found using SKT, and the time series plot (Figure 4.2.2) suggests that this trend may be the result of a small number of high DOC samples in recent years rather than a genuine and sustained increase.

■ Epilithic diatoms

(Figure 4.2.3, Table 4.2.4)

The epilithon of Allt a'Mharcaidh is dominated by *Synedra minuscula*, *Achnanthes minutissima* and *Fragilaria vaucheriae*, species typical of mildly acidic softwater streams. These taxa have shown marked variation in their relative abundance between years, *A. minutissima* showing relatively high abundances from 1991-1992 and 1994-1995. *F. vaucheriae* and rare taxa, including *Gomphonema angustatum* [agg.] and *Diatoma hyemale* var. *mesodon*, have undergone a decline in relative abundance since the onset of monitoring, while *Achnanthes modestiformis* has increased slightly. The species assemblage in 1998 samples was particularly unusual, with relatively high representation of *Brachysira vitrea*, *B. brebissonii*, *Frustulia rhomboides* var. *saxonica* and *Achnanthes marginulata*. These species have relatively low pH optima and their increase is likely to reflect a sustained period of depressed pH over the summer of 1998 resulting from unusually high flow conditions (see Section 7.4.1). RDA analysis shows time as an explanatory variable to be insignificant at the 0.01 level and no trend is apparent in diatom inferred pH for the site.

■ Macroinvertebrates

(Figure 4.2.4, Table 4.2.4)

The macroinvertebrate community of Allt a'Mharcaidh is diverse and dominated throughout the monitoring period by the acid sensitive mayfly *Baetis* spp.. Several other acid sensitive mayflies are also present in lower numbers, including *Rhithrogena semicolorata* and *Heptagenia lateralis*. The site also contains a diverse assemblage of stoneflies of which *Leuctra inermis* is most abundant, while other common taxa include *Brachyptera risi*, *Protonemura* spp., *Amphinemura sulcicollis* and the predatory species *Isoperla grammatica* and

Table 4.2.3

Significant trends in chemical determinands (July 1988 - March 1998)

Determinand	Units	Annual trend (Regression)	Annual trend (Seasonal Kendall)
DOC	*mg* l^{-1}	*+0.11****	-

** Trend significant at p < 0.05; ** trend significant at p < 0.01; *** trend significant at p < 0.001*

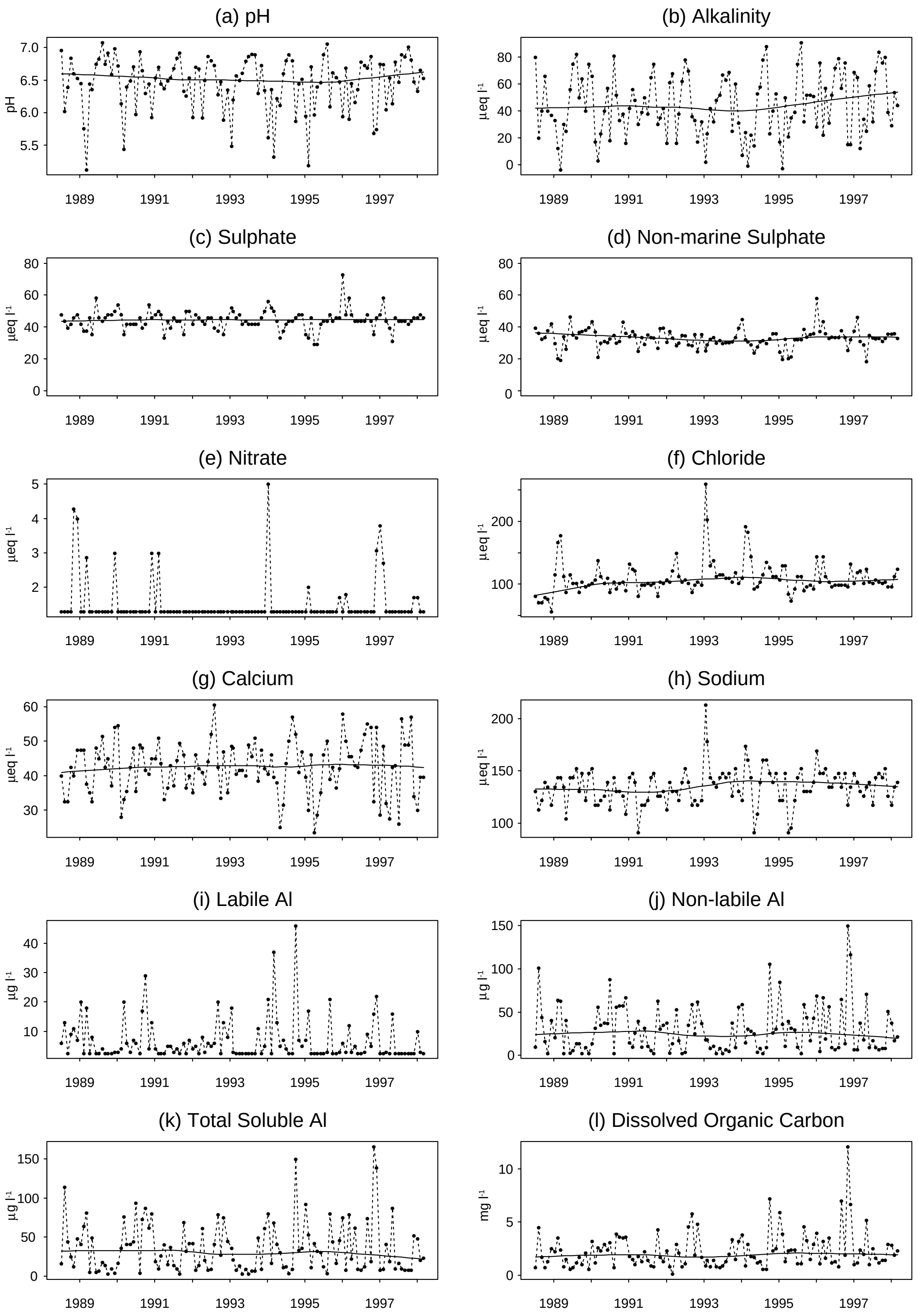


Figure 4.2.2

Allt a'Mharcaidh: summary of major chemical determinands (April 1988 - March 1998)

Smoothed line represents LOESS curve (Section 3.1.2)

Table 4.2.4

Allt a'Mharcaidh: trend statistics for epilithic diatom, macrophyte and macroinvertebrate summary data (1988 - 1998)

	Total sum of squares	Number of taxa	Mean N_2 diversity	λ_1RDA/λ_2RDA	λ_1RDA/λ_1PCA
Epilithic diatoms	306	94	4.2	0.52	0.49
Macrophytes	5	7	1.9	1.09	0.64
Invertebrates	173	33	4.7	0.30	0.27

Variance explained (%)	within year	between years	linear trend	p unrestricted	p restricted
Epilithic diatoms	33.9	66.1	9.8	<0.01	0.05
Macrophytes	*	*	30.1	0.01	<0.01
Invertebrates	33.5	66.5	7.5	<0.01	0.27

Chloroperla tripunctata. The macroinvertebrate community remains relatively persistent with no marked changes in either species abundance or composition. Time as a linear trend is not significant at a 0.01 level, using RDA and associated permutation tests.

■ Fish

(Figure 4.2.5(i), (ii))

Trout densities at this site are the third highest of those found in the Network sites. Although

Table 4.2.5

Allt a'Mharcaidh: relative abundance of aquatic macrophyte flora (1988 - 1997) (see Section 3.2.3 for key to indicator values)

(% cover of 50 m survey stretch)

Year	88	89	90	91	92	93	95	96	97
INDICATOR SPECIES									
Lemanaea sp.[1]	0.0	0.4	0.0	1.4	0.0	0.0	0.4	0.0	0.4
Brachythecium plumosum[1]	<0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Brachythecium rivulare[1]	<0.1	<0.1	<0.1	0.0	0.0	0.0	<0.1	0.0	<0.1
Fontinalis antipyretica[2]	<0.1	<0.1	0.3	<0.1	0.2	1.3	2.3	1.3	0.5
Hygrohypnum ochraceum[1]	6.6	10.0	8.9	9.2	9.4	5.7	7.2	9.7	2.4
OTHER SUBMERGED SPECIES									
Filamentous green algae	0.5	0.7	2.5	0.3	1.3	3.2	27.1	0.9	<0.1
Racomitrium aciculare	0.1	0.2	0.7	1.0	1.3	0.0	<0.1	0.2	0.2
Scapania undulata	1.1	0.8	1.2	0.7	1.4	1.1	2.0	3.0	2.0
total macrophyte cover excluding filamentous algae	7.8	11.0	11.1	10.9	12.3	8.1	11.5	14.2	5.1
TOTAL NUMBER OF SPECIES	7	7	6	6	5	4	7	5	7

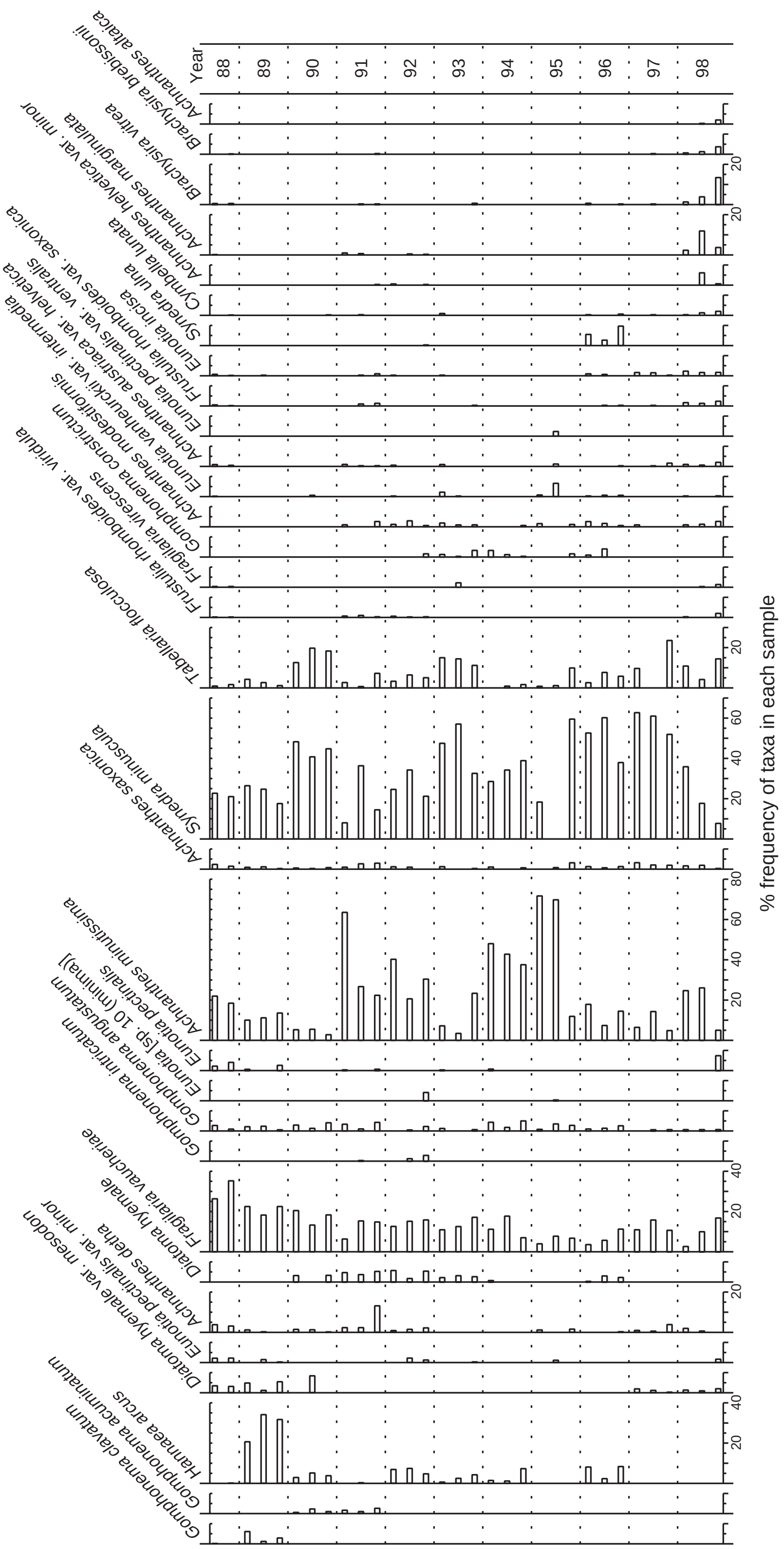


Figure 4.2.3

Allt a'Mharcaidh: summary of epilithic diatom data (1988 - 1998)

Percentage frequency of all taxa occurring at >2% abundance in any one sample

population densities of 0+ trout show some variation over the ten years of monitoring, there is no apparent trend in this fluctuation. Most years show good recruitment with 1991, 1996 and 1997 showing the highest densities. Population densities of >0+ trout are more stable and show a significant ($p = <0.05$) positive linear trend over the ten years data. Condition factor has fluctuated over time with 1989 and 1990 showing the highest condition factors but no significant long term trends are apparent. It is interesting to note that 1991 had the highest 0+ trout population density, one of the lowest condition factors and the smallest coefficient of variation of the CF. Length frequency graphs show a balanced population structure but some evidence of recruitment failure in the year prior to 1988. Salmon data show considerable between-year variation but no trends with time in either age class (Figure 4.2.5ii). The highest densities of 0+ salmon were recorded in 1992 and 1997.

Aquatic macrophytes

(Tables 4.2.4-5)

The aquatic macrophyte flora of the Allt a'Mharcaidh is dominated by the acid sensitive moss *Hygrohypnum ochraceum*, which covered large areas of the survey stretch for much of the monitoring period. Cover of this species was substantially reduced in 1997, probably as a result of physical scouring following a major storm event in the early summer. Cover of the acid tolerant liverwort, *Scapania undulata* appears to have remained unaffected. The Allt a'Mharcaidh is notable for the occasional bloom of the red alga *Lemanaea* sp. which is intolerant of acid conditions. Its occurrence in 1989, 1991, 1995 and 1997 coincides with years of low summer rainfall as recorded at the nearby Meteorological Station at Aviemore, and could reflect prolonged periods of elevated alkalinity. "Sample year" is significant at the 0.01 level according to RDA and associated permutation test. The trend appears to be driven by slight increases in the cover of the moss *Fontinalis antipyretica* and the liverwort *Scapania undulata* and is unlikely to signify any chemical change at the site.

Summary

The Allt a'Mharcaidh is a relatively well-buffered site in a region of low acid deposition. Although large episodic pH and alkalinity depressions have been recorded, alkalinity values significantly below zero have not been observed. No definite trends have been identified for any chemical determinand or most biological groups, although data suggest a gradual increase in the density of older trout with time. The aquatic moss cover was severely reduced following extreme spate conditions in 1997 and there is also evidence that inter-annual variation in the flow regime has an important influence on other components of the macrophyte, diatom and macroinvertebrate species assemblages.

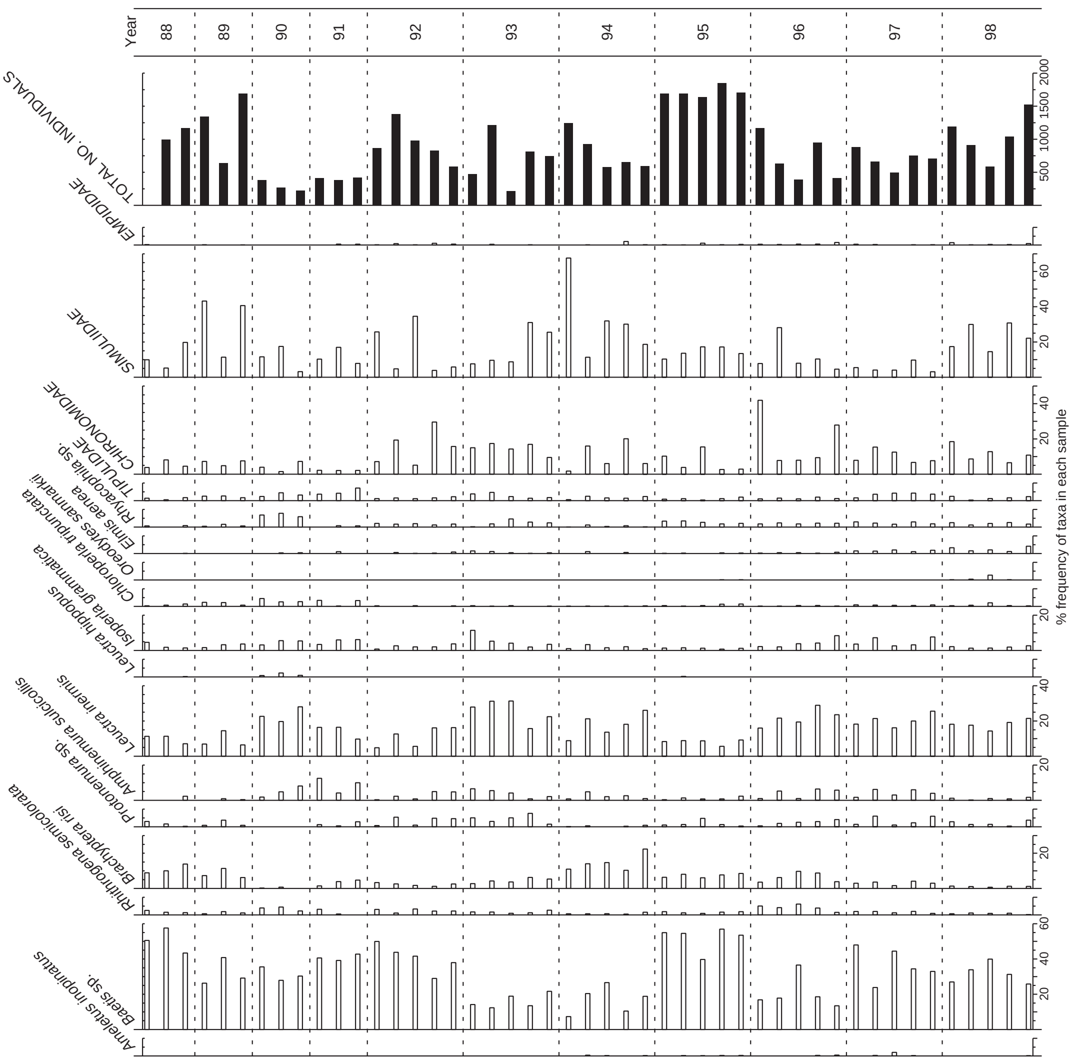


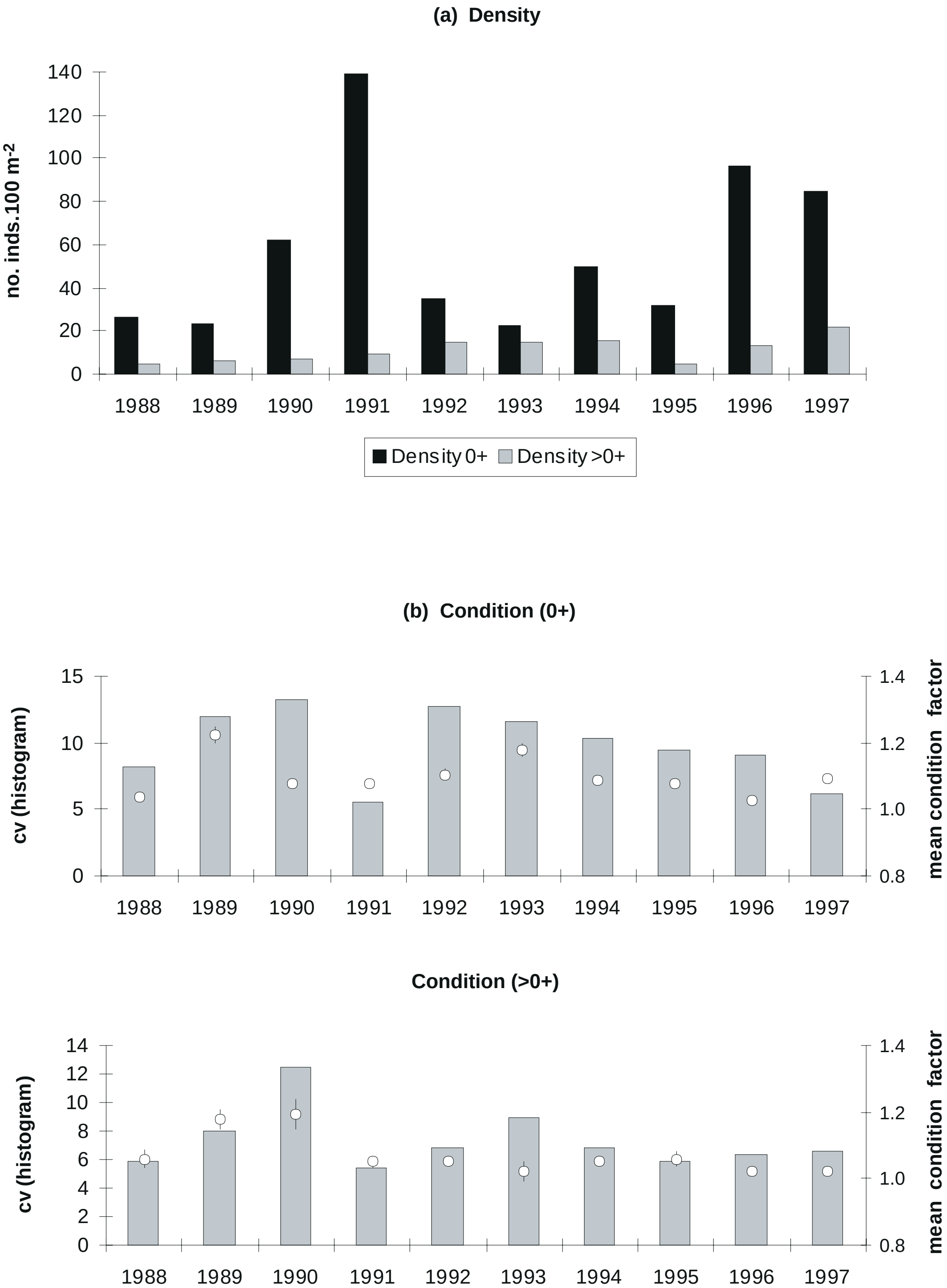
Figure 4.2.4

Allt a'Mharcaidh: summary of macroinvertebrate data (1988 - 1998)

Percentage frequency of taxa in individual samples

Figure 4.2.5 (i)

Allt a'Mharcaidh: summary of fish data (1988 - 1997)
(a) Trout population density for 0+ and >0+ age classes (individuals 100 m^{-2})
(b) Mean condition factor (with standard deviation) of the trout population and its coefficient of variation (histogram)



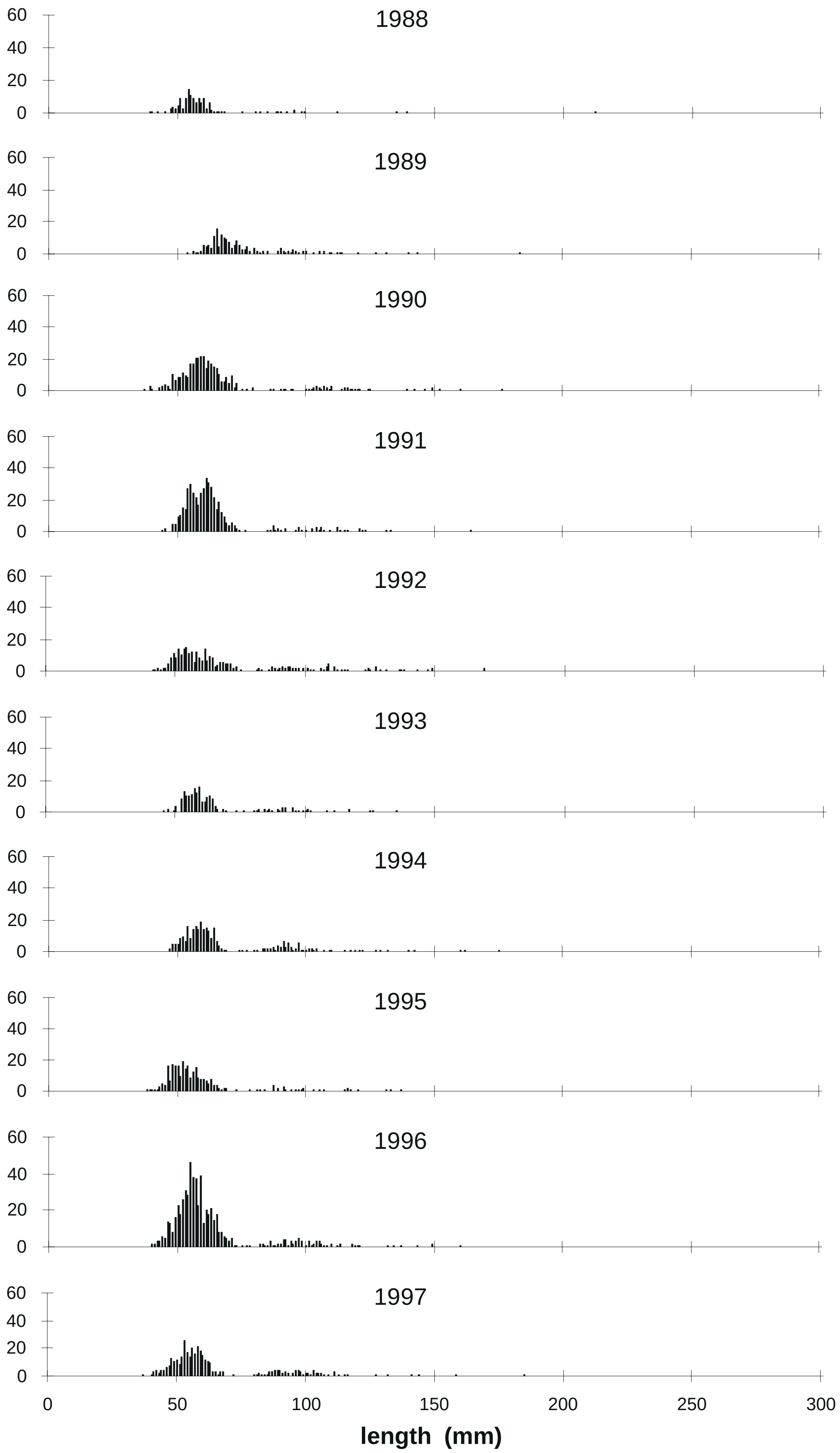
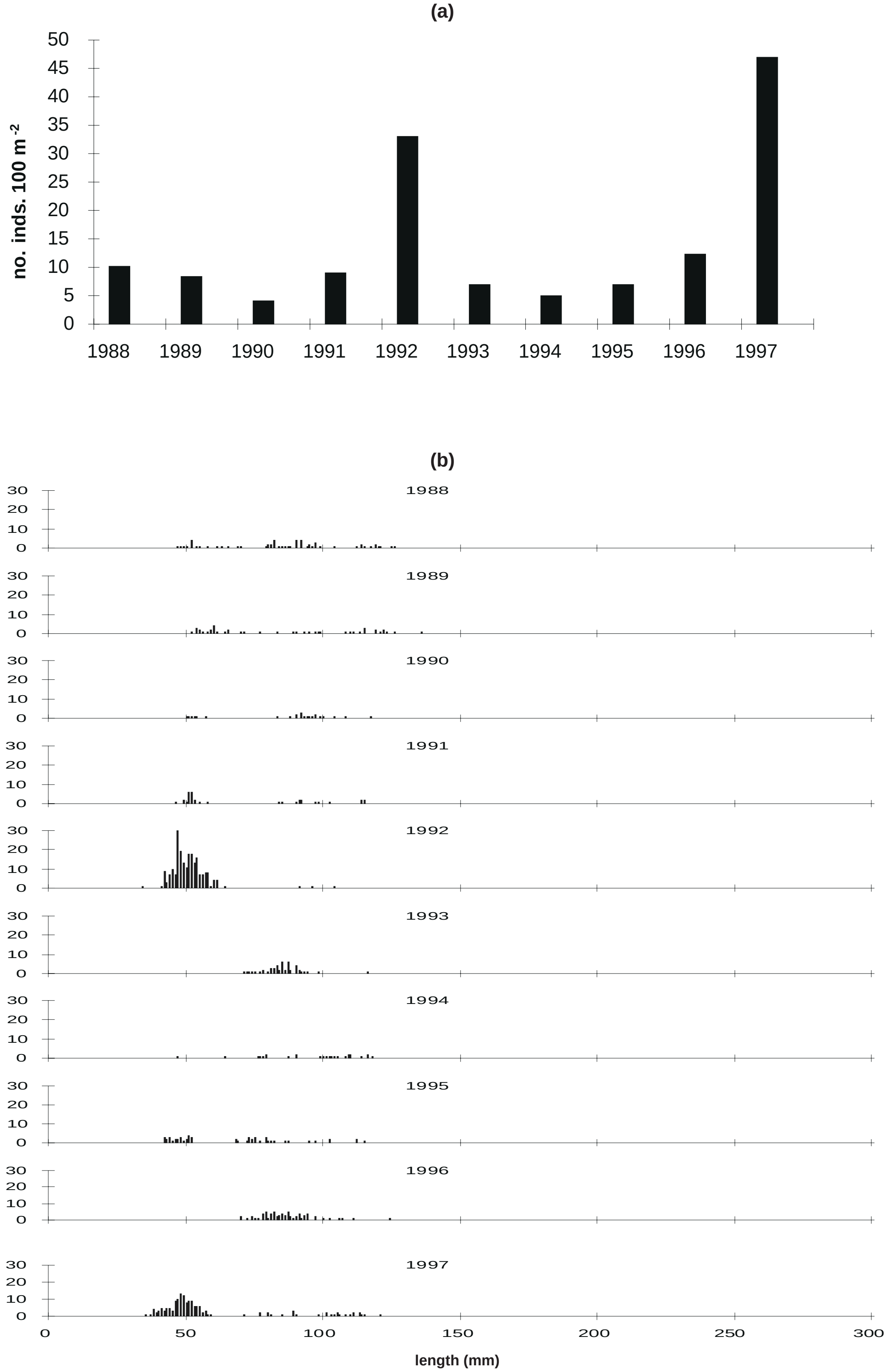


Figure 4.2.5 (i)

Allt a'Mharcaidh: summary of fish data (1988 - 1997)
(c) Trout length frequency summaries (1988 - 1997)

Figure 4.2.5 (ii)

Allt a'Mharcaidh: summary of fish data (1988-1997)
(a) Mean site density of salmon (all age classes)
(b) Salmon length frequency summaries (1988-1997)



4.3 Allt na Coire nan Con

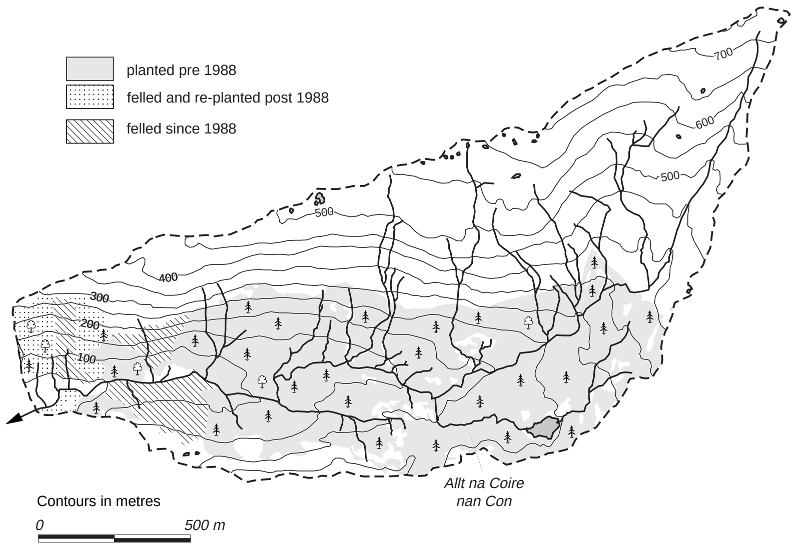


Figure 4.3.1

Allt na Coire nan Con: catchment

■ Site Review

Allt na Coire nan Con, in the Strontian region of northwest Scotland, is a fast flowing stream within a partially forested catchment. The bulk of the catchment was planted (predominantly with spruce and larch) around 1970. Grazing on the upper slopes is confined to deer. Considerable felling and some re-planting has been carried out, particularly over the last 5 years (see Figure 4.3.1), including areas close to the survey and sampling stretches.

■ Water Chemistry

(Figure 4.3.2, Table 4.3.2-3)

Mean pH (5.85) and alkalinity (22 μeq l^{-1}) are somewhat lower than at Loch Coire nan Arr, the other northwest Scotland site, and mean xSO_4 (30 μeq l^{-1}) substantially higher. A number of acidic episodes have been recorded, with pH falling below 5.0 and alkalinity becoming negative during the most severe events. Sea-salt inputs are extremely high, since the catchment is very close to the west coast. As winter sea-salt deposition events

Table 4.3.1

Allt na Coire nan Con: site characteristics

Grid reference	*NM 793688*
Catchment area	*790 ha*
Minimum catchment altitude	*10 m*
Maximum catchment altitude	*756 m*
Catchment Geology	*schists and gneiss*
Catchment Soils	*peaty podsols,*
	peaty gleys, peats
Catchment vegetation	*conifers 42%*
	recently felled 4%
	moorland 54%
Mean annual rainfall	*2582 mm*
1996 deposition	
Total S	*22 kg ha^{-1} yr^{-1}*
non-marine S	*12 kg ha^{-1} yr^{-1}*
Oxidised N	*5 kg ha^{-1} yr^{-1}*
Reduced N	*6 kg ha^{-1} yr^{-1}*

Table 4.3.2

Allt na Coire nan Con: summary of chemical determinands, June 1988 - March 1998

Determinand		Mean	Max	Min
pH		*5.85*	*6.70*	*4.96*
Alkalinity	μeq l^{-1}	*21.6*	*98.0*	*-11.0*
Ca	μeq l^{-1}	*57.5*	*107.5*	*22.5*
Mg	μeq l^{-1}	*67.5*	*175.0*	*25.0*
Na	μeq l^{-1}	*262.2*	*569.6*	*152.2*
K	μeq l^{-1}	*9.0*	*18.5*	*2.6*
SO_4	μeq l^{-1}	*61.3*	*110.4*	*35.4*
xSO_4	μeq l^{-1}	*30.2*	*81.5*	*-7.7*
NO_3	μeq l^{-1}	*4.3*	*17.1*	*< 1.4*
Cl	μeq l^{-1}	*296.3*	*816.9*	*126.8*
Soluble Al	μg l^{-1}	*65.7*	*131.0*	*12.0*
Labile Al	μg l^{-1}	*17.4*	*98.0*	*< 2.5*
Non-labile Al	μg l^{-1}	*48.5*	*110.0*	*10.0*
DOC	mg l^{-1}	*3.9*	*10.0*	*< 0.1*
Conductivity	μS cm^{-1}	*46.3*	*108.0*	*20.0*

tend to coincide with periods of high rainfall, it is likely that the major winter acid episodes result from the net effects of marine ion displacement of H^+ ions and base cation dilution. NO_3, although still low (mean 4.3 μeq l^{-1}), is present at measurable concentrations during winter periods, suggesting the commencement of nitrogen saturation. Since estimated moorland S and N deposition are similar at the two north western sites (Tables 4.1.1 and 4.3.1), the more impacted nature of Allt na Coire nan Con may result from elevated dry deposition inputs to the large area of coniferous forest.

SKT analysis suggests a decrease in Cl over the study period, but this is not detected using regression. Since the only significant source of Cl is marine, it is likely that any apparent trend in this anion is the result of natural climatic variation. This is supported by the time series data and LOESS fit (Figure 4.3.2f) showing a period of raised Cl during the early part of the record.

Both trend detection methods indicate highly significant increases in DOC over the monitoring period, which appears to have taken place at an approximately constant rate (Table 4.3.3, Figure 4.3.2). The total estimated increase of 2.8 mg l^{-1} over the ten years is similar to that at Loch Coire nan Arr, but from a higher initial value. An associated increase is also apparent for non-labile Al. The issue of DOC trends is discussed in Section 5.2.3.

Epilithic diatoms

(Figure 4.3.3, Table 4.3.4)

The epilithic diatom flora of Allt na Coire nan Con shows considerable inter-annual variability. Samples from the early years of monitoring were dominated by *Achnanthes saxonica* (pH optima 5.7). This species was less abundant between 1993 - 1997, when *Synedra minuscula*, *A. minutissima* and *Brachysira vitrea* (all of which have slightly higher pH preferences) increased, but it became dominant again in 1998. The acidophilous species *Tabellaria flocculosa* was the dominant taxa in 1993. Diatom inferred pH values correlate closely with summer rainfall totals for the nearby Meteorological Station (Inverailort), suggesting that the species assemblage has been strongly influenced by natural pH variations linked to varying summer flow conditions (see section 7.4.1). "Sample year" is insignificant as a linear trend using RDA and restricted permutation test.

Macroinvertebrates

(Figure 4.3.4, Table 4.3.4)

The macroinvertebrate fauna is typical of a mildly acid oligotrophic stream, and is characterised by chironomidae, Simulidae and a diverse fauna of both mayflies and stoneflies. The acid sensitive mayfly *Rhithrogena semicolorata* dominated the first seven years of

Table 4.3.3

Allt na Coire nan Con: significant trends in chemical determinands (June 1988 - March 1998)

Determinand	Units	Annual trend (Regression)	Annual trend (Seasonal Kendall)
C1	μeq 1^{-1}	-	*-7.65**
DOC	mg 1^{-1}	*+0.21****	*+0.25***
Non-labile Al	μg 1^{-1}	*+1.13***	*+1.00**

** Trend significant at p < 0.05; ** trend significant at p < 0.01; *** trend significant at p < 0.001*

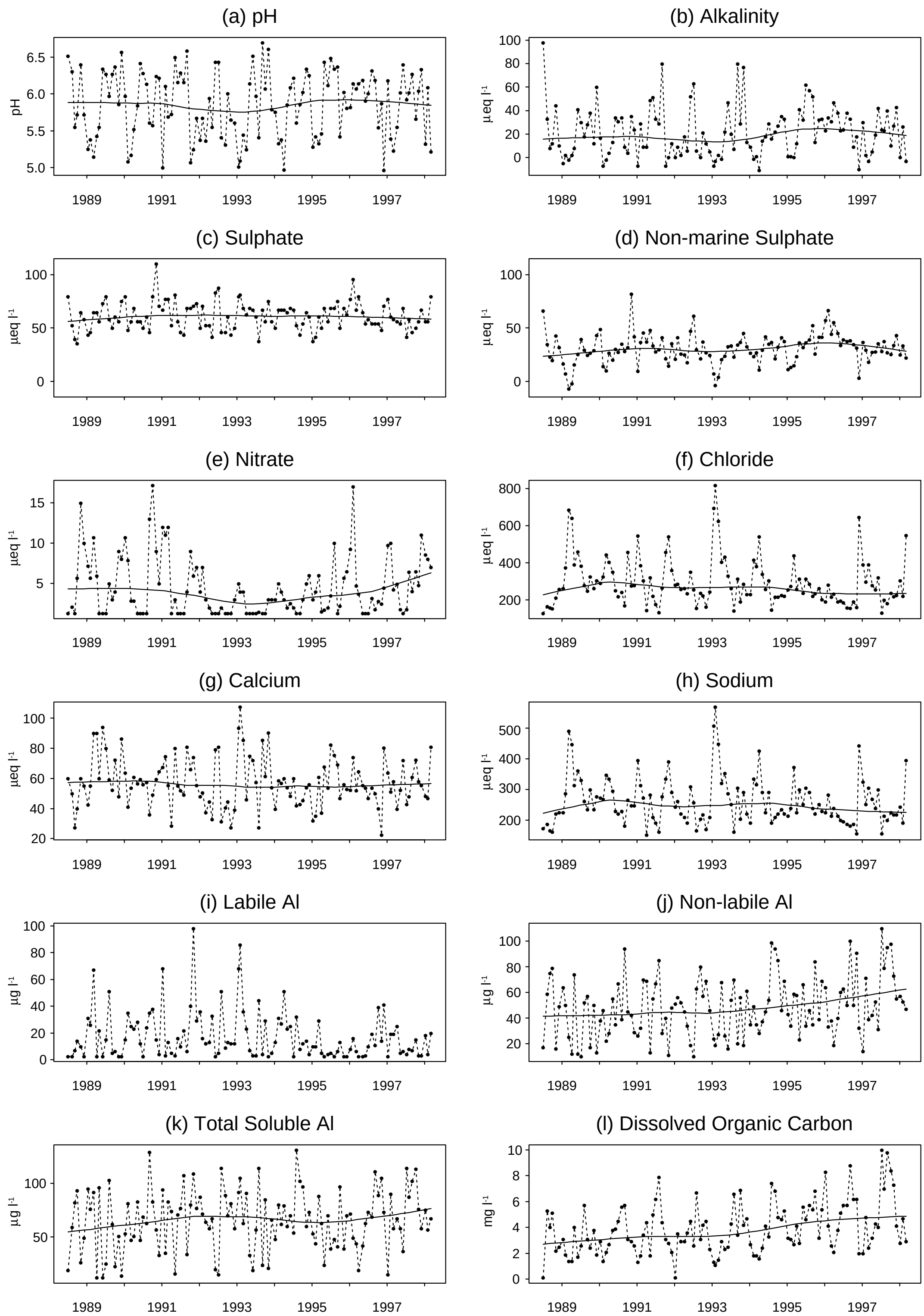


Figure 4.3.2

Allt na Coire nan Con: summary of major chemical determinands (June 1988 - March 1998)

Smoothed line represents LOESS curve (Section 3.1.2)

Table 4.3.4

Allt na Coire nan Con: trend statistics for epilithic diatom, macrophyte and macroinvertebrate summary data (1988 - 1998)

	Total sum of squares	Number of taxa	Mean N_2 diversity	λ_1RDA/λ_2RDA	λ_1RDA/λ_1PCA
Epilithic diatoms	*325*	*65*	*3.3*	*0.36*	*0.36*
Macrophytes	*27*	*7*	*2.4*	*1.16*	*0.80*
Invertebrates	*781*	*37*	*5.1*	*0.88*	*0.67*

Variance explained (%)	within year	between years	linear trend	p unrestricted	p restricted
Epilithic diatoms	*29.0*	*71.0*	*11.8*	*<0.01*	*0.03*
Macrophytes	*	*	*45.8*	*<0.01*	*<0.01*
Invertebrates	*49.4*	*50.6*	*15.8*	*0.00*	*<0.01*

the study period, while *Baetis* spp. was present throughout and showed an increase in numbers in 1996. *Siphlonurus lacustris* appeared in 1993 and *Heptagenia lateralis*, which first appeared in 1992, has shown an increase in abundance in the latter years of the study. The stonefly community includes the detritivores *Brachyptera risi*, *Leuctra inermis* and *Amphinemura sulcicollis* as well as predators *Isoperla grammatica* and *Chloroperla tripunctata*. Several 'new' species of caddisfly were recorded after 1992, among them *Chaetopteryx villosa*, *Silo pallipes* and *Lepidostoma hirtum*, the latter intolerant of very acid conditions. Moderately acid sensitive Coleoptera *Hydraena gracilis* and *Elmis aenea* were first recorded in 1994. 1990 was a very poor

Table 4.1.5

Allt na Coire nan Con: relative abundance of aquatic macrophyte flora (1988 - 1997) (see Section 3.2.3 for key to indicator values)

(% cover of 50 m survey stretch)

Year	88	89	90	91	92	93	95	96	97
INDICATOR SPECIES									
Hygrohypnum ochraceum[1]	*16.0*	*16.2*	*16.6*	*9.4*	*3.7*	*1.5*	*0.2*	*0.4*	*0.1*
Hyocomium armoricum[1]	*<0.1*	*3.6*	*0.4*	*0.7*	*0.3*	*0.1*	*<0.1*	*0.1*	*0.2*
OTHER SUBMERGED SPECIES									
Filamentous green algae	*<0.1*	*<0.1*	*0.1*	*31.9*	*<0.1*	*0.0*	*0.0*	*0.0*	*0.0*
Marsupella emarginata	*0.2*	*<0.1*	*0.0*	*0.1*	*0.0*	*0.0*	*0.0*	*0.0*	*<0.1*
Racomitrium aciculare	*0.5*	*3.9*	*<0.1*	*0.0*	*0.0*	*0.0*	*<0.1*	*0.0*	*0.0*
Scapania undulata	*0.8*	*0.4*	*2.5*	*2.1*	*1.1*	*0.4*	*0.3*	*0.7*	*0.0*
Juncus bulbosus var. *fluitans*	*0.0*	*0.0*	*<0.1*	*0.0*	*0.0*	*0.0*	*<0.1*	*0.0*	*0.0*
total macrophyte cover excluding filamentous algae	*17.5*	*24.1*	*19.5*	*12.4*	*5.4*	*2.1*	*0.6*	*1.2*	*0.5*
TOTAL NUMBER OF SPECIES	*6*	*6*	*6*	*5*	*4*	*5*	*4*	*5*	*3*

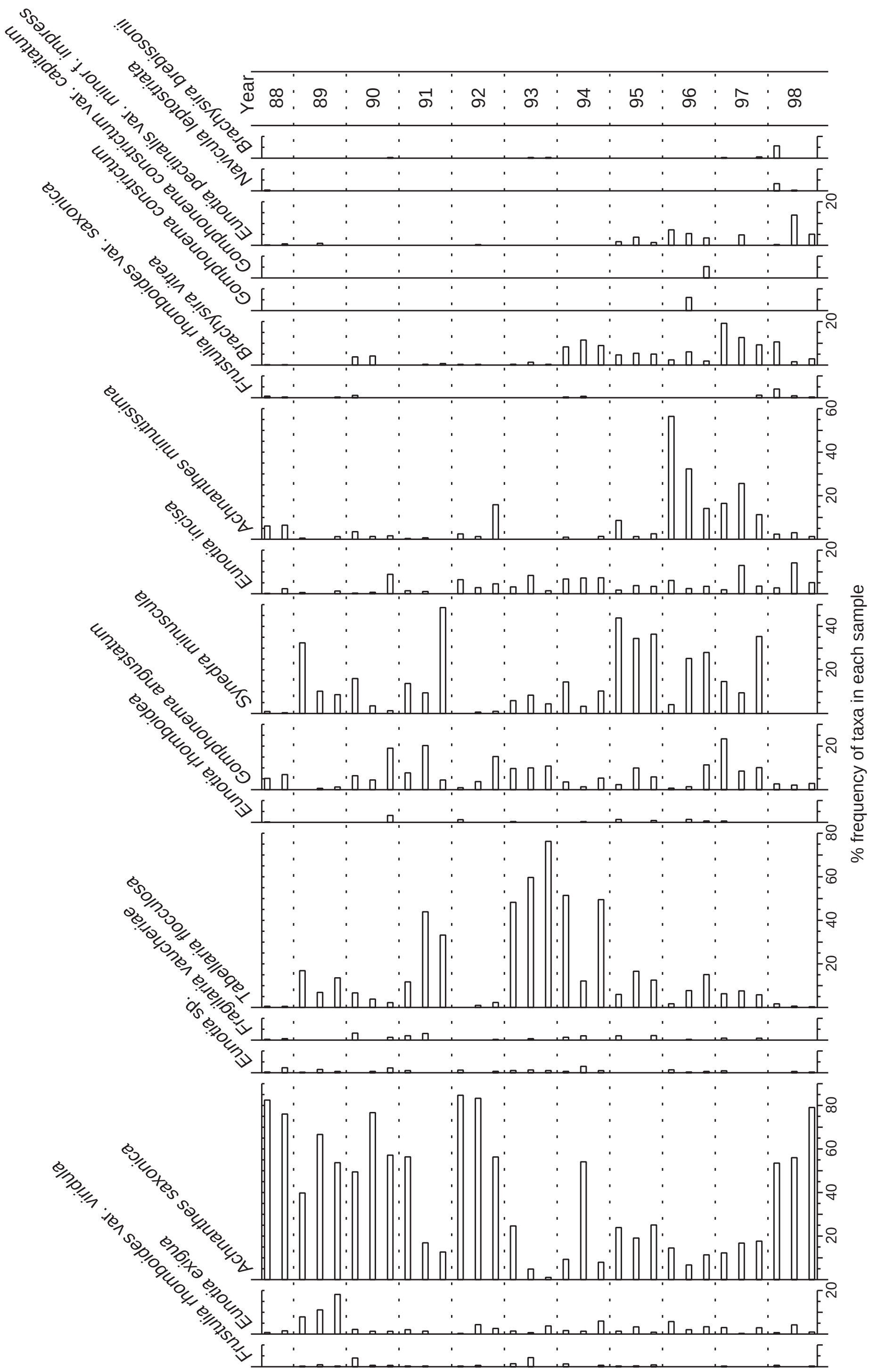


Figure 4.3.3

Allt na Coire nan Con: summary of epilithic diatom data (1988 - 1998)

Percentage frequency of all taxa occurring at >2% abundance in any one sample

year both in number of species and abundance. Time as a linear trend accounts for 15.8% of the total variance and is significant at the 0.01 level. There is some indication of an improvement in conditions as species richness has increased in the second half of the study period, although this could be linked to a decline in spring flow conditions (Section 7.4.2).

Fish

(Figure 4.3.5)

Trout densities at this site are intermediate for those found on the Network. Mean population densities of both 0+ and >0+ trout show no trends over the ten years. However, in common with several other Scottish sites, densities of 0+ fish showed a peak in 1991, and higher than average recruitment also occurred in 1990 and 1995. Very low densities of >0+ fish were recorded in three consecutive years between 1992-1994 despite the high recruitment observed in 1991. Significant negative linear trends are apparent in the coefficient of variation of CF for the 0+ group ($p<0.01$ df = 8) and the condition factor of the >0+ group ($p<0.01$ df = 8). The causes of these apparently conflicting trends are unclear, with the former suggesting improved conditions for newly recruited trout and the latter possibly suggesting deterioration. Neither trend appears to relate to temporal variation in density.

Macrophytes

(Tables 4.3.4-5)

The aquatic macroflora of Allt na Coire nan Con was dominated by the acid sensitive moss *Hygrohypnum ochraceum* during the first few years of monitoring. However, the cover of this species reduced substantially after 1991 and by 1997 only a few isolated plants were present in the survey stretch. Given the absence of any deterioration in water chemistry, it seems most likely that the reduction in cover has resulted from physical scouring during storm events. These could have become more abrupt following clear felling within the catchment and the consequent effects on catchment hydrology. In addition, the amount of timber debris in the survey channel has increased in recent years; this is perhaps indicative of a general increase in the suspended load of the stream which would also have had a detrimental effect on plant growth. As at the Allt a'Mharcaidh, where a recent storm event is also suspected to have had an impact on the dominant moss, the ubiquitous and acid-tolerant liverwort *Scapania undulata* does not show a similar reduction in cover. The changes in cover with time are statistically significant at the 0.01 level according to RDA and associated restricted permutation tests and almost certainly result from the physical influences described above.

Summary

Allt na Coire nan Con is not chronically acidic, but moderate levels of anthropogenic S and N are present in runoff, thought to have been increased by the presence of forestry within the catchment. Acidic episodes have been observed, driven by sea-salt deposition and high rainfall events and the reduction in these in the latter half of the record could account for the observed changes in the macroinvertebrate community. The summer flow regime appears to have exerted a strong influence on the diatom flora, while possible changes in the hydrological pathway and increased suspended load as a result of catchment felling may have contributed to the reduction in aquatic moss cover. However at this stage there is little evidence of the effect of tree felling on water chemistry. Strong rising trends have been observed in DOC and non-labile Al. Since these are observed in several other Scottish sites they are not likely to reflect within catchment changes.

Figure 4.3.4

Allt na Coire nan Con: summary of macroinvertebrate data (1988 - 1998)

Percentage frequency of taxa in individual samples

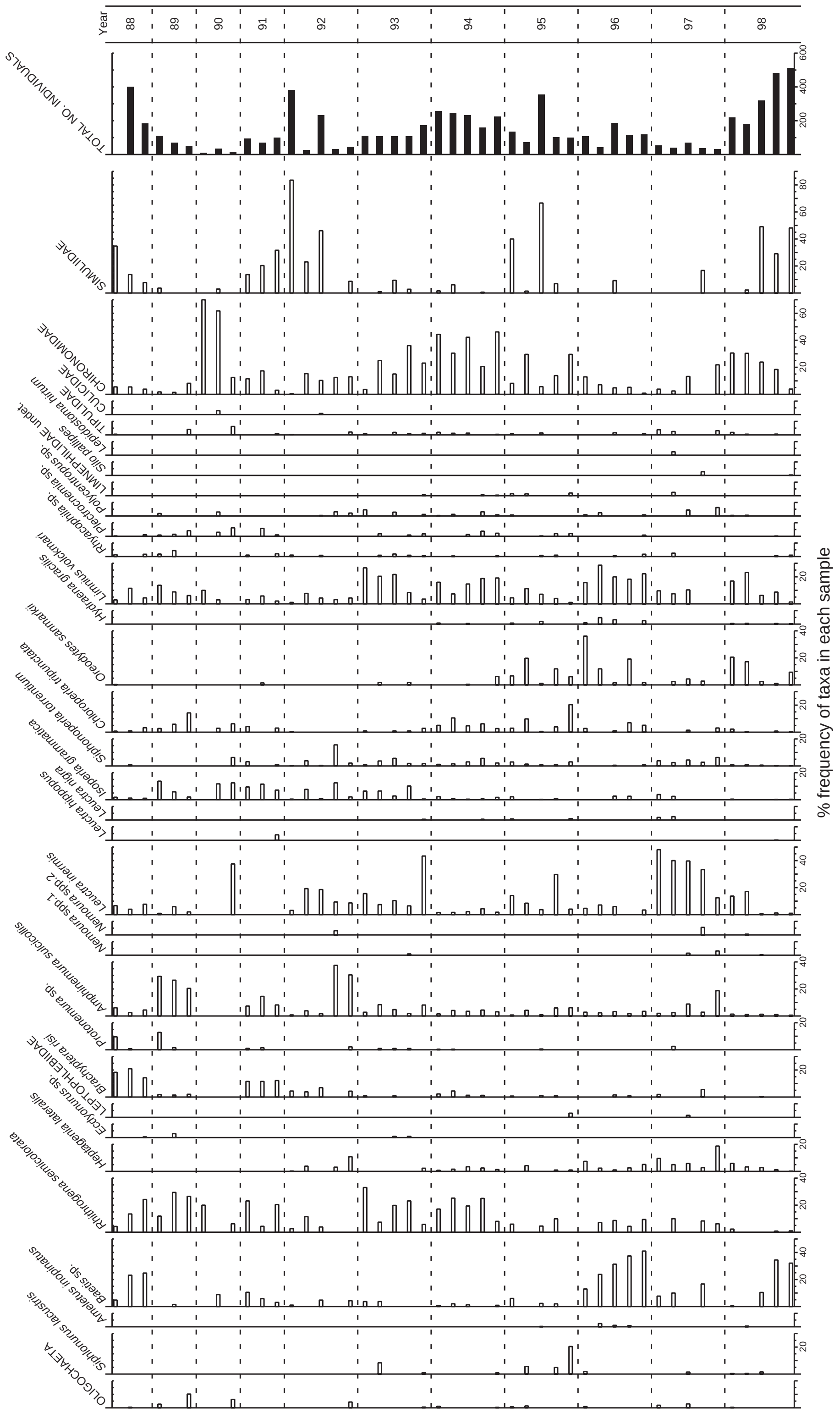
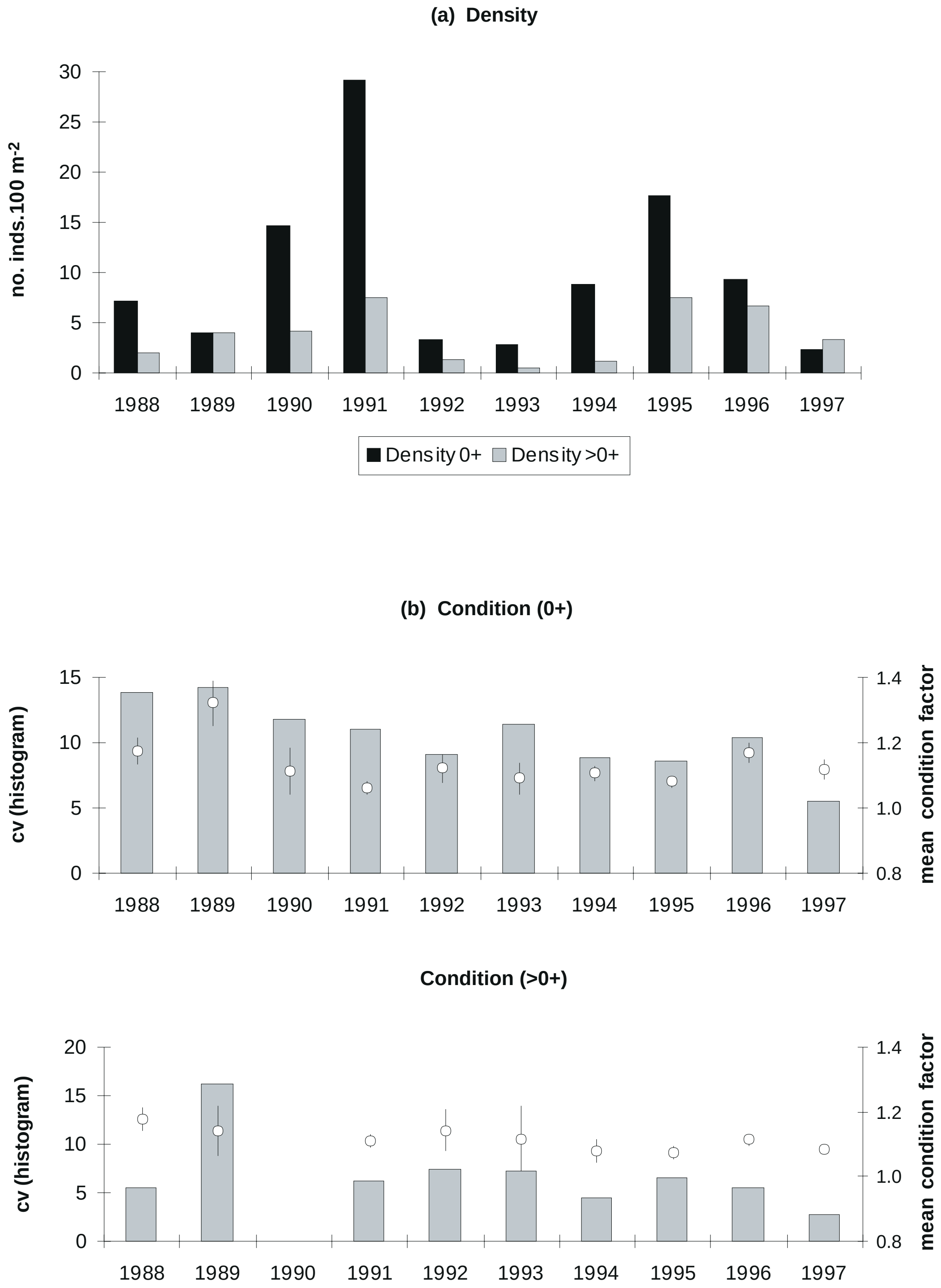


Figure 4.3.5 (i)

Allt na Coire nan Con: summary of fish data (1988 - 1997)
(a) Trout population density for 0+ and >0+ age classes (individuals 100 m-²)
(b) Mean condition factor (with standard deviation) of the trout population and its coefficient of variation (histogram)



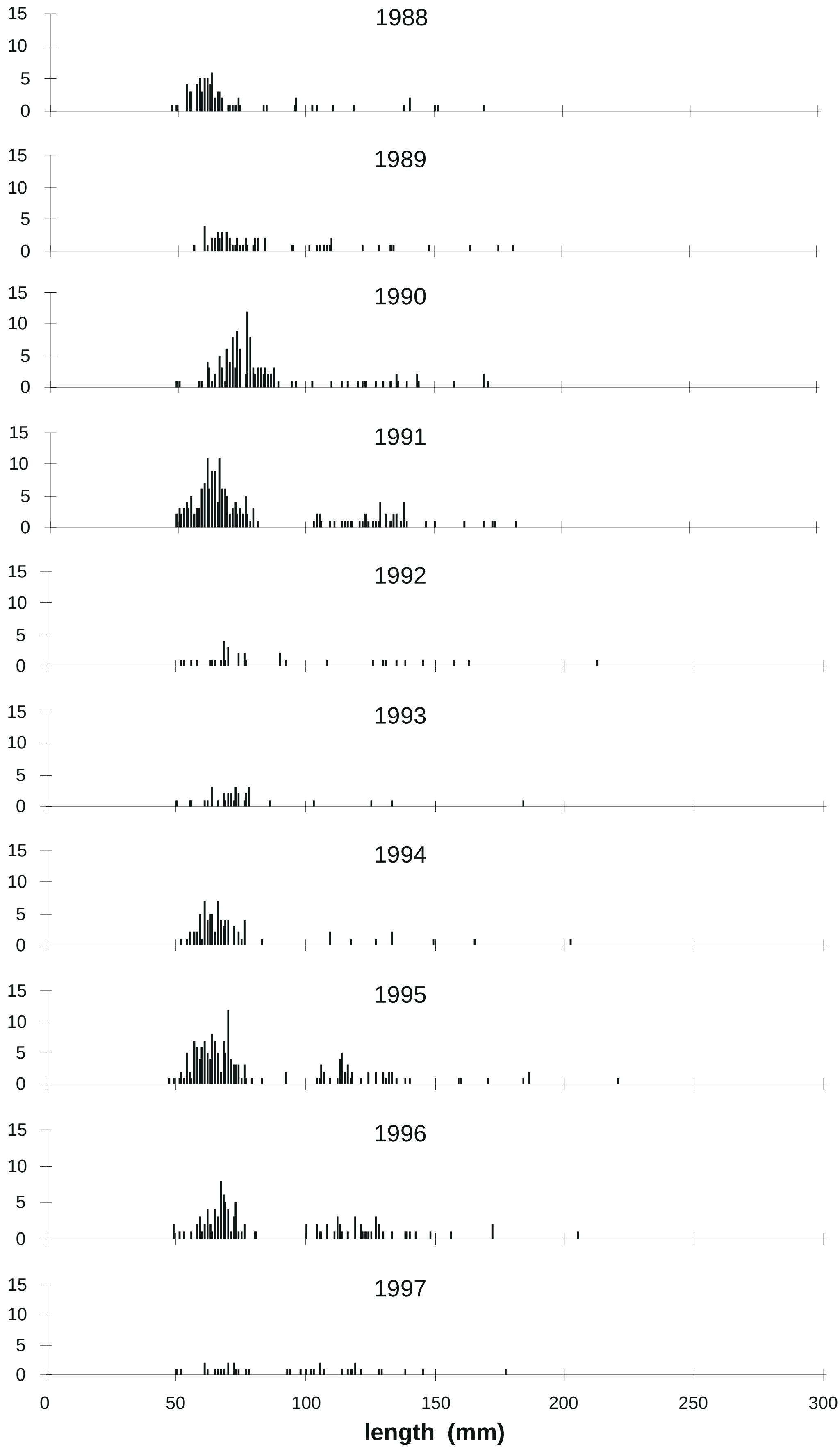
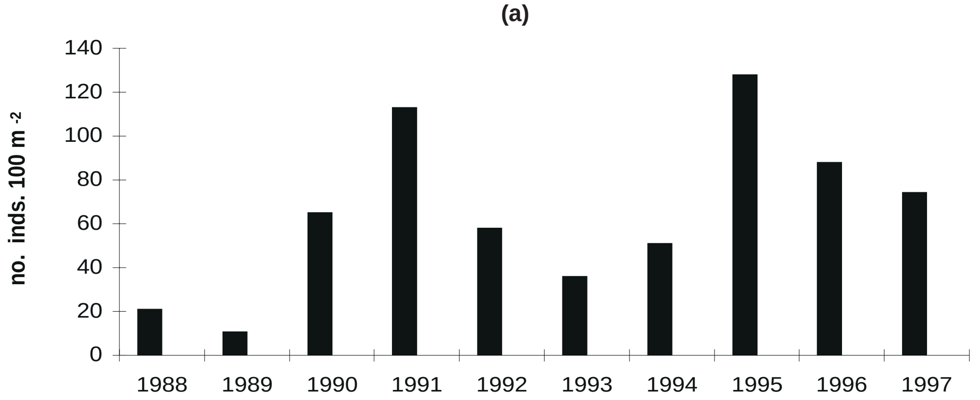


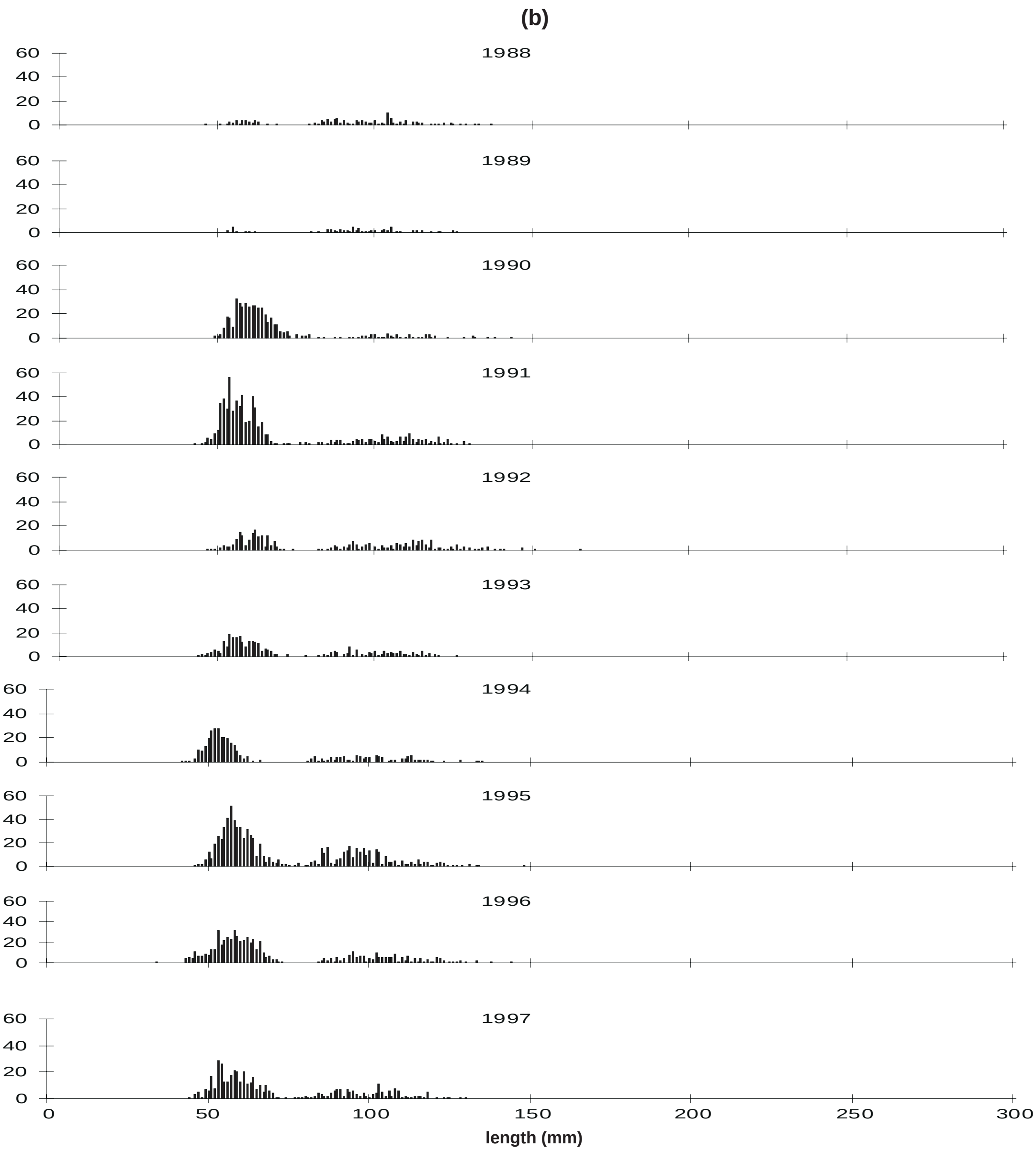
Figure 4.3.5 (i)

Allt na Coire nan Con: summary of fish data (1988 - 1997)
(c) Trout length frequency summaries (1988 - 1997)

Figure 4.3.5 (ii)

Allt na Coire nan Con: summary of fish data (1988-1997)
(a) Mean site density of salmon (all age classes)
(b) Salmon length frequency summaries





4.4 Lochnagar

Site Review

At an altitude of 785 m in the Grampian Mountains of northeast Scotland, Lochnagar is the highest of the UKAWMN lakes. Palaeoecological pH reconstruction indicates that Lochnagar acidified from around pH 5.6, in the mid-nineteenth century, to around pH 5.0 by the 1940s (Patrick *et al.* 1989, Patrick *et al.* 1995). Although prone to a considerable duration of ice cover during some winters, the extent of the freezing period has been highly variable over the past decade, with ice only present for a few days during the winter of 1997-1998. Scientific work at Lochnagar has increased since its inclusion in the EU funded mountain lakes projects AL:PE, MOLAR, CHILL and, most recently, EMERGE, in addition to a DETR study of the impact of heavy metals deposition and additional sampling carried out for the Environmental Change Network. There have been no physical disturbances in the catchment, other than occasional scree falls from the corrie back-wall, since the onset of monitoring in 1988.

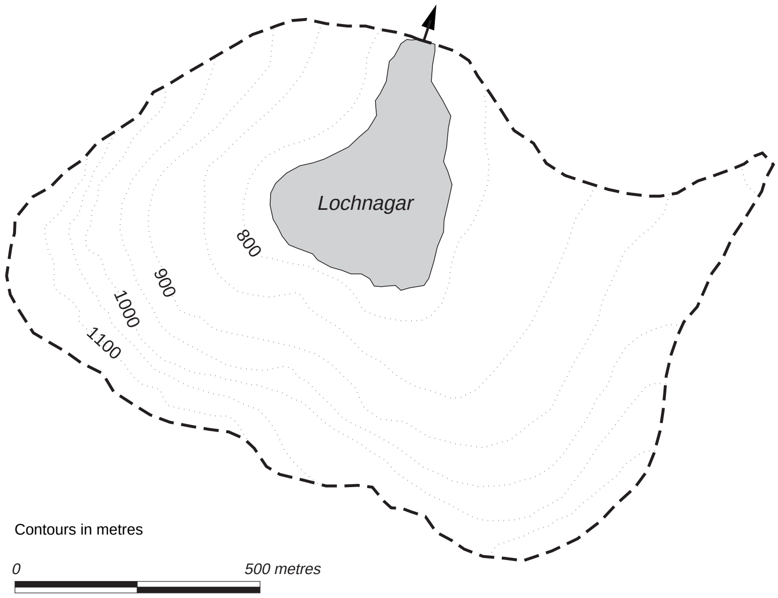


Figure 4.4.1

Lochnagar: catchment

Table 4.4.1

Lochnagar: site characteristics

Grid reference	*NO 252859*
Lake altitude	*785 m*
Maximum depth	*26 m*
Mean depth	*8.4 m*
Volume	*8.2×10^5 m^3*
Lake area	*9.8 ha*
Catchment area (excl. lake)	*91.9 ha*
Catchment: Lake area ratio	*9.37*
Catchment Geology	*granite*
Catchment Soils	*peats*
Catchment vegetation	*alpine - moorland 100%*
Net relief	*370 m*
Mean annual rainfall	*1536 mm*
1996 deposition	
Total S	*16 kg ha^{-1} yr^{-1}*
non-marine S	*13 kg ha^{-1} yr^{-1}*
Oxidised N	*6 kg ha^{-1} yr^{-1}*
Reduced N	*8 kg ha^{-1} yr^{-1}*

Table 4.4.2

Lochnagar: summary of chemical determinands, June 1988 - March 1998

Determinand		Mean	Max	Min
pH		*5.33*	*5.81*	*4.95*
Alkalinity	µeq l^{-1}	*0.6*	*12.0*	*-10.0*
Ca	µeq l^{-1}	*29.0*	*50.0*	*21.5*
Mg	µeq l^{-1}	*33.3*	*58.3*	*25.0*
Na	µeq l^{-1}	*93.9*	*173.9*	*69.6*
K	µeq l^{-1}	*7.4*	*12.8*	*2.6*
SO_4	µeq l^{-1}	*57.7*	*85.4*	*45.8*
xSO_4	µeq l^{-1}	*48.3*	*74.4*	*35.4*
NO_3	µeq l^{-1}	*15.7*	*30.7*	*< 1.4*
Cl	µeq l^{-1}	*89.3*	*166.2*	*50.7*
Soluble Al	µg l^{-1}	*41.8*	*147.0*	*4.0*
Labile Al	µg l^{-1}	*25.5*	*137.0*	*< 2.5*
Non-labile Al	µg l^{-1}	*16.5*	*41.0*	*< 2.5*
DOC	mg l^{-1}	*1.1*	*3.4*	*0.2*
Conductivity	µS cm^{-1}	*21.8*	*35.0*	*4.0*

Water Chemistry

(Figure 4.4.2, Table 4.4.2-3)

Lochnagar is acidic with a ten year mean pH of 5.33 and a mean alkalinity of 0.6 μeq l^{-1}. Unlike the other sites in northern Scotland, mean labile Al concentrations exceed those of non-labile Al. Much of the Lochnagar catchment comprises bare granite or thin soils, resulting in a very limited buffering capacity (mean Ca=29 μeq l^{-1}) and therefore high sensitivity to acid deposition. The mean xSO_4 concentration of 48 μeq l^{-1} is higher than at the other northern Scotland sites, and NO_3 is also moderately high with a mean of 15.7 μeq l^{-1}. It is probable that, due to the sparse soil and vegetation cover, and low ambient temperature, the catchment has little ability to immobilise incoming N deposition, and has therefore reached a more advanced stage of N saturation than lower altitude catchments in the same region. Marine ion concentrations are lower and less variable than at west coast sites, and in general it appears that the site is not subject to major episodic variations, with ranges of pH (4.95 to 5.81) and alkalinity (-10 to 12 μeq l^{-1}) among the lowest in the Network. Seasonal variations are also weak or absent, perhaps reflecting the low level of biological activity within the catchment.

Trend analyses (Table 4.4.3) indicate that the chemistry of Lochnagar has changed substantially over the last decade. Both SKT and regression suggest that xSO_4 has fallen slightly (5 or 8 μeq l^{-1} respectively), whilst NO_3 has risen over the same period (11 or 14 μeq l^{-1}). The combined effect of these trends should be a reduction in pH and alkalinity, and a declining trend is indeed observed for pH using regression, although not SKT. Examination of time series and LOESS plots confirm that a reasonably linear xSO_4 decline has taken place over the last ten years. However the increase in NO_3 and associated decrease in pH appear to have occurred during a short period, from 1992-1995, since when concentrations have remained fairly stable. The possibility that the NO_3 increase reflects a short term climatic fluctuation, possibly due to climatic variability, cannot therefore be ruled out at this stage; further sampling should help to clarify this issue. As at most other UKAWMN, regression analysis suggests that DOC has risen during the last ten years, in this case by approximately 0.8 mg l^{-1}.

Epilithic diatoms

(Figure 4.4.3, Table 4.4.4)

The epilithic diatom flora of Lochnagar is relatively diverse and dominated by acidophilous taxa. *Achnanthes marginulata* (pH optima 5.2) is generally the most abundant species, although *Tabellaria flocculosa* (pH optima 5.4) was more abundant in 1991 and more recently in 1997-1998. *Eunotia incisa* (pH optima 5.1) was relatively abundant from 1990-1992 but has since declined. Diatom inferred pH (derived from weighted averaging) demonstrates that the

Table 4.4.3

Significant trends in chemical determinands (July 1988 - March 1998)

Determinand	Units	Annual trend (Regression)	Annual trend (Seasonal Kendall)
pH		*-0.020**	-
SO_4	μeq l^{-1}	*-0.94**	*-0.52**
xSO_4	μeq l^{-1}	*-1.00***	*-0.67***
NO_3	μeq l^{-1}	*+1.43****	*+1.13**
DOC	mg l^{-1}	*+0.08**	-

** Trend significant at $p < 0.05$; ** trend significant at $p < 0.01$; *** trend significant at $p < 0.001$*

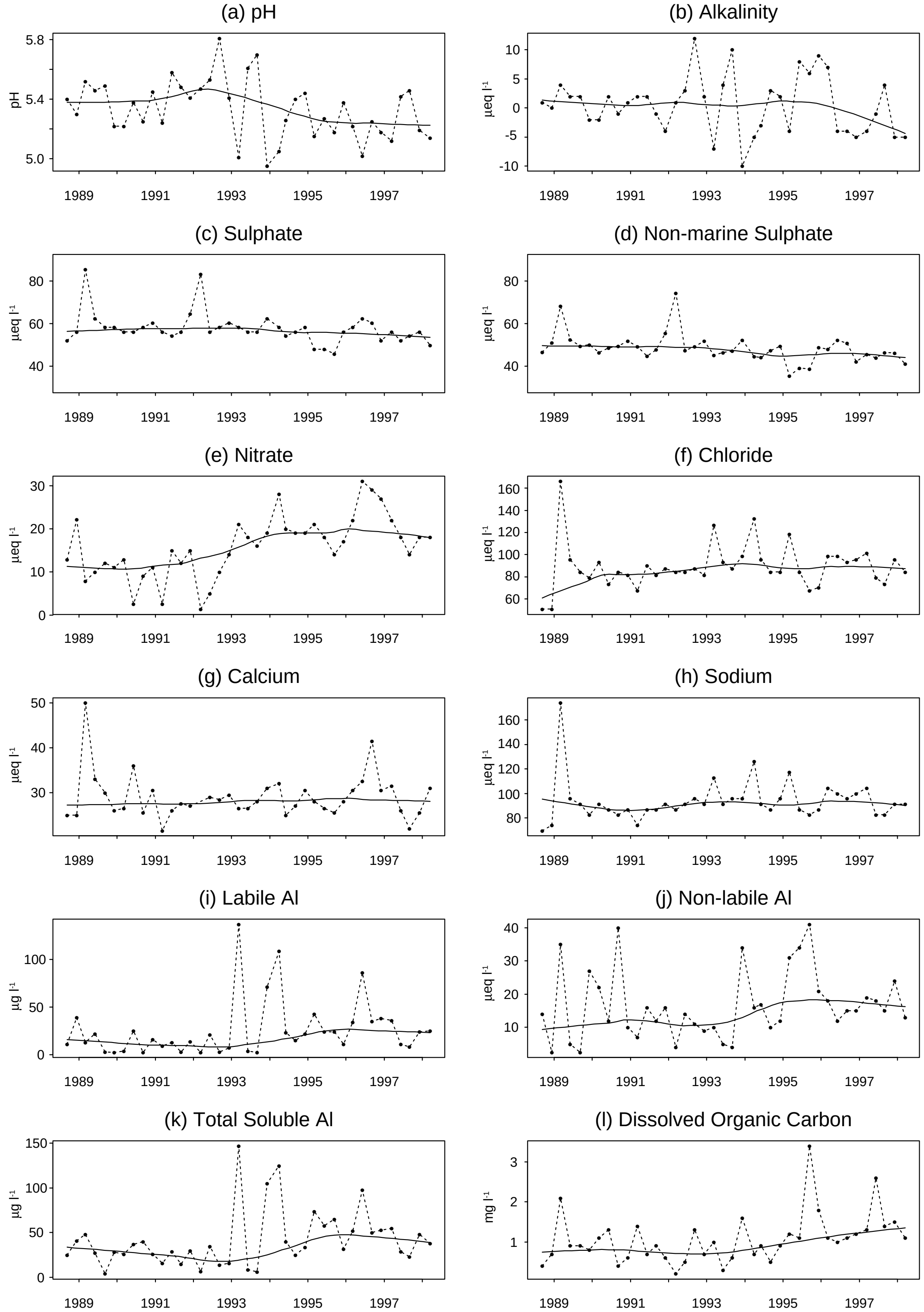


Figure 4.4.2

Lochnagar: summary of major chemical determinands (September 1988 - March 1998)

Smoothed line represents LOESS curve (Section 3.1.2)

Table 4.4.4

Lochnagar: trend statistics for epilithic diatom, macrophyte and macroinvertebrate summary data (1988 - 1998)

	Total sum of squares	Number of taxa	Mean N_2 diversity	λ_1RDA/λ_2RDA	λ_1RDA/λ_1PCA
Epilithic diatoms	481	145	7.2	0.26	0.26
Macrophytes	18	11	6.5	0.32	0.30
Invertebrates	871	25	2.5	0.52	0.40

Variance explained (%)	within year	between years	linear trend	p unrestricted	p restricted
Epilithic diatoms	56.3	43.7	5.2	0.06	0.44
Macrophytes	-	-	15.8	0.34	0.12
Invertebrates	43.0	57.0	10.4	0.00	0.00

assemblage reflects the deterioration in pH evident from water chemistry samples since 1993. Despite this, RDA and associated restricted permutation test show no significant linear time trend over the full period, at the 0.01 level. The sediment trap record for Lochnagar only began in 1991 and the sample for 1992 was lost (Figure 4.4.6). No trends are evident in this limited dataset, although there are clear similarities in species representation with the epilithon.

Macroinvertebrates

(Figure 4.4.4, Table 4.4.4)

The impoverished macroinvertebrate fauna is typical of a moderately acidic, high altitude lake. The fauna is dominated by chironomids and the stonefly *Capnia* spp., which is patchy in its occurrence (only one individual was recorded in

Table 4.4.5

Lochnagar: relative abundance of aquatic macrophyte flora (1988 - 1997) (see Section 3.2.3 for key to indicator values)

Abundance Taxon Year	88	89	90	91	92	93	95	97
INDICATOR SPECIES								
Sphagnum auriculatum[4]	3	3	3	3	3	3	3	3
Juncus bulbosus var. *fluitans*[4]	1	2	2	2	2	2	2	3
OTHER SUBMERGED SPECIES								
Filamentous green algae	1	3	0	2	1	1	2	1
Fontinalis antipyretica	1	0	1	1	1	1	1	1
Racomitrium aciculare	0	0	1	0	0	0	1	1
Cephalozia connivens	0	0	1	0	0	0	0	0
Marsupella emarginata	0	0	0	0	1	0	0	0
Nardia compressa	1	1	3	2	3	2	2	2
Plectocolea obovata	0	1	1	0	0	0	0	0
Scapania undulata	3	3	3	3	3	3	3	3
Isoetes lacustris	2	2	2	2	2	2	2	2
TOTAL NUMBER OF SPECIES	7	7	9	7	8	7	8	8

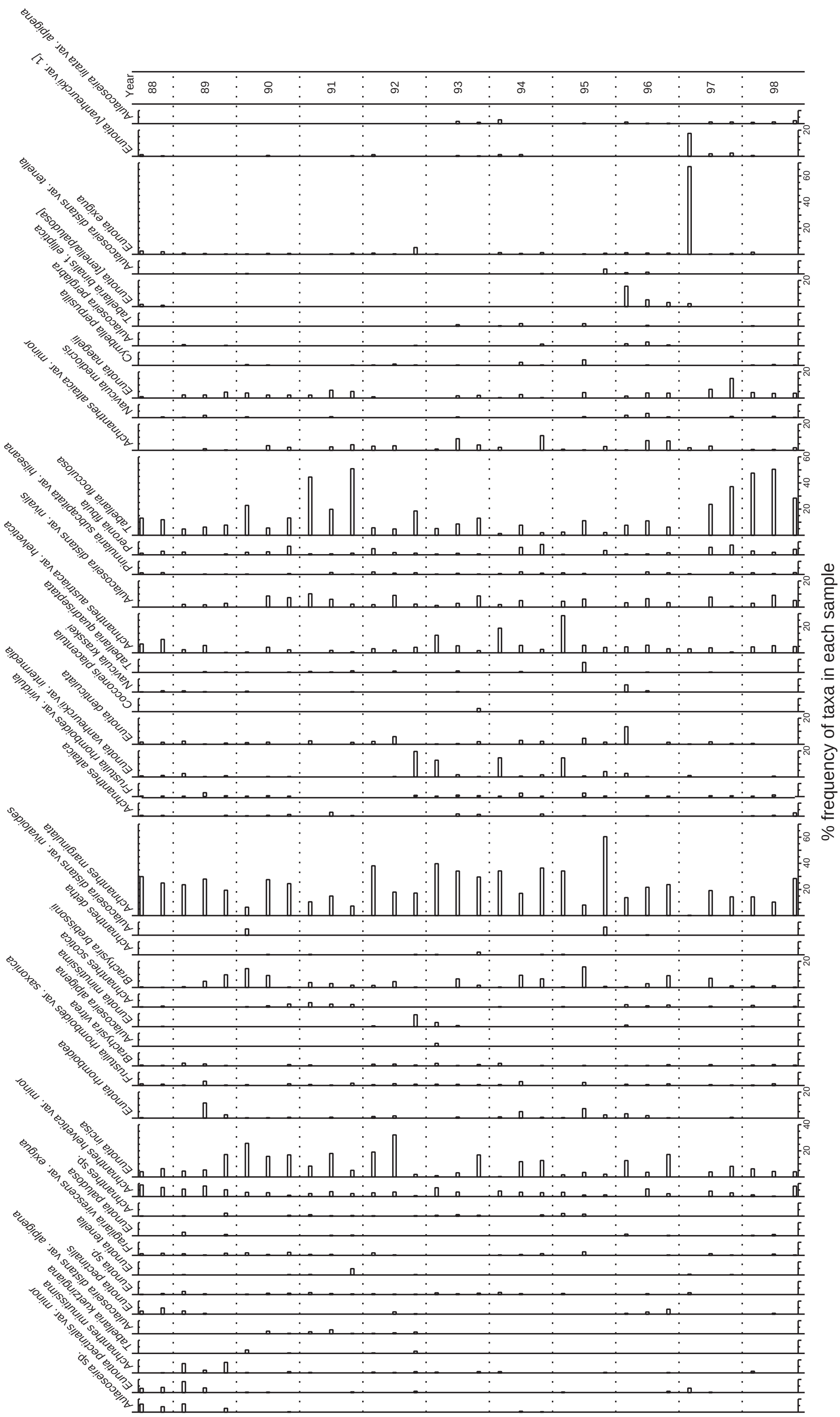


Figure 4.4.3

Lochnagar: summary of epilithic diatom data (1988 - 1998)

Percentage frequency of all taxa occurring at >2% abundance in any one sample

1994). Several other species of stonefly are present including *Diura bicaudata* and *Siphonoperla torrentium*. Acid tolerant stoneflies *Nemurella pictetii* and *Protonemura* spp. appeared after 1991. Other common taxa include the water beetle, *Oreodytes davisii*, and members of the caddisfly family, the Limnephilidae, and the Tipulidae. Time as a linear trend is significant at the 0.01 level. The apparent shift in stonefly species, from *Nemoura* spp. to *Nemurella picteti*, the increase in the relative abundance of *Plectrocnemia* sp. and *Polycentropus* sp., and the general decline in species richness, are all indicative of increasing acidity.

Fish

(Figure 4.4.5)

The outflow stream of Lochnagar has been fished since 1989. The electrofishing site is significantly downstream of the water chemistry sampling point and it is likely that geological buffering results in less acid conditions than those experienced at the actual outflow. This could explain why, when the Loch trout population is believed to be impoverished, densities within the fishing stretch are high, and indeed the highest found in the Network. Densities of 0+ group fish were relatively low for the site in 1993, 1996 and 1997, but no trends are apparent over the nine years of data. Densities of >0+ group are variable, three years (1990, 1991 & 1996) being significantly above average. Condition factor and the coefficient of variation of the condition factor for both age groups also show no time trends. Length frequency graphs indicate a healthy population structure, although numbers of larger fish (>100 mm) are relatively low in certain years. This feature does not seem to be linked to the recruitment reductions mentioned above.

Aquatic macrophytes

(Tables 4.4.4-5)

The impoverished macroflora of Lochnagar reflects the extreme altitude and acidity of the site. *Isoetes lacustris* and *Juncus bulbosus* var. *fluitans* are the only vascular species which appear able to withstand a combination of adverse factors including low nutrient availability, the effects of ice scouring, low ambient temperature and strong wave action. The Loch is dominated by liverworts, and particularly *Nardia compressa*, while the moss *Fontinalis antipyretica* is present in a few isolated locations. The cover of *Juncus bulbosus* var. *fluitans* along two of the three fixed transects has expanded in recent years, and there is also evidence for an increase in other areas of the loch. Expansion of this species in low altitude soft-water lakes in the Netherlands is well documented and attributed to N enrichment, particularly from ammonium sources (Roelofs *et al*., 1984, Schuurkes *et al*. , 1987). It is unlikely that the NH_4 supply to the Loch has increased recently but the observed changes may be linked to rising NO_3 concentrations. Despite this observation, linear change in relative abundance with time is insignificant according to RDA and associated restricted permutation test.

Summary

Due to its high altitude and thin soils, Lochnagar appears to have been significantly acidified by low-moderate levels of acid deposition. Trend analyses indicate that although xSO_4 concentrations are now declining at the site, a large rise in NO_3 over the past decade has led to an overall worsening of Loch acidity. This appears to be reflected in the changing species assemblages of epilithic diatoms and macroinvertebrates, and possibly in the expansion of cover of the acidophilous aquatic macrophyte *Juncus bulbosus* var. *fluitans*. The density of newly recruited trout, downstream of the Loch outflow, has fallen over the last two years of monitoring but is still considered high for an acid system.

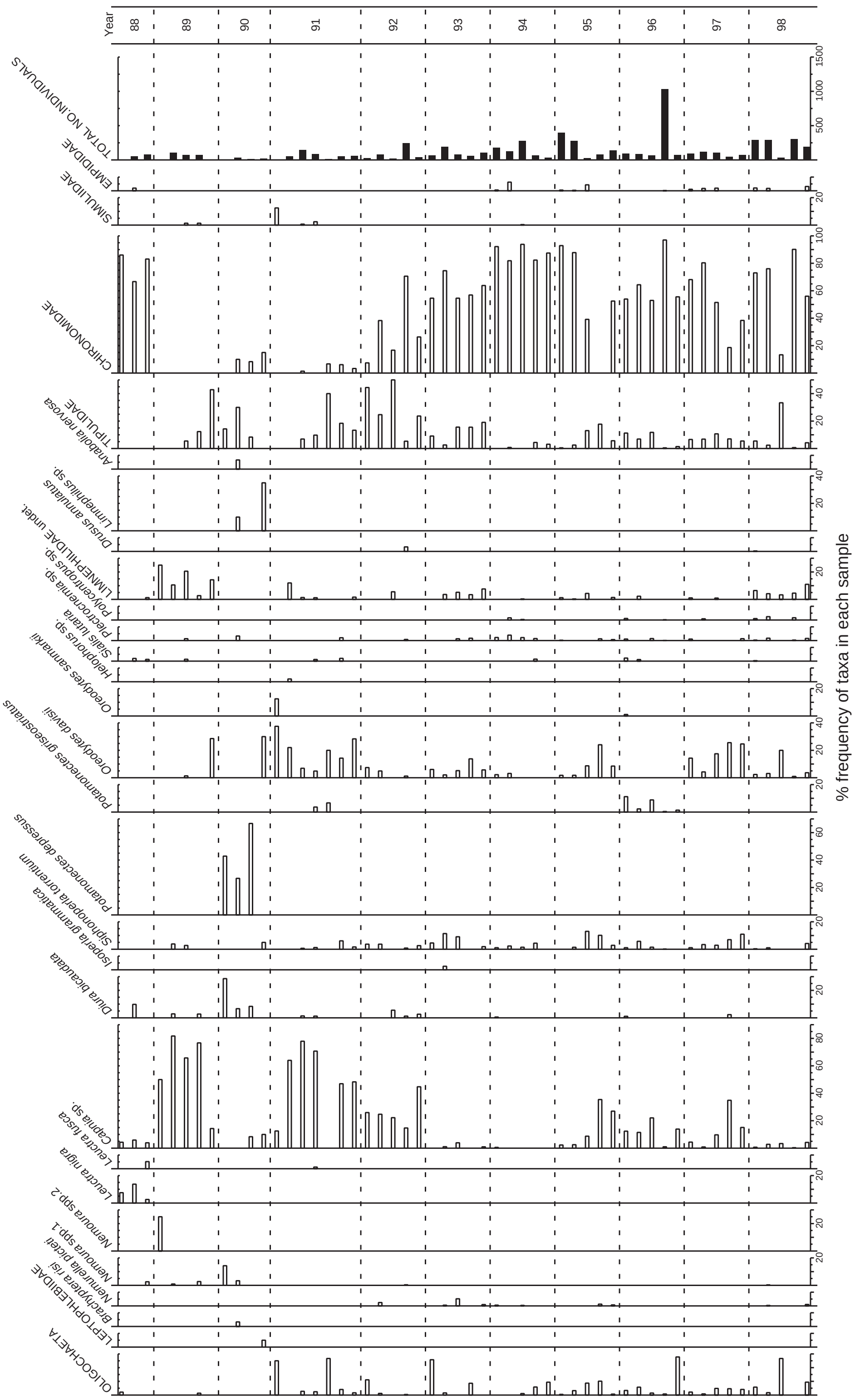


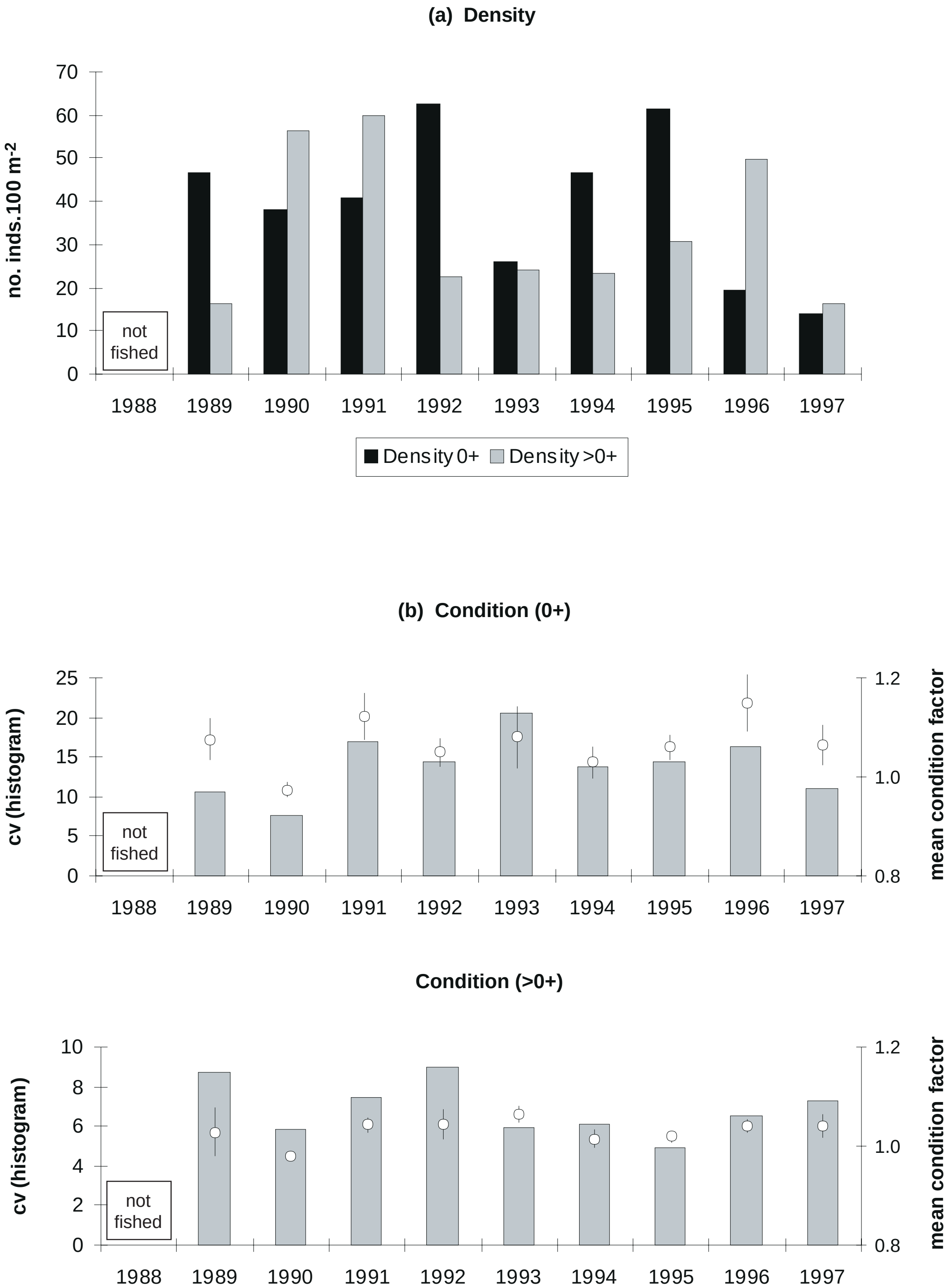
Figure 4.4.4

Lochnagar: summary of macroinvertebrate data (1988 - 1998)

Percentage frequency of taxa in individual samples

Figure 4.4.5

Lochnagar: summary of fish data (1989 - 1997)
(a) Trout population density for 0+ and >0+ age classes (individuals 100 m^{-2})
(b) Mean condition factor (with standard deviation) of the trout population and its coefficient of variation (histogram)



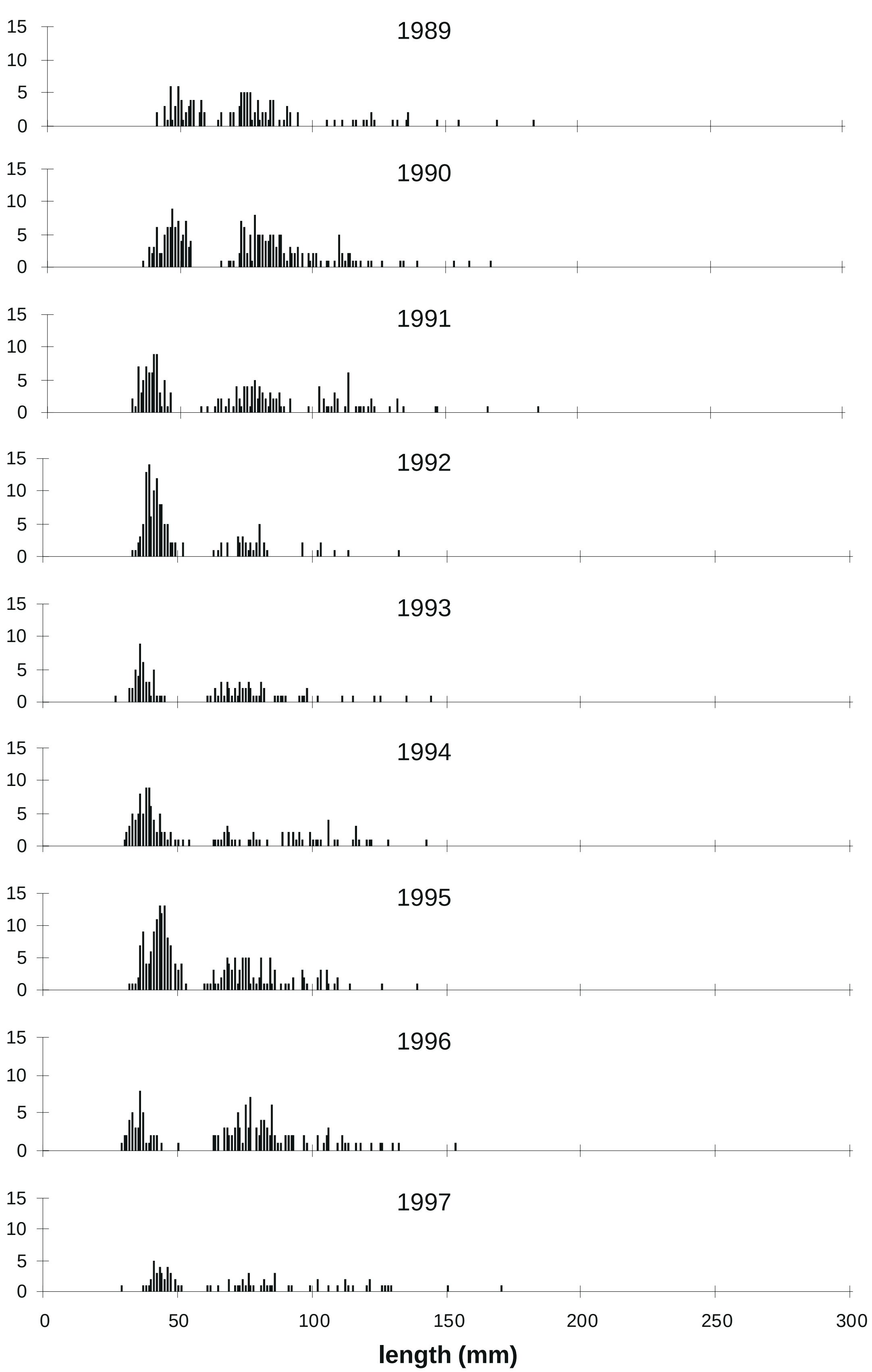


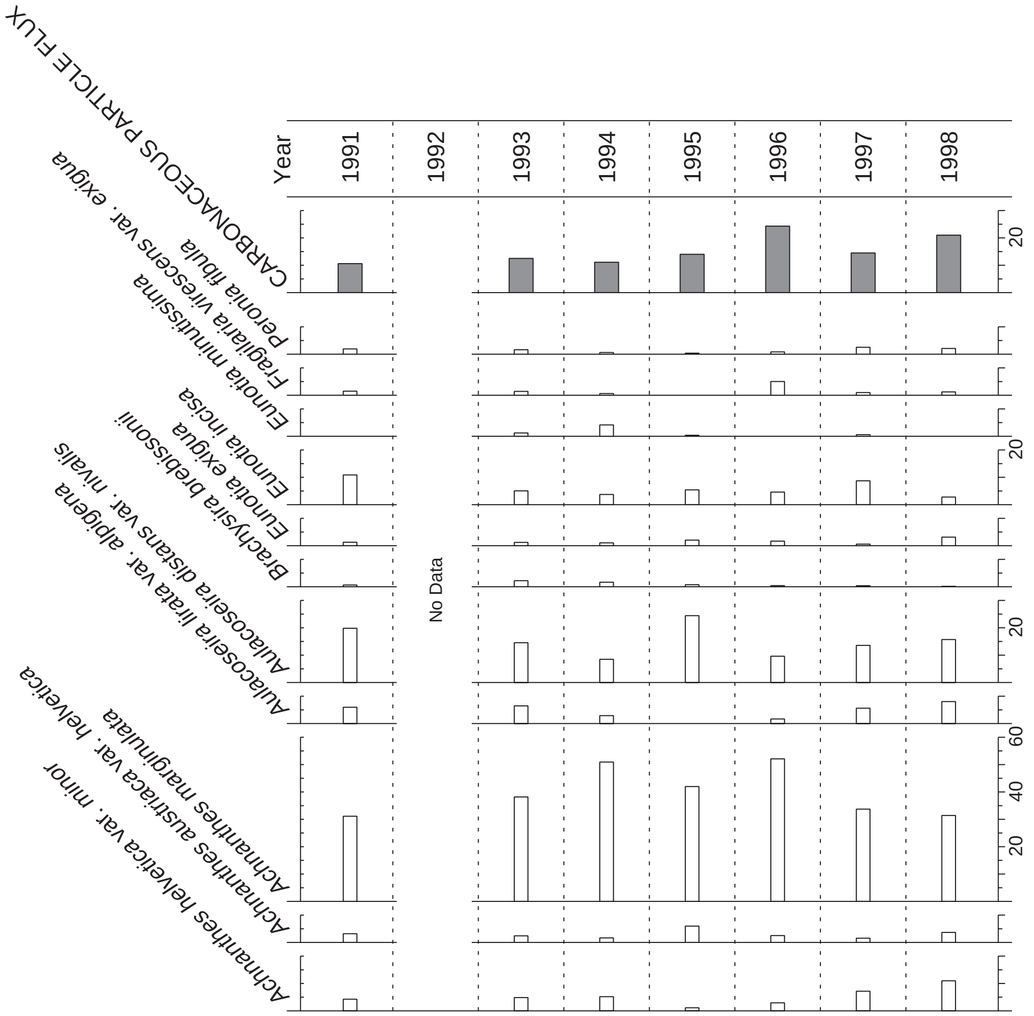
Figure 4.4.5

Lochnagar: summary of fish data (1989 - 1997) (c) Trout length frequency summaries

Figure 4.4.6

Lochnagar: summary of sediment trap data for diatoms and carbonaceous particles

Relative frequency of diatom taxa (>2% in at least one sample) at time of trap retrieval and estimated carbonaceous particle flux (no. trap^{-1} day^{-1}) for preceding year



4.5 Loch Chon

Site Review

Loch Chon is a relatively large loch in the Trossachs region of central Scotland. Its recent palaeoecological history was studied in the SWAP programme (Battarbee & Renberg, 1990). This work suggested that the loch has undergone dramatic acidification over the last 150 years, with the pH falling from around 6.4 to around 5.0 by 1992 (Patrick *et al*., 1989; Kreiser *et al*., 1990). An accelerated rate of acidification in recent decades was attributed to afforestation of the catchment. Today large areas of the catchment are covered by mature coniferous forest. In 1995, a small forestry access road was constructed parallel to the west shore, but to date felling has been restricted to small areas to the northwest of the site (Figure 4.5.1). Local agriculture at the north end of the loch may have caused mild nutrient enrichment in the north bay, where the aquatic macroflora is more diverse, but its influence on the site as a whole appears to be negligible.

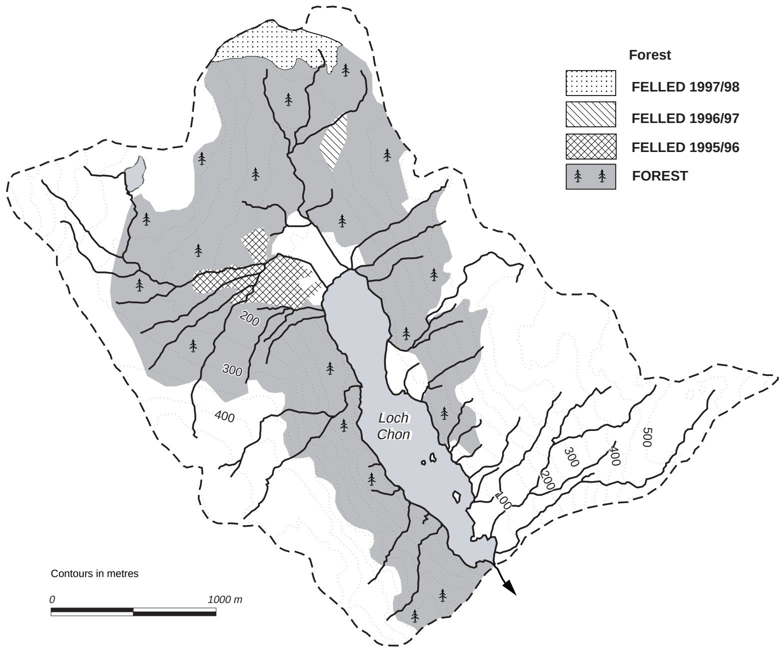


Figure 4.5.1

Loch Chon: catchment

Table 4.5.1

Loch Chon: site characteristics

Grid reference	*NN 421051*
Lake altitude	*100 m*
Maximum depth	*25 m*
Mean depth	*7.6 m*
Volume	*7.3×10^6 m^3*
Lake area	*100 ha*
Catchment area (excl. lake)	*1570 ha*
Catchment: Lake area ratio	*15.7*
Catchment Geology	*mica schists and grits*
Catchment Soils	*peaty gleys, peaty podzols*
Catchment vegetation	*conifers - 44%*
	moorland - 52%
	recently felled - 4%
Net relief	*500 m*
Mean annual rainfall	*2258 mm*
1996 deposition	
Total S	*29 kg ha^{-1} yr^{-1}*
non-marine S	*23 kg ha^{-1} yr^{-1}*
Oxidised N	*10 kg ha^{-1} yr^{-1}*
Reduced N	*13 kg ha^{-1} yr^{-1}*

Table 4.5.2

Loch Chon: summary of chemical determinands, June 1988 - March 1998

Determinand		Mean	Max	Min
pH		*5.60*	*6.47*	*4.99*
Alkalinity	µeq l^{-1}	*9.6*	*71.0*	*-8.0*
Ca	µeq l^{-1}	*78.0*	*101.0*	*64.5*
Mg	µeq l^{-1}	*50.8*	*75.0*	*41.7*
Na	µeq l^{-1}	*190.9*	*304.3*	*117.4*
K	µeq l^{-1}	*7.4*	*12.1*	*2.6*
SO_4	µeq l^{-1}	*71.9*	*91.7*	*39.6*
xSO_4	µeq l^{-1}	*48.5*	*70.4*	*24.0*
NO_3	µeq l^{-1}	*12.1*	*24.3*	*< 1.4*
Cl	µeq l^{-1}	*223.1*	*411.3*	*112.7*
Soluble Al	µg l^{-1}	*59.3*	*126.0*	*14.0*
Labile Al	µg l^{-1}	*19.9*	*69.0*	*< 2.5*
Non-labile Al	µg l^{-1}	*39.5*	*80.0*	*12.0*
DOC	mg l^{-1}	*3.2*	*6.2*	*1.7*
Conductivity	µS cm^{-1}	*39.5*	*61.0*	*23.0*

Water Chemistry

(Figure 4.5.2, Table 4.5.2-3)

Loch Chon is a moderately acidic site, with a mean pH of 5.60 and a mean alkalinity of 10 μeq l^{-1}. Mean xSO_4 is 49 μeq l^{-1} and mean NO_3 12 μeq l^{-1}. Large seasonal cycles are observed for a number of determinands including pH and Al species. Sea-salt inputs are fairly high, with large inter-annual variability evident in time series and LOESS plots for Na and Cl (Figures 4.5.2f,h). Peaks in marine ion concentrations occurred in 1989 and again 1993, each time followed by a period of steady decline. These marine ion 'cycles' are thought to have a significant impact on surface water chemistry and trend detection at this and other near-coast sites through a sea-salt effect operating over a prolonged, rather than only at an episodic, timescale (Evans *et al*., in press; Section 5.3).

Trend analyses suggest that both pH and alkalinity are increasing at Loch Chon: pH by approximately 0.4 units over ten years and alkalinity by 10-14 μeq l^{-1}. These increases are reasonably well supported by time series plots (Figures 4.5.2a,b), although in recent years values appear to have levelled off or perhaps begun to decline. At this stage no definite reduction in xSO_4 can be identified, and it is therefore uncertain whether genuine chemical recovery has taken place. The observed marine ion cycles may provide an alternative explanation for acidity changes (see Section 5.3.2). NO_3 appears to have risen since 1994, producing a positive trend using regression analysis but not SKT. As at Lochnagar, additional sampling is required to establish whether this represents a sustained increase or simply a short-lived climatic fluctuation. DOC has again shown a highly significant and sustained increase over the monitoring period, estimated using SKT at 2 mg l^{-1} over the ten years.

Longer term data for the Caorainn Achaidh Burn, which drains a predominantly moorland catchment 3 km west of Loch Chon, are discussed in Chapter 6.

Epilithic diatoms

(Figure 4.5.3, Table 4.5.4)

Major changes are evident in the relative abundance of epilithic diatom species in samples from Loch Chon. RDA and associated permutation tests show that "sample year" is highly significant at the 0.01 level. The time trend appears to be strongly influenced by relative declines in *Achnanthes marginulata* (pH optima 5.2) and *Eunotia incisa* (pH optima 5.1) and increases in *Brachysira brebissonii* (pH optima 5.3) and *B.vitrea* (pH optima 5.9). These changes are therefore consistent with a "recovery" response and are supported by the observed improvements in water chemistry. Caution should be taken in interpretation of these trends for the reasons given in the water chemistry section, and further years of

Table 4.5.3

Significant trends in chemical determinands (July 1988 - March 1998)

Determinand	Units	Annual trend (Regression)	Annual trend (Seasonal Kendall)
pH		*+0.043**	*+0.044**
Alkalinity	μeq l^{-1}	-	*+1.00**
NO_3	μeq l^{-1}	*+0.86***	-
DOC	mg l^{-1}	*+0.16***	*+0.20***
labile Al	μg l^{-1}	*-2.72***	*-2.00***

** Trend significant at $p < 0.05$; ** trend significant at $p < 0.01$; *** trend significant at $p < 0.001$*

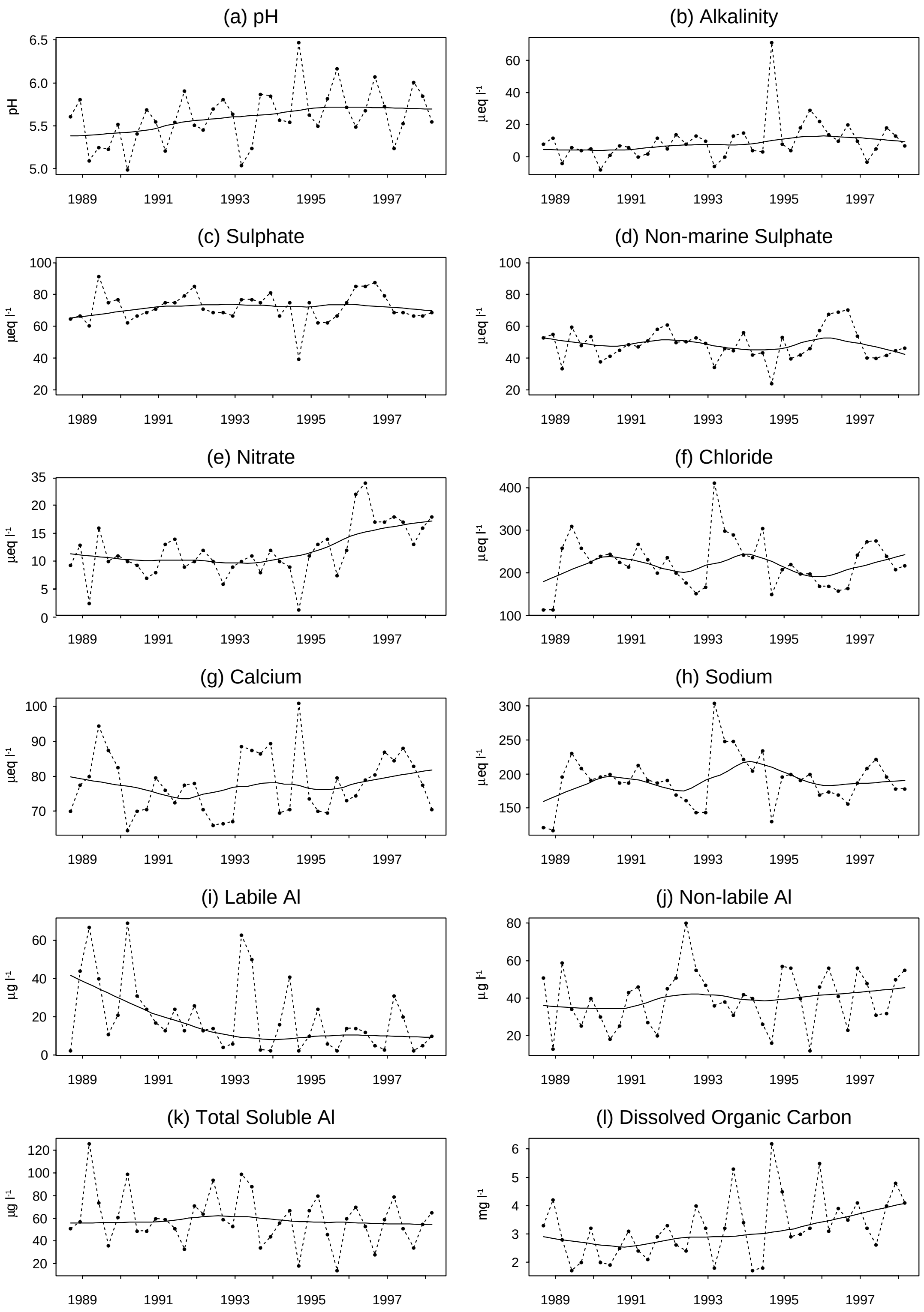


Figure 4.5.2

Loch Chon: summary of major chemical determinands (September 1988 - March 1998)

Smoothed line represents LOESS curve (Section 3.1.2)

Table 4.5.4

Loch Chon: trend statistics for epilithic diatom, macrophyte and macroinvertebrate summary data (1988 - 1998)

	Total sum of squares	Number of Taxa	MeanN_2 diversity	λ_1RDA/λ_2RDA	λ_1RDA/λ_1PCA
Epilithic diatoms	*390*	*114*	*7.5*	*0.82*	*0.60*
Macrophytes	*35*	*27*	*16.6*	*0.94*	*0.85*
Invertebrates	*581*	*68*	*2.3*	*0.87*	*0.65*

Variance explained (%)	within year	between years	linear trend	p unrestricted	p restricted
Epilithic diatoms	*45.6*	*54.4*	*15.5*	*<0.01*	*<0.01*
Macrophytes	*	*	*31.5*	*0.04*	*0.19*
Invertebrates	*37.4*	*62.6*	*14.1*	*<0.01*	*<0.01*

monitoring are necessary to ascertain to what extent they represent long term uni-directional as opposed to cyclical change. Interestingly, the most abundant species, *Navicula leptostriata*, which has a relatively acid preference (pH optima 5.1), was most abundant during 1989-1990 and in 1993, periods when sea-salt deposition and January rainfall was highest and loch water was most acid. Diatom inferred pH (derived from weighted averaging) correlates highly with both measured pH and Cl concentration (see Section 7.3). This suggests that climatic effects have been major factors influencing species composition. The diatom assemblage of sediment trap samples shows some temporal similarity to that of the epilithon, in that *B. vitrea* has increased markedly with time (Figure 4.5.6). More generally however, there are marked differences. Comparison between the sediment trap time series and a sediment core profile taken at the onset of monitoring provide some evidence that real recovery in the diatom flora is underway (Figure 7.4, Section 7.2.5). The positive trend in *B.vitrea* and the negative trends in *Cymbella perpusilla* and, possibly, *Eunotia incisa*, are the reverse of those recorded in the latter stages of acidification in the sediment core. The relative contributions of emission induced improvements in water chemistry and climatic effects to this apparent reversal in the sediment diatom assemblage will only be ascertained with further monitoring.

■ Macroinvertebrates

(Figure 4.5.4, Table 4.5.4)

The macroinvertebrate fauna of Loch Chon is the most diverse and abundant of all the monitoring sites. The fauna is typical of a moderately acid lake and is dominated by the acid tolerant mayfly family, the Leptophlebiidae, which make up at least 60% of the total composition in all years. Other mayflies present included *Siphlonurus lacustris*, *Ameletus inopinatus* and *Heptagenia lateralis* which was recorded in high numbers in 1992 only. Several species of acid tolerant detritivorous stoneflies (*Nemoura* spp., *Leuctra inermis* and *Leuctra nigra*) have been recorded sporadically. Acid tolerant caddisflies such as *Polycentropus* spp., *Plectrocnemia* spp. and *Holocentropus* spp. were present throughout the study period. There is a very diverse community of corixids; *Hespercorixa sahlbergii* and *Cymatia bonsdorffi* dominated the first 4 years and *Arctocorisa germari* and *Sigara distincta* characterised the second half of the monitoring period. Time as a linear trend is significant at the 0.01 level. The trend appears to be mainly driven by changes in the species composition of

Table 4.5.5

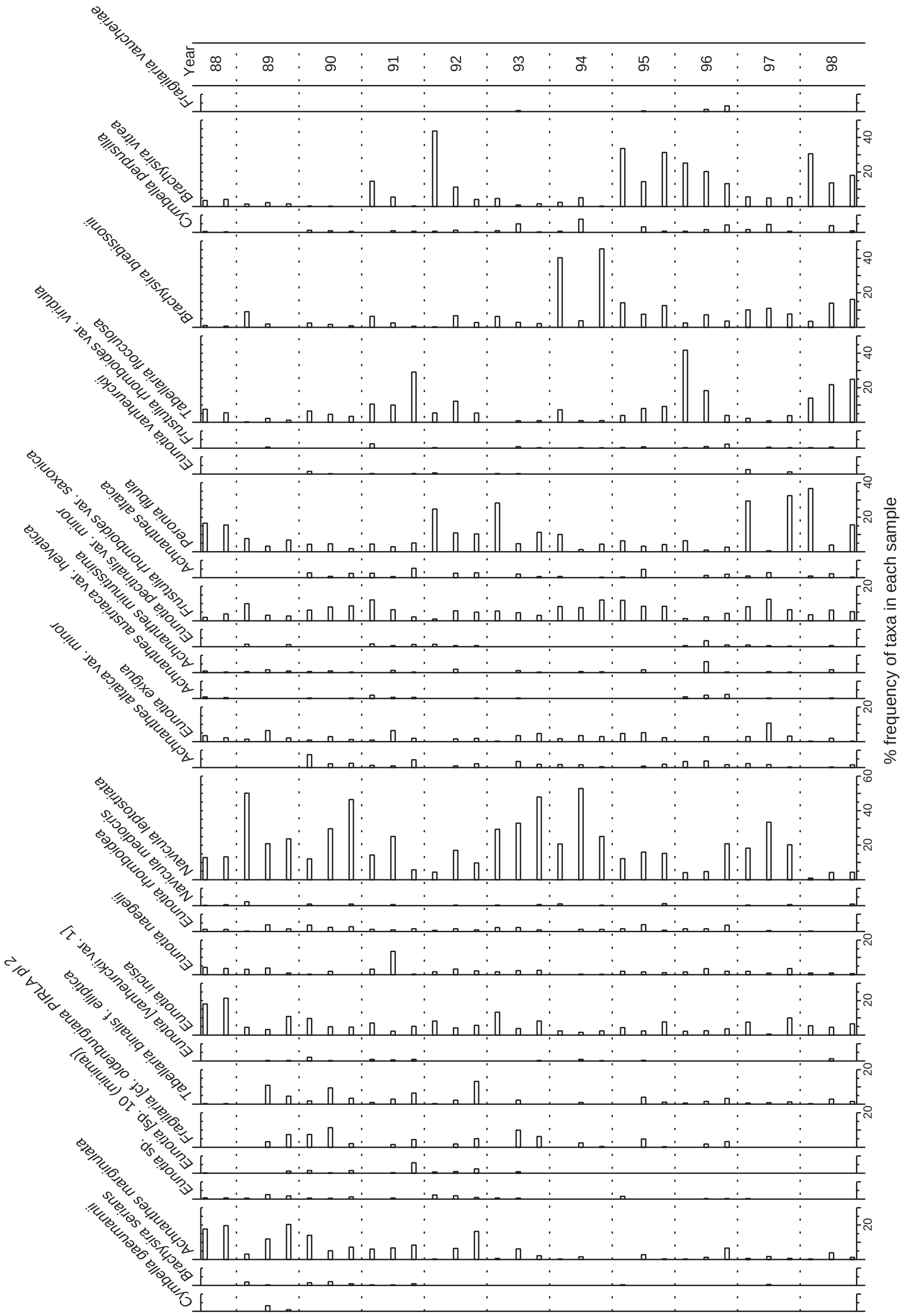
Loch Chon: relative abundance of aquatic macrophyte flora (1988 - 1997)
(see Section 3.2.3 for key to indicator values)

Abundance Taxon Year	88	89	90	91	92	93	95	97
INDICATOR SPECIES								
Myriophyllum alterniflorum[2]	3	3	3	3	3	3	3	3
Utricularia sp.[2]	2	2	2	2	2	2	2	2
Callitriche sp.[3]	0	0	1	1	1	1	1	0
Potamogeton berchtoldii[3]	0	0	0	0	0	1	1	1
Sphagnum auriculatum[4]	3	3	2	2	3	3	3	3
Juncus bulbosus var. fluitans[4]	5	5	5	5	5	5	5	5
OTHER SUBMERGED OR FLOATING SPECIES								
Batrachospermum sp.	4	3	2	2	2	2	2	2
Filamentous green algae	4	4	4	4	4	3	4	2
Calliergon cordifolium	0	0	1	0	0	0	0	0
Fontinalis squamosa	1	1	1	1	1	1	1	1
Marsupella emarginata	0	0	0	1	1	0	1	0
Scapania undulata	0	0	0	1	1	0	1	1
Isoetes lacustris	3	3	3	3	3	3	3	3
Littorella uniflora	3	3	4	4	4	4	4	4
Subularia aquatica	0	0	0	0	0	0	1	1
Elatine hexandra	0	0	0	0	0	0	1	1
Lobelia dortmanna	3	4	3	3	3	3	3	3
Nuphar lutea	1	1	2	2	2	2	2	2
Nymphaea alba	1	1	2	2	2	2	2	2
Potamogeton natans	0	0	1	0	0	0	0	0
Potamogeton polygonifolius	0	0	1	0	0	0	0	0
Sparganium angustifolium	2	2	2	2	2	2	2	2
EMERGENT SPECIES								
Equisetum fluviatile	1	1	2	2	1	1	1	1
Hydrocotyle vulgaris	1	1	2	2	2	2	2	1
Menyanthes trifoliata	1	1	1	1	1	1	1	1
Ranunculus flammula	3	3	3	3	3	3	3	3
Carex rostrata	2	3	3	2	3	3	3	2
Eleocharis palustris	3	3	3	3	3	3	3	2
Glyceria fluitans	1	1	2	2	2	3	2	1
Juncus acutifloris/articulatus	4	4	5	5	5	5	5	4
Juncus effusus	2	2	2	2	2	2	2	2
Phragmites australis	2	2	2	2	2	2	2	2
TOTAL NUMBER OF SPECIES	23	23	27	26	26	25	29	27

Figure 4.5.3

Loch Chon: summary of epilithic diatom data (1988 - 1998)

Percentage frequency of all taxa occurring at >2% abundance in any one sample



Corixidae and Coleoptera. These species are aquatic both as nymphs and adults, but their distribution is thought to be influenced more by short term variations in weather conditions, particularly as these affect dispersal, rather than changes in water chemistry. However, species richness has shown a general increase which appears to follow the trend of rising pH, with particularly low numbers of species recorded in the high sea-salt /low pH years of 1990 and 1993. Further years of monitoring are therefore required to assess the extent to which these changes are sustained and therefore indicative of recovery.

■ Fish

(Figure 4.5.5)

The outflow stream from Loch Chon has been electrofished since 1989. Trout densities at this site are the fourth highest found in the Network sites. The mean population density of both 0+ and >0+ trout varies widely between years. As at several other Scottish sites, density patterns of 0+ fish are heavily influenced by the high recruitment year of 1991, but if this year is disregarded the data show a steady increase with time. Condition factor of 0+ fish appears to have increased gradually since 1990 although its coefficient of variation has remained stable through time. There is also evidence for a general increase in the condition factor of the >0+ group while its coefficient of variation shows marked variation between years. The length frequency graph demonstrates that despite the large recruitment in 1991 there was only a small subsequent increase in >0+ fish in 1992.

■ Aquatic macrophytes

(Tables 4.5.4-5)

The aquatic macroflora of Loch Chon is diverse and typical for moderately acid lakes with sheltered habitats. The isoetids *Lobelia dortmanna* and *Littorella uniflora* dominate much of the shallows with *Isoetes lacustris*, *Myriophyllum alterniflorum* and *Juncus bulbosus* var. *fluitans* abundant in deeper water. Sheltered areas include emergent stands of *Phragmites australis*, *Equisetum fluviatile* and *Carex rostrata*, and floating leaved beds of *Nuphar lutea*, *Nymphaea alba* and *Potamogeton natans*. The fine leaved pondweed *P. berchtoldii*, *Subularia aquatica* and *Elatine hexandra* were recorded for the first time in the bay at the north end of the Loch in 1995 and again in 1997. It is possible that the appearance of these species has resulted from the recent amelioration in acidity, although it is also feasible that the bay has been subject to slight and localised nutrient enrichment from local agriculture. Apart from these recent changes the flora for the bulk of the Loch remains unchanged throughout the decade.

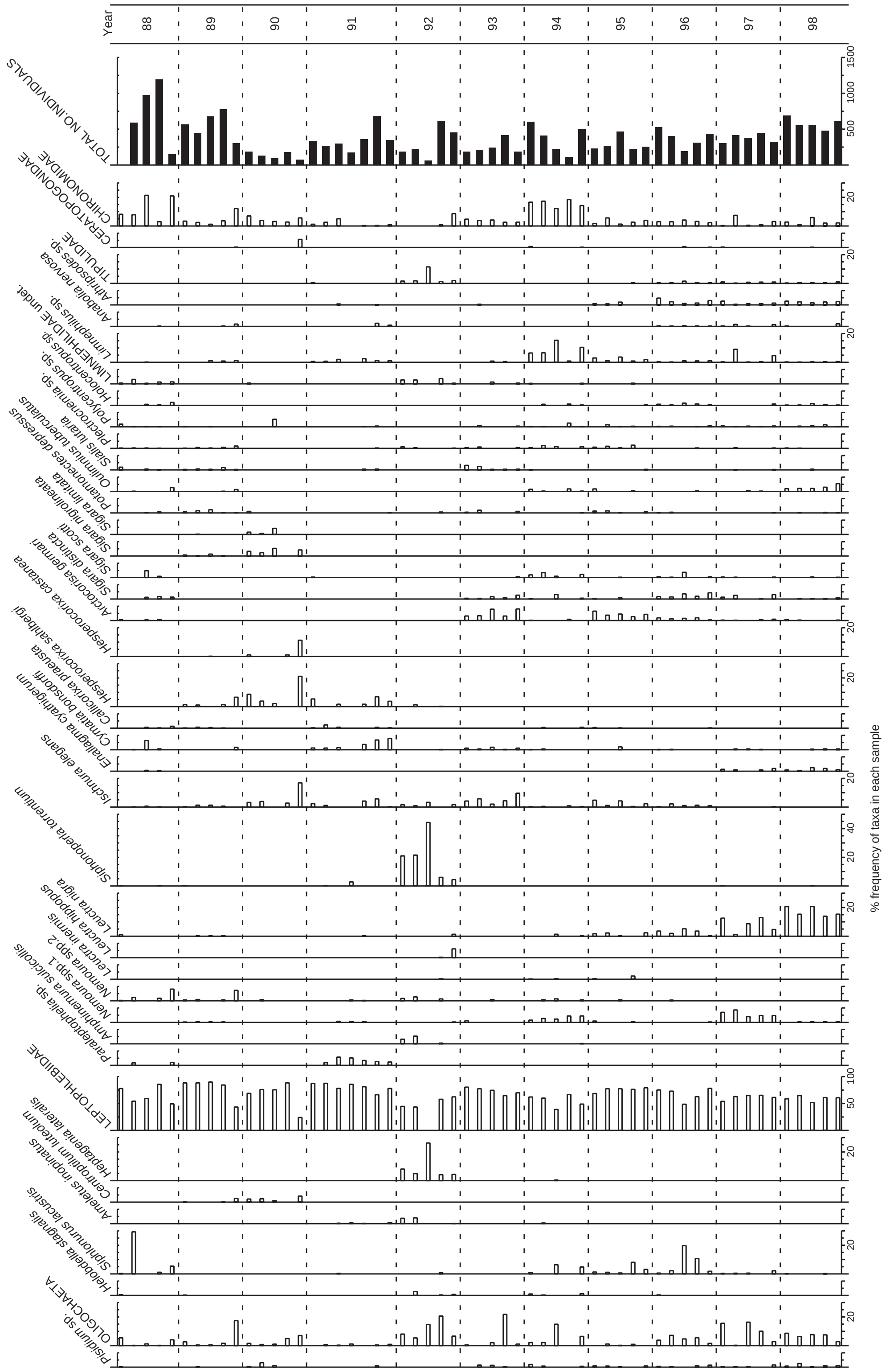
■ Summary

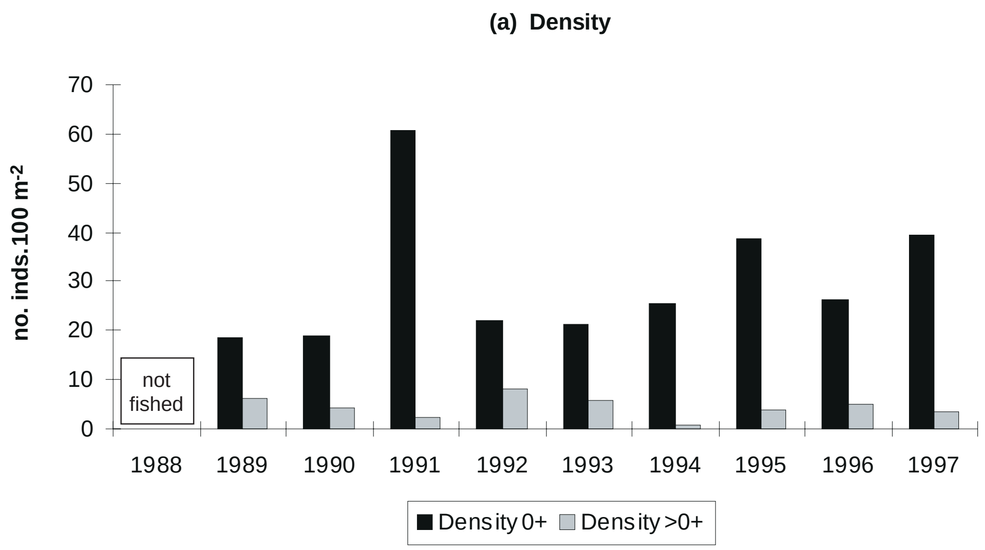
Loch Chon has a pH intermediate among UKAWMN sites. Afforestation has clearly intensified acidification as the site is much more acidic than the nearby unafforested Loch Tinker. There is some evidence of increased pH and alkalinity over the last decade but since this has not been matched by a reduction in xSO_4 or NO_3 it is currently unclear whether this improvement is the result of reductions in acid deposition. Large natural fluctuations in marine ion concentrations and rainfall may provide alternative explanations for the observed changes in acidity. Epilithic diatoms, sediment trap diatoms, aquatic macrophytes, macro-invertebrates and the trout population, all provide indications of improved conditions. Further monitoring is essential to determine the extent to which apparent “recovery” at this site is a real response to emissions reductions as opposed to part of a climatic cycle.

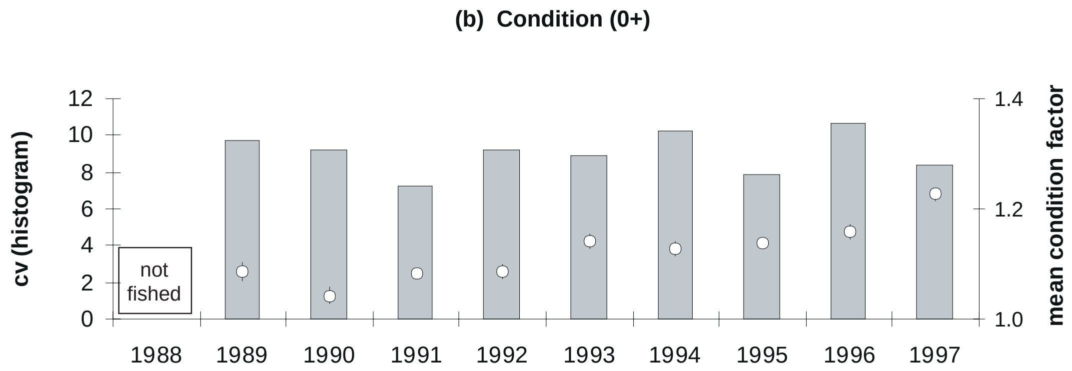
Figure 4.5.4

Loch Chon: summary of macroinvertebrate data (1988 - 1998)

Percentage frequency of taxa in individual samples







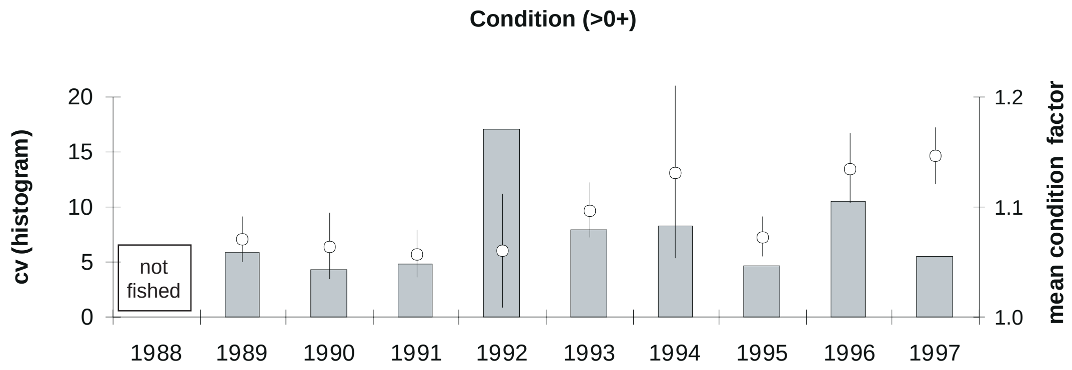


Figure 4.5.5

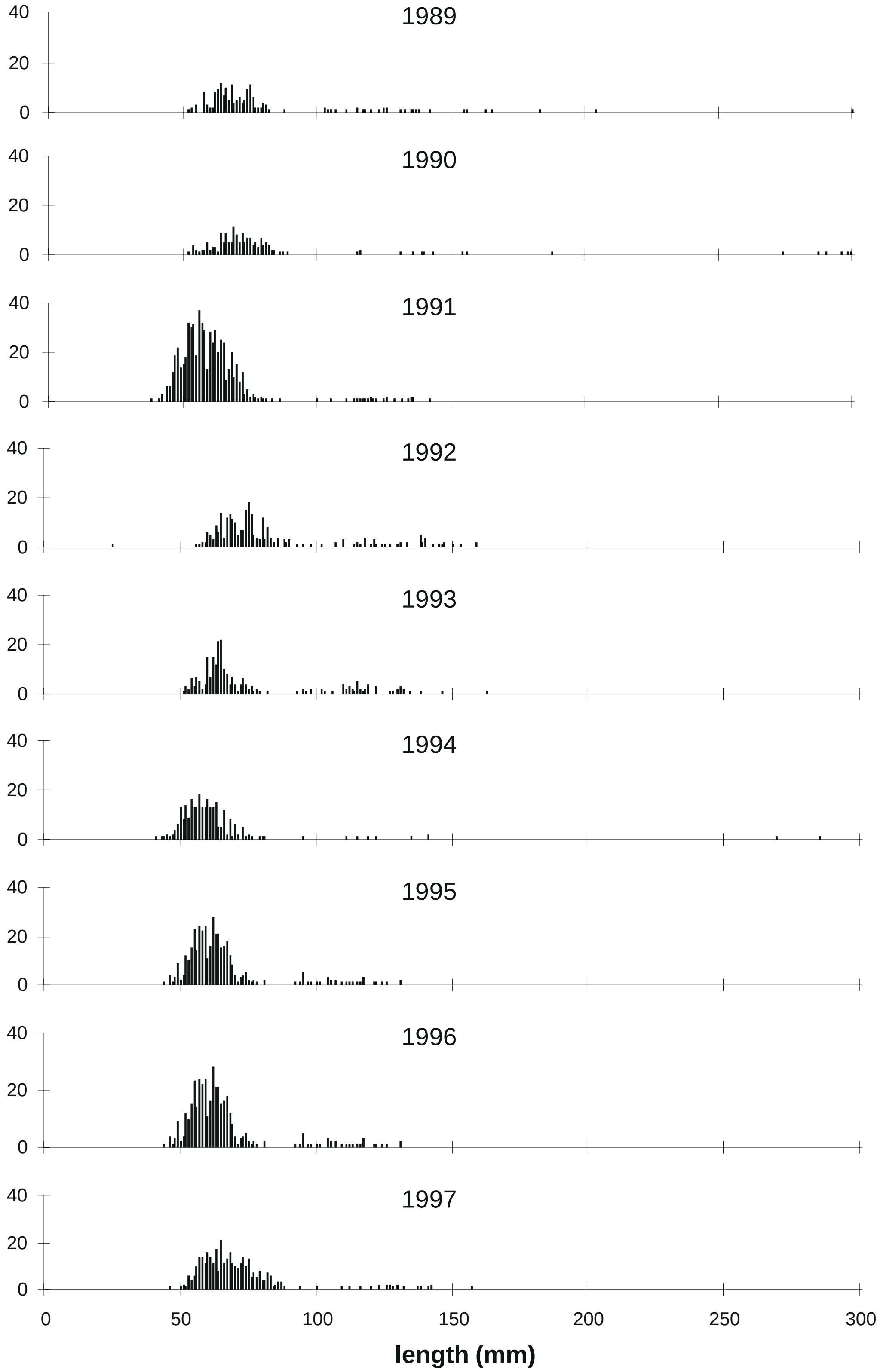
Loch Chon: summary of fish data (1989 - 1997)

(a) Trout population density for 0+ and >0+ age classes (individuals 100 m^{-2})

(b) Mean condition factor (with standard deviation) of the trout population and its coefficient of variation (histogram)

Figure 4.5.5

Loch Chon: summary of fish data (1989 - 1997)
(c) Trout length frequency summaries (1989 - 1997)



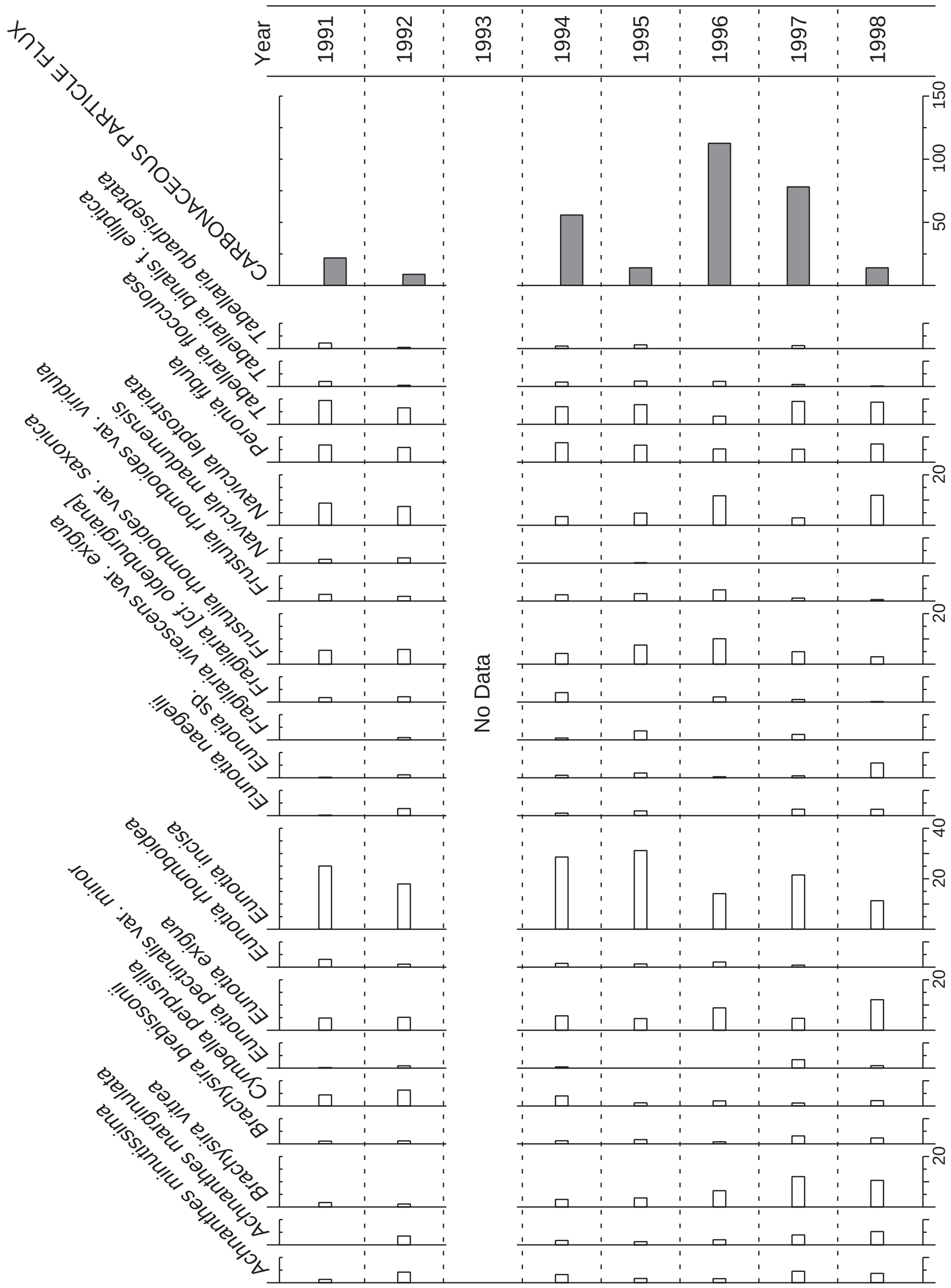


Figure 4.5.6

Loch Chon: summary of sediment trap data for diatoms and carbonaceous particles

Relative frequency of diatom taxa (>2% in at least one sample) at time of trap retrieval and estimated carbonaceous particle flux (no. $trap^{-1}$ day^{-1}) for preceding year

4.6 Loch Tinker

■ Site Review

Loch Tinker lies in a non-forested upland moorland catchment to the east of Loch Chon, and the two sites have been used as a experimental / control pair to examine the influence of forestry on acidification (Kreiser *et al.* 1990) and other aspects of water quality (Section 5.5.1). In the former study, pH reconstruction using the fossil diatom assemblage of sediment cores suggested that the loch had acidified from around pH 6.5 in the mid-19th century, to around pH 5.5 by 1991. There has been no physical disturbance within the catchment of the loch during the monitoring period. Full site descriptions of Loch Tinker are provided in Patrick *et al.* (1991) and Patrick *et al.* (1995).

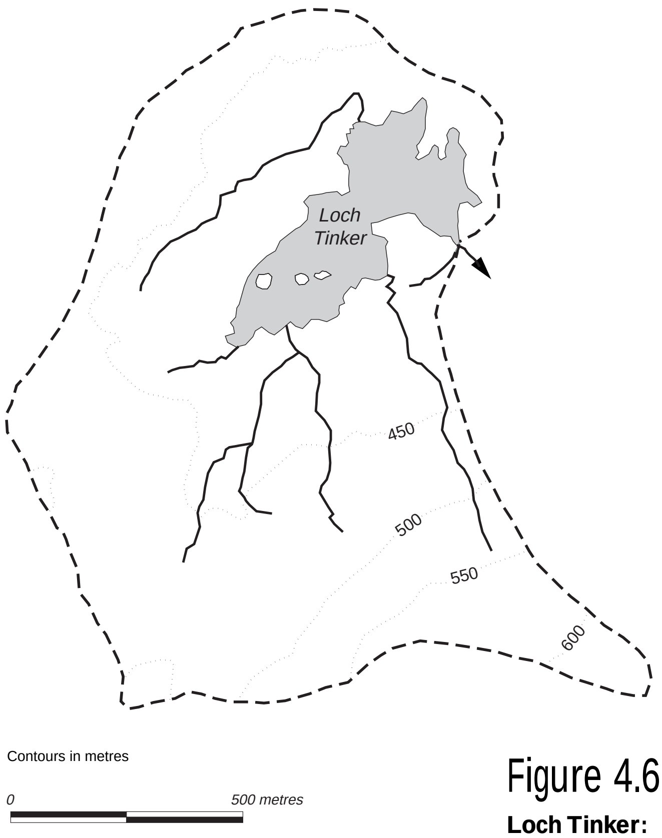


Figure 4.6.1

Loch Tinker: catchment

Table 4.6.1

Loch Tinker: site characteristics

Grid reference	*NN 445068*
Lake altitude	*420 m*
Maximum depth	*9.8 m*
Mean depth	*3.5 m*
Volume	*4.0 x 10^5 m^3*
Lake area	*11.3 ha*
Catchment area (excl. lake)	*112 ha*
Catchment: Lake area ratio	*9.9*
Catchment Geology	*mica schists and grits*
Catchment Soils	*blanket peats*
Catchment vegetation	*moorland - 100%*
Net relief	*280 m*
Mean annual rainfall	*2345 m*
1996 deposition	
Total S	*29 kg ha^{-1} yr^{-1}*
non-marine S	*23 kg ha^{-1} yr^{-1}*
Oxidised N	*10 kg ha^{-1} yr^{-1}*
Reduced N	*13 kg ha^{-1} yr^{-1}*

Table 4.6.2

Loch Tinker: summary of chemical determinands, June 1988 - March 1998

Determinand		Mean	Max	Min
pH		*6.13*	*6.56*	*5.42*
Alkalinity	µeq l^{-1}	*37.6*	*96.0*	*-2.0*
Ca	µeq l^{-1}	*85.0*	*127.0*	*35.0*
Mg	µeq l^{-1}	*48.3*	*91.7*	*33.3*
Na	µeq l^{-1}	*142.6*	*321.7*	*78.3*
K	µeq l^{-1}	*8.5*	*17.9*	*2.6*
SO_4	µeq l^{-1}	*55.6*	*110.4*	*37.5*
xSO_4	µeq l^{-1}	*38.5*	*99.2*	*17.7*
NO_3	µeq l^{-1}	*2.9*	*14.3*	*< 1.4*
Cl	µeq l^{-1}	*162.8*	*439.4*	*70.4*
Soluble Al	µg l^{-1}	*20.3*	*45.0*	*5.0*
Labile Al	µg l^{-1}	*3.3*	*14.0*	*< 2.5*
Non-labile Al	µg l^{-1}	*18.4*	*44.0*	*< 2.5*
DOC	mg l^{-1}	*4.7*	*8.1*	*1.9*
Conductivity	µS cm^{-1}	*31.4*	*62.0*	*21.0*

Water Chemistry

(Figure 4.6.2, Tables 4.6.2-3)

This moorland site is adjacent to the forested Loch Chon, and shows generally similar temporal variations. However it is considerably less acid, with a mean pH of 6.13, mean alkalinity of 38 μeq l^{-1} and lower Al concentrations. Mean xSO_4 is also lower, at 39 μeq l^{-1}, whilst Ca concentrations are higher (mean 85 μeq l^{-1}) (see Section 5.5.1). Palaeolimnological data indicate that Loch Tinker has acidified at a steady rate since the mid-19th century, but that unlike Loch Chon there has been no substantial pH reduction since around 1950 (Kreiser *et al.*, 1990). NO_3 concentrations at Loch Tinker were < 5 μeq l^{-1} for much of the monitoring period, but a pulse of 14 μeq l^{-1} was recorded in Spring 1996. Seasonality is high for both pH and alkalinity, and variations in marine ions are large, and similar to those at Loch Chon.

The chemistry of Loch Tinker has shown little overall change during the monitoring period. The only significant trend, identified using SKT, is a rise in DOC of around 1.8 mg l^{-1} over the decade.

Epilithic diatoms

(Figure 4.6.3,Table 4.6.4)

As for the neighbouring site (Loch Chon), RDA and associated restricted permutation tests show that “sample year” is significant at the 0.01 level in explaining changes in the relative abundance of epilithic diatoms at Loch Tinker. The trend appears to be influenced by relatively rare taxa, and more specifically, increases in *Brachysira brebissonii*, *Cymbella microcephala*, *Nitzschia gracilis* and declines in *Fragilaria vaucheriae*, *Eunotia rhomboidea* and *Synedra acus*. There is no systematic difference between the pH and DOC optima of the declining and increasing groups and these changes therefore do not indicate a shift in either variable over the last decade. Species composition is relatively stable between years, with *Brachysira vitrea* dominant in nearly all samples and persistence also seen in other relatively abundant taxa, e.g. *Tabellaria flocculosa*, *Achnanthes minutissima*, *Frustulia rhomboides* var. *saxonica* and *Cymbella lunata*. Given the absence of evidence for any trends in water chemistry (with the exception of a small rise in DOC) explanations for the subtle changes in the rarer species are unclear. The diatom species assemblage of sediment trap samples taken since 1991 exhibits even greater stability between years than the epilithon assemblage (Figure 4.6.6.), and in contrast to the epilithon there is no evidence of trends in the rare taxa described above.

Macroinvertebrates

(Figure 4.6.4, Table 4.6.4)

The macrobenthos is typical of a moderately acid lake, dominated by chironomids and the freshwater bivalve *Pisidium* spp. The most acid tolerant mayfly family the Leptophlebiidae and Oligochaetae characterised the first few years of the monitoring period, with numbers declining after 1991. The second half of the survey was characterised by several caddisfly species, of

Table 4.6.3

Significant trends in chemical determinands (July 1988 - March 1998)

Determinand	Units	Annual trend (Regression)	Annual trend (Seasonal Kendall)
DOC	mg l^{-1}	-	*+0.183**

** Trend significant at p < 0.05; ** trend significant at p < 0.01; *** trend significant at p < 0.001*

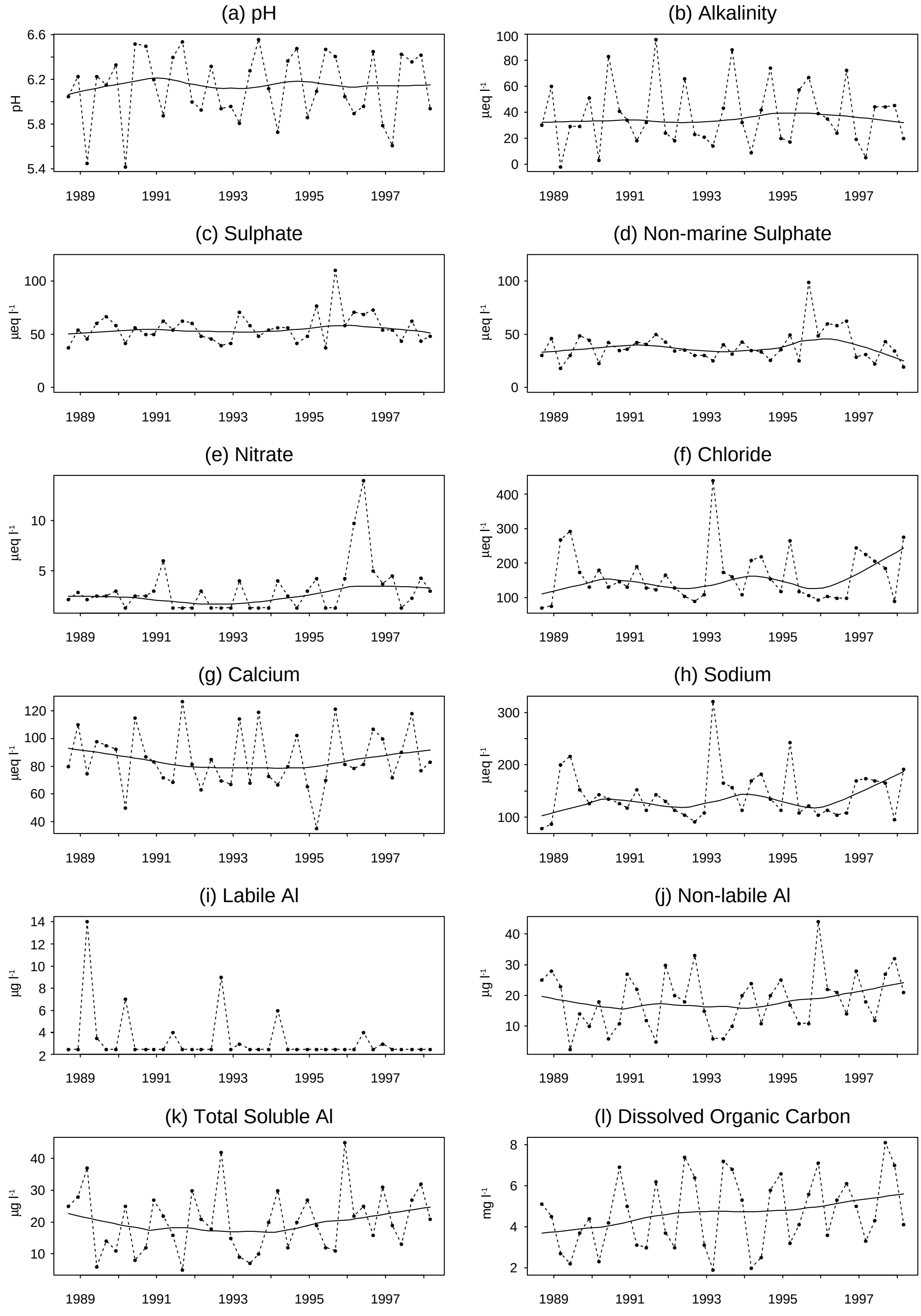


Figure 4.6.2

Loch Tinker: summary of major chemical determinands (September 1988 - March 1998)

Smoothed line represents LOESS curve (Section 3.1.2)

Table 4.6.4

Loch Tinker: trend statistics for epilithic diatom, macrophyte and macroinvertebrate summary data (1988 - 1998)

	Total sum of squares	Number of Taxa	Mean N_2 diversity	λ_1RDA/λ_2RDA	λ_1RDA/λ_1PCA
Epilithic diatoms	*318*	*145*	*6.9*	*0.64*	*0.50*
Macrophytes	*45.3*	*21*	*14.0*	*0.94*	*0.79*
Invertebrates	*1011*	*36*	*2.4*	*0.81*	*0.73*

Variance explained (%)	within year	between years	linear trend	p unrestricted	p restricted
Epilithic diatoms	*53.0*	*47.0*	*9.4*	*<0.01*	*<0.01*
Macrophytes	*	*	*34.7*	*0.05*	*0.25*
Invertebrates	*54.8*	*45.2*	*15.5*	*<0.01*	*<0.01*

which *Mystacides* spp. dominated (this species increased in abundance after 1995) and was accompanied by *Sericostoma personatum, Anabolia nervosa* and *Limnephilus* spp.. Other characteristic species include the beetle *Oulimnius tuberculatus, Sialis lutaria* and the Polycentropodids *Plectrocnemia* spp. and *Polycentropus* spp. which both occurred in intermittent years. There have been sporadic recordings of stoneflies in low numbers and Corixids were only present in 1990 and 1991. 1989 and 1990 were both poor years in terms of species richness and abundance. There is a significant linear trend through time in the macroinvertebrate data and given the relative decline in Leptophlebids could be indicative of slightly improved conditions. However, there is no upward trend in species richness with time which might be expected to accompany a "recovery" response.

Fish

(Figure 4.6.5)

The outflow stream of Loch Tinker has been fished since 1989. Mean trout densities are extremely low and statistical analysis of trends in the data are therefore inappropriate. Length frequency graphs clearly show the years of recruitment failure and the decline in older trout present.

Aquatic macrophytes

(Tables 4.6.4-5)

Although at considerably higher altitude than Loch Chon and less acid, Loch Tinker is characterised by a similar assemblage of aquatic plants. The main floristic differences between sites probably arise from the greater exposure of this site to wind and the more peaty nature of the water at this site which results in a more restricted depth range for the deeper growing species such as *Isoetes lacustris*. The acidophilous *Juncus bulbosus* var. *fluitans* is far less abundant in Loch Tinker, perhaps reflecting the more alkaline conditions. In the five year interpretative report (Patrick *et al.*), two species were identified as having been lost to the site. *Sparganium angustifolium*, which was not recorded for three years after 1989 has re-appeared since 1995. However, there has been no record of the acid sensitive charophyte *Nitella* sp. since 1988. Interestingly, and in common with Loch Chon, *Subularia aquatica* was recorded at the site for the first time in 1997. There is little information on the pH tolerance of this oligotrophic species and the environmental

Table 4.6.5

Loch Tinker: relative abundance of aquatic macrophyte flora (1988 - 1997)
(see Section 3.2.3 for key to indicator values)

Abundance Taxon Year	88	89	90	91	92	93	95	97
INDICATOR SPECIES								
Nitella flexilis[1]	1	0	0	0	0	0	0	0
Myriophyllum alterniflorum[2]	3	3	3	3	3	3	3	3
Utricularia sp.[2]	0	0	1	1	1	1	2	1
Callitriche hamulata[3]	2	2	2	2	2	2	2	2
Sphagnum auriculatum[4]	1	1	1	2	2	2	2	2
Juncus bulbosus var. *fluitans*[4]	2	2	2	2	2	2	2	2
OTHER SUBMERGED OR FLOATING SPECIES								
Batrachospermum sp.	1	1	1	2	2	2	0	2
Filamentous green algae	1	2	3	3	2	2	1	1
Fontinalis antipyretica	0	1	1	1	1	2	1	1
Marsupella emarginata	0	0	0	0	1	0	0	0
Equisetum fluviatile	4	4	4	4	4	4	4	4
Isoetes lacustris	0	1	2	2	2	2	2	2
Littorella uniflora	2	2	3	4	4	4	4	4
Lobelia dortmanna	3	4	4	4	4	4	4	4
Subularia aquatica	0	0	0	0	0	0	2	2
Glyceria fluitans	1	1	2	2	2	2	2	1
Potamogeton natans	3	3	3	3	3	3	3	3
Potamogeton polygonifolius	0	0	1	1	1	1	2	1
Sparganium angustifolium	2	1	0	0	0	1	2	1
EMERGENT SPECIES								
Menyanthes trifoliata	1	1	1	1	1	2	1	1
Ranunculus flammula	0	1	2	2	2	2	2	2
Carex rostrata	4	4	4	4	4	4	3	4
Eleocharis palustris	2	2	2	2	2	2	2	2
Juncus acutifloris/articulatus	2	2	2	2	2	2	2	2
Juncus effusus	2	2	2	2	2	2	2	2
TOTAL NUMBER OF SPECIES	18	20	21	21	22	22	22	23

significance of its apparently recent establishment is unclear. There is no other evidence for floristic change at Loch Tinker over the last decade.

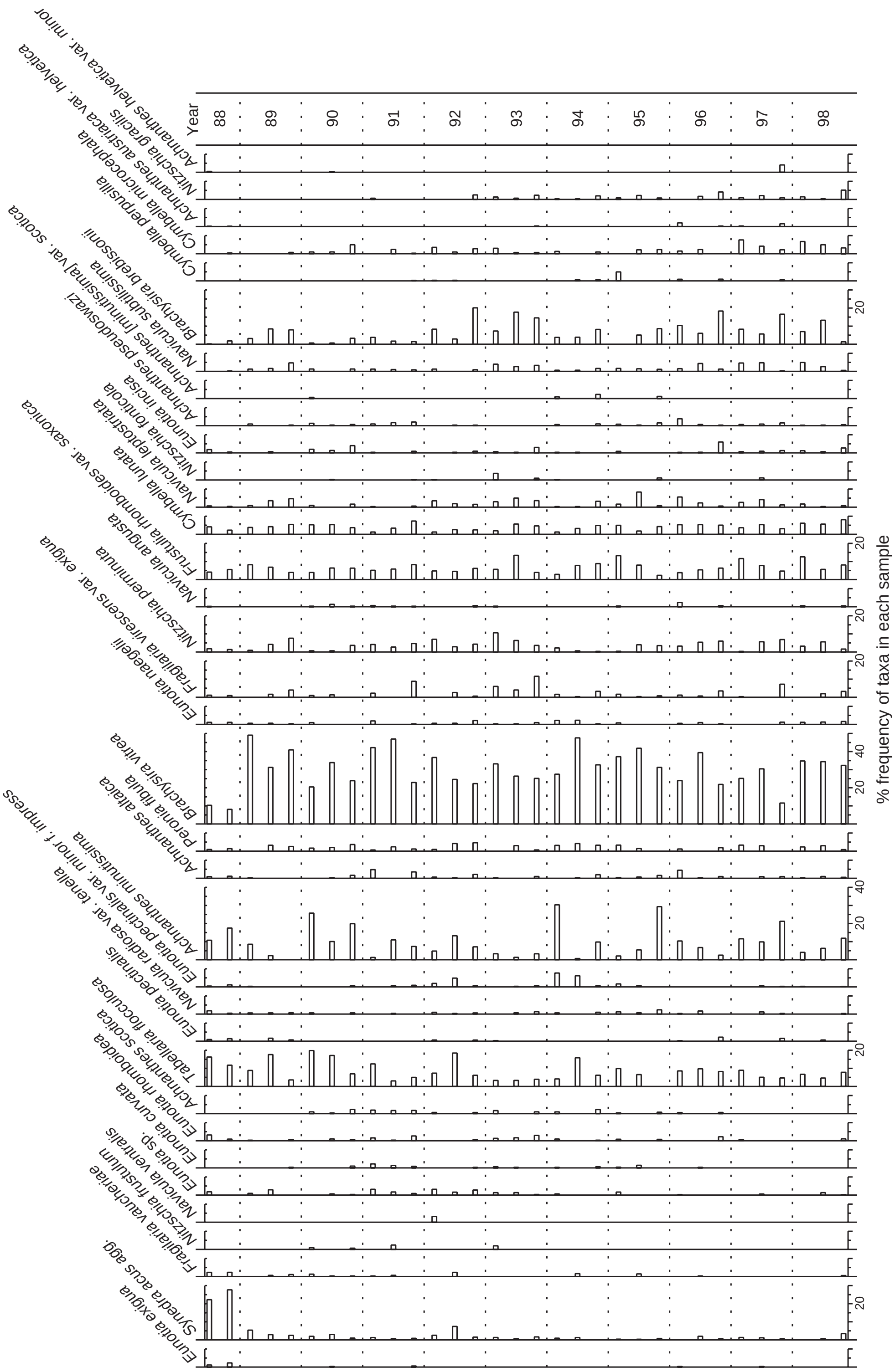
■ Summary

Loch Tinker is a relatively well buffered site, and is significantly less acidic than the neighbouring forested catchment, Loch Chon. Apart from natural variations related to seasonality and marine ion deposition, the chemistry of the Loch has remained largely constant over the last ten years. Linear trends have been observed in epilithic diatoms and macroinvertebrates, but these are not indicative of any amelioration in acidity, while the trout population of the outflow has remained at a very low density.

Figure 4.6.3

Loch Tinker: summary of epilithic diatom data (1988 - 1998)

Percentage frequency of all taxa occurring at >2% abundance in any one sample



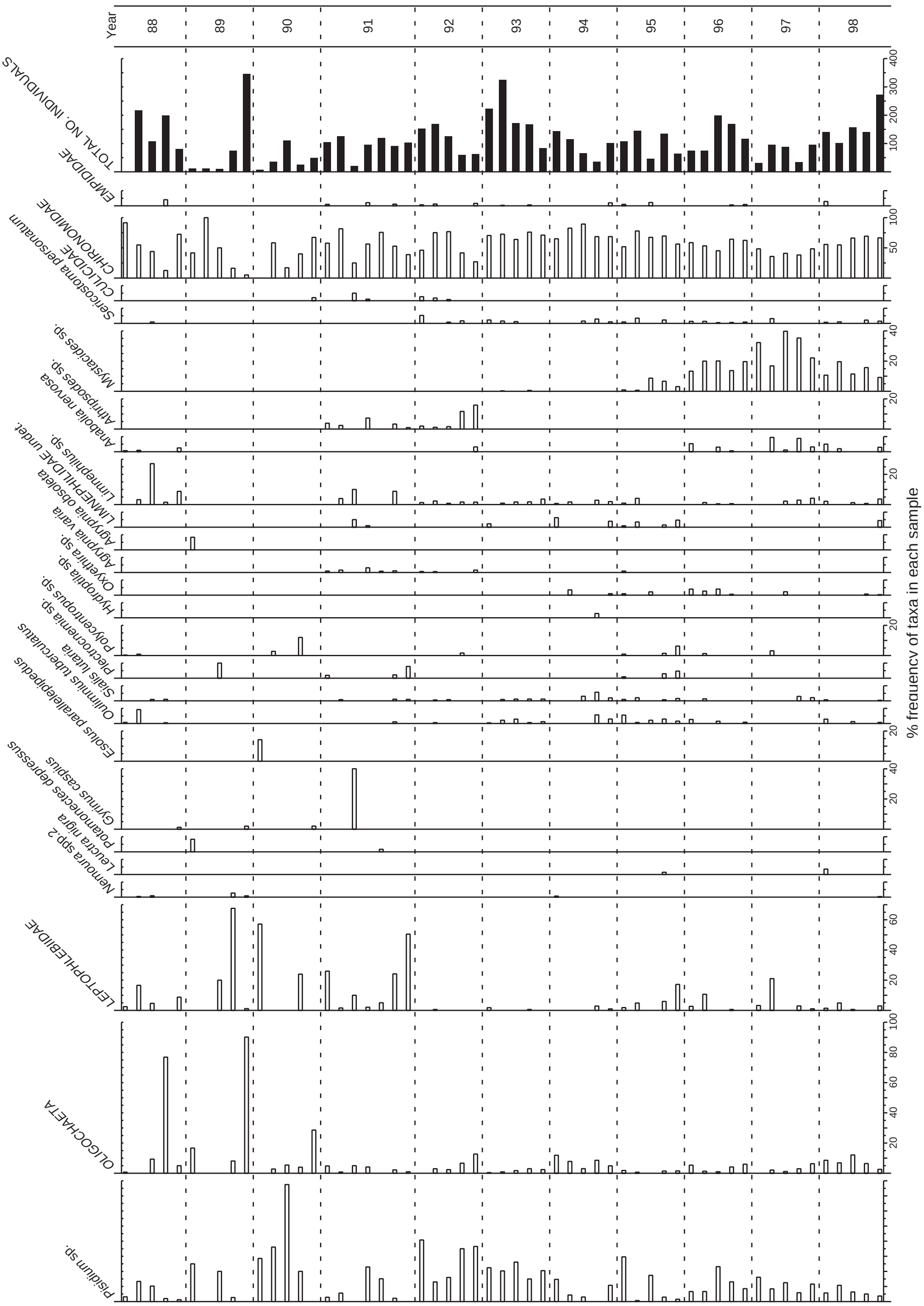


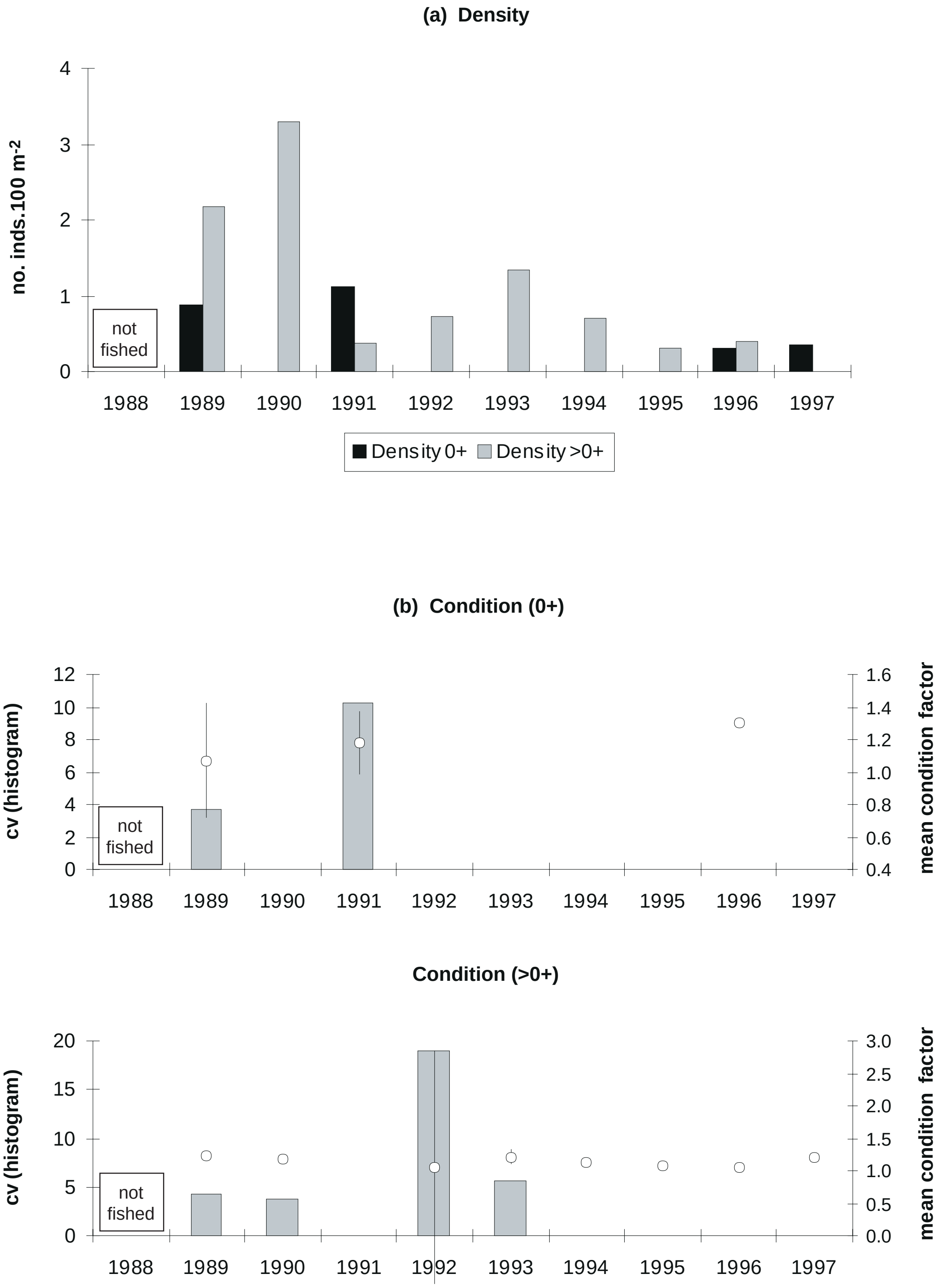
Figure 4.6.4

Loch Tinker: summary of macroinvertebrate data (1988 - 1998)

Percentage frequency of taxa in individual samples

Figure 4.6.5

Loch Tinker outflow: summary of fish data (1989 - 1997)
(a) Trout population density for 0+ and >0+ age classes (individuals 100 m^{-2})
(b) Mean condition factor (with standard deviation) of the trout population and its coefficient of variation (histogram)



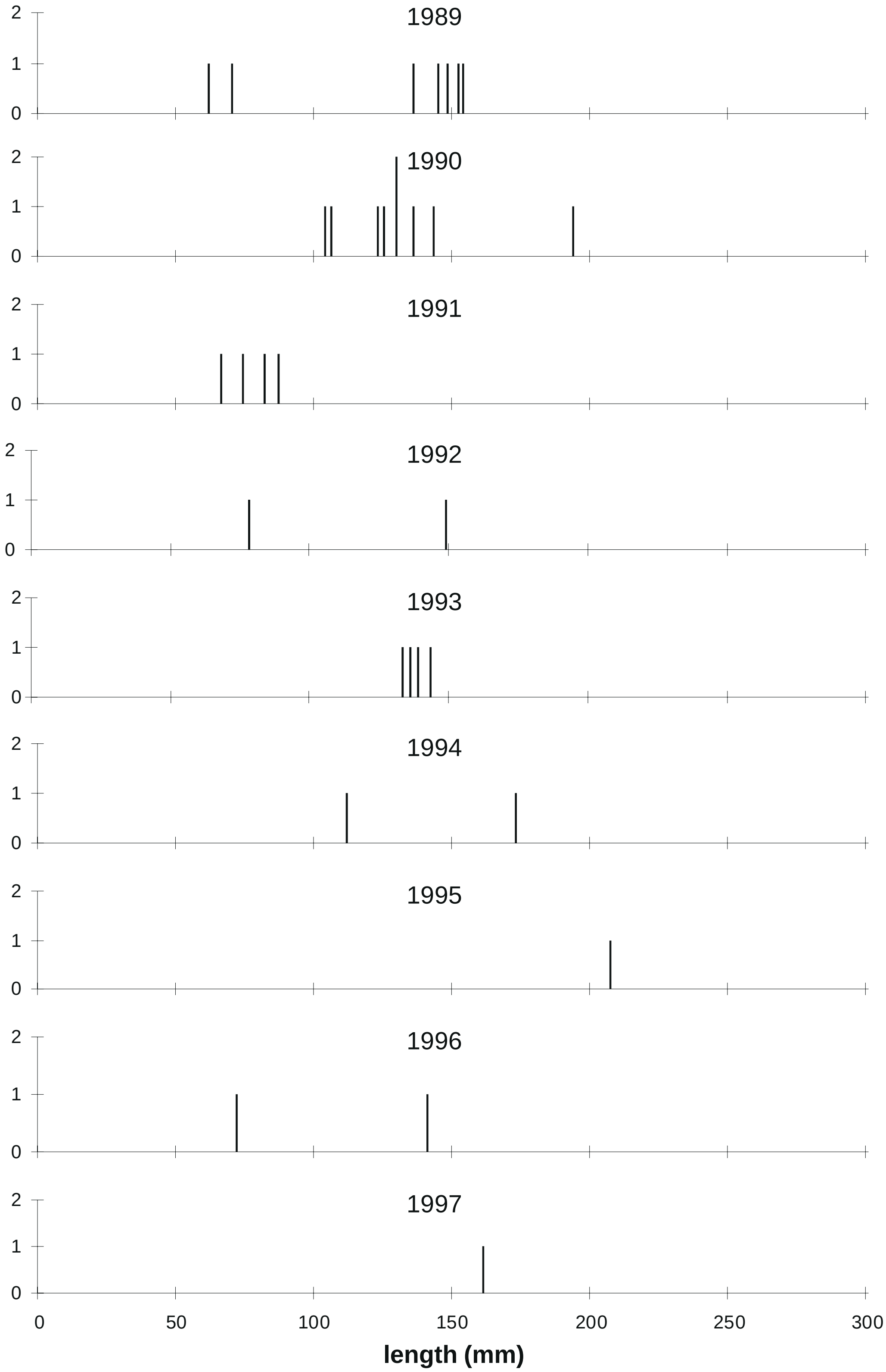


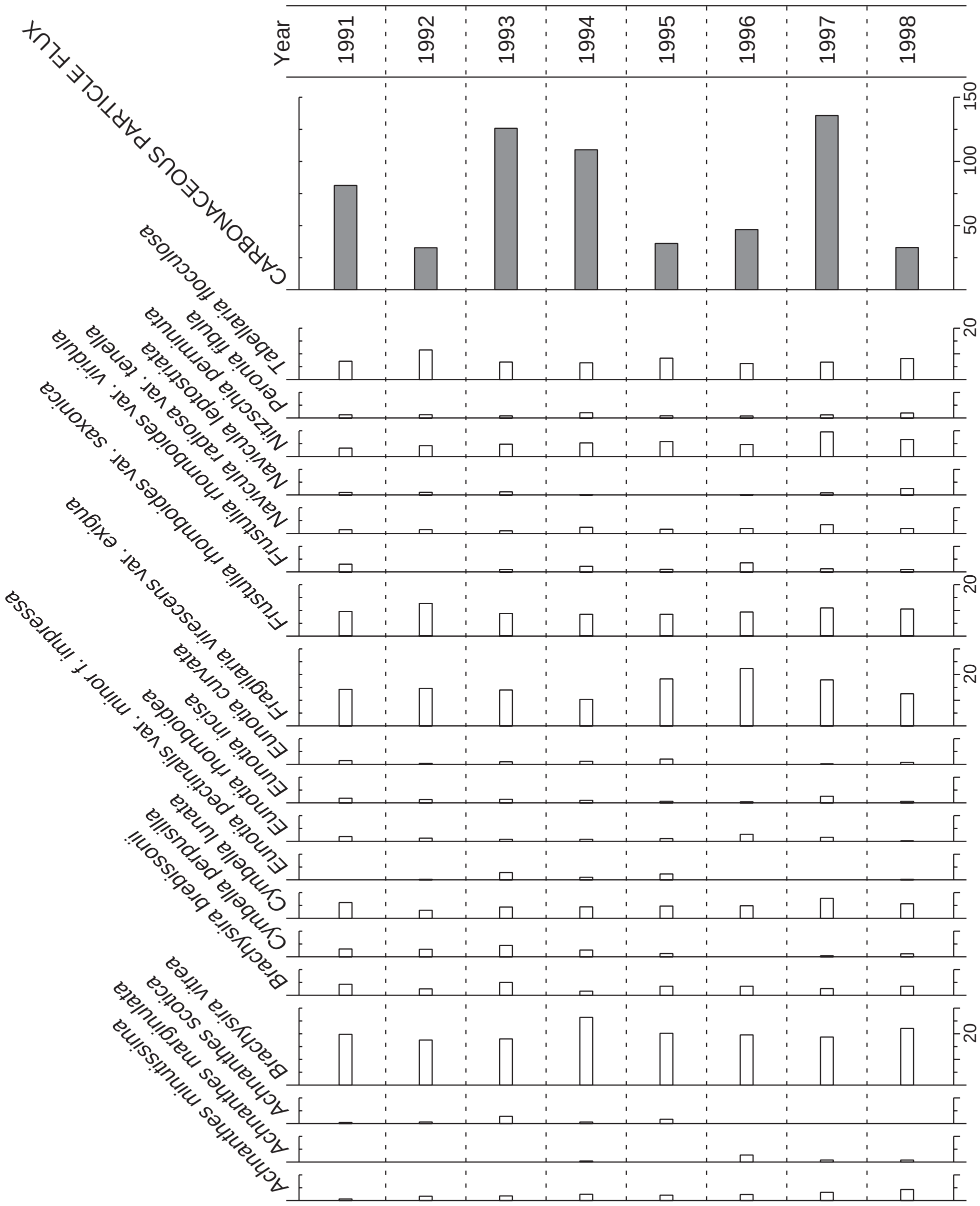
Figure 4.6.5

Loch Tinker: summary of fish data (1989 - 1997)
(c) Trout length frequency summaries

Figure 4.6.6

Loch Tinker: summary of sediment trap data for diatoms and carbonaceous particles

Relative frequency of diatom taxa (>2% in at least one sample) at time of trap retrieval and estimated carbonaceous particle flux (no. trap^{-1} day^{-1}) for preceding year



4.7 Round Loch of Glenhead

Site Review

Round Loch of Glenhead, in the Galloway region of southwest Scotland, has been central to studies on acidification since the problem was first investigated in the UK (e.g. Flower *et al.*, 1987; Harriman *et al.*, 1987; Battarbee *et al.*, 1988). Although severely acidified, palaeoecological work on a sediment core taken in 1989 indicated that the site had undergone a slight and very recent improvement in pH (Allott *et al.* 1992). There has been no physical disturbance in the Loch catchment since the onset of monitoring.

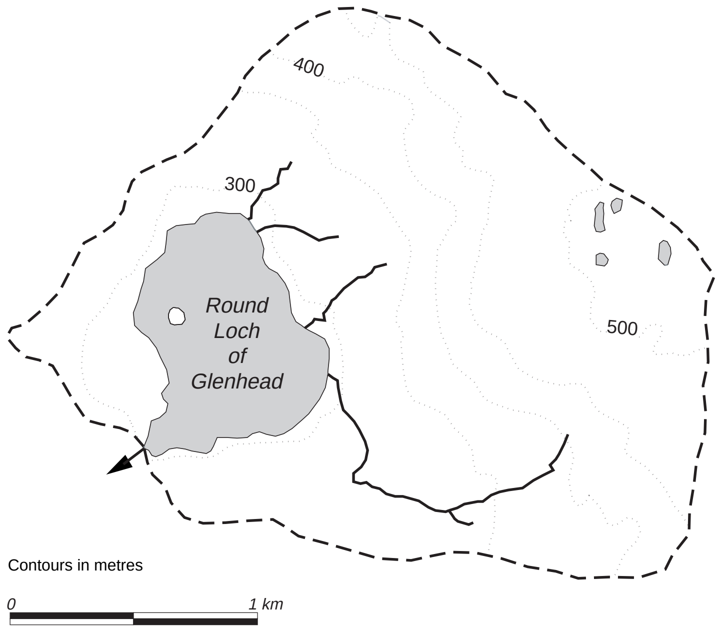


Figure 4.7.1

Round Loch of Glenhead: catchment

Table 4.7.1

Round Loch of Glenhead: site characteristics

Grid reference	*NX 450804*
Lake altitude	*295 m*
Maximum depth	*13.5 m*
Mean depth	*4.28 m*
Volume	*5.3 x 10^5 m^3*
Lake area	*12.5 ha*
Catchment area (excl. lake)	*95.1 ha*
Catchment: Lake area ratio	*7.5*
Catchment Geology	*tonalite, tonalite/granite*
Catchment Soils	*peat, peaty podsols*
Catchment vegetation	*moorland - 100%*
Net relief	*236 m*
Mean annual rainfall	*2342 mm*
1996 deposition	
Total S	*35 kg ha^{-1} yr^{-1}*
non-marine S	*28 kg ha^{-1} yr^{-1}*
Oxidised N	*13 kg ha^{-1} yr^{-1}*
Reduced N	*21 kg ha^{-1} yr^{-1}*

Table 4.7.2

Round Loch of Glenhead: summary of chemical determinands, June 1988 - March 1998

Determinand		Mean	Max	Min
pH		*4.90*	*5.21*	*4.72*
Alkalinity	μeq l^{-1}	*-12.2*	*6.0*	*-22.0*
Ca	μeq l^{-1}	*33.0*	*42.0*	*25.0*
Mg	μeq l^{-1}	*45.8*	*66.7*	*33.3*
Na	μeq l^{-1}	*174.3*	*247.8*	*130.4*
K	μeq l^{-1}	*8.2*	*12.8*	*2.6*
SO_4	μeq l^{-1}	*67.5*	*114.6*	*45.8*
xSO_4	μeq l^{-1}	*47.1*	*89.8*	*31.9*
NO_3	μeq l^{-1}	*7.1*	*24.3*	*< 1.4*
Cl	μeq l^{-1}	*195.2*	*298.6*	*121.1*
Soluble Al	μg l^{-1}	*95.1*	*146.0*	*55.0*
Labile Al	μg l^{-1}	*60.2*	*111.0*	*9.0*
Non-labile Al	μg l^{-1}	*34.9*	*70.0*	*16.0*
DOC	mg l^{-1}	*3.0*	*5.0*	*1.6*
Conductivity	μS cm^{-1}	*36.7*	*49.0*	*28.0*

Water Chemistry

(Figure 4.7.2, Tables 4.7.2-3)

Round Loch of Glenhead is chronically acidic, with a mean pH of 4.9 (range 4.7 to 5.2), a negative mean alkalinity, and high concentrations of labile Al. The catchment has a low buffering capacity, with a mean lake-water Ca of only 33 μeq l^{-1}, and a mean xSO_4 of 47 μeq l^{-1}. NO_3 concentrations are low, with a mean of 7 μeq l^{-1}, although concentrations generally remain above detection limits throughout the year.

Trend analyses suggest that Cl, Na and Mg have all declined significantly over the last decade (Table 4.7.3). However, it is considered likely, that these apparent trends are the result of natural variations in marine ion deposition. This is supported by time series (Figure 4.7.2) showing a period of elevated Na and Cl during 1989-1992. As at Lochs Chon and Tinker, increased marine base cations may cause a displacement of non-marine cations from soil exchange sites through the sea-salt effect (Section 5.3). This is evident at Round Loch for both Ca (Figure 4.7.2g), which is higher during the earlier part of the record, and for labile Al (Figure 4.7.2i), which clearly tracks Na and Cl concentrations throughout the monitoring period. Observed declining trends for both determinands may therefore also be linked to marine ion variations.

Both regression and SKT identify a rising trend in NO_3. Although this may be partly influenced by high concentrations during 1996, a more general increase is evident from Figure 4.7.2e in both winter maxima and summer minima over the ten years. DOC and non-labile Al have also risen fairly steadily over this time, as at other sites. Significant rising trends identified after five years for SO_4 and xSO_4 (Patrick *et al.*, 1995) are no longer observed, and time series (Figures 4.7.2c,d) suggest that concentrations peaked around 1992-1994. More recent data suggest that sulphate concentrations have now begun to decline.

Some sampling was undertaken at Round Loch of Glenhead prior to the initiation of the UKAWMN, and this is discussed in Section 6.

Epilithic diatoms

(Figure 4.7.3, Table 4.7.4)

The epilithon of the Round Loch of Glenhead is dominated by the acidobiontic species, *Tabellaria quadriseptata*, *Eunotia incisa*, *Brachysira brebissonii* and *Frustulia rhomboides* var. *saxonica*. Of these, the former is most abundant in the majority of samples and, given its pH optima of 4.9, provides an indication of the severely acid conditions of this site. An increase in the proportion of *Navicula*

Table 4.7.3

Significant trends in chemical determinands (July 1988 - March 1998)

Determinand	Units	Annual trend (Regression)	Annual trend (Seasonal Kendall)
Cl	μeq l^{-1}	*-8.99***	*-9.43**
Na	μeq l^{-1}	*-6.78****	*-6.52**
Mg	μeq l^{-1}	*-1.33***	*-1.19**
Ca	μeq l^{-1}	*-0.75***	*-0.73**
NO_3	μeq l^{-1}	*+0.86****	*+0.61**
DOC	mg l^{-1}	*+0.09**	*+0.13***
Non-labile Al	μg l^{-1}	*+1.94***	*+2.31**
Labile Al	μg l^{-1}	-	*-2.63**

** Trend significant at $p < 0.05$; ** trend significant at $p < 0.01$; *** trend significant at $p < 0.001$*

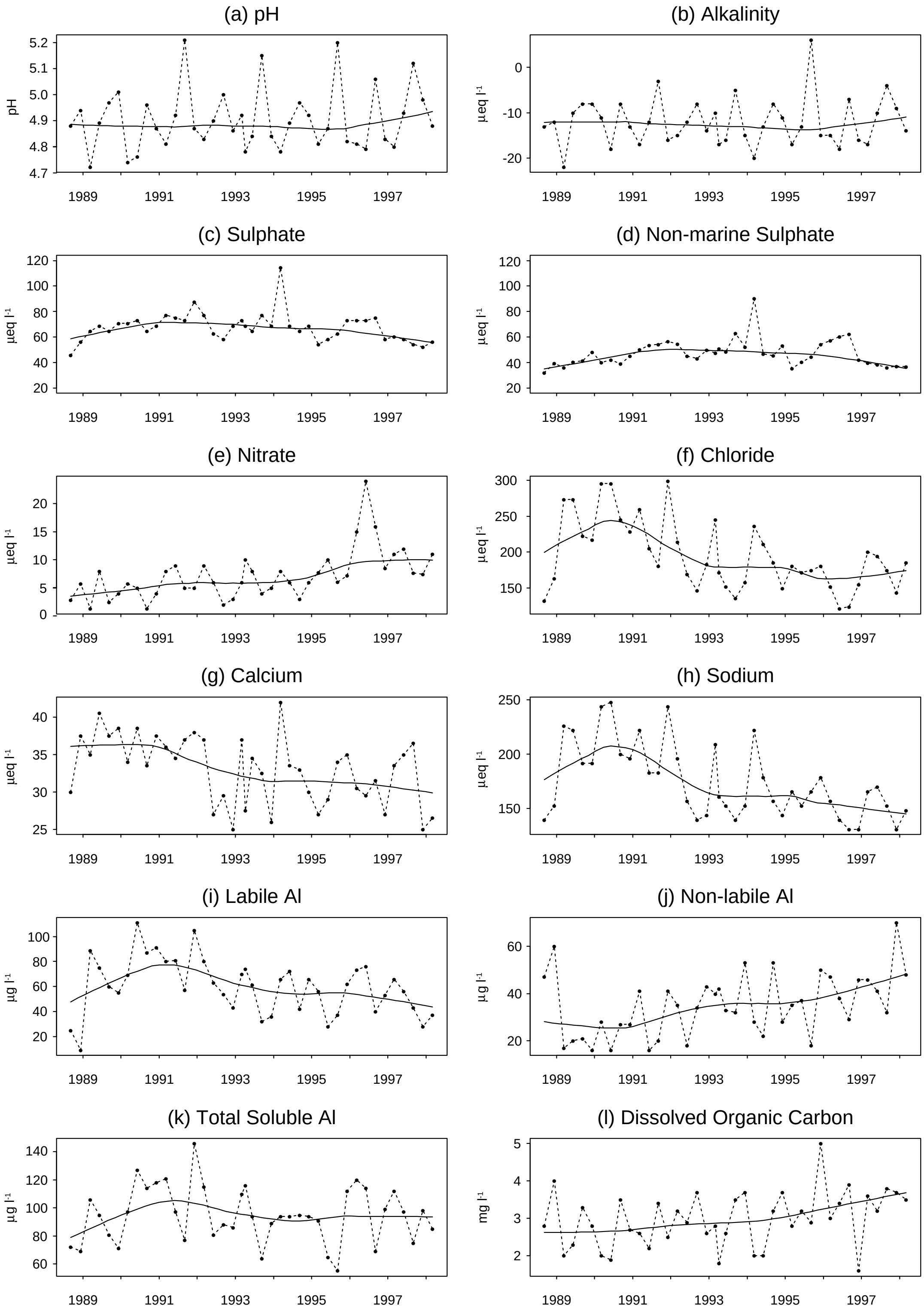


Figure 4.7.2

Round Loch of Glenhead: summary of major chemical determinands (September 1988 - March 1998)

Smoothed line represents LOESS curve (Section 3.1.2)

Table 4.7.4

Round Loch of Glenhead: trend statistics for epilithic diatom, macrophyte and macroinvertebrate summary data (1988 - 1998)

	Total sum of squares	Number of Taxa	Mean N_2 diversity	λ_1RDA/λ_2RDA	λ_1RDA/λ_1PCA
Epilithic diatoms	*289*	*87*	*6.8*	*0.29*	*0.27*
Macrophytes	*39*	*17*	*8.9*	*0.55*	*0.53*
Invertebrates	*486*	*26*	*1.8*	*0.14*	*0.14*

Variance explained (%)	within year	between years	linear trend	p unrestricted	p restricted
Epilithic diatoms	*53.2*	*46.8*	*6.8*	*0.02*	*0.13*
Macrophytes	*	*	*22.9*	*0.16*	*0.24*
Invertebrates	*72.5*	*27.5*	*2.9*	*0.09*	*0.50*

leptostriata during 1995-1997 is indicative of a mild amelioration of pH over this period. However, RDA and associated permutation test shows that "sample year" is not significant at the 0.01 level and there is no temporal pattern in the diatom inferred pH derived from weighted averaging. The epilithon assemblage is floristically very similar to the assemblage of sediment trap samples which have been collected since 1991 (Figure 4.7.6). These also show no evidence of any time trend.

Macroinvertebrates

(Figure 4.7.4, Table 4.7.4)

Round Loch of Glenhead has a relatively species poor fauna characterised by the most acid tolerant mayfly family, the Leptophlebiidae, chironomids and the caddisflies *Plectrocnemia* spp. and *Polycentropus* spp.. Detritivorous stoneflies of the genus *Nemoura spp.* were recorded intermittently. Other common taxa include the water beetles *Potamonectes depressus* and *Potamonectes griseostriatus* and several other species of caddisfly. Fluctuations in faunal abundance have occurred, with 1992 and 1996 being particularly poor years. The species composition has remained relatively persistent and RDA shows that a linear trend with time is insignificant.

Fish

(Figure 4.7.5)

The outflow stream of Round Loch of Glenhead has been electrofished since 1989. Mean population numbers are low. Densities of 0+ trout rose during the first three years but have since declined, with a total recruitment failure in 1993 followed by consistently low numbers. Densities of >0+ fish show two years of higher population density (1994 and 1995); however neither follow on from a high recruitment year and most years show low densities. The length frequency histograms also indicate the poor population structure present at the site. The mean condition factor of both age classes has remained stable and their coefficients of variance show no trends. HABSCORE HQS values have remained relatively constant and observed densities are well below those predicted.

Aquatic macrophytes

(Tables 4.7.4-5)

The relatively impoverished aquatic flora of this loch reflects the acidity of the system. The submerged vascular flora is restricted to the acid tolerant isoetid species, *Isoetes lacustris*, *Lobelia dortmanna* and *Littorella uniflora*, and the

Table 4.7.5

Round Loch of Glenhead: relative abundance of aquatic macrophyte flora (1988 - 1997) (see Section 3.2.3 for key to indicator values)

Abundance Taxon Year	88	89	90	91	92	93	95	97
INDICATOR SPECIES								
Sphagnum auriculatum[4]	1	1	1	1	1	1	1	1
Juncus bulbosus var. *fluitans*[4]	4	4	4	4	4	4	4	4
OTHER SUBMERGED OR FLOATING SPECIES								
Batrachospermum sp.	1	2	2	1	1	0	1	1
Filamentous green algae	3	3	4	3	5	1	4	2
Mnium hornum	0	1	0	0	0	1	0	0
Racomitrium aquaticum	0	1	0	0	0	0	0	0
Diplophyllum albicans	0	1	0	0	0	0	0	0
Marsupella emarginata	0	0	1	1	1	0	1	1
Nardia compressa	0	1	3	3	3	3	3	3
Scapania undulata	1	1	1	1	0	1	1	1
Isoetes lacustris	3	3	4	4	4	3	4	3
Littorella uniflora	2	2	2	2	1	2	2	2
Lobelia dortmanna	4	4	5	5	5	5	5	5
Glyceria fluitans	1	1	0	0	0	0	0	0
Potamogeton polygonifolius	1		1	0	0	0	0	1
Sparganium angustifolium	1	1	1	1	2	1	2	2
EMERGENT SPECIES								
Ranunculus flammula	0	1	2	2	2	2	2	2
Carex rostrata	1	1	1	1	1	1	1	1
Eleocharis palustris	2	2	0	0	0	0	0	1
Juncus acutifloris/articulatus	0	2	2	2	2	2	2	2
TOTAL NUMBER OF SPECIES	13	18	15	14	13	13	14	16

acidophilous rush *Juncus bulbosus* var. *fluitans* which is particularly abundant in some sandy, shallow water locations. Rocks within the littoral are covered with liverworts, and chiefly by *Nardia compressa*. The acidophilous moss *Sphagnum auriculatum* is only present in a few locations. Apart from reductions in the emergent species *Carex rostrata* and *Eleocharis palustris*, which appear to have been affected by grazing by deer, there is no evidence of change in floristic composition over the decade and no significant time trend according to RDA and associated permutation test.

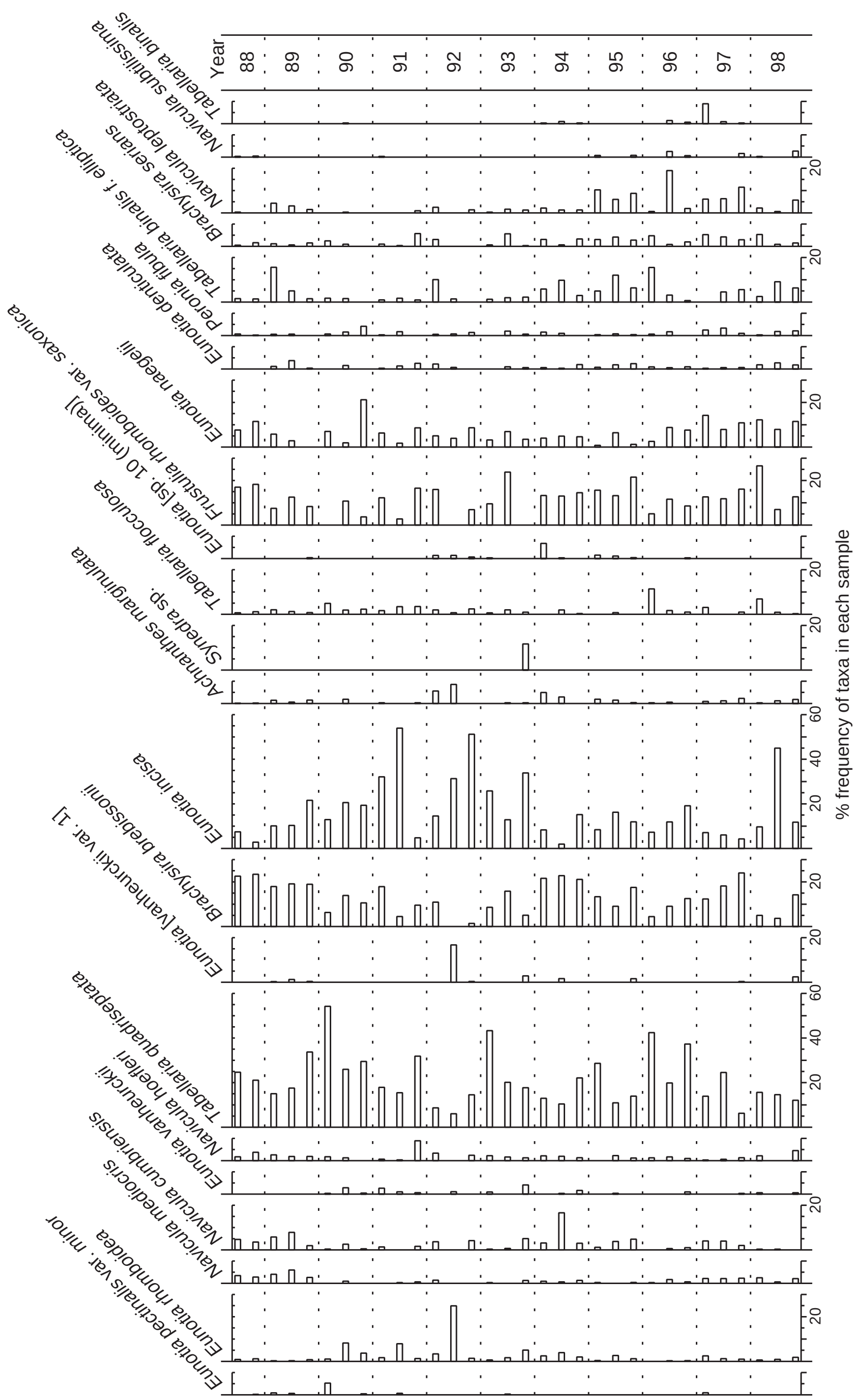
Summary

Round Loch of Glenhead is a severely impacted site with little ability to neutralise incoming acid deposition. A pronounced cyclical change in marine ions has taken place during the last ten years, which can be linked to climatically-driven fluctuations in deposition inputs, and which may have had a significant impact on variations in acidity related variables such as labile Al. NO_3 concentrations, although low, appear to have risen over the decade, whilst SO_4 and xSO_4 concentrations rose to a peak in the middle part of the record and have since declined. No overall trend has been observed in either pH or alkalinity or in any biological group. However, by including chemical measurements made prior to UKAWMN monitoring, it is clear that large reductions in xSO_4 have occured over a longer time scale and there is also evidence for a slight improvement in pH. This is consistent with the palaeoecological evidence which suggested small improvements, according to the fossil diatom assemblage, in the mid- to late 1980s.

Figure 4.7.3

Round Loch of Glenhead: summary of epilithic diatom data (1988 - 1998)

Percentage frequency of all taxa occurring at >2% abundance in any one sample



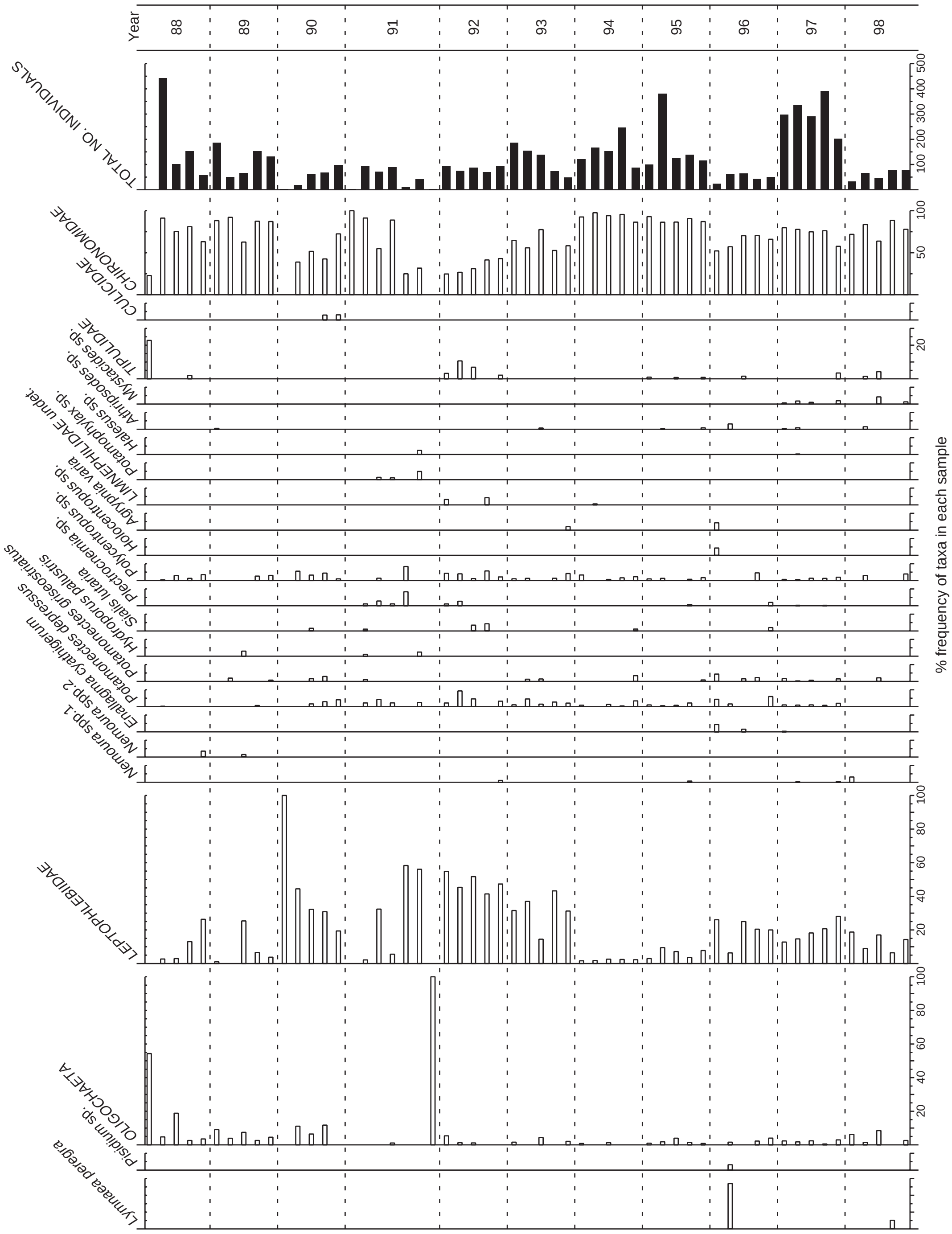


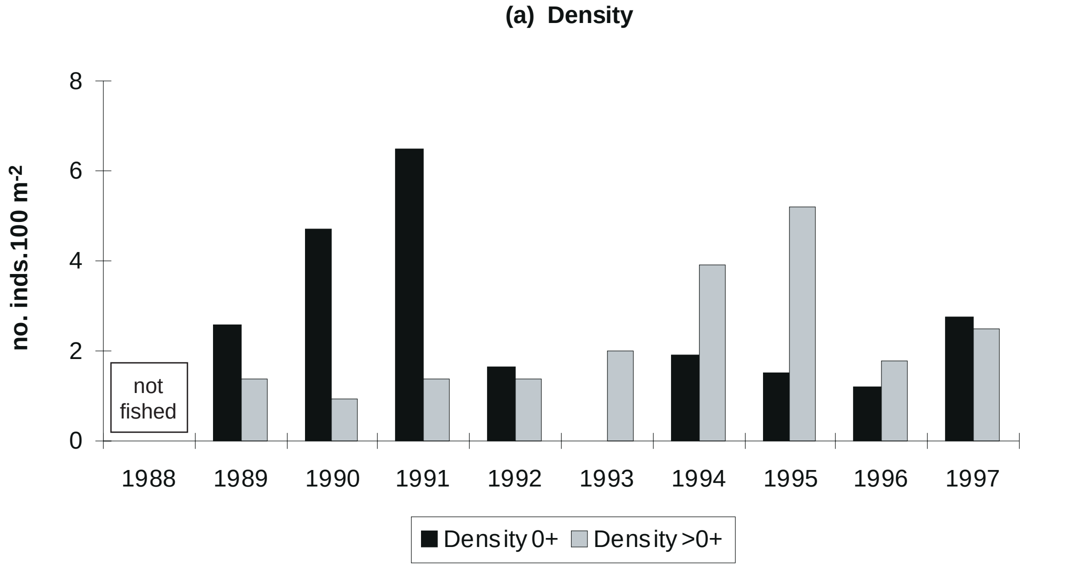
Figure 4.7.4

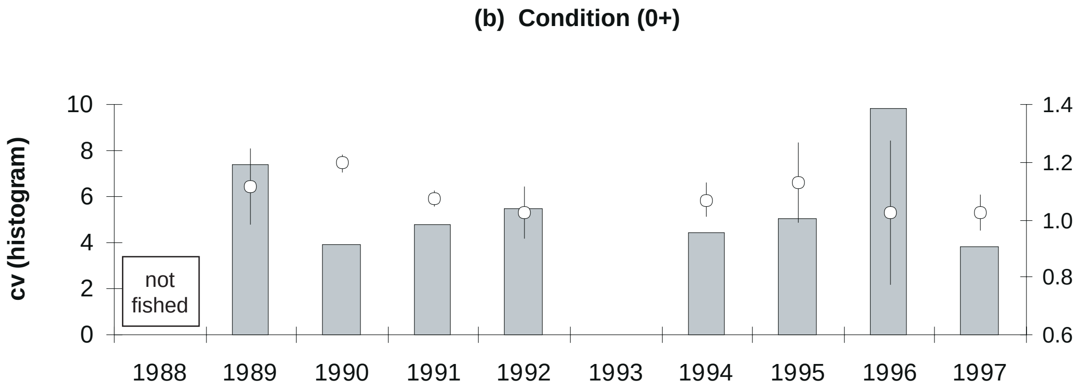
Round Loch of Glenhead: summary of macroinvertebrate data (1988 - 1998)

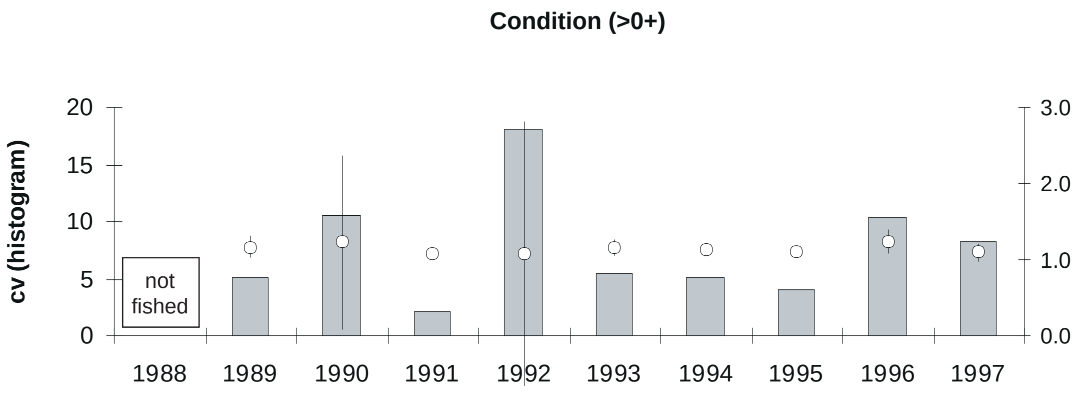
Percentage frequency of taxa in individual samples

Figure 4.7.5

Round Loch of Glenhead: summary of fish data (1989 - 1997)
(a) Trout population density for 0+ and >0+ age classes (individuals 100 m^{-2})
(b) Mean condition factor (with standard deviation) of the trout population and its coefficient of variation (histogram)







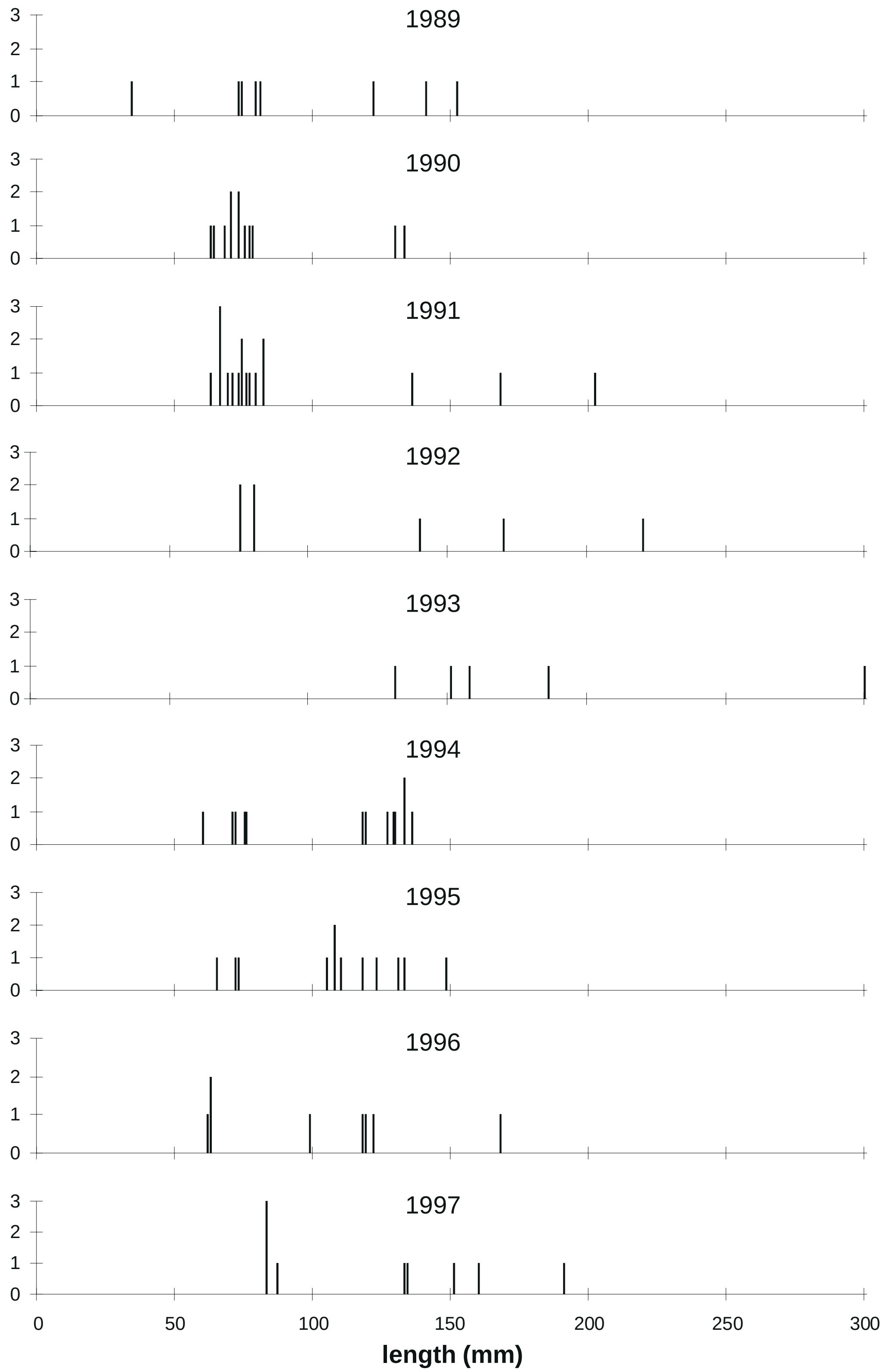


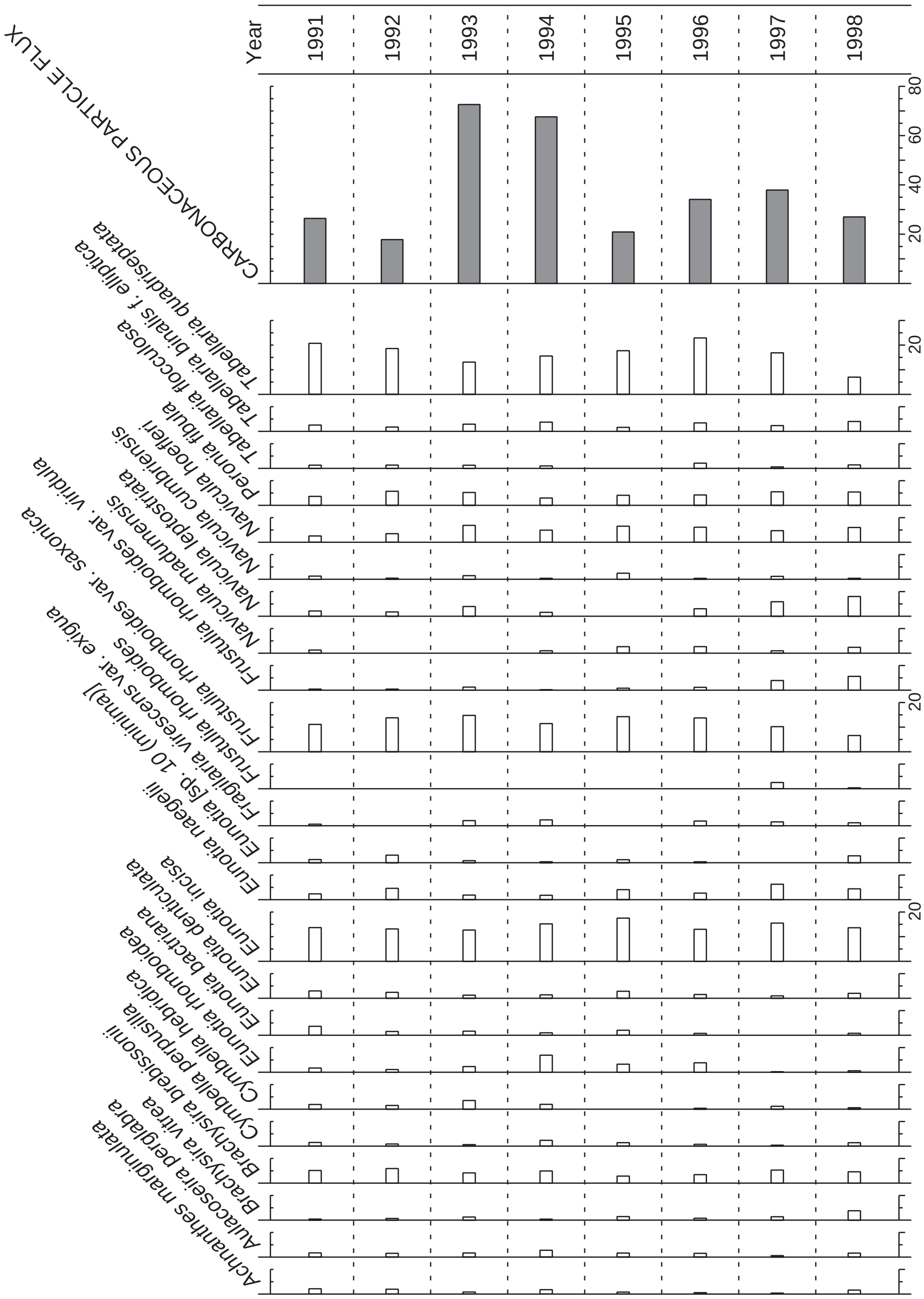
Figure 4.7.5

Round Loch of Glenhead: summary of fish data (1989 - 1997)
(c) Trout length frequency summaries

Figure 4.7.6

Round Loch of Glenhead: summary of sediment trap data for diatoms and carbonaceous particles

Relative frequency of diatom taxa (>2% in at least one sample) at time of trap retrieval and estimated carbonaceous particle flux (no. trap^{-1} day^{-1}) for preceding year



4.8 Loch Grannoch

■ Site Review

Loch Grannoch is a large loch in the Galloway region of southwest Scotland. In contrast to the neighbouring site, Round Loch of Glenhead, a large proportion of the catchment is under managed coniferous forest, part of which is approaching maturity. Despite this, no felling had been carried out over the period analysed in this report. Flower *et al.* (1990) observed a floristic difference between the diatom assemblage of a surface sediment sample, taken in 1988, and that of the upper layers of a sediment core taken two years previously. This was attributed to phosphorus and potassium fertiliser application in the catchment, peaking in 1985, which is likely to have raised nutrient levels in the Loch. There was little indication at the time that this had affected Loch pH. Paleoecological pH reconstruction, using the

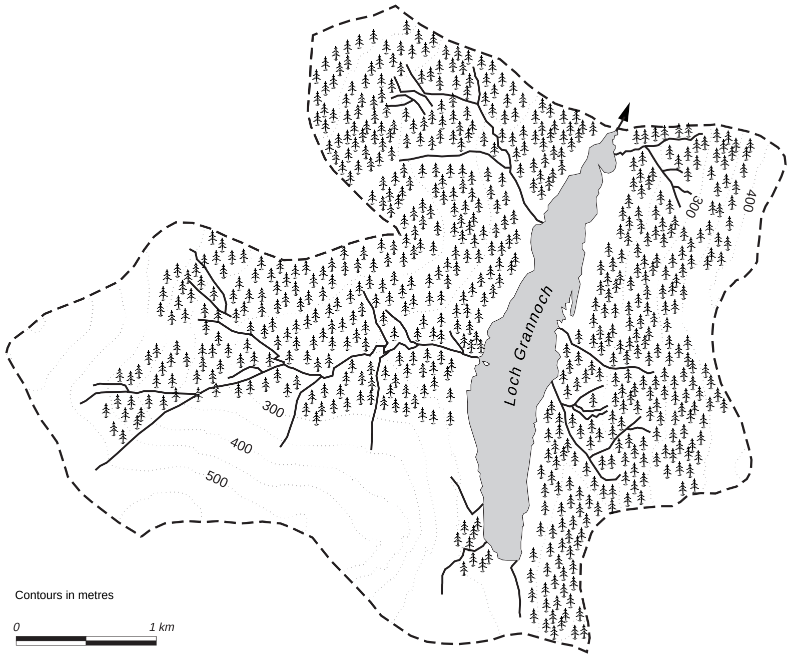


Figure 4.8.1

Loch Grannoch: catchment

Table 4.8.1

Loch Grannoch: site characteristics

Grid reference	*NX 542700*
Lake altitude	*210 m*
Maximum depth	*20.5 m*
Mean depth	*6.4 m*
Volume	*7.4 x 10^6 m^3*
Lake area	*114.3 ha*
Catchment area (excl. lake)	*1287 ha*
Catchment: Lake area ratio	*11.3*
Catchment Geology	*granite*
Catchment Soils	*peats, peaty podsols, peaty gleys, skeletal soils*
Catchment vegetation	*conifers - 70% moorland 30%*
Net relief	*391 m*
Mean annual rainfall	*2286 mm*
1996 deposition	
Total S	*32 kg ha^{-1} yr^{-1}*
non-marine S	*26 kg ha^{-1} yr^{-1}*
Oxidised N	*12 kg ha^{-1} yr^{-1}*
Reduced N	*21 kg ha^{-1} yr^{-1}*

Table 4.8.2

Loch Grannoch: summary of chemical determinands, September 1988 - March 1998

Determinand		Mean	Max	Min
pH		*4.61*	*5.04*	*4.27*
Alkalinity	µeq l^{-1}	*-27.8*	*2.0*	*-58.0*
Ca	µeq l^{-1}	*48.0*	*62.5*	*31.0*
Mg	µeq l^{-1}	*54.2*	*75.0*	*25.0*
Na	µeq l^{-1}	*223.0*	*313.0*	*147.8*
K	µeq l^{-1}	*6.4*	*10.3*	*2.6*
SO_4	µeq l^{-1}	*98.5*	*143.8*	*66.7*
xSO_4	µeq l^{-1}	*71.7*	*114.2*	*48.3*
NO_3	µeq l^{-1}	*17.1*	*39.3*	*2.9*
Cl	µeq l^{-1}	*257.2*	*425.4*	*157.7*
Soluble Al	µg l^{-1}	*313.3*	*715.0*	*106.0*
Labile Al	µg l^{-1}	*225.2*	*552.0*	*38.0*
Non-labile Al	µg l^{-1}	*80.9*	*283.0*	*22.0*
DOC	mg l^{-1}	*4.3*	*12.8*	*2.7*
Conductivity	µS cm^{-1}	*52.5*	*78.0*	*31.0*

fossil diatom assemblage from a more recent sediment core, suggest that the loch has progressively acidified, from at least the mid-nineteenth century (pH 5.2) to pH 4.5 by 1989 (Patrick *et al*., 1995).

Water Chemistry

(Figure 4.8.2, Table 4.8.2-3)

Mean lake-water pH and alkalinity at Loch Grannoch are the second lowest in the Network; pH has only exceeded 5.0, and alkalinity exceeded zero, in one sample (summer of 1996). Al concentrations are extremely high, and are dominated by the labile fraction. Mean xSO_4, at 72 µeq l^{-1}, is significantly above that at the nearby Round Loch of Glenhead, appearing to confirm that afforestation has enhanced pollutant inputs (see Section 5.5.2). Significant NO_3 leaching is occurring, with mean concentrations of 17 ueq l^{-1} and a strong seasonal cycle with concentrations ranging over an order of magnitude from 3 to 39 µeq l^{-1}.

Variations in surface water chemistry over the monitoring period have been very similar to those at Round Loch of Glenhead. Marine ions showed a pronounced peak in 1989-1991 (e.g. Figures 4.8.2f,h) producing apparent declining trends in Cl, Na, Mg and Ca. SO_4, and xSO_4 concentrations rose until the mid-1990s but have since shown a marked decline (Figures 4.8.2c,d). No significant trends were obtained for pH or alkalinity, but LOESS curves (Figures 4.8.2a,b) suggest that both may have declined slightly since monitoring began. This would be consistent with MAGIC modelling work by Jenkins *et al*. (1997a), predicting worsening acidification of the Loch despite reduced deposition under a scenario of continued forestry. Alternatively, pH may have been temporarily raised around the onset of monitoring, by the effect of fertiliser run-off enhancing within-lake productivity (see epilithic diatom Section). Time series also suggest that NO_3 may have risen (Figure 4.8.2e), although any change is difficult to identify with confidence given the degree of seasonality. A significant increase was observed in DOC using SKT, of around 1.3 mg l^{-1} over the decade.

Epilithic diatoms

(Figure 4.8.3, Table 4.8.4)

Marked changes in the epilithic flora of Loch Grannoch support the water chemistry evidence that Loch Grannoch has acidified over the past decade. *Tabellaria quadriseptata*, indicative of severely acid conditions, has increased substantially in relative abundance, and particularly since 1994. Prior to 1993, representation of *T. quadriseptata* had never exceeded 5% in any sample but by 1998 it comprised over 50% of valves counted in all samples. This increase has been reciprocally matched by reductions in *Asterionella ralfsii*,

Table 4.8.3

Significant trends in chemical determinands (July 1988 - March 1998)

Determinand	Units	Annual trend (Regression)	Annual trend (Seasonal Kendall)
Cl	µeq 1^{-1}	*-8.90**	*-8.45**
Na	µeq 1^{-1}	*-5.48***	*-6.52**
Mg	µeq 1^{-1}	-	*-1.67**
Ca	µeq 1^{-1}	*-1.45****	*-1.65**
DOC	mg l^{-1}	*+0.21**	*+0.13***

** Trend significant at $p < 0.05$; ** trend significant at $p < 0.01$; *** trend significant at $p < 0.001$*

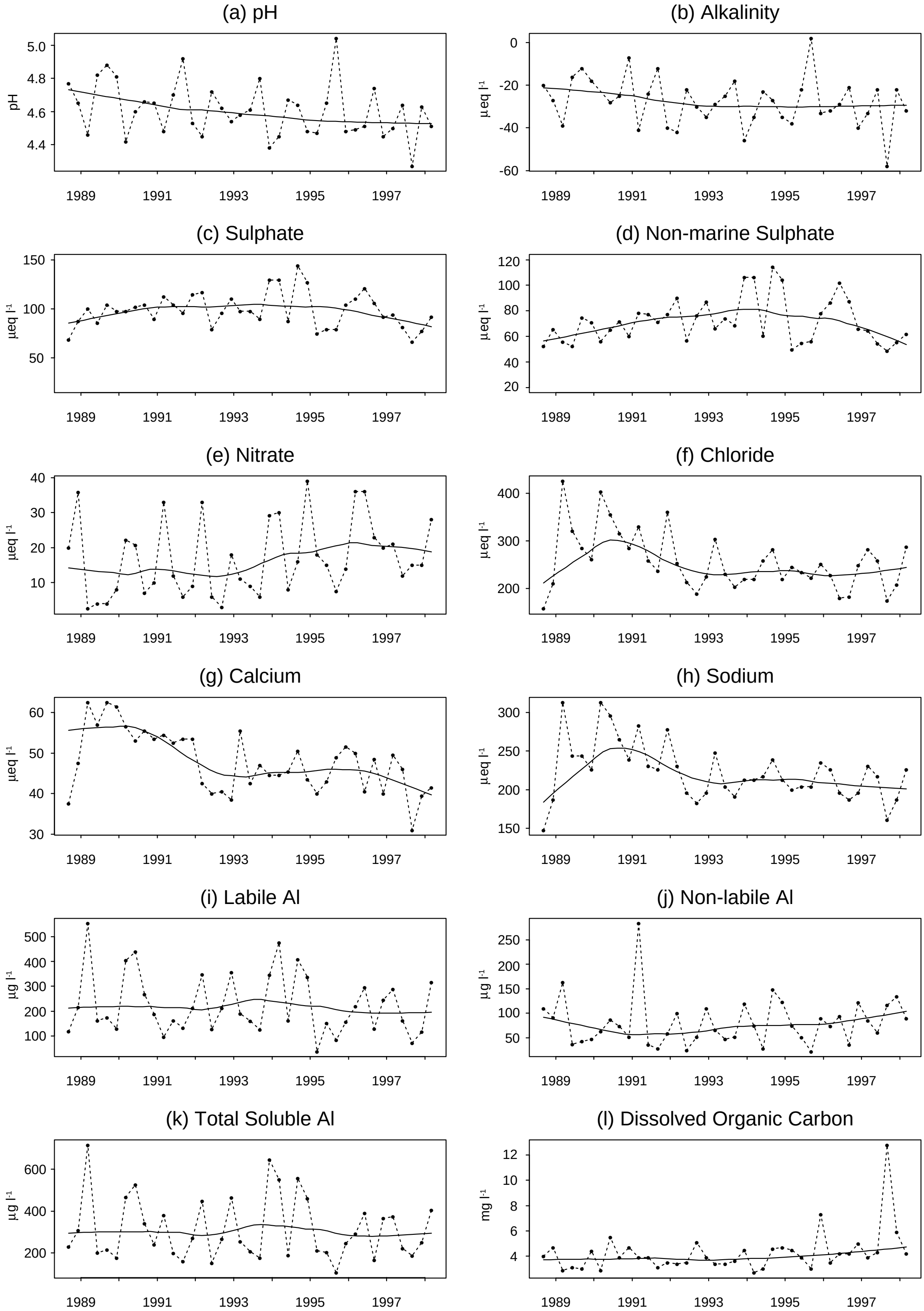


Figure 4.8.2

Loch Grannoch: summary of major chemical determinands (September 1988 - March 1998)

Smoothed line represents LOESS curve (Section 3.1.2)

Table 4.8.4

Loch Grannoch: trend statistics for epilithic diatom, macrophyte and macroinvertebrate summary data (1988 - 1998)

	Total sum of squares	Number of Taxa	MeanN_2 diversity	λ_1RDA/λ_2RDA	λ_1RDA/λ_2PCA
Epilithic diatoms	*601*	*102*	*4.3*	*1.57*	*0.82*
Macrophytes	*31*	*22*	*12.8*	*0.83*	*0.59*
Invertebrates	*820*	*44*	*2.8*	*1.02*	*0.64*

Variance explained (%)	within year	between years	linear trend	p unrestricted	p restricted
Epilithic diatoms	*40.1*	*59.9*	*26.0*	*< 0.01*	*< 0.01*
Macrophytes	*	*	*25.5*	*0.05*	*0.07*
Invertebrates	*46.6*	*53.4*	*13.1*	*< 0.01*	*< 0.01*

Pinnularia subcapitata var. *hilseana* and *Tabellaria flocculosa*, the latter two having slightly higher pH optima and the former the same as *T. quadriseptata* (pH optima 4.9). *A. ralfsii* was only observed in the Loch in abundance for the first time in 1988, and being characteristic of peatland disturbance and nutrient enrichment (Liehu *et al.*, 1986), its occurence was attributed to phosphorus and potassium fertiliser application which peaked around 1985. Sediment cores demonstrate that, prior to the expansion of this species, *T. quadriseptata* was the dominant diatom, and sediment trap samples (Figure 4.8.6) suggest that the last ten years has seen a gradual return to the pre-1988 flora, with *T. quadriseptata* at similar abundances now to then. These data therefore provide an alternative explanation for the recently observed pH decline, as this would be expected following a decline in within-lake productivity, following a decline in lake nutrients. For the epilithic diatom assemblage, time as a linear variable is highly significant at the 0.01 level according to RDA and associated permutation tests, and can account for 26% of between-sample variance. This is close to the maximum variance which can be explained by the 1st axis in Principal Components Analysis (i.e. 32%) and therefore emphasises the strength of the unidirectional change in the species assemblage with time.

■ Macroinvertebrates

(Figure 4.8.4, Table 4.8.4)

The macroinvertebrate fauna is dominated by the acid tolerant mayfly family, the Leptophlebiidae, and by the Chironomidae. Other mayflies present include *Siphlonurus lacustris* and *Ameletus inopinatus* which have both shown an increase in abundance in the last few years. Only two individuals of the acid sensitive *Baetis* spp. were recorded, in 1993 and 1994. The stonefly community was most abundant in the first four years of monitoring and included acid tolerant *Nemoura* spp. and *Nemurella pictetii*. More recently the stoneflies have been impoverished and were absent in 1998. The first few years were also characterised by a diverse community of corixids and water beetles. These have declined in recent years with only *Potamonectes depressus* being present throughout the survey. Of the caddisflies, *Plectrocnemia* spp. and *Polycentropus* spp. were both present in most years up to 1995, while *Cyrnus* spp. appeared in 1994. Several species of case-bearing caddis have been recorded intermittently (e.g. *Agrypnia varia*, *Anabolia nervosa* and *Oecetis ochracea*). Time as a linear trend is significant at the 0.01 level according to RDA and associated permutation tests. There appears to have been a

Table 4.8.5

Loch Grannoch: relative abundance of aquatic macrophyte flora (1988 - 1997)
(see Section 3.2.3 for key to indicator values)

Abundance Taxon Year	88	89	90	91	92	93	95	97
INDICATOR SPECIES								
Drepanocladus fluitans[4]	1	1	1	1	2	1	2	1
Sphagnum auriculatum[4]	3	3	3	3	4	4	4	4
Juncus bulbosus var. *fluitans*[4]	2	2	2	2	3	2	3	2
OTHER SUBMERGED OR FLOATING LEAF SPECIES								
Filamentous green algae	2	3	3	1	1	1	1	2
Amblystegium sp.	0	1	1	0	1	0	1	0
Atrichum sp.	1	0	0	0	0	0	0	0
Brachythecium sp.	1	1	0	0	0	0	0	0
Calliergon sp.	1	1	0	0	1	0	1	0
Hygrohypnum sp.	1	1	2	1	0	1	0	1
Mnium hornum	1	1	1	1	1	0	1	0
Plagiomnium sp.	0	1	0	0	0	0	0	0
Cephalozia connivens	0	0	1	0	0	0	0	0
Marsupella emarginata	0	1	1	1	1	1	1	0
Nardia compressa	4	4	4	4	4	4	4	4
Isoetes lacustris	4	4	4	4	4	4	4	4
Littorella uniflora	3	3	3	3	3	3	3	3
Lobelia dortmanna	2	2	2	2	2	3	3	3
Nymphaea alba	0	1	1	1	1	2	2	1
Glyceria fluitans	0	1	1	0	0	0	0	0
EMERGENT SPECIES								
Equisetum fluviatile	2	2	2	2	2	2	2	2
Ranunculus flammula	1	1	1	1	1	1	1	1
Carex rostrata	2	2	2	2	2	2	2	2
Eleocharis palustris	2	2	2	2	2	2	2	2
Juncus acutifloris/articulatus	2	2	2	2	2	2	2	2
Phragmites australis	2	2	2	2	2	2	2	2
TOTAL NUMBER OF SPECIES	19	23	21	18	19	17	19	16

shift in species representation to a fauna indicative of less acid conditions, although the concomitant decline observed in species richness would normally be associated with worsening conditions. It is interesting to note that, although water chemistry LOESS plots suggest an overall deterioration in pH over the decade, there is an upward trend in March pH which appears to relate to a decline in climatically driven episodic effects.

■ Fish

(Figure 4.8.5)

The outflow of Loch Grannoch has been electrofished since 1989, although very few fish have been captured. The length frequency histogram shows that all these fish were old specimens and no recruitment has taken place at the site since at least 1989.

Aquatic macrophytes

(Tables 4.8.4-5)

As for the neighbouring Round Loch of Glenhead, the submerged aquatic macrophyte flora of Loch Grannoch is also limited to the relatively few species tolerant of high levels of acidity, i.e., *Isoetes lacustris*, *Lobelia dortmanna*, *Littorella uniflora* and *Juncus bulbosus* var. *fluitans*. Several emergent species, including *Phragmites australis* and *Equisetum fluviatile*, in addition to floating-leaved stands of *Nymphaea alba*, are also present in restricted locations, probably benefiting from the shelter offered by a more complex shoreline. The acidophilous moss *Sphagnum auriculatum* forms a substantial carpet over large areas of the Loch bottom at the north end, while another moss associated with particularly acid conditions, *Drepanocladus fluitans* has also been recorded at low abundance, in most years. There is no significant time trend in the DAFOR adundance data using RDA and associated restricted permutation test.

Summary

Loch Grannoch is severely acidified, with conditions seemingly worsened by the presence of forestry. Non-marine sulphate concentrations are high, and significant nitrogen leaching is occurring. Time series suggest that, if anything, pH and alkalinity are continuing to decline at the site, but trends are partly obscured by both pronounced seasonal cycles for a number of determinands, and the impact of large interannual fluctuations in marine ions. It is also possible that recent changes represent a gradual return to conditions prior to fertilizer application to the catchment in the mid-1980s. The trout population of the outflow burn has remained particularly low, while the aquatic macrophyte assemblage has been stable. Species changes in the other two biological groups provide conflicting indications of direction of change in acidity. The macroinvertebrates may have benefited from a general improvement in spring acidity resulting from a reduction in sea-salt deposition and spring rainfall generated episodes, while the epilithic diatoms seem to indicate a more general deterioration in conditions experienced during the growing season.

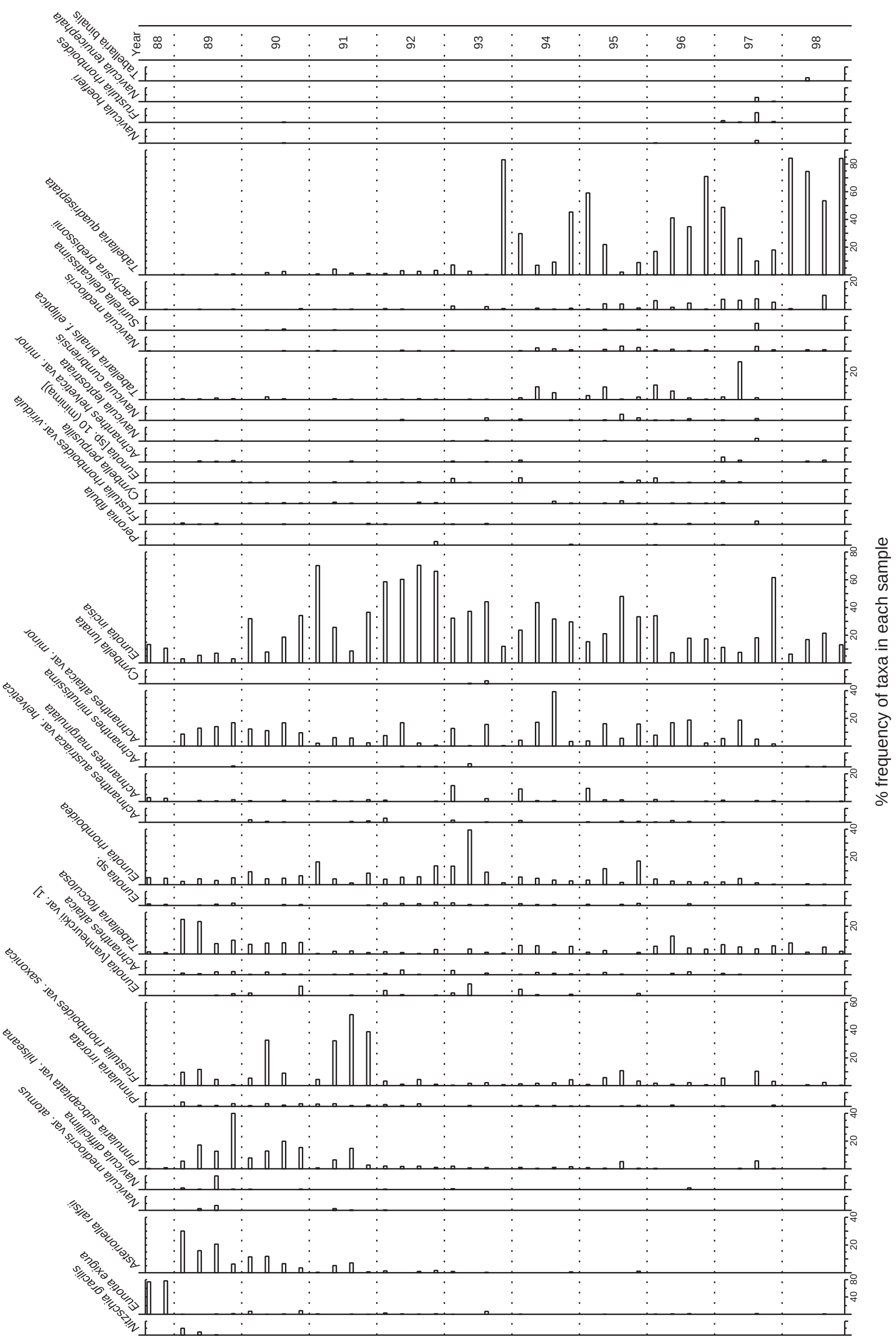


Figure 4.8.3

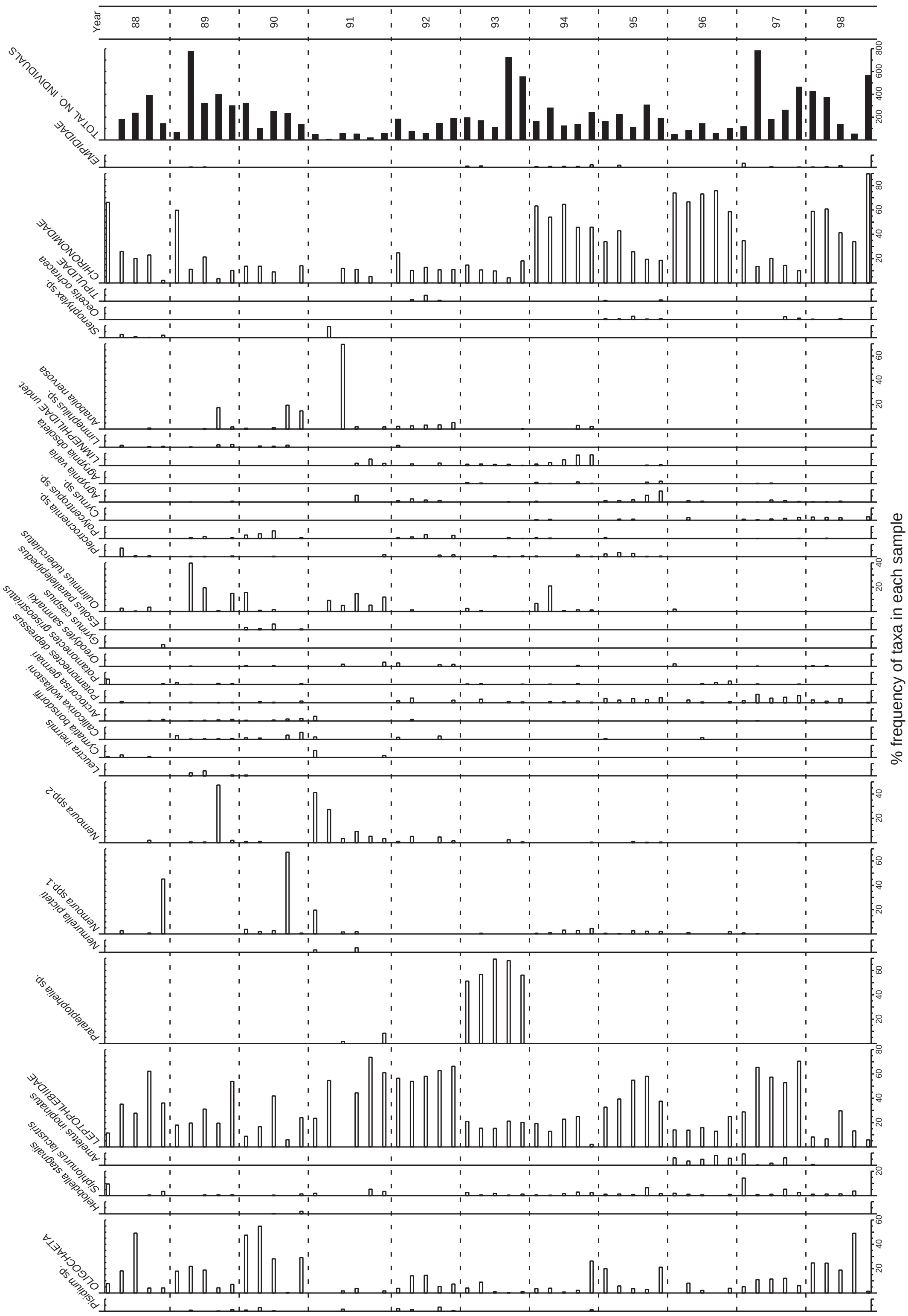
Loch Grannoch: summary of epilithic diatom data (1988 - 1998)

Percentage frequency of all taxa occurring at >2% abundance in any one sample

Figure 4.8.4

Loch Grannoch: summary of macroinvertebrate data (1988 - 1998)

Percentage frequency of taxa in individual samples



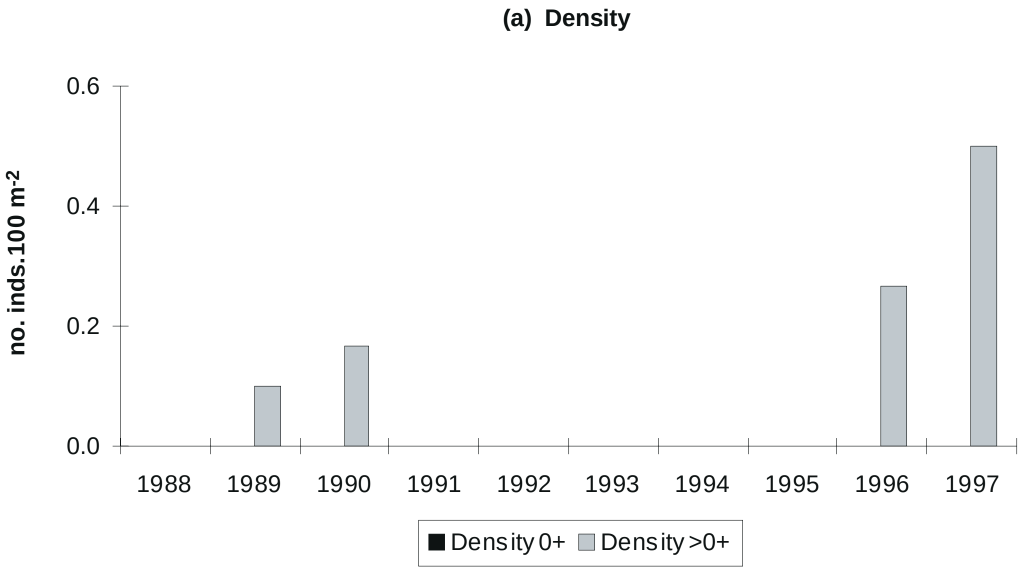
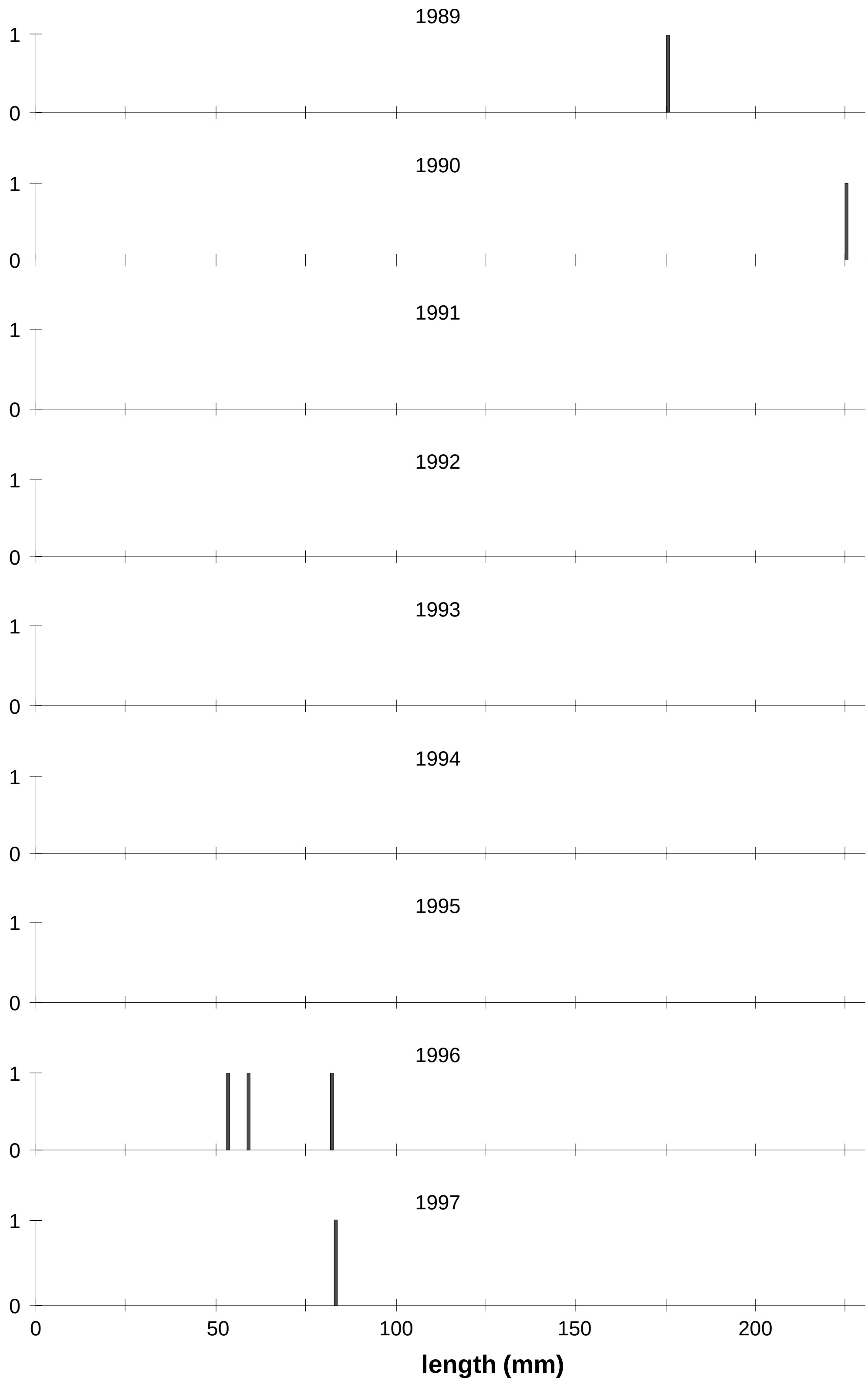


Figure 4.8.5

Loch Grannoch: summary of fish data (1989 - 1997)
(a) Trout population density for 0+ and >0+ age classes (individual 100 m^{-2})

Figure 4.8.5

Loch Grannoch: summary of fish data (1989 - 1997)
(c) Trout length frequency summaries



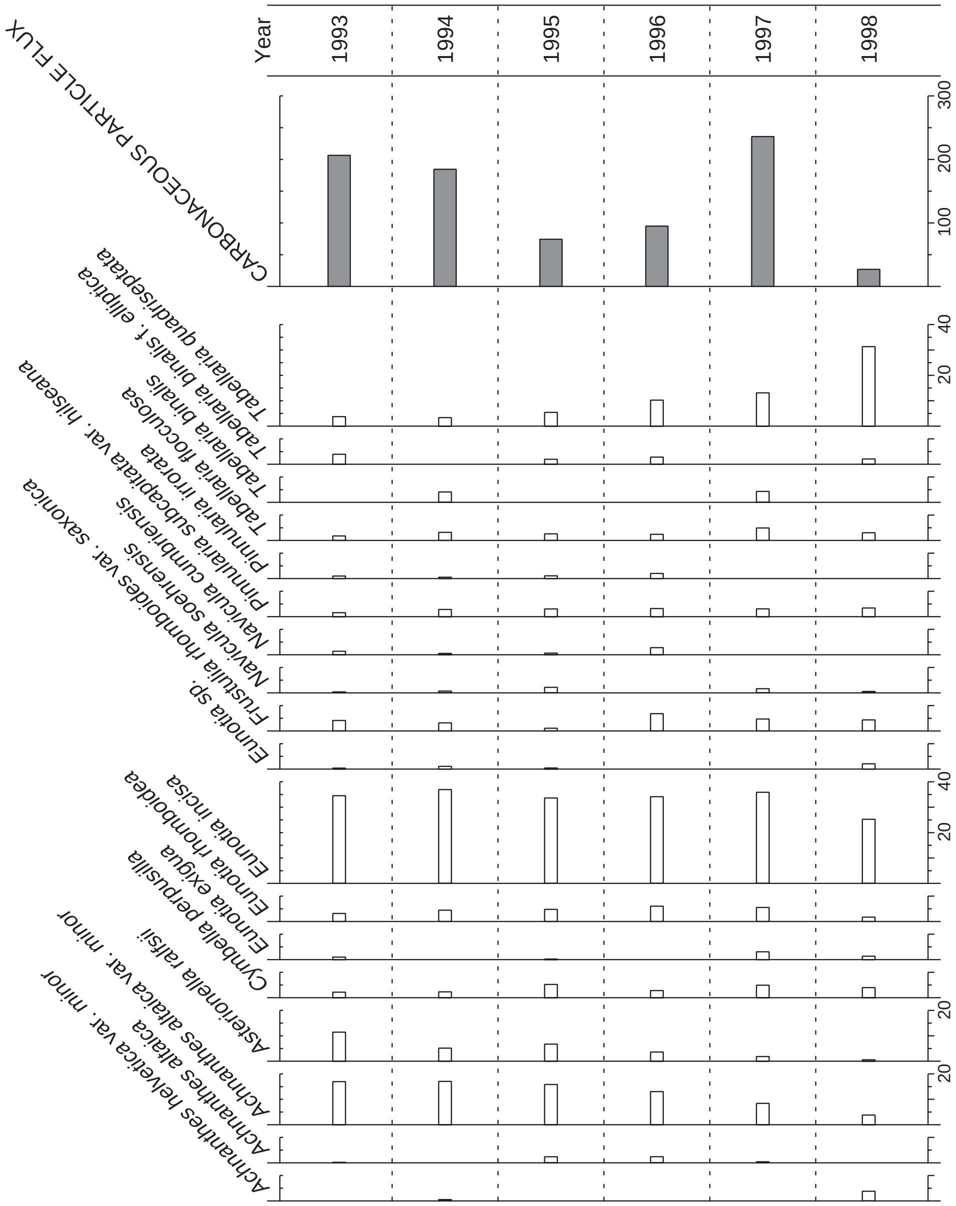


Figure 4.8.6

Loch Grannoch: summary of sediment trap data for diatoms and carbonaceous particles

Relative frequency of diatom taxa (>2% in at least one sample) at time of trap retrieval and estimated carbonaceous particle flux (no. trap^{-1} day^{-1}) for preceding year

4.9 Dargall Lane

Site Review

The Dargall Lane burn, a tributary of Loch Dee, runs approximately 2 km to the south of Round Loch of Glenhead in the Galloway region of southwest Scotland. The site has been subject to considerable hydrochemical and biological investigation since 1980 (e.g. Burns *et al.*, 1984; Cosby *et al.*, 1986; Harriman *et al.*, 1997; Langan, 1987; Giusti & Neal, 1993). No catchment disturbances have been observed since the onset of monitoring by the UKAWMN in 1988.

Water Chemistry

(Figure 4.9.2, Tables 4.9.2-3)

Dargall Lane is less acidic than the two Galloway lochs, although mean alkalinity is only 4 µeq l^{-1} and frequently becomes negative. Mean xSO_4 is higher than at Round Loch of Glenhead, the other moorland site in the region, and Giusti (1999) has argued that weathering of shales at Dargall Lane may constitute a significant internal SO_4 source.

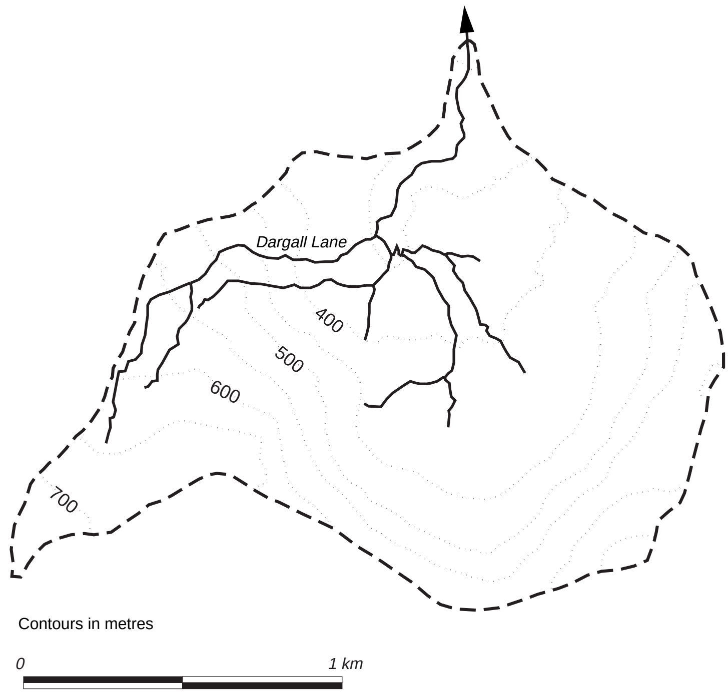


Figure 4.9.1

Dargall Lane: catchment

Table 4.9.1

Dargall Lane: site characteristics

Grid reference	*NX 449786*
Catchment area	*210 ha*
Minimum Catchment altitude	*225 m*
Maximum Catchment altitude	*716 m*
Catchment Geology	*greywackes, shales, mudstones, black shale*
Catchment Soils	*podsols, peaty gleys, blanket peat*
Catchment vegetation	*moorland - 100%*
Mean annual rainfall	*2426 mm*
1996 deposition	
Total S	*30 kg ha^{-1} yr^{-1}*
non-marine S	*25 kg ha^{-1} yr^{-1}*
Oxidised N	*11 kg ha^{-1} yr^{-1}*
Reduced N	*19 kg ha^{-1} yr^{-1}*

Table 4.9.2

Dargall Lane: summary of chemical determinands, July 1988 - March 1998

Determinand		Mean	Max	Min
pH		*5.52*	*6.45*	*4.91*
Alkalinity	µeq l^{-1}	*4.0*	*44.0*	*-12.0*
Ca	µeq l^{-1}	*49.5*	*80.5*	*23.0*
Mg	µeq l^{-1}	*53.3*	*83.3*	*25.0*
Na	µeq l^{-1}	*168.7*	*282.6*	*91.3*
K	µeq l^{-1}	*9.2*	*17.9*	*2.6*
SO_4	µeq l^{-1}	*79.8*	*110.4*	*41.7*
xSO_4	µeq l^{-1}	*60.2*	*90.6*	*31.7*
NO_3	µeq l^{-1}	*10.7*	*45.7*	*< 1.4*
Cl	µeq l^{-1}	*186.2*	*366.2*	*95.8*
Soluble Al	µg l^{-1}	*49.3*	*143.0*	*3.0*
Labile Al	µg l^{-1}	*32.6*	*133.0*	*<2.5*
Non-labile Al	µg l^{-1}	*17.0*	*65.0*	*<2.5*
DOC	mg l^{-1}	*1.7*	*5.9*	*0.3*
Conductivity	µS cm^{-1}	*35.3*	*59.0*	*21.0*

Higher Ca concentrations (mean 50 μeq l^{-1}) compared to Round Loch suggest that base cation weathering may also be higher. NO_3 concentrations show a strong seasonal cycle, exceeding 40 μeq l^{-1} during some winters but falling below detection limits for at least three months during every summer of the record (Figure 4.9.2e).

Although this stream exhibits a wider range of chemical variation than the two loch sites, changes in marine ions over time have been similar, with a peak in 1990. Again, this has led to the detection of declining trends for Cl, Na, Mg, and Ca (Table 4.9.3). There is some evidence for reduced acidity at the site, with increasing alkalinity and declining labile Al identified by both SKT and regression, and declining SO_4 by regression. However no accompanying trend is obtained for xSO_4, and time series plots (Figures 4.9.2,c,d) suggest concentrations peaked in the mid-1990s followed by a decrease, as at the other Galloway sites. The more acidic conditions in the early part of the record may be thus in part due to the 'sea-salt' displacement of soil acid cations by elevated marine base cations (Section 5.3) and by a changing flow regime (flow recorded at the time of sampling was generally highest around 1990). DOC and non-labile Al both show significant rising trends, DOC having increased by 1 mg l^{-1} during the last ten years. Dargall Lane has been monitored at high resolution since 1983. These data therefore present a longer term perspective of water chemistry trends and are presented in Chapter 6.

Epilithic diatoms

(Figure 4.9.3, Table 4.9.4)

Dargall Lane has undergone considerable variation in epilithic diatom species relative abundances during the past decade. *Peronia fibula* (pH optima 5.3) has been consistently abundant, but there has been an apparent shift from *Eunotia* species with relatively low pH optima (e.g. *E. naegelii* (5.0); *E. incisa* (5.1))in the early 1990s to an abundance of *Tabellaria flocculosa* (pH optima 5.4) between 1992-1997. These changes are consistent with LOESS plots for pH and alkalinity at this site which indicate apparent amelioration in water chemistry over the same period. *Eunotia* species increased in abundance again in 1998, indicating that the observed changes are perhaps more cyclical and climatically driven, rather than linear "recovery" responses. "Sample year" is not significant at the 0.01 level according to RDA analysis and associated permutation test.

Table 4.9.3

Significant trends in chemical determinands (July 1988 - March 1998)

Determinand	Units	Annual trend (Regression)	Annual trend (Seasonal Kendall)
Alkalinity	μeq l^{-1}	*+0.92**	*+0.85**
SO_4	μeq l^{-1}	*-0.75**	-
Cl	μeq l^{-1}	*-6.59****	*-5.63**
Na	μeq l^{-1}	*-4.43****	*-4.35**
Mg	μeq l^{-1}	*-1.33****	*-1.39**
Ca	μeq l^{-1}	*-0.95***	*-1.17**
DOC	mg l^{-1}	*+0.11****	*+0.10***
Non-labile Al	μg l^{-1}	-	*+0.86**
Labile Al	μg l^{-1}	*-2.15**	*-1.33**

** Trend significant at $p < 0.05$; ** trend significant at $p < 0.01$; *** trend significant at $p < 0.001$*

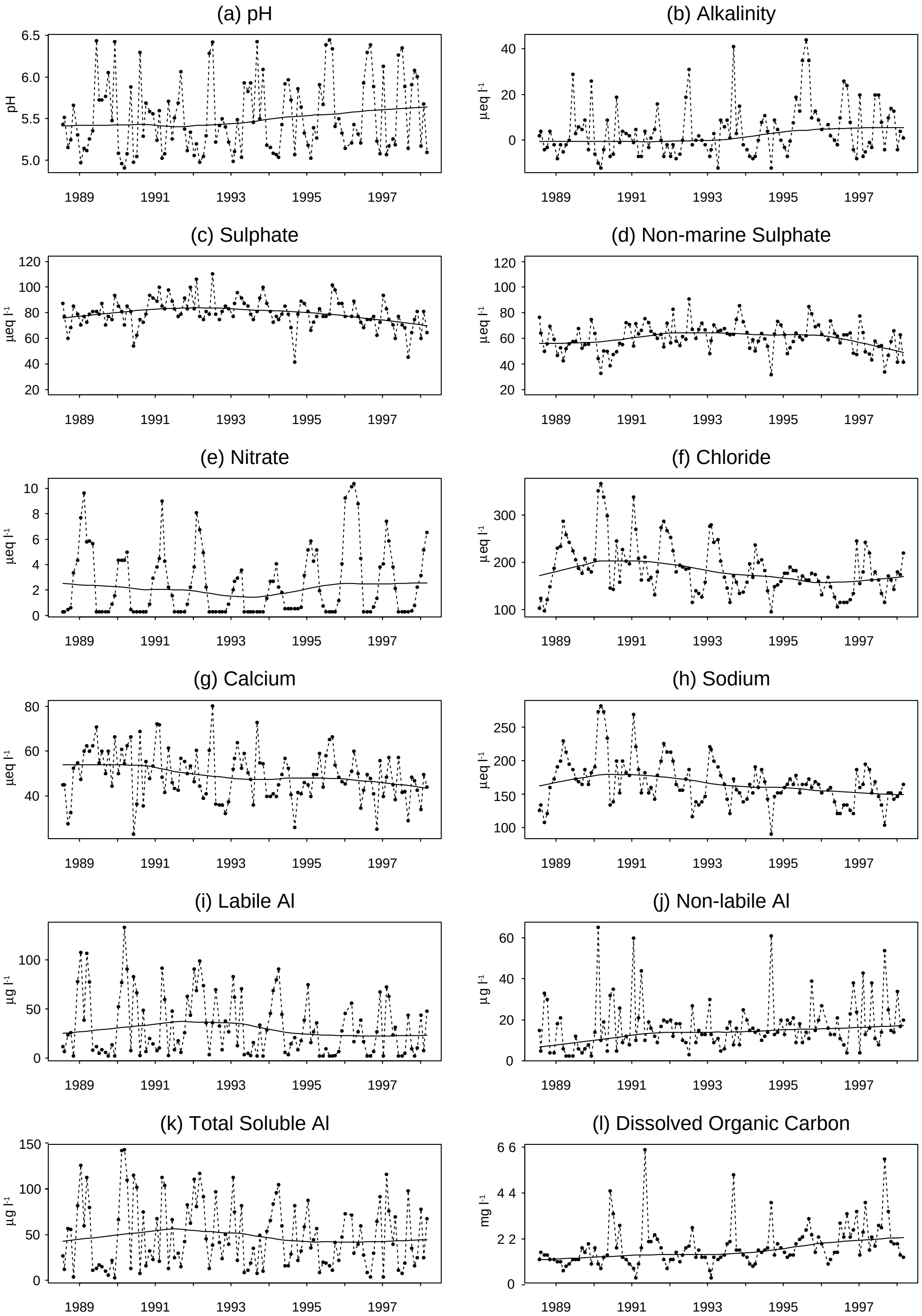


Figure 4.9.2

Dargall Lane: summary of major chemical determinands (September 1988 - March 1998)

Smoothed line represents LOESS curve (Section 3.1.2)

Table 4.9.4

Dargall Lane: trend statistics for epilithic diatom, macrophyte and macroinvertebrate summary data (1988 - 1998)

	Total sum of squares	Number of Taxa	MeanN_2 diversity	λ_1RDA/λ_2RDA	λ_1RDA/λ_1PCA
Epilithic diatoms	155	79	4.4	0.24	0.21
Macrophytes	25.5	6	1.9	0.12	0.12
Invertebrates	395	24	4.8	0.19	0.18

Variance explained (%)	within year	between years	linear trend	p unrestricted	p restricted
Epilithic diatoms	41.8	58.2	6.6	0.04	0.22
Macrophytes	*	*	8.0	0.55	0.78
Invertebrates	45.6	54.4	6.0	0.02	0.43

■ Macroinvertebrates

(Figure 4.9.4, Table 4.9.4)

The fauna of Dargall Lane is characterised by acid tolerant species. Detritivorous stoneflies dominate with *Amphinemura sulcicollis* occurring in the highest densities. Other stoneflies include *Leuctra inermis*, *Leuctra hippopus* and the predatory *Isoperla grammatica* and *Siphonoperla torrentium.* The acid tolerant *Plectrocnemia* spp. was recorded throughout the study. Over the monitoring period there has been an increase in species richness with a few species not tolerant of acid conditions such as *Oxyethira* spp. and *Hydropsyche siltalai* appearing in the last 5 years. This shift in species composition may therefore indicate a decrease in acidity (however see Section 7.4.2). RDA shows no significant linear trend between years.

■ Fish

(Figure 4.9.5)

Although this site has been electrofished since 1988, weighing of fish only commenced in the following year. Total trout density is intermediate for UKAWMN sites. Mean population density of both 0+ and >0+ fish has varied widely between years and no temporal trends are apparent. The condition factor of the 0+ fish underwent a steady decline between 1989 and 1995, but the past two years have seen an increase back to 1989 levels. There are no significant linear trends in the mean condition factor or coefficient of variation of the condition factor for either age group.

■ Aquatic macrophytes

(Tables 4.9.4-5)

The aquatic macroflora of the Dargall Lane consists almost exclusively of bryophytes, and in particular the acid tolerant liverwort species, *Scapania undulata* and *Nardia compressa*. A third species, *Marsupella emarginata* is also recorded consistently. Estimates of the cover of individual species appear to have been affected by the sporadic occurence of filamentous green algae which has a strong influence on the overall cover estimates of each survey section. There is no evidence of a linear time trend in species cover according to RDA and associated permutation test.

Table 4.9.5

Dargall Lane: relative abundance of aquatic macrophyte flora (1988 - 1997) (see Section 3.2.3 for key to indicator values)

Abundance Taxon Year	88	89	90	91	92	93	95	96	97
INDICATOR SPECIES									
Nardia compressa[4]	*0.3*	*9.0*	*31.4*	*34.6*	*25.9*	*23.3*	*26.8*	*24.0*	*5.9*
OTHER SUBMERGED OR FLOATING SPECIES									
Filamentous green algae	*10.9*	*25.4*	*9.8*	*5.5*	*0.6*	*0.6*	*9.3*	*0.8*	*46.5*
Marsupella emarginata	*0.0*	*<0.1*	*0.0*	*0.3*	*2.3*	*0.1*	*1.1*	*0.6*	*0.0*
Pellia sp.	*0.0*	*0.0*	*<0.1*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*
Scapania undulata	*15.4*	*15.6*	*7.9*	*6.7*	*5.9*	*4.1*	*14.8*	*8.3*	*2.1*
Juncus bulbosus var. *fluitans*	*<0.1*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*
total macrophyte cover excluding filamentous algae	*15.7*	*24.6*	*39.3*	*41.6*	*34.1*	*27.5*	*42.7*	*32.9*	*8.0*
TOTAL NUMBER OF SPECIES	*4*	*4*	*4*	*4*	*4*	*4*	*4*	*4*	*3*

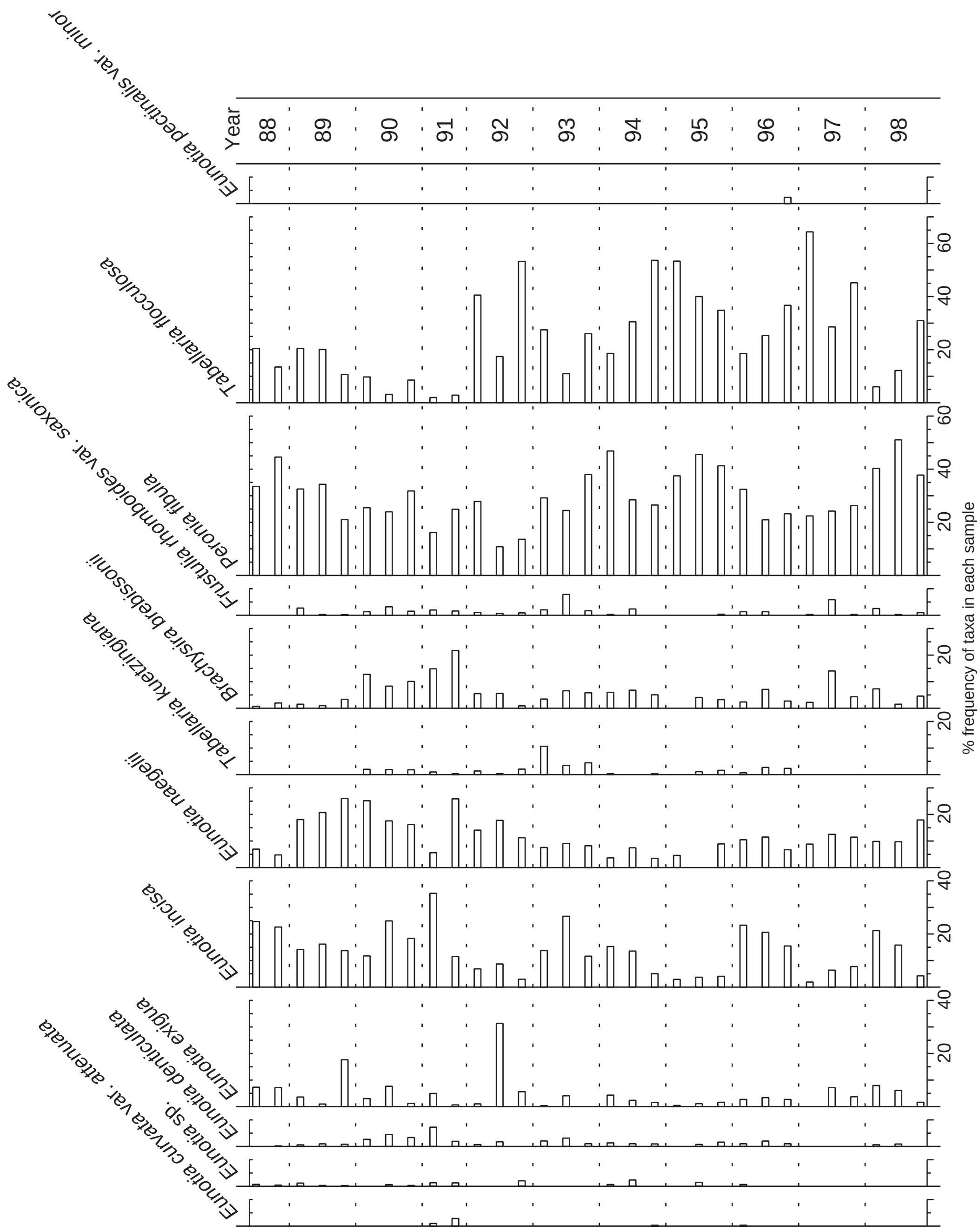
Summary

Dargall Lane is less acidic than the nearby loch sites, due to a higher supply of base cations within the catchment, but it frequently becomes acidic during higher flows. An apparent increase in alkalinity over the monitoring period is not accompanied by clear changes in xSO_4 or NO_3. This may therefore, as at other sites, represent a response to a decline in marine ion inputs and rainfall which were high during the early part of the record. Changes in the epilithic diatom and macroinvertebrate communities are consistent with a general reduction in acidity in recent years although neither are significant as linear trends. DOC and non-labile Al concentrations have both risen significantly since 1988.

Figure 4.9.3

Dargall Lane: summary of epilithic diatom data (1988 - 1998)

Percentage frequency of all taxa occurring at >2% abundance in any one sample



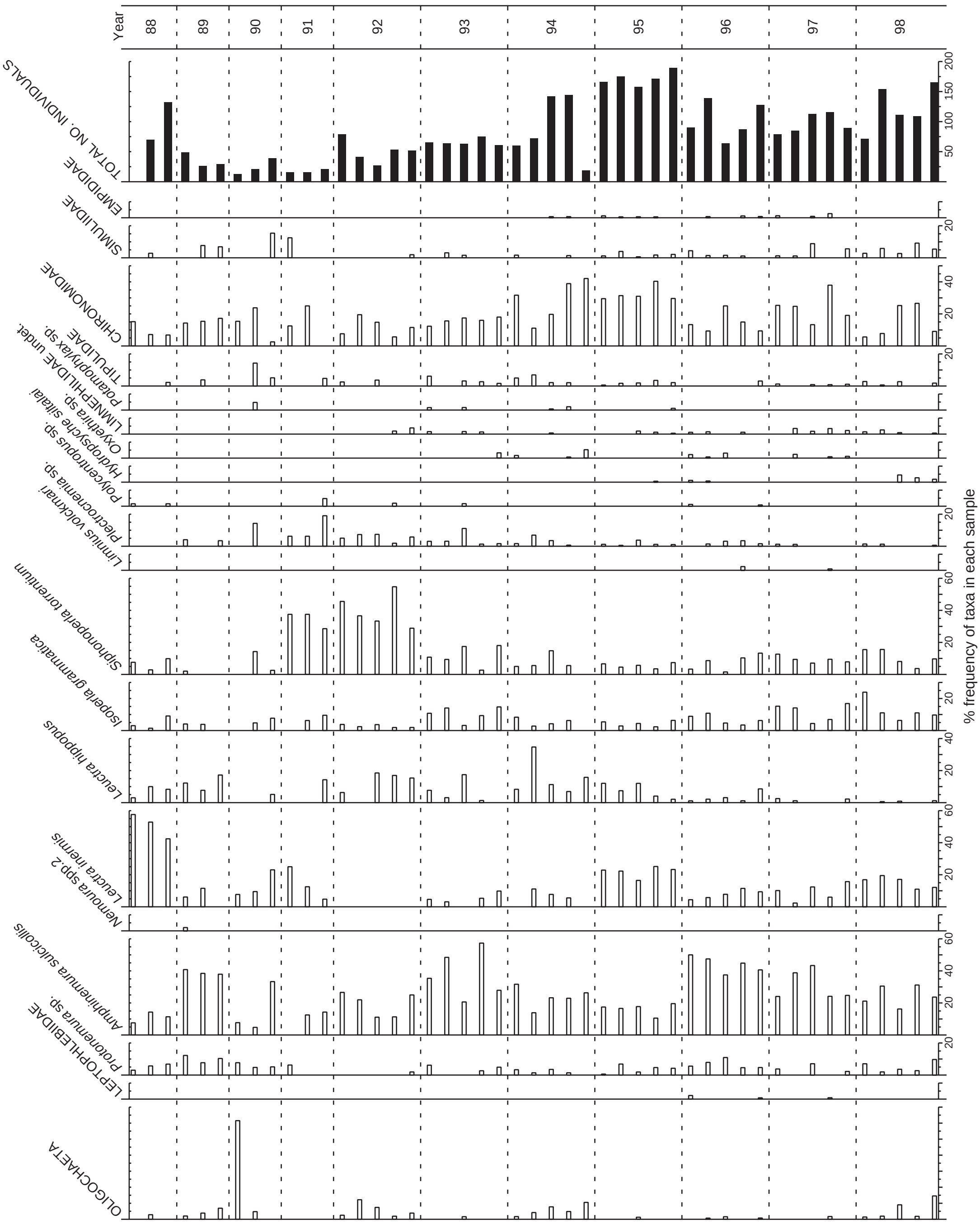


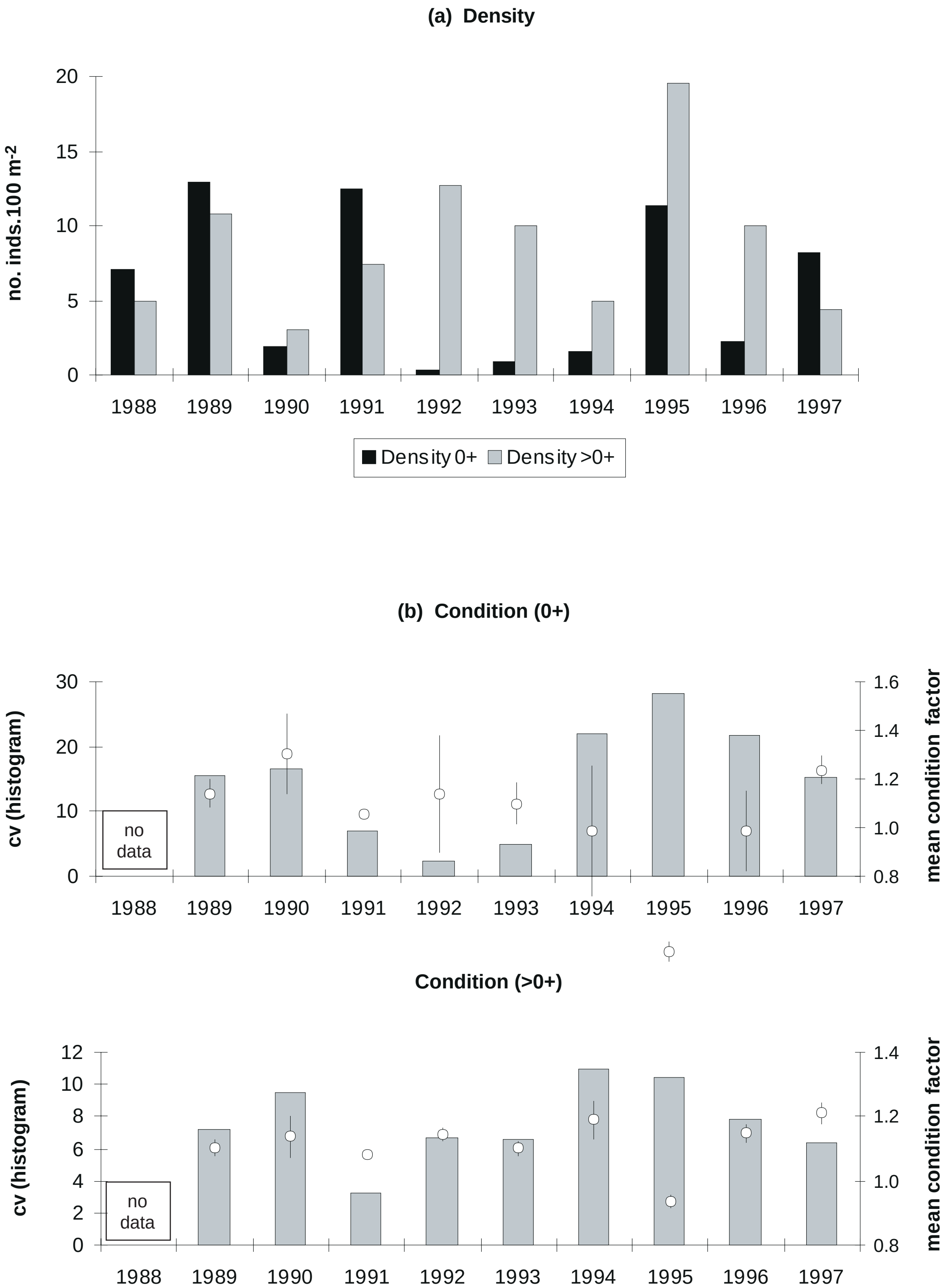
Figure 4.9.4

Dargall Lane: summary of macroinvertebrate data (1988 - 1998)

Percentage frequency of taxa in individual samples

Figure 4.9.5

Dargall Lane: summary of fish data (1988 - 1997)
(a) Trout population density for 0+ and >0+ age classes (individuals 100 m^{-2})
(b) Mean condition factor (with standard deviation) of the trout population and its coefficient of variation (histogram)



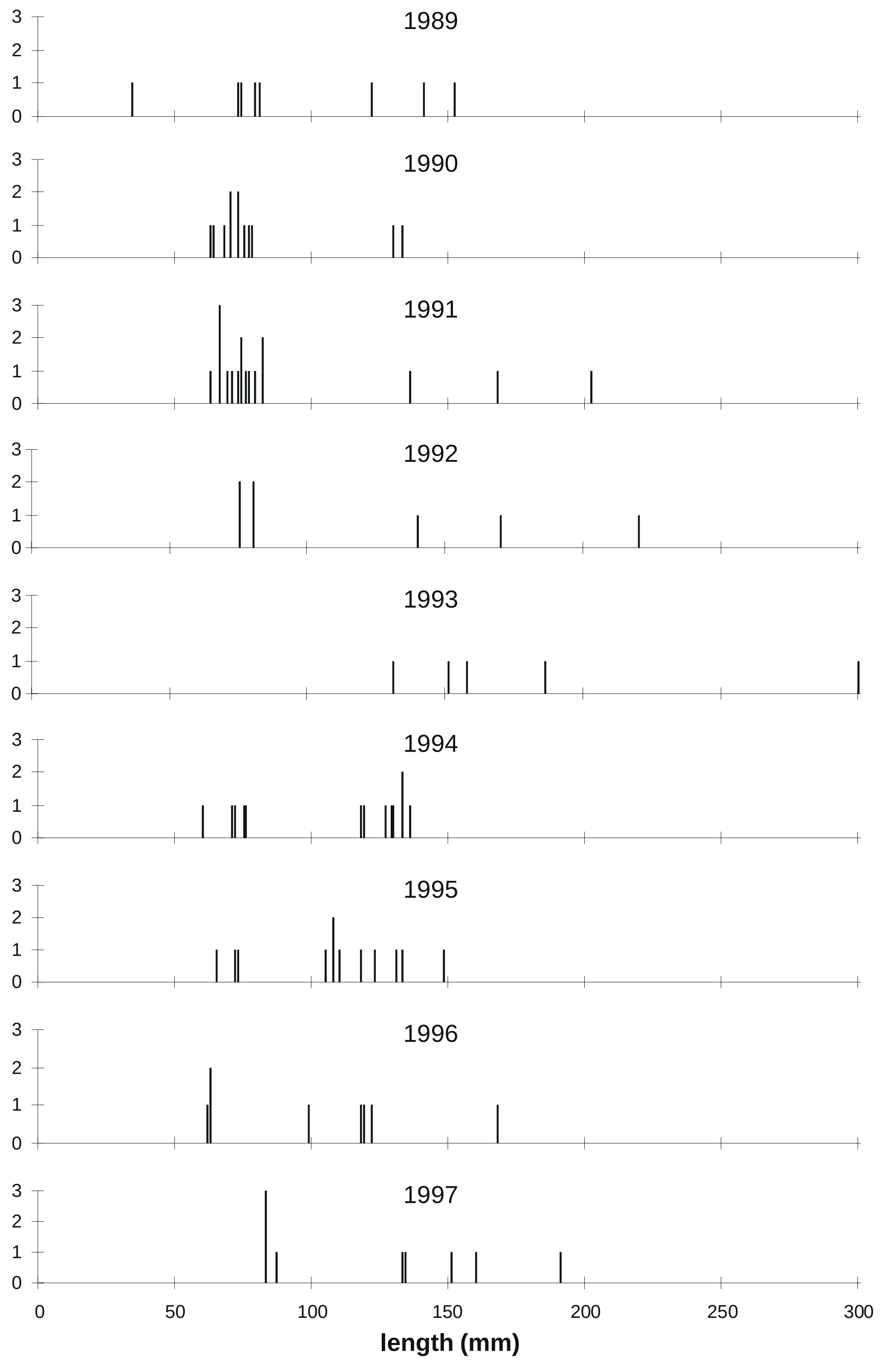


Figure 4.9.5

Dargall Lane: summary of fish data (1989 - 1997)
(c) Trout length frequency summaries

4.10 Scoat Tarn

Site Review

Scoat Tarn is one of the highest of the Tarns in the English Lake District. Diatom-based pH reconstruction, using a sediment core taken in 1989, suggests that the site has acidified from around pH 5.9 in the early nineteenth century, to pH 4.7 in the 1980s (Patrick *et al.* 1995). There is no evidence of any physical disturbance or changes in grazing regime in the catchment over the past decade. Since the recent addition of an atmospheric deposition collector within the catchment, samples are also being analysed by the UK Acid Deposition Network. This should enhance understanding of the relationship between deposition and surface water chemistry at the site over the coming years.

Water Chemistry

(Figure 4.10.2, Tables 4.10.2-3)

With a mean pH of 4.99 and a mean alkalinity of 8 μeq l^{-1}, Scoat Tarn is the fifth most acidic site in

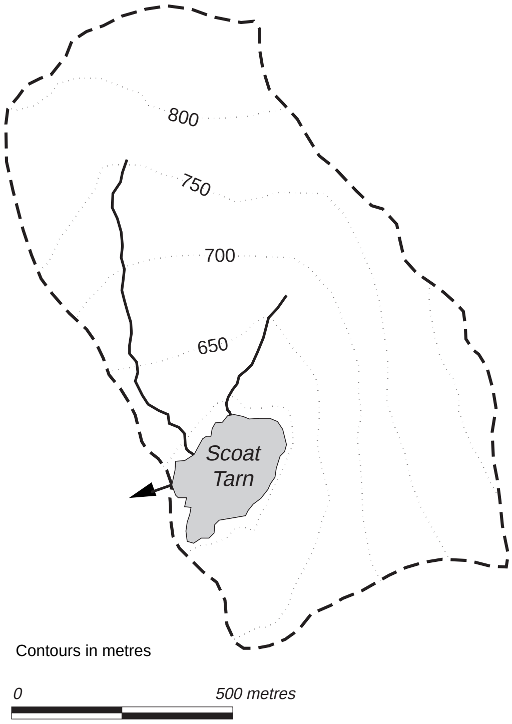


Figure 4.10.1

Scoat Tarn: catchment

Table 4.10.1

Scoat Tarn: site characteristics

Grid reference	*NY 159104*
Lake altitude	*602 m*
Maximum Depth	*20 m*
Mean Depth	*10 m*
Volume	*4.2 x 10^5 m^3*
Lake Area	*5.2 ha*
Catchment area (excl. lake)	*95 ha*
Catchment: Lake area ratio	*18.2*
Catchment Geology	*Borrowdale volcanics*
Catchment Soils	*shallow peaty rankers*
Catchment vegetation	*moorland - 100%*
Net Relief	*239 m*
Mean annual rainfall	
1996 deposition	*3482 mm*
Total S	*31 kg ha^{-1} yr^{-1}*
non-marine S	*26 kg ha^{-1} yr^{-1}*
Oxidised N	*12 kg ha^{-1} yr^{-1}*
Reduced N	*23 kg ha^{-1} yr^{-1}*

Table 4.10.2

Scoat Tarn: summary of chemical determinands, June 1988 - March 1998

Determinand		Mean	Max	Min
pH		*4.99*	*5.23*	*4.57*
Alkalinity	μeq l^{-1}	*-8.4*	*6.0*	*-26.0*
Ca	μeq l^{-1}	*32.5*	*48.0*	*23.0*
Mg	μeq l^{-1}	*48.3*	*75.0*	*33.3*
Na	μeq l^{-1}	*163.9*	*265.2*	*126.1*
K	μeq l^{-1}	*7.9*	*15.4*	*2.6*
SO_4	μeq l^{-1}	*60.8*	*72.9*	*35.4*
xSO_4	μeq l^{-1}	*41.5*	*54.2*	*16.5*
NO_3	μeq l^{-1}	*21.4*	*47.9*	*5.7*
Cl	μeq l^{-1}	*185.6*	*326.8*	*118.3*
Soluble Al	μg l^{-1}	*121.4*	*300.0*	*12.2*
Labile Al	μg l^{-1}	*108.9*	*293.8*	*2.5*
Non-labile Al	μg l^{-1}	*12.6*	*76.0*	*3.0*
DOC	mg l^{-1}	*0.9*	*2.7*	*<0.1*
Conductivity	μS cm^{-1}	*35.1*	*49.0*	*24.0*

the UKAWMN. Alkalinity has only been positive during one period in 1995, and Al concentrations are high and dominated by the labile fraction. Although xSO_4 concentrations are slightly lower than at the Galloway sites (mean 41.5 μeq l^{-1}), NO_3 concentrations are higher, with a mean of 21.4 μeq l^{-1}. The mean $NO_3/(NO_3 + xSO_4)$ ratio of 0.34 demonstrates that NO_3 is a major contributor to acidity at this site. In five of the ten years of data, NO_3 concentrations exceeded those of xSO_4 on an equivalent basis in spring, implying that NO_3 is the main acidifying anion at a time when pH and alkalinity tend to be lowest. Ca concentrations are low (mean 32.5 μeq l^{-1}), indicating that the thin soils of this high elevation catchment have little capacity to buffer acid inputs.

Time series for Scoat Tarn (Figure 4.10.2) show striking similarities to those observed in Galloway; concentrations of Cl and Na rise to a pronounced peak in 1990-1991 before falling to much lower levels in the later part of the record. This suggests strongly that the two regions, both of which border the Irish Sea, have experienced the same variability in marine ion deposition over the last decade. Again this appears to have influenced non-marine ions, with Ca showing the same cyclical variation over the monitoring period. As a result of these changes, declining trends are observed for both Na and Ca using regression analysis. An increase in pH and decrease in labile Al are observed using both trend detection methods, which would seem to indicate recovery at the site. However since high marine cation inputs are likely to have caused displacement of H^+ and Al from the soil during the early part of the record, while higher winter/spring rainfall probably reduced the proportion of the flow contribution from groundwater, it is possible that these trends are the result of climatic variation. This hypothesis is supported by the lack of clear trends for xSO_4, which appears to show the same mid-1990s peak as at the Galloway sites, or for NO_3, which shows no clear pattern other than a strong seasonal cycle. DOC, as at other sites, exhibits a highly significant rising trend, with an estimated increase of 1 mg l^{-1} from a 1988-1989 mean concentration of only 0.5 mg l^{-1}. Although the rate of increase is similar to many other sites, the proportional increase is relatively large and might be expected to have an observable effect on water transparency. However, secchi disc measurements taken each summer provide no evidence of any decrease in light attenuation in the visible spectrum at this time of year.

Epilithic diatoms

(Figure 4.10.3, Table 4.10.4)

Scoat Tarn is dominated by *Eunotia* taxa which tend to have low pH optima, and particularly *E.incisa* (pH optima 5.1). As at several other sites, *E. incisa* was particularly abundant in 1989 (only 1 sample collected), 1990, and in 1998. Uni-directional trends in species abundance have only occurred with a few relatively rare taxa. For

Table 4.10.3

Significant trends in chemical determinands (July 1988 - March 1998)

Determinand	Units	Annual trend (Regression)	Annual trend (Seasonal Kendall)
pH		*+0.021***	*+0.013**
Na	μeq l^{-1}	*-3.83**	-
Ca	μeq l^{-1}	*-0.85**	-
DOC	mg l^{-1}	*+0.12****	*+0.10****
Labile Al	μg l^{-1}	*-6.89**	*-7.67**

** Trend significant at $p < 0.05$; ** trend significant at $p < 0.01$; *** trend significant at $p < 0.001$*

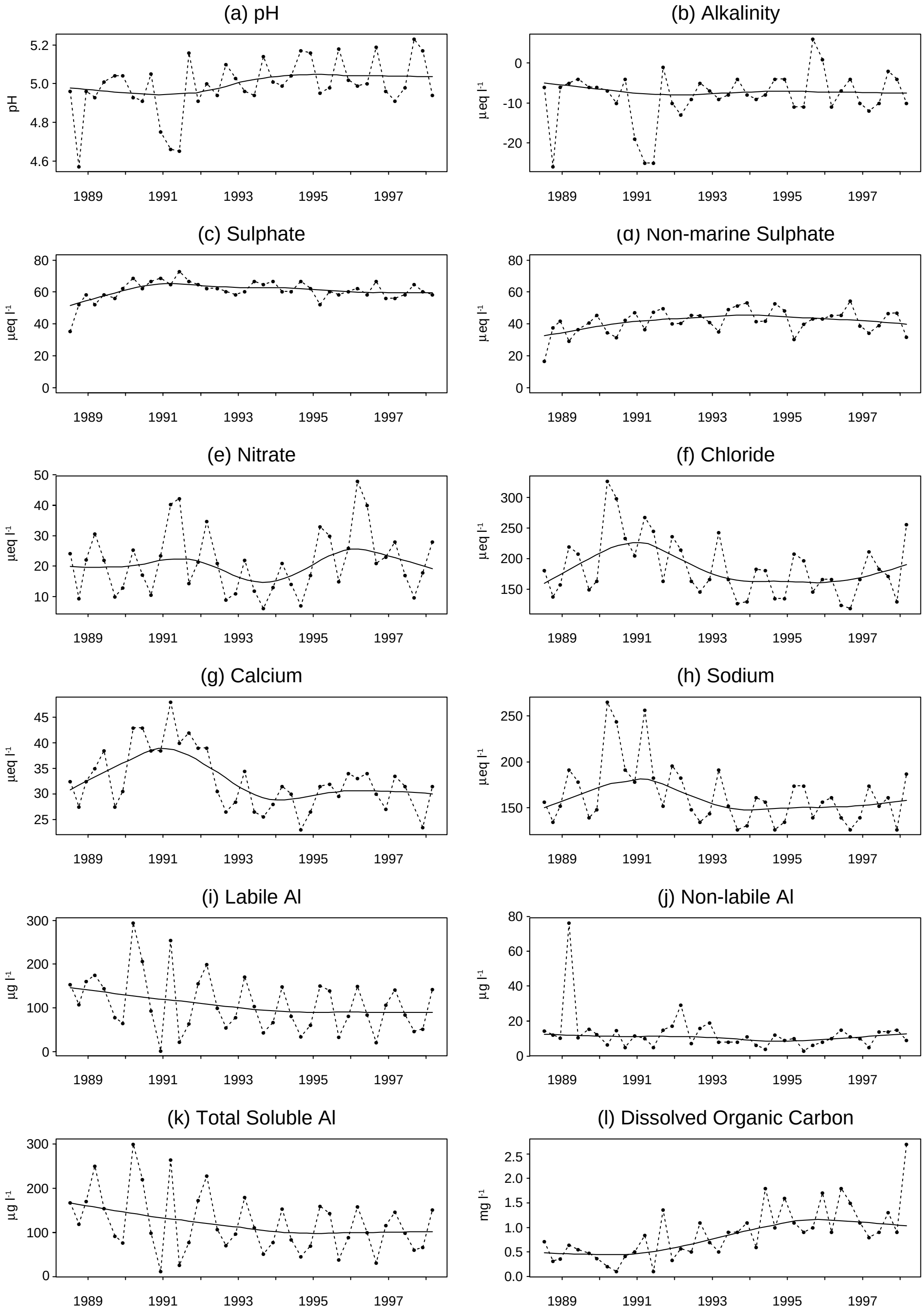


Figure 4.10.2

Scoat Tarn: summary of major chemical determinands (July 1989 - March 1997)

Smoothed line represents LOESS curve (Section 3.1.2)

Table 4.10.4

Scoat Tarn: trend statistics for epilithic diatom, macrophyte and macroinvertebrate summary data (1988 - 1998)

	Total sum of squares	Number of Taxa	MeanN_2 diversity	λ_1RDA/λ_2RDA	λ_1RDA/λ_1PCA
Epilithic diatoms	360	149	7.0	0.51	0.47
Macrophytes	38	24	13.6	0.66	0.51
Invertebrates	1185	31	1.2	0.69	0.61

Variance explained (%)	within year	between years	linear trend	p unrestricted	p restricted
Epilithic diatoms	50.1	49.9	9.2	<0.01	0.02
Macrophytes	*	*	19.9	0.17	0.33
Invertebrates	65.5	34.5	12.0	<0.01	<0.01

example *E. monodon* and *E. bigibba* were only recorded until 1991, while *E. vanheurckii* and *Aulacoseira distans* var. *nivalis* have increased slightly in more recent years. These apparently temporal changes are slight compared to the overall variability between samples and "sample year" is not significant according to RDA and associated restricted permutation test. The diatom species assemblage of sediment trap samples collected since 1991 also show no obvious time trend (Figure 4.10.6). The species balance in these samples differs from the epilithon, with *Tabellaria binalis* the dominant taxon and *E.incisa* relatively rare.

■ Macroinvertebrates

(Figure 4.10.4, Table 4.10.4)

The fauna, typical of an acid lake, is species poor and dominated by chironomids. The first four years were characterised by a diversity of dytiscid beetles such as *Agabus arcticus*, *A. bipustulatus* and *Hydroporus lacustris*. However, in more recent years these species have been absent. Other common taxa include the acid tolerant caddisfly group, the polycentropodids. *Plectrocnemia* spp. was the dominant caddisfly in the first eight years of the survey. *Polycentropus* spp. was first observed in 1995, and *Cyrnus* spp. in 1996. Detritivorous acid tolerant stoneflies (*Nemoura* spp., *Leuctra hippopus* and *Leuctra nigra*) were recorded in low numbers in intermittent years. One mayfly individual, *Ephemerella ignita* was recorded in 1997. There is a significant linear time trend, but changes are largely within the acid tolerant polycentropodid group and are not indicative of a change in acidity.

■ Fish

(Figure 4.10.5)

The outflow stream from Scoat Tarn has been electrofished since 1989. Population densities are very low and no 0+ trout have been caught. Densities of >0+ fish, whilst fluctuating, increased slightly between 1989-1994. Since then there have been three successive years of decline and densities in 1997 were the lowest recorded. Neither the mean condition factor nor the coefficient of variation of the condition factor shows any pattern over the years. The length frequency histograms illustrate the atypical nature of the population present at this site.

The trout population of the sampling stretch does not therefore demonstrate any response to the significant decline in the concentration of soluble labile Al over the nine years. However, given the low concentration of DOC, Al levels are still in excess of those considered to be physiologically detrimental.

Table 4.10.5

Scoat Tarn: relative abundance of aquatic macrophyte flora (1988 - 1997)

Abundance Taxon Year	88	89	90	91	92	93	95	97
INDICATOR SPECIES								
Sphagnum auriculatum[4]	3	3	3	3	3	3	3	3
Juncus bulbosus var. *fluitans*[4]	3	2	2	2	2	2	2	2
OTHER SUBMERGED OR FLOATING SPECIES								
Filamentous green algae	2	2	2	2	2	2	1	1
Amblystegium sp.	1	1	0	2	0	1	0	1
Brachythecium sp.	0	1	0	0	0	1	0	0
Campylopus sp.	0	1	0	0	0	0	0	0
Dicranella sp.	1	1	1	0	0	1	0	1
Hygrohypnum eugyrium	0	0	0	1	0	0	0	0
Hyocomium armoricum	1	1	1	1	1	1	1	1
Pohlia sp.	0	1	0	0	0	0	0	0
Polytrichum sp.	1	1	1	1	0	1	0	1
Racomitrium aquaticum	2	2	1	1	1	1	1	1
Rhytidiadelphus squarrosus	1	1	1	0	0	1	0	1
Sphagnum auriculatum	3	3	3	3	3	3	3	3
Cephalozia bicuspidata	1	3	3	3	3	3	3	3
Diplophyllum albicans	0	1	0	0	0	0	0	0
Marsupella emarginata	1	2	2	1	2	0	2	1
Nardia compressa	2	2	4	4	4	4	4	3
Plectocolea obovata	2	2	2	2	1	2	1	1
Scapania undulata	0	1	1	1	1	0	1	0
Isoetes echinospora	1	1	1	1	1	0	0	1
Isoetes lacustris	4	4	4	4	4	4	4	4
Littorella uniflora	3	3	3	3	3	3	3	3
Lobelia dortmanna	2	2	2	1	1	1	1	1
Sparganium angustifolium	1	1	1	1	1	1	1	1
TOTAL NUMBER OF SPECIES	18	23	18	18	15	17	14	18

■ Aquatic macrophytes

(Tables 4.10.4-5)

The aquatic macrophyte flora of Scoat Tarn is very similar to that of the other more acid lakes in the UKAWMN. The isoetids, *Isoetes lacustris*, *Lobelia dortmanna* and *Littorella uniflora* and the acidophilous rush *Juncus bulbosus* var. *fluitans* are the only submerged vascular species. In comparison to the more peat-stained waters of sites, such as Loch Tinker, these plants are able to survive at greater depths, and the deepest growing species, *I. lacustris,* is found to a depth of 4.2 m. Perhaps surprisingly, despite a doubling in DOC over the decade, which might have led to a reduction in transparency, there is no evidence of any reduction in the depth limit of *I. lacustris* with time. The acid tolerant *Sparganium angustifolium* which has floating leaves, is present in the bay of one inflow stream. Scoat

Tarn also supports a diverse aquatic bryophyte flora, amongst which the acidophilous species *Sphagnum auriculatum* is dominant. Again, due to the high transparency, bryophytes are able to grow at considerable depths (i.e. >10 m). "Sample year" is insignificant as a linear trend according to RDA and associated permutation test.

Summary

Scoat Tarn is chronically acidic, with alkalinity below zero in 95% of samples. NO_3 is a more important contributor to acidity here than at any other UKAWMN site, with concentrations frequently exceeding those of xSO_4 during spring. Marine ions exhibit major inter-annual variations, which appear to have a significant impact on lake acidity, whilst DOC and non-labile Al have both increased. Apparent chemical improvements are likely to be climatically driven and do not appear to have had a significant influence on the biology of the Tarn.

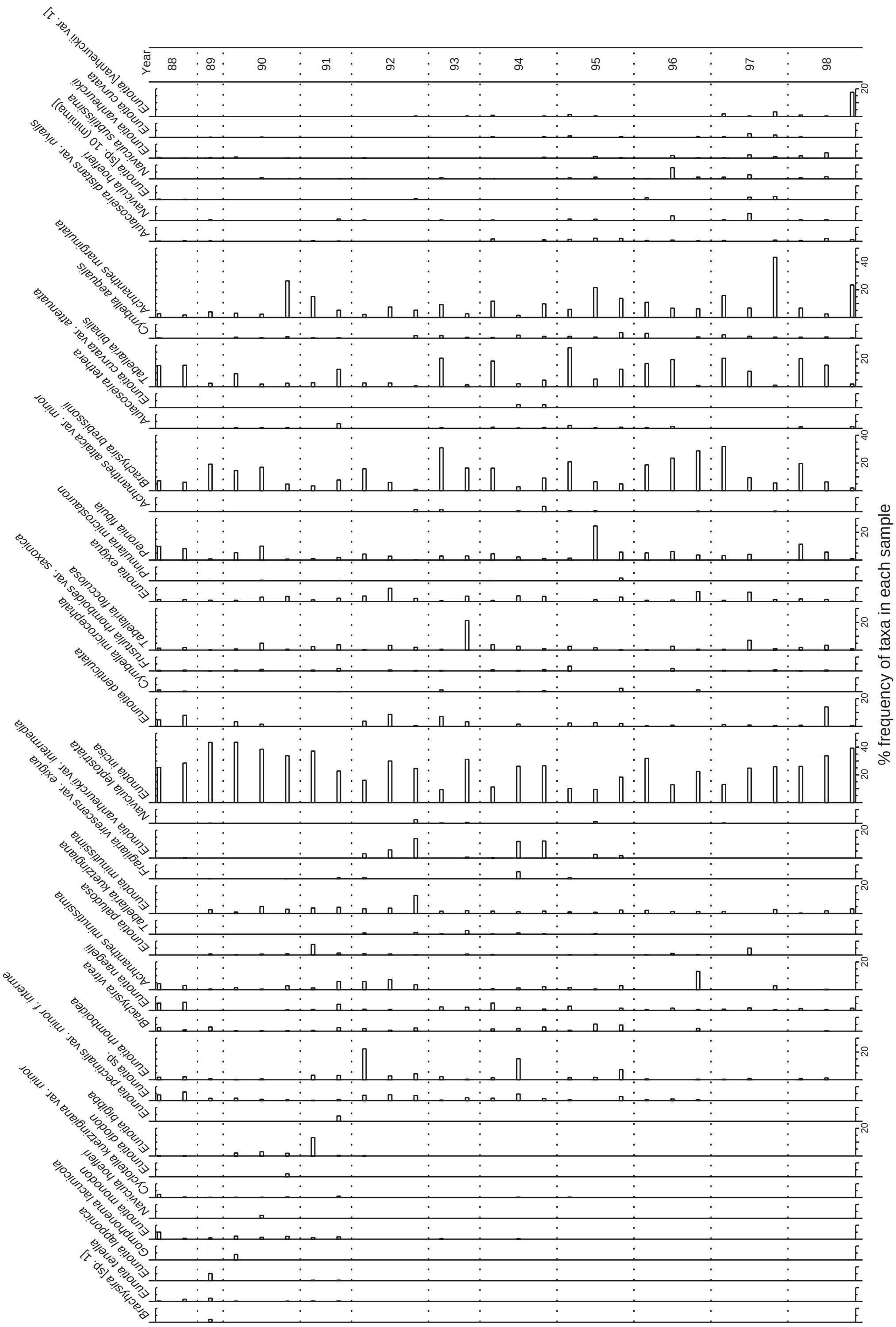


Figure 4.10.3

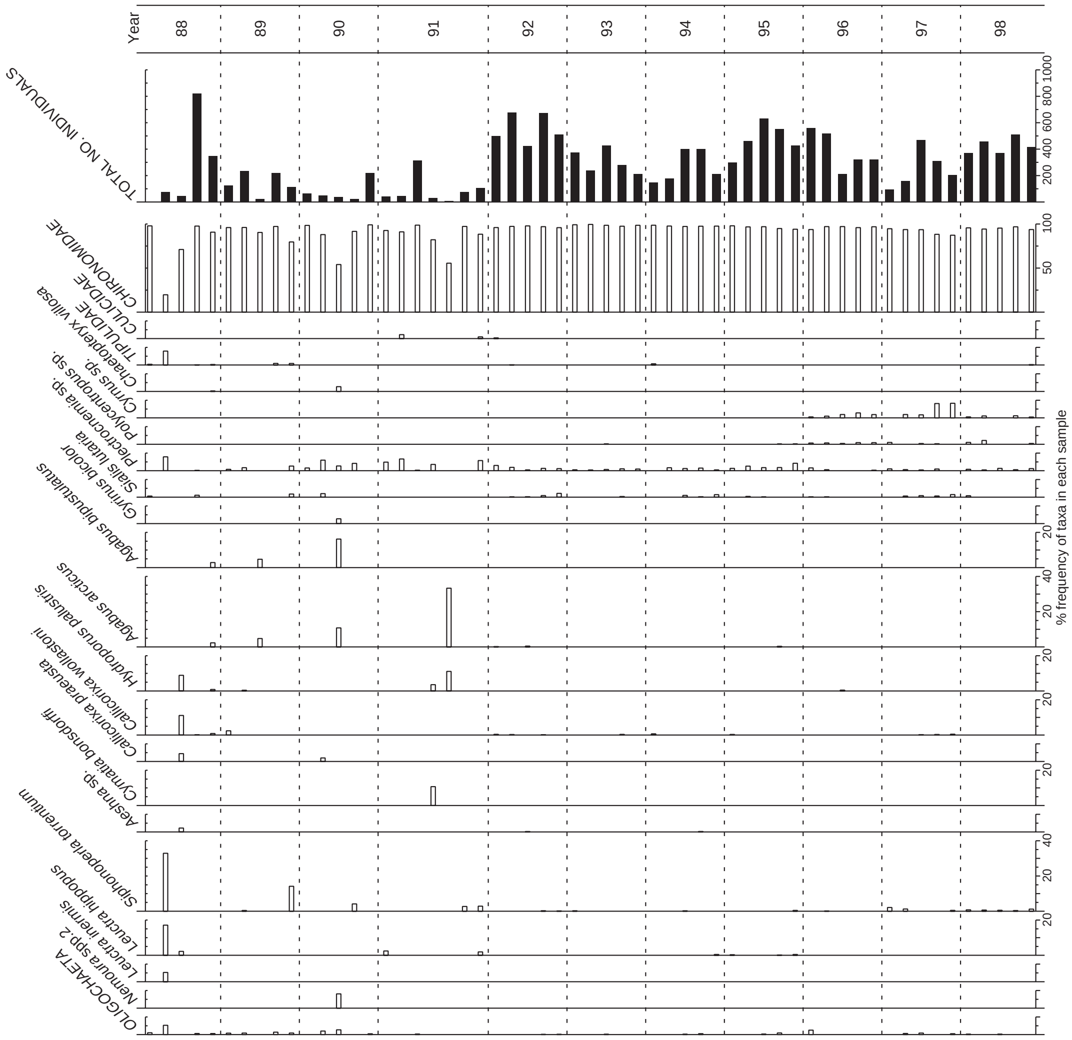
Scoat Tarn: summary of epilithic diatom data (1988 - 1998)

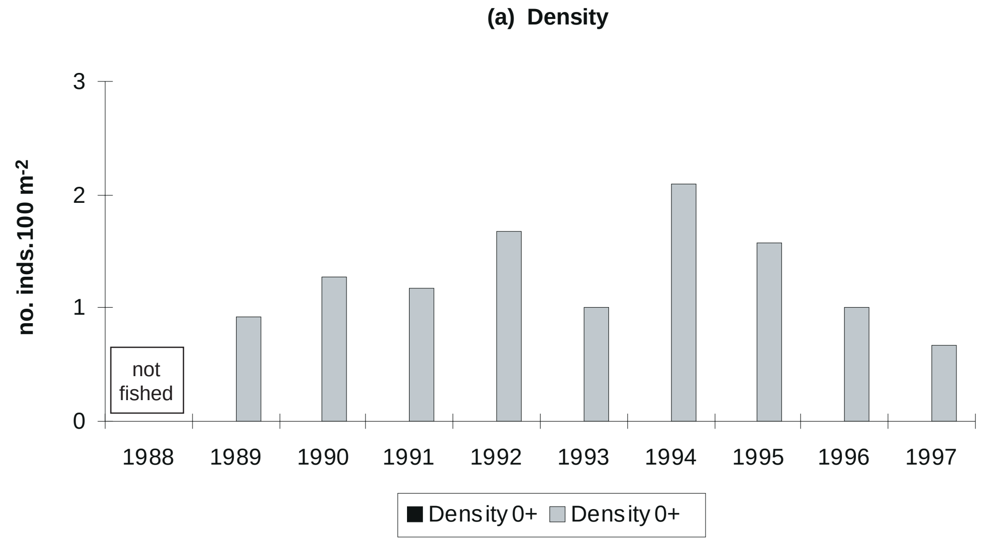
Percentage frequency of all taxa occurring at >2% abundance in any one sample

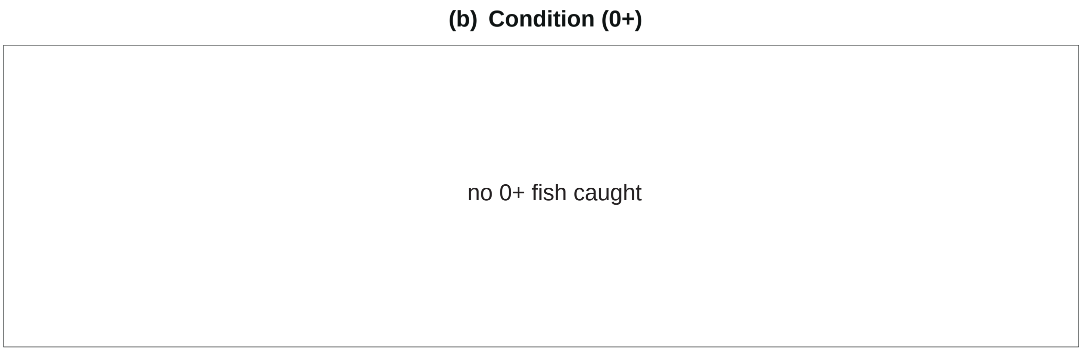
Figure 4.10.4

Scoat Tarn: summary of macroinvertebrate data (1988 - 1998)

Percentage frequency of taxa in individual samples







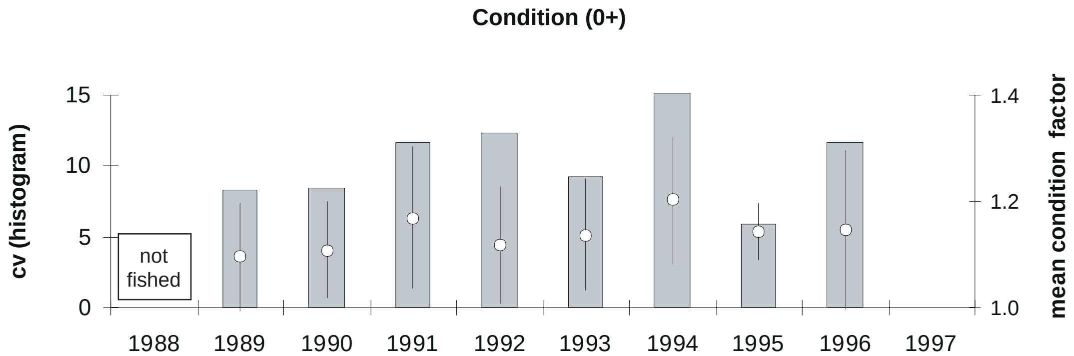


Figure 4.10.5

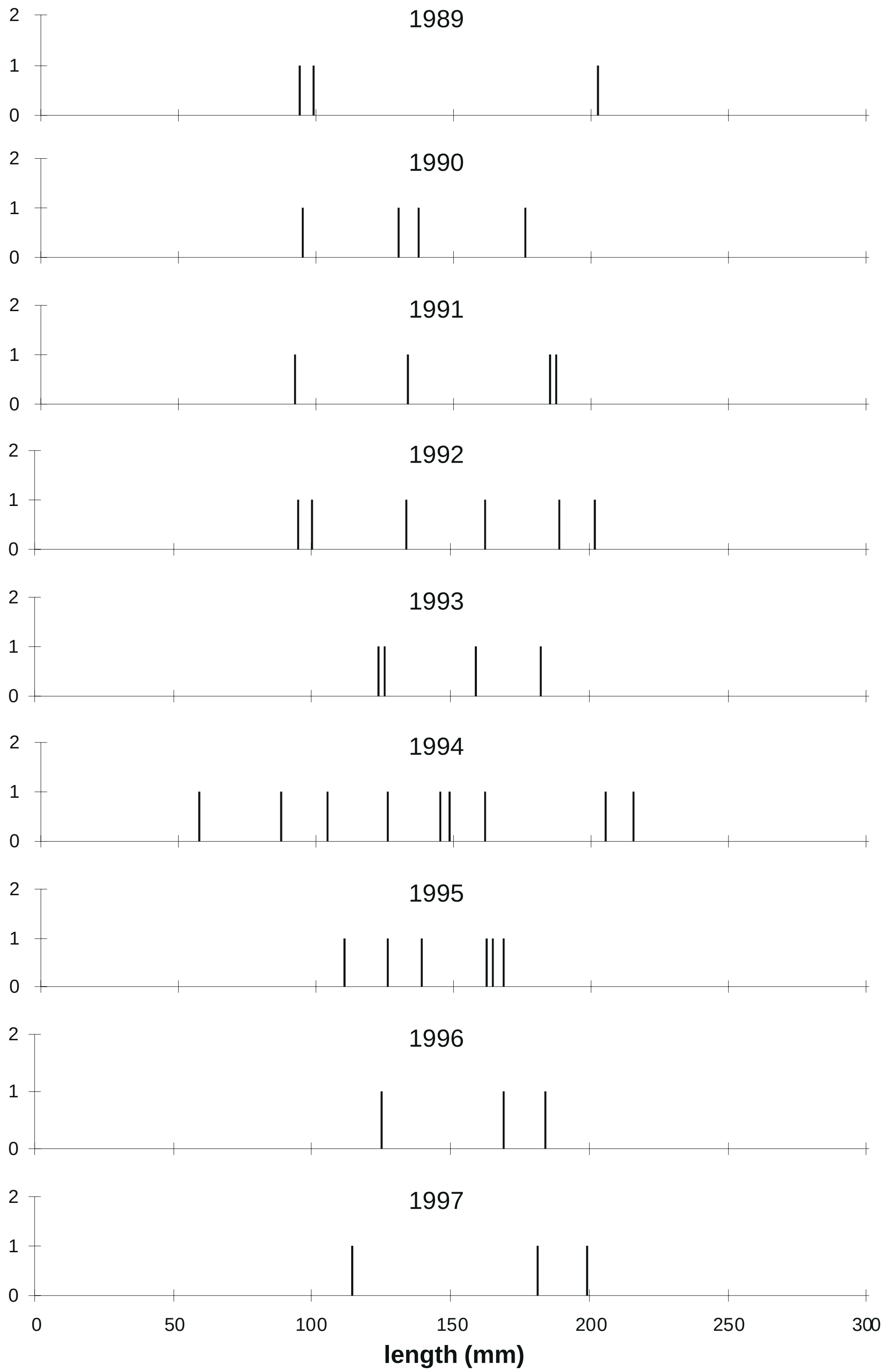
Scoat Tarn: summary of fish data (1989 - 1997)

(a) Trout population density for 0+ and >0+ age classes (individuals 100 m^{-2})

(b) Mean condition factor (with standard deviation) of the trout population and its coefficient of variation (histogram)

Figure 4.10.5

Scoat Tarn: summary of fish data
(c) Trout length frequency summaries (1989 - 1997)



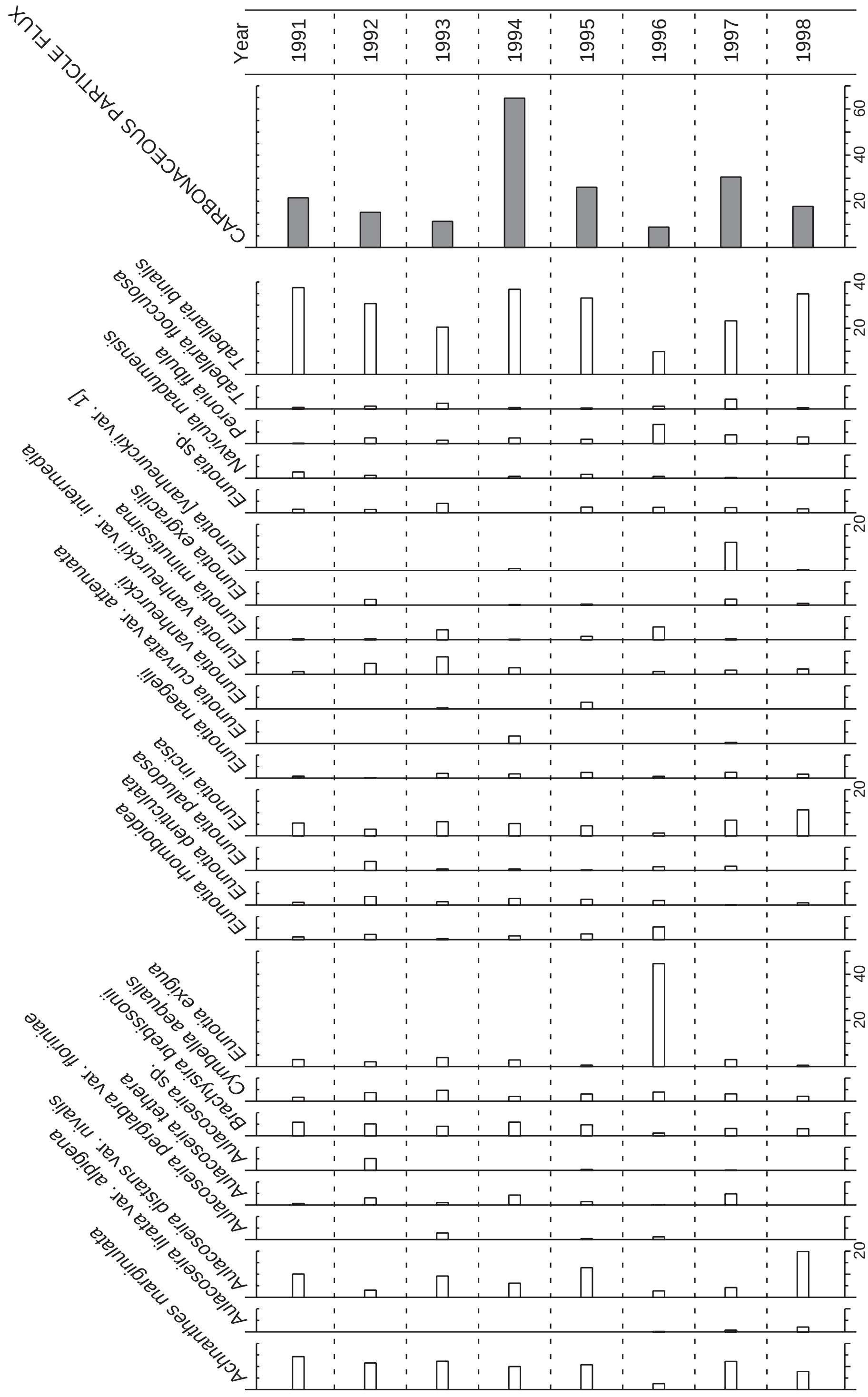


Figure 4.10.6

Scoat Tarn: summary of sediment trap data for diatoms and carbonaceous particles

Relative frequency of diatom taxa (>2% in at least one sample) at time of trap retrieval and estimated carbonaceous particle flux (no. $trap^{-1}$ day^{-1}) for preceding year

4.11 Burnmoor Tarn

Site Review

In contrast to the neighbouring and highly acidic Scoat Tarn, Burnmoor Tarn benefits from a more weatherable catchment geology and is relatively alkaline. Diatom based pH reconstruction of a sediment core indicates that the site became slightly more acid around the turn of the 20th century (Patrick *et al.*, 1995). Recently however it was observed that at particularly high flows, the more acid Hardrigg Beck can spill over into the outflow end of the Tarn and this may occasionally have an large impact on the chemistry of the Tarn outflow and possibly on the main basin. Catchment vegetation is subject to more intensive grazing than at most other sites and cattle are likely to provide localised nutrient enrichment and physical disturbance of the littoral zone. There is no indication of any major change in the grazing regime or other catchment disturbance since the onset of monitoring in 1988.

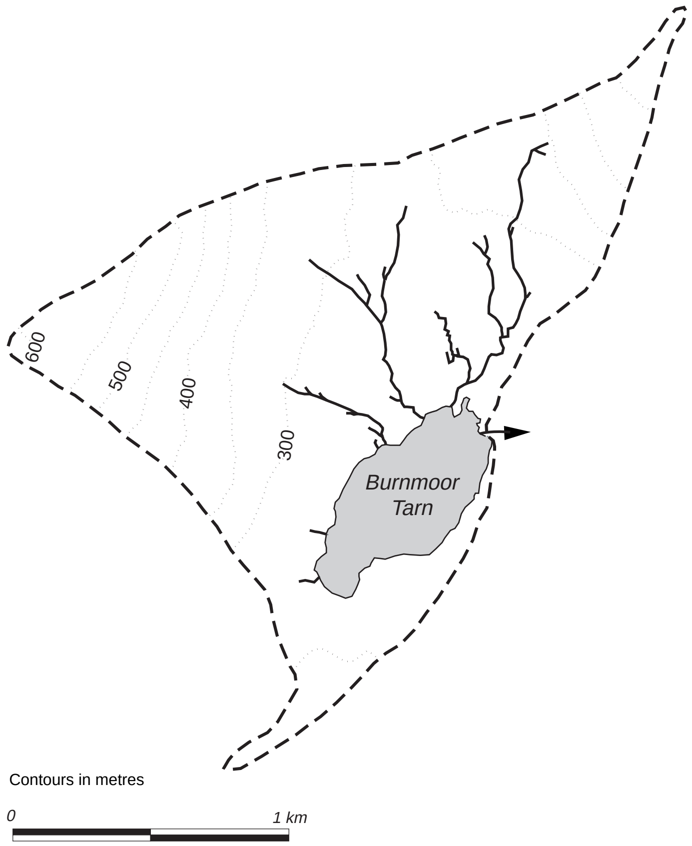


Figure 4.11.1

Burnmoor Tarn: catchment

Table 4.11.1

Burnmoor Tarn: site characteristics

Grid reference	*NY 184044*
Lake altitude	*252 m*
Maximum Depth	*13 m*
Mean Depth	*5.1 m*
Volume	*8.9×10^5 m^3*
Lake Area	*24 ha*
Catchment area (excl. lake)	*226 ha*
Catchment: Lake area ratio	*9.4*
Catchment Geology	*andesite lava and granite*
Catchment Soils	*podsols, shallow peat, rankers*
Catchment vegetation	*moorland - 100%*
Net Relief	*350 m*
Mean annual rainfall	*2210 mm*
1996 deposition	
Total S	*25 kg ha^{-1} yr^{-1}*
non-marine S	*21 kg ha^{-1} yr^{-1}*
Oxidised N	*9 kg ha^{-1} yr^{-1}*
Reduced N	*19 kg ha^{-1} yr^{-1}*

Table 4.11.2

Burnmoor Tarn: summary of chemical determinands, June 1988 - March 1998

Determinand		Mean	Max	Min
pH		*6.48*	*6.99*	*4.38*
Alkalinity	µeq l^{-1}	*47.8*	*96.0*	*-44.0*
Ca	µeq l^{-1}	*89.5*	*118.5*	*32.0*
Mg	µeq l^{-1}	*65.0*	*83.3*	*33.3*
Na	µeq l^{-1}	*192.2*	*243.5*	*126.1*
K	µeq l^{-1}	*8.5*	*15.4*	*2.6*
SO_4	µeq l^{-1}	*81.5*	*118.8*	*56.3*
xSO_4	µeq l^{-1}	*59.4*	*102.3*	*38.3*
NO_3	µeq l^{-1}	*5.0*	*12.9*	*<1.4*
Cl	µeq l^{-1}	*209.9*	*287.3*	*129.6*
Soluble Al	µg l^{-1}	*8.1*	*42.0*	*<2.5*
Labile Al	µg l^{-1}	*3.0*	*14.0*	*<2.5*
Non-labile Al	µg l^{-1}	*6.9*	*35.0*	*<2.5*
DOC	mg l^{-1}	*2.0*	*4.7*	*0.9*
Conductivity	µS cm^{-1}	*41.6*	*54.0*	*23.0*

Water Chemistry

(Figure 4.11.2, Tables 4.11.2-3)

Burnmoor Tarn is a well-buffered site, with the second highest mean pH and alkalinity in the Network. Al concentrations are generally low, with labile Al commonly below detection limits, and Ca concentrations are high with a mean of 90 $\mu eq\ l^{-1}$. NO_3 concentrations are low (mean 5 $\mu eq\ l^{-1}$), although they exhibit strong seasonality.

Time series for Burnmoor Tarn (Figure 4.11.2) are dominated by a very severe episode in late 1993, when pH dropped from an antecedent value of 6.75 to 4.38, and alkalinity from 67 to -44 $\mu eq\ l^{-1}$. Strong concurrent increases were observed in xSO_4 and labile Al, as well as a decrease in Ca. It is thought that this extreme episode may be the due to the unusual hydrology of the site, with Hardrigg Beck partially diverting into the outflow end of the tarn at high flows. Whereas the catchment of Burnmoor Tarn is predominantly low-lying, with thick soils and till deposits, Hardrigg Beck drains the steep, high-elevation slopes of Scafell. It is therefore likely to have chemical characteristics closer to that of Scoat Tarn, and water from this source entering the lake during episodes could cause the major changes observed. It is uncertain whether such episodes are a regular feature of the site, although a second, less severe episode was recorded in the winter of 1991-1992, and, given the quarterly sampling frequency, it is possible that other episodes occurred but were not recorded.

To some extent, the 1993 episode masks other trends at this site. However, the cyclical variations in marine ions clearly match those at Scoat Tarn and the Galloway sites, with a peak in 1991 (Figure 4.11.2). Declining trends are consequently observed for Cl, Na, Mg and Ca (Table 4.11.3).

No clear trends are observed for pH, alkalinity, xSO_4 or NO_3, but significant increases are again identified for DOC (1.8 mg l^{-1} over ten years) and non-labile Al.

Epilithic diatoms

(Figure 4.11.3, Table 4.11.4)

Burnmoor Tarn is dominated by species typical of mildly acid lakes. The more dominant taxa, *Achnanthes minutissima* and *Brachysira vitrea* vary considerably in relative abundance throughout the last decade. Abundance of the latter species (pH optima 5.9) was reduced from 1989-1991 while that of *Tabellaria flocculosa* (pH optima 5.4) was elevated. The planktonic species, *Cyclotella kuetzingiana* var. *minor* was relatively abundant in the early years of monitoring, declined to low levels by 1994 and

Table 4.11.3

Significant trends in chemical determinands (July 1988 - March 1998)

Determinand	Units	Annual trend (Regression)	Annual trend (Seasonal Kendall)
Cl	$\mu eq\ l^{-1}$	*-6.17***	-
Na	$\mu eq\ l^{-1}$	*-5.13****	*-4.96**
Mg	$\mu eq\ l^{-1}$	*-1.48****	*-1.42**
Ca	$\mu eq\ l^{-1}$	*-2.15**	-
DOC	mg l^{-1}	*+0.11****	*+0.18***
Non-labile Al	$\mu g\ l^{-1}$	-	*+0.25**

** Trend significant at $p < 0.05$; ** trend significant at $p < 0.01$; *** trend significant at $p < 0.001$*

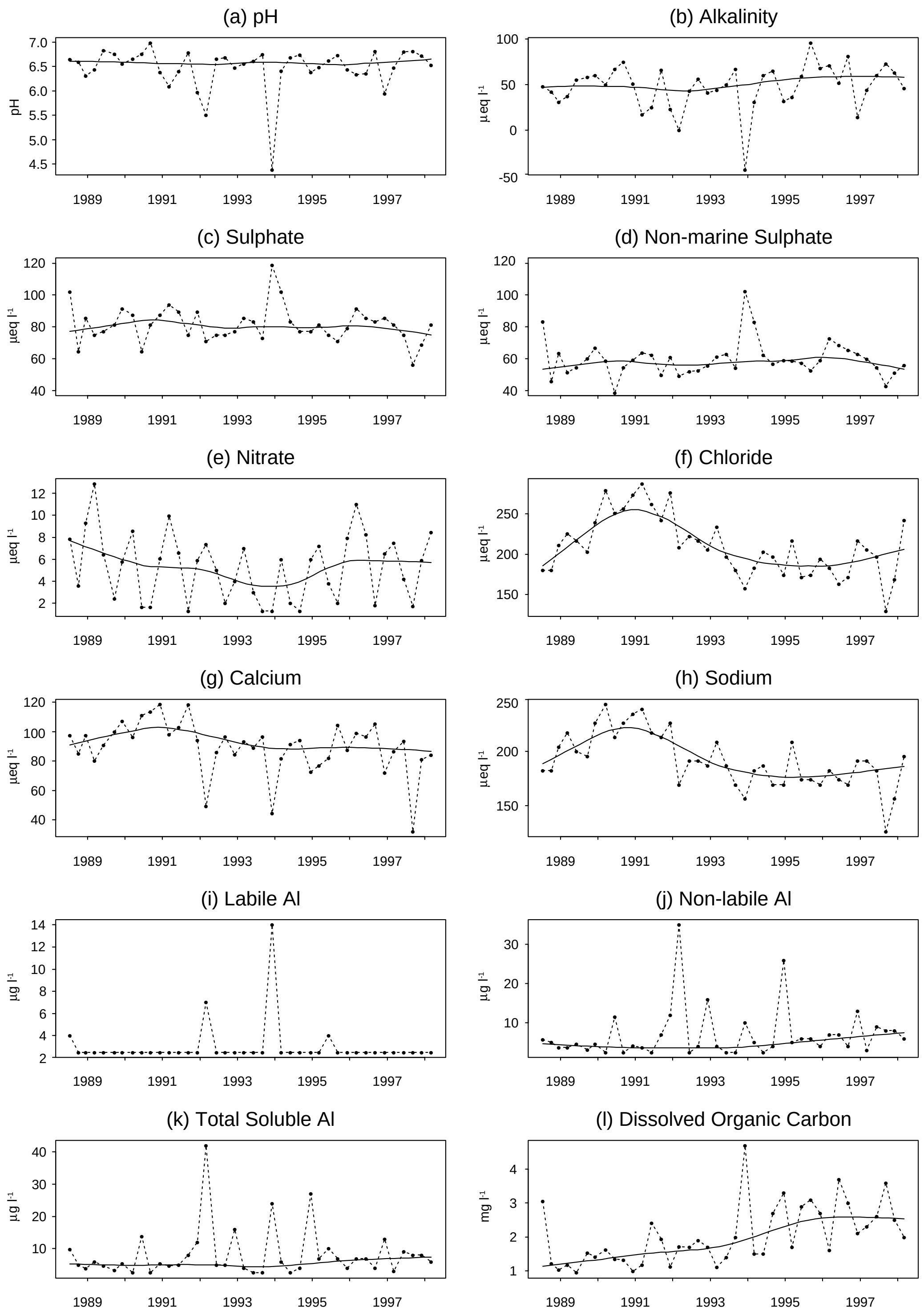


Figure 4.11.2

Burnmoor Tarn: summary of major chemical determinands (September 1988 - March 1998)

Smoothed line represents LOESS curve (Section 3.1.2)

Table 4.11.4

Burnmoor Tarn: trend statistics for epilithic diatom, macrophyte and macroinvertebrate summary data (1988 - 1998)

	Total sum of squares	Number of Taxa	MeanN_2 diversity	λ_1RDA/λ_2RDA	λ_1RDA/λ_1PCA
Epilithic diatoms	*300*	*142*	*6.5*	*0.73*	*0.63*
Macrophytes	*20*	*15*	*9.1*	*0.38*	*0.38*
Invertebrates	*895*	*39*	*3.1*	*0.67*	*0.50*

Variance explained (%)	within year	between years	linear trend	p unrestricted	p restricted
Epilithic diatoms	*43.0*	*57.0*	*10.6*	*<0.01*	*<0.01*
Macrophytes	*	*	*14.2*	*0.46*	*0.39*
Invertebrates	*60.7*	*39.3*	*11.6*	*<0.01*	*<0.01*

has since increased again. Several rare taxa have increased in relative abundance since about 1993, including *Denticula tenuis*, *Navicula subtilissima*, *Cymbella cesatii* and *Synedra acus.* These changes appear to account for the significant linear trend according to RDA and associated permutation test. Diatom inferred pH, derived from weighted averaging, is indicative of a general improvement in conditions since 1992 (see Section 7.2.1) and this is evident in the spring/summer water chemistry. However, given the well buffered nature of this site it seems most likely that the changes reflect climatic variations, particularly as they affect the rainfall regime at this time of year. The diatom assemblage collected by sediment trap contains a larger proportion of *C. kuetzingiana* var. *minor* and its representation increased steadily since traps were first emptied in 1992 until 1997, before falling back slightly in 1998.

■ Macroinvertebrates

(Figure 4.11.4, Table 4.11.4)

Burnmoor Tarn is characterised by a typically oligotrophic, slightly acid fauna. The first three years of the monitoring period were dominated by chironomids and oligochaetes. From 1991, acid tolerant Leptophlebid mayflies increased in abundance and became the dominant taxon. Other acid tolerant species, including Polycentropodid caddisflies *Plectrocnemia spp.*, *Polycentropus* spp. and *Cyrnus spp.*, have all occurred sporadically in low numbers. Other characteristic species include the acid tolerant freshwater bivalve *Pisidium* spp., the moderately acid tolerant leech *Erpobdella octoculata,* and the acid sensitive crustacean *Gammarus lacustris*, which was recorded in highest densities in 1996. The mayfly *Caenis horaria*, which first occurred in 1996, had its greatest abundance most recently in 1998. Time as a linear trend is significant at the 0.01 level according to RDA and associated permutation test. The trend appears to be largely influenced by the appearance and disappearance of several species of water beetle and an increase in abundance of Leptophlebiidae in recent years. These changes are not indicative of a change in water chemistry.

■ Fish

(Figure 4.11.5)

The outflow of Burnmoor Tarn has been electrofished since 1989. Population density is low and although densities of 0+ fish rose between 1989 and 1991 they crashed in 1992, since when there has only been one successful

Table 4.11.5

Burnmoor Tarn: relative abundance of aquatic macrophyte flora (1988 - 1997)

Abundance Taxon Year	88	89	90	91	92	93	95	97
INDICATOR SPECIES								
Nitella flexilis[1]	3	3	4	3	3	3	3	3
Myriophyllum alterniflorum[2]	2	2	2	2	2	2	2	2
Utricularia sp.[2]	1	0	2	2	0	0	2	1
Drepanocladus fluitans[4]	0	0	1	0	0	0	0	0
Sphagnum auriculatum[4]	1	0	0	1	0	1	0	0
Juncus bulbosus var. *fluitans*[4]	3	3	3	3	3	3	3	3
OTHER SUBMERGED OR FLOATING SPECIES								
Filamentous green algae	2	2	3	3	4	3	2	2
Fontinalis sp.	1	1	1	1	1	1	1	0
Rhytidiadelphus squarrosus	0	0	0	1	0	0	0	1
Isoetes lacustris	3	3	3	3	3	3	3	3
Elatine hexandra	0	0	0	0	0	0	1	0
Littorella uniflora	2	2	2	2	2	2	2	2
Lobelia dortmanna	5	5	5	5	4	4	4	4
Ranunculus flammula	1	1	2	2	2	2	2	1
Juncus effusus	1	1	1	1	1	1	1	1
Juncus acutifloris/articulatus	2	2	2	2	2	2	2	2
Potamogeton polygonifolius	1	1	1	1	1	1	2	1
Scirpus fluitans	1	1	1	1	1	1	1	1
TOTAL NUMBER OF SPECIES	15	13	15	16	13	14	15	14

recruitment (1995). Population densities of >0+ fish declined between 1989 and 1992 and only two fish were caught in each of the following three years. However, since then they have shown some recovery. The length frequency graphs show the abnormal structure of the population at this site. Neither the mean condition factor nor its coefficient of variation, for either age class, shows any temporal trend over the years, although there has been a general decline in the condition factor of 0+ fish since 1991 with a possible improvement in the last two years. It is interesting to note that the years of recruitment failure generally coincide with the years with highest soluble labile Al concentrations. It is possible that, for the hydrological reasons given in the chemistry section, trout populations in the outflow are sensitive to occasional extreme spates of acidity and high Al levels despite the generally well buffered chemistry of the lake.

■ Aquatic macrophytes

(Tables 4.11.4-5)

Burnmoor Tarn contains a relatively diverse submerged aquatic macrophyte flora which is typical for a well buffered oligotrophic lake. The acid tolerant isoetid species *Isoetes lacustris*, *Littorella uniflora* and *Lobelia dortmanna* are all common at the site, while more sensitive species such as the charophyte *Nitella flexilis*, *Utricularia* sp., and *Myriophyllum alterniflorum* are present at lower abundances. A single specimen of the six-stamened waterwort *Elatine* *hexandra* was recovered in a grab sample in 1995. RDA and associated permutation test shows time to be insignificant as a linear variable at the 0.01 level.

Summary

Although not normally acidic, the outflow and possibly the main basin of Burnmoor Tarn experience infrequent, but extremely severe acidic episodes. These are thought to result from the overflow of water from the adjacent Hardrigg Beck, which drains a more acid-sensitive catchment, into the tarn during high flows. Few trends are observed at the site, although DOC and non-labile Al appear to have risen since 1988. As at Scoat Tarn and the Galloway sites, cyclical variations in marine ions have occurred during this time. Changes in epilithic diatoms and fish populations may relate to the occasional acid episodes, but the linear trend in macroinvertebrates is more difficult to explain.

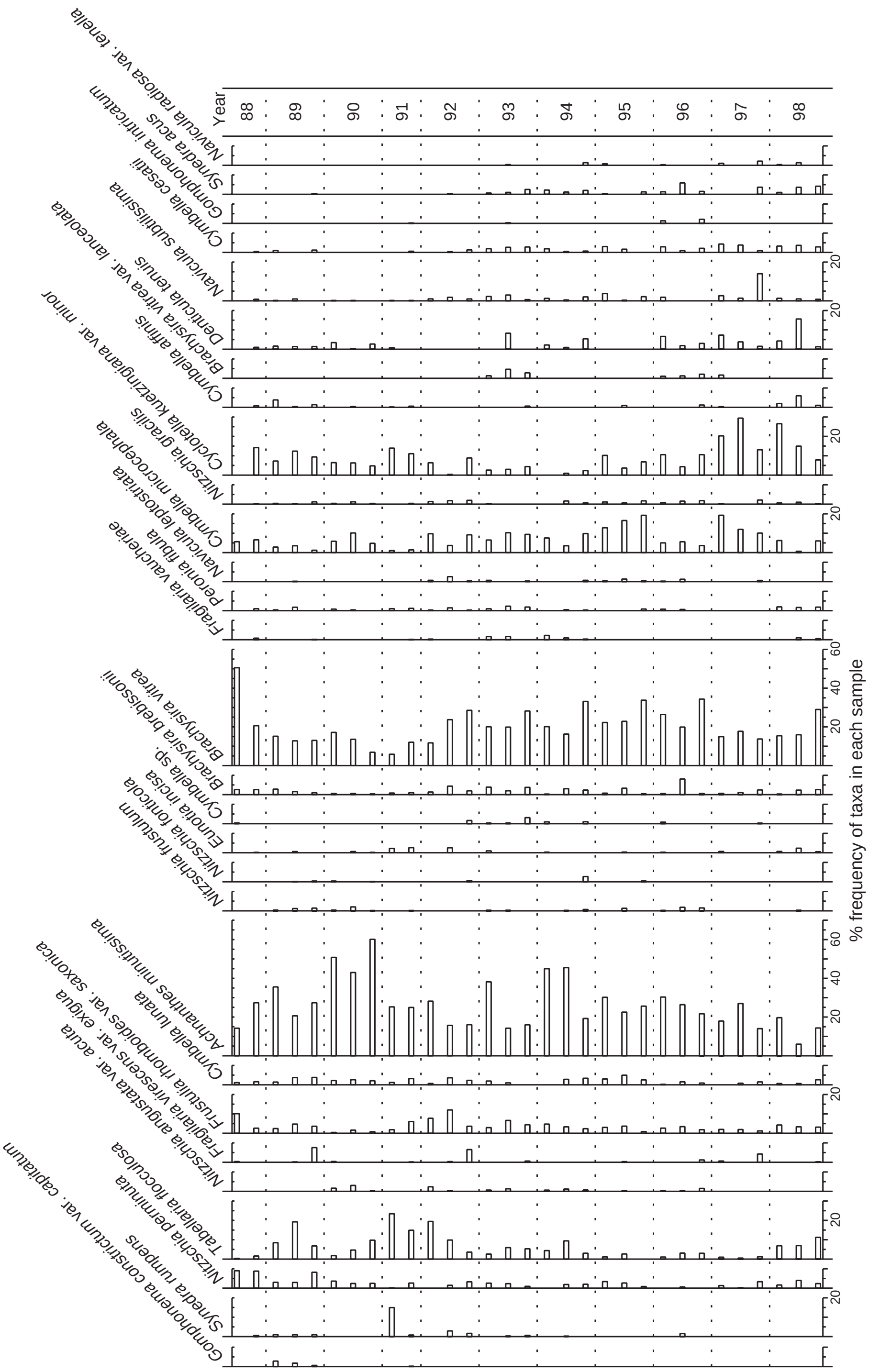


Figure 4.11.3

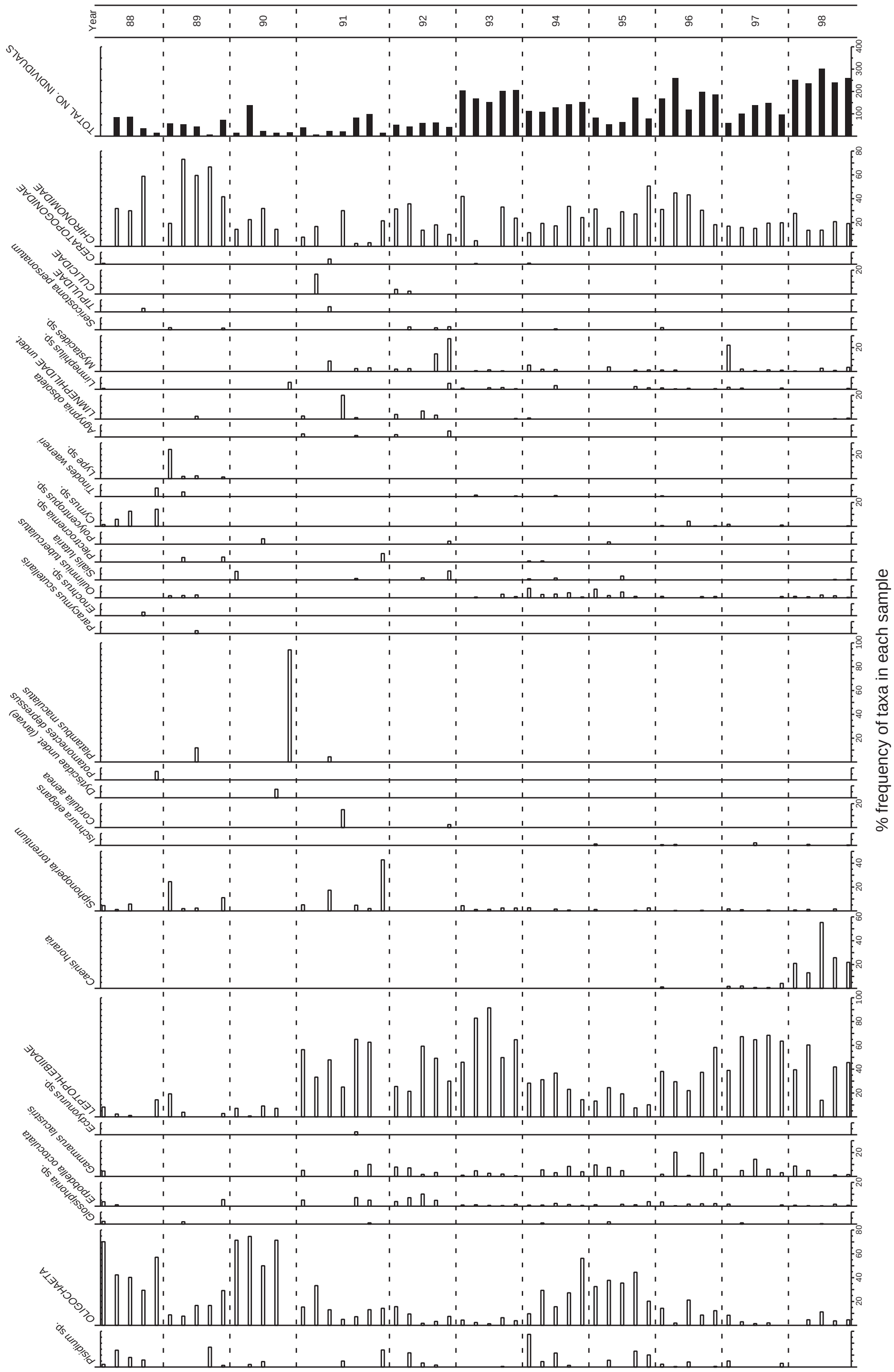
Burnmoor Tarn: summary of epilithic diatom data (1988 - 1998)

Percentage frequency of all taxa occurring at >2% abundance in any one sample

Figure 4.11.4

Burnmoor Tarn: summary of macroinvertebrate data (1988 - 1998)

Percentage frequency of taxa in individual samples



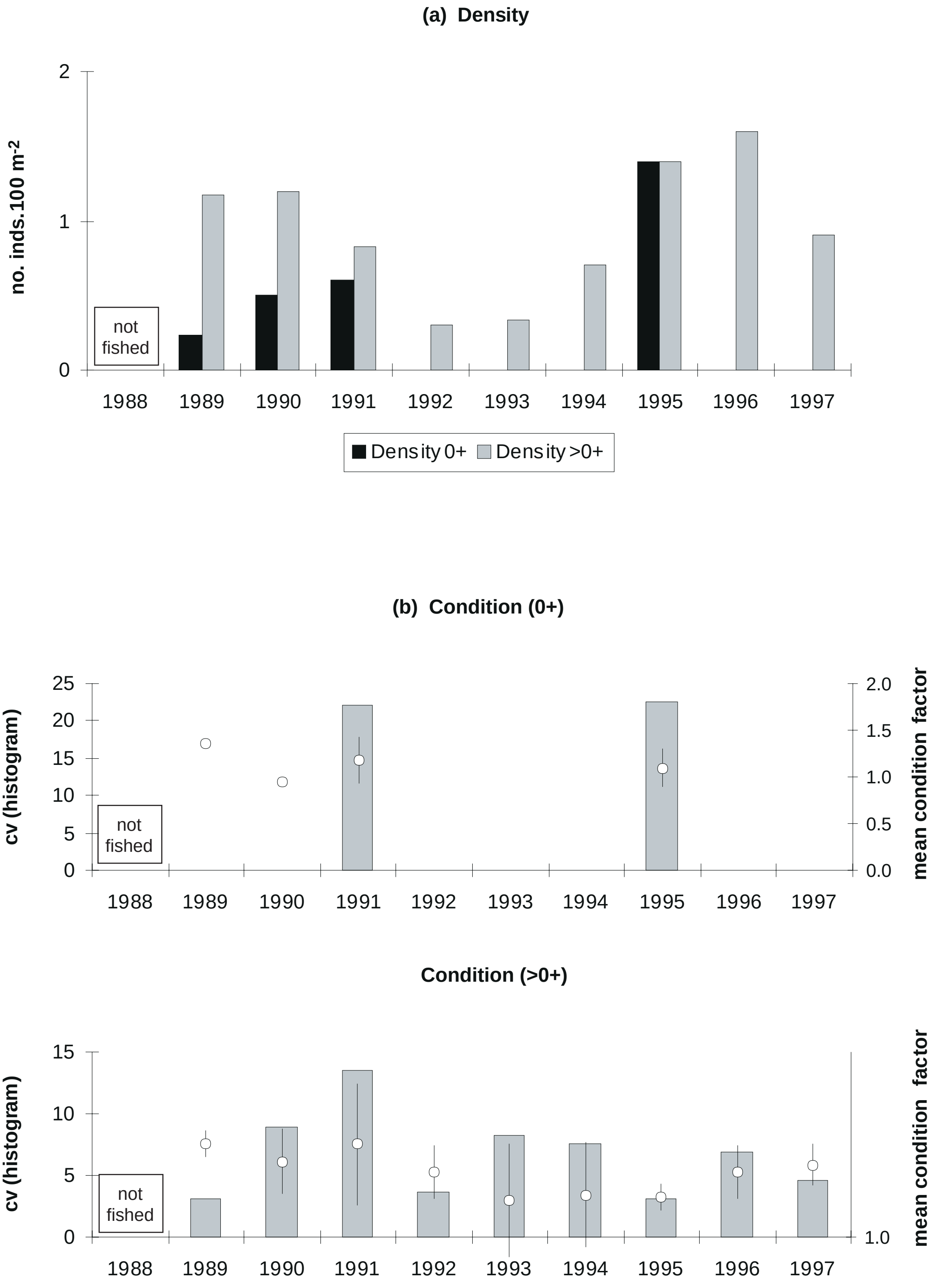
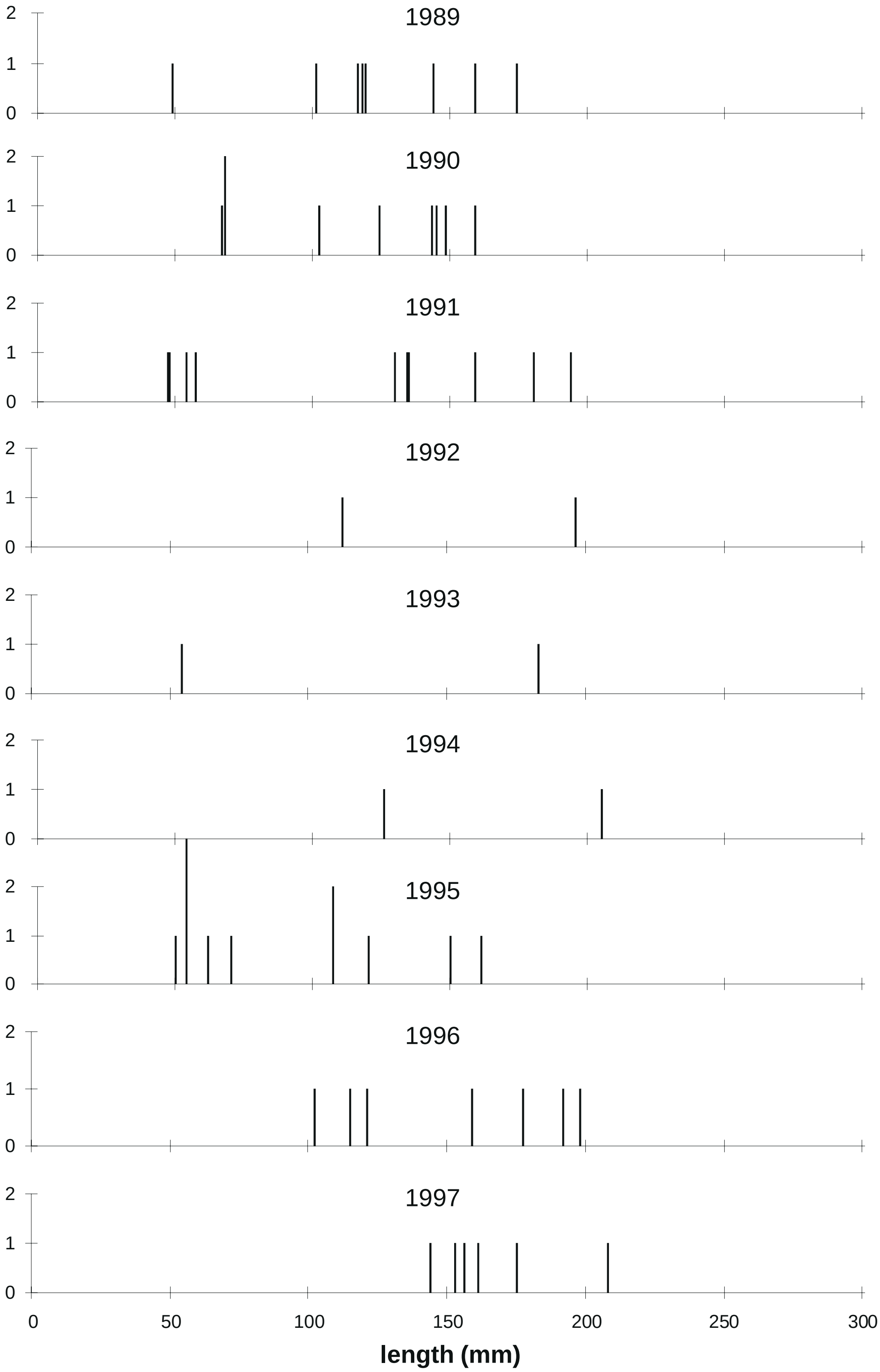


Figure 4.11.5

Burnmoor Tarn: summary of fish data (1989 - 1997)
(a) Trout population density for 0+ and >0+ age classes (individuals 100 m^{-2})
(b) Mean condition factor (with standard deviation) of the trout population and its coefficient of variation (histogram)

Figure 4.11.5

Burnmmor Tarn: summary of fish data (1989 - 1997)
(c) Trout length frequency summaries



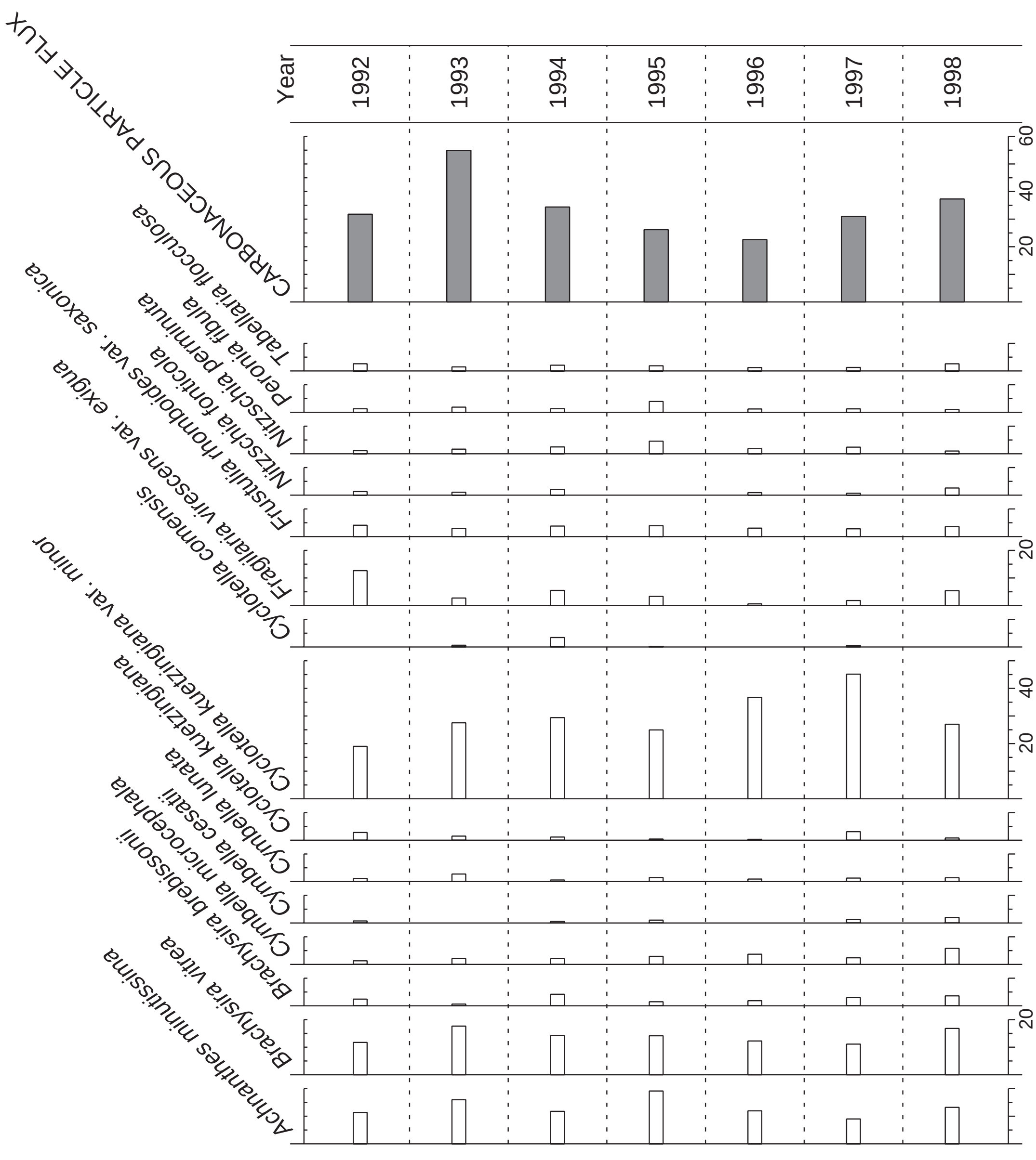
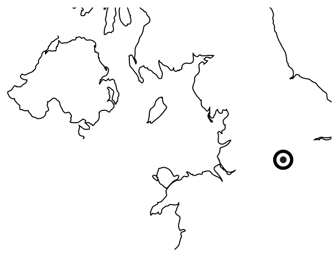


Figure 4.11.6

Burnmmor Tarn: summary of sediment trap data for diatoms and carbonaceous particles

Relative frequency of diatom taxa (>2% in at least one sample) at time of trap retrieval and estimated carbonaceous particle flux (no. trap^{-1} day^{-1}) for preceding year



4.12 River Etherow

Site Review

The River Etherow flows into the Woodhead reservoir to the east of Manchester in the southern Pennines. This severely deposition impacted site has been subject to considerable hydro-chemical and hydro-biological research (e.g. Say *et al.*, 1981; Harding *et al.*, 1981; Evans & Jenkins, 2000) and detailed studies of catchment nitrogen dynamics are currently ongoing (Curtis, pers. comm.). It is likely that the water chemistry is occasionally influenced by road-salt, blown or washed in from the nearby A628 trunk road.

Water Chemistry

(Figure 4.12.2, Tables 4.12.2-3)

The South Pennines region, which is close to major industrial centres such as Manchester, receives some of the highest S and N deposition in the UK

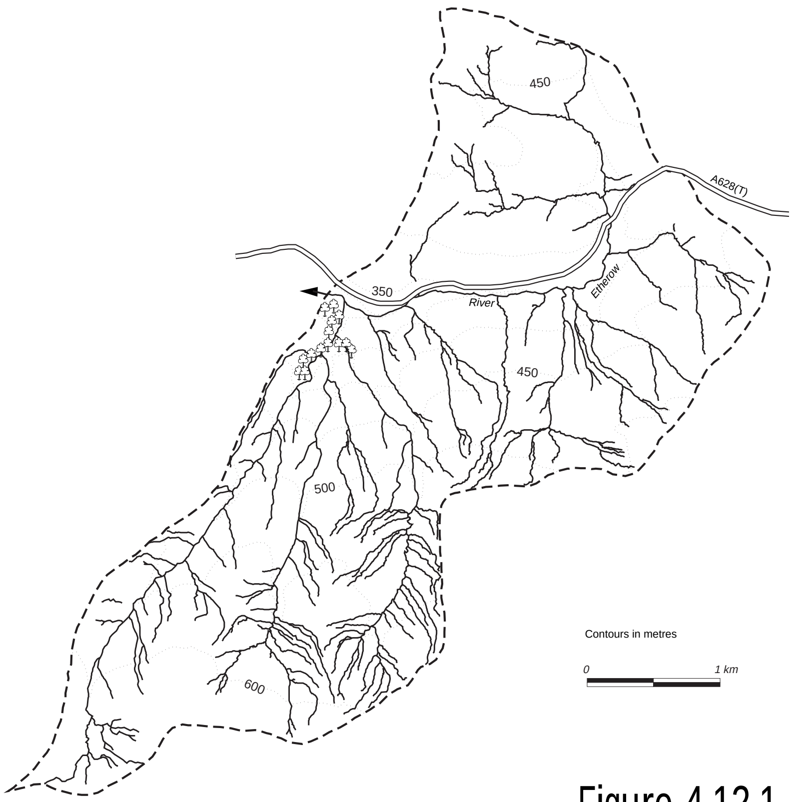


Figure 4.12.1

River Etherow: catchment

Table 4.12.1

River Etherow: site characteristics

Grid reference	*SK 116996*
Catchment area	*1300 ha*
Minimum catchment altitude	*280 m*
Maximum catchment altitude	*633 m*
Catchment Geology	*millstone grit*
Catchment Soils	*peaty podsols, blanket peat*
Catchment vegetation	*moorland - 100%*
Mean annual rainfall	*1572 mm*
1996 deposition	
Total S	*39 kg ha^{-1} yr^{-1}*
non-marine S	*38 kg ha^{-1} yr^{-1}*
Oxidised N	*14 kg ha^{-1} yr^{-1}*
Reduced N	*25 kg ha^{-1} yr^{-1}*

Table 4.12.2

River Etherow: summary of chemical determinands, July 1988 - March 1998

Determinand		Mean	Max	Min
pH		*5.48*	*7.22*	*3.79*
Alkalinity	µeq l^{-1}	*7.2*	*231.0*	*-165.0*
Ca	µeq l^{-1}	*172.0*	*350.0*	*40.0*
Mg	µeq l^{-1}	*165.8*	*291.7*	*25.0*
Na	µeq l^{-1}	*302.2*	*647.8*	*100.0*
K	µeq l^{-1}	*19.0*	*64.6*	*2.6*
SO_4	µeq l^{-1}	*272.3*	*408.3*	*85.4*
xSO_4	µeq l^{-1}	*239.6*	*372.9*	*73.5*
NO_3	µeq l^{-1}	*48.6*	*90.7*	*7.1*
Cl	µeq l^{-1}	*310.1*	*704.2*	*112.7*
Soluble Al	µg l^{-1}	*143.7*	*580.0*	*<2.5*
Labile Al	µg l^{-1}	*66.3*	*394.0*	*<2.5*
Non-labile Al	µg l^{-1}	*77.8*	*238.0*	*<2.5*
DOC	mg l^{-1}	*5.28*	*34.00*	*0.30*
Conductivity	µS cm^{-1}	*85.0*	*161.0*	*33.0*

(RGAR, 1997). This is reflected in surface water chemistry with mean concentrations of xSO_4 (240 µeq l^{-1}) and NO_3 (49 µeq l^{-1}) the highest in the network. NO_3 concentrations are high throughout the year, with little seasonal variation, indicative of Stage 3 (i.e. complete) N saturation (Stoddard, 1994). Nevertheless, because xSO_4 levels are so high, the mean ratio of $NO_3/(NO_3+xSO_4)$ is only 0.17, implying that NO_3 is proportionally a less important contributor to acidity than at Scoat Tarn.

The mean Ca concentration of 172 µeq l^{-1} indicates that this site is relatively well buffered, and mean alkalinity (7 µeq l^{-1}) and pH (5.5) are therefore higher than might be expected given the high acid anion concentrations. However, the river is highly episodic, and much of the base cation buffering capacity is lost due to dilution at high flows. As a result, alkalinity and pH minima (-165 µeq l^{-1} and 3.79 respectively) are substantially lower than at any other site in the Network (lowest values recorded elsewhere -86 µeq l^{-1} and 4.1). Labile Al concentrations are high, peaking at almost 400 µg l^{-1}, with the non-labile fraction also significant due to high DOC levels.

The River Etherow is one of the few sites in the UKAWMN showing a clear decrease in sulphate levels, with both SO_4 and xSO_4 exhibiting large and significant declining trends over the last ten years. It is estimated that the reduction in xSO_4 has been approximately 60-80 µeq l^{-1} since 1988, a decrease of around 25-30% on the first year mean. Time series and LOESS curves (Figures 4.12.2c,d) show that decreases occurred fairly steadily over the monitoring period. Due to analytical problems prior to a laboratory change in April 1991 (Section 3), the early part of the alkalinity record is missing, and no clear trends are observed in the remaining data. The pH record, although complete, also shows no trend. This may be due to the masking effect of extreme short-term variability (Figure 4.12.2a); clear rising trends in pH have been observed at a number of reservoir sites in the south Pennine region (Evans & Jenkins, 2000), but it is also possible that changes in other ions are offsetting the reduction in xSO_4. Declining trends in both Ca and Mg, identified using regression, suggest that with reduced acid inputs, the leaching of base cations from soil exchange sites has also decreased. This base cation response to reduced acid deposition corresponds to that predicted by Reuss *et al.* (1987). In addition, there is a significant upward trend in NO_3, which has risen by an estimated 15-21 µeq l^{-1} since 1988. NO_3 is thus becoming increasingly significant as a contributor to the acid anion total, and a Seasonal Kendall analysis of $NO_3/(NO_3+xSO_4)$ gave a highly significant estimated increase of 0.04 over the ten year period.

As noted above, road salt may provide a source of Na and Cl at the Etherow. This, and the inland

Table 4.12.3

Significant trends in chemical determinands (July 1988 - March 1998)

Determinand	Units	Annual trend (Regression)	Annual trend (Seasonal Kendall)
SO_4	µeq l^{-1}	*-8.15****	*-5.56**
xSO_4	µeq l^{-1}	*-8.04****	*-5.85**
Mg	µeq l^{-1}	*-3.25***	-
Ca	µeq l^{-1}	*-2.85**	-
NO_3	µeq l^{-1}	*+2.07****	*+1.50**
DOC	mg l^{-1}	*+0.48**	*+0.27****
Non-labile Al	µg l^{-1}	*+4.27**	*+5.00***

** Trend significant at $p < 0.05$; ** trend significant at $p < 0.01$; *** trend significant at $p < 0.001$*

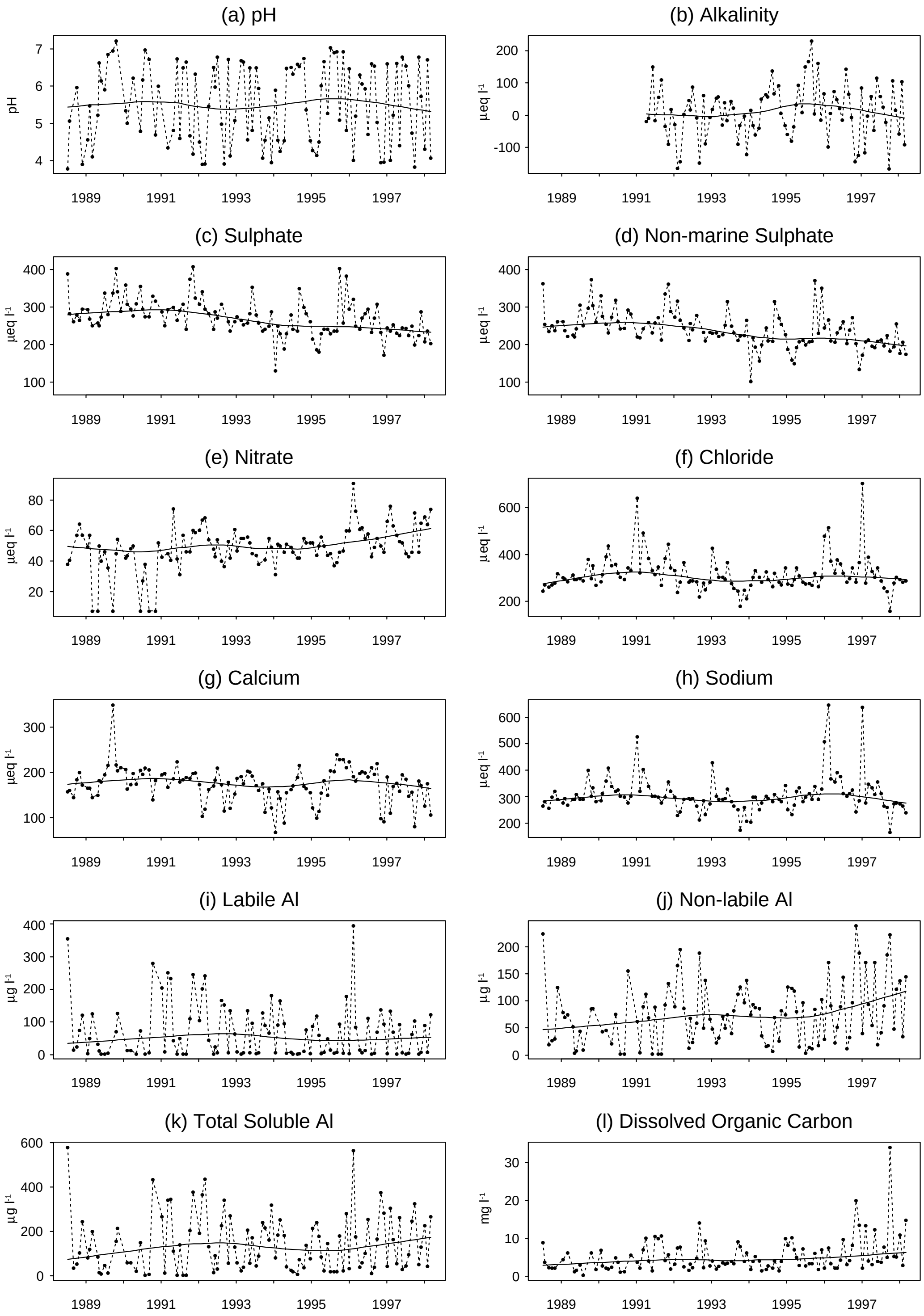


Figure 4.12.2

River Etherow: summary of major chemical determinands (September 1988 - March 1998)

Smoothed line represents LOESS curve (Section 3.1.2)

Table 4.12.4

River Etherow: trend statistics for epilithic diatom, macrophyte and macroinvertebrate summary data (1988 - 1998)

	Total sum of squares	Number of Taxa	Mean N_2 diversity	λ_1RDA/λ_2RDA	λ_1RDA/λ_1PCA
Epilithic diatoms	*318*	*66*	*3.1*	*0.11*	*0.11*
Macrophytes	*2*	*5*	*1.0*	*1.82*	*0.65*
Invertebrates	*346*	*29*	*3.5*	*0.54*	*0.43*

Variance explained (%)	within year	between years	linear trend	p unrestricted	p restricted
Epilithic diatoms	*23.0*	*77.0*	*4.4*	*0.21*	*0.70*
Macrophytes	*	*	*63.3*	*0.01*	*<0.01*
Invertebrates	*29.7*	*70.3*	*17.7*	*<0.01*	*0.06*

location, may explain the low variability in these ions relative to most other sites. Nevertheless, the time series for Cl (Figure 4.12.2f) does appear to show a small peak in 1990, comparable to those observed elsewhere, and there may therefore be some climatic influence. A highly significant DOC increase has occurred at this site, with concentrations having risen by 2.7 mg l^{-1} since 1988 based on the SKT trend estimate. This increase largely appears to have come from higher peak concentrations (Figure 4.12.2l). An associated, although less significant, increase is identified for non-labile Al.

■ Epilithic diatoms

(Figure 4.12.3, Table 4.12.4)

The epilithic diatom assemblage of the River Etherow has undergone large inter-annual variation, with the abundance of the most dominant species, *Achnanthes minutissima* (pH optima 6.3) and *Eunotia exigua* (pH optima 5.1) shifting markedly between years. In 1993 both these species occurred in relatively low abundance and the samples were relatively diverse, with elevated representation of the acidophilous species *Frustulia rhomboides* var. *saxonica*, *Brachysira brebissonii*, *B. vitrea* and *Eunotia rhomboidea*. *Pinnularia divergentissima* was recorded for the first time in 1997 and was again present in 1998. Floristic differences between years appear to be associated with variation in hydrological characteristics of the River Etherow and therefore with variation in climate. Years in which *A.minutissima* dominates are generally characterised by prolonged periods of elevated pH (at least according to monthly spot samples) in the spring and early summer, e.g. 1989, 1994 and 1995. Rainfall data for the nearby Meteorological Station (Emley Moor) demonstrates that spring and early summer in these years were relatively dry, resulting in relatively alkaline, base-flow dominated conditions. *E. exigua* is most abundant in the wetter years which exhibit more episodic chemical characteristics, resulting from the increased influence of acidic surface runoff. The link between summer rainfall and the diatom community is illustrated by the relationship between diatom inferred pH (using weighted averaging) and June-July rainfall data (Section 7.3.1). RDA and associated permutation test show that time is not significant at the 0.01 level.

■ Macroinvertebrates

(Figure 4.12.4, Table 4.12.4)

The macroinvertebrate community of the River Etherow has undergone a considerable increase in species richness over the past decade. The site

Table 4.12.5

River Etherow: relative abundance of aquatic macrophyte flora (1988 - 1997)
(see Section 3.2.3 for key to indicator values)

Abundance Taxon Year	88	89	90	91	92	93	95	96	97
SUBMERGED SPECIES									
Filamentous green algae	<0.1	1.2	<0.1	<0.1	1.0	0.0	0.0	<0.1	<0.1
Atrichum crispum	0.0	0.0	<0.1	0.0	0.0	0.0	0.0	0.0	0.0
Mnium hornum	<0.1	<0.1	0.0	0.0	0.0	0.0	0.0	<0.1	0.0
Polytrichum sp.	0.0	0.0	0.0	0.0	<0.1	<0.1	<0.1	<0.1	0.0
Scapania undulata	18.7	18.5	14.8	14.9	9.0	6.3	6.7	12.6	3.6
Juncus bulbosus var. *fluitans*	<0.1	<0.1	<0.1	0.0	0.0	0.0	0.0	<0.1	0.0
EMERGENT SPECIES									
Juncus effusus	<0.1	<0.1	<0.1	<0.1	0.0	<0.1	<0.1	0.0	<0.1
total macrophyte cover excluding filamentous algae	18.7	18.5	14.8	14.9	9.0	6.3	6.7	12.6	3.6
TOTAL NUMBER OF SPECIES	5	5	5	3	3	2	2	5	3

is dominated by acid tolerant detritivorous stoneflies. *Leuctra inermis* was the dominant stonefly throughout and occurred in very high numbers while *Amphinemura sulcicollis* and *Protonemura* spp. were both numerous. *Brachyptera risi* showed an increase in abundance in the last five years of the survey. The predatory stonefly *Siphonoperla torrentium* was present throughout, with the exception of 1992 which was an impoverished year both in species richness and abundance. Of the mayflies, *Ameletus inopinatus* was recorded in relatively high numbers throughout while the acid sensitive *Baetis* spp. first appeared in 1992, was absent between 1994 and 1996 and reappeared in 1997. Other characteristic species include *Rhyacophila* spp., *Plectrocnemia* spp., Tipulids and chironomids. Possible causes for the apparent increase in diversity are unclear as there is no evidence to suggest improvements in acidity status. However, it is interesting to note that - inter-annual variation in species richness is well correlated with that for the majority of the other streams in the Network (Section 7.4.2) and it is therefore possible that climatic factors, and particularly spring rainfall/flow, may be important. Despite these changes the species composition does not show a linear trend with time according to RDA and associated restricted permutation test.

Fish

On sampling in 1989 this site was found to be fishless. As it is situated above a fishless reservoir which prohibits any possibility of fish colonising the reach from downstream, no further sampling has been carried out.

Aquatic macrophytes

(Tables 4.12.4-5)

The ubiquitous and highly acid tolerant liverwort species, *Scapania undulata*, has been the only consistent representative of the aquatic macrophyte flora over the past decade. The cover of this species in the survey stretch has declined since 1988. Given its broad chemical tolerance it seems most likely that its reduction results from physical scouring associated with storm events. Alternatively, it is possible that the large increase in DOC at the site has restricted its available habitat through the effect of light limitation. Reduction in the cover of *S.undulata* appears to drive the significant time trend in species cover identified by RDA and associated restricted permutation test.

Summary

The River Etherow has the highest xSO_4 and NO_3 concentrations in the UKAWMN, due to high deposition levels. Mean pH and alkalinity are not as low as might be expected, due to a large internal supply of base cations, but the site is extremely episodic, with chemistry at high flows the most acidic in the UKAWMN. Consistent with the regional pattern of deposition reductions, the Etherow is one of the few sites to have shown clear reduction in xSO_4 (by 25-30%) since 1988. This has not yet been accompanied by identifiable recovery in either pH or alkalinity, possibly due to limitations in the data and high short-term variability, although it also appears that other ionic changes are offsetting the reduction in xSO_4. In particular, NO_3 has risen significantly, and is becoming an increasingly important contributor to site acidity. The considerable inter-annual variation in the epilithic diatom species assemblage, the increase in the number of macroinvertebrate species with time, and the reduction in cover of aquatic liverworts, may be primarily related to changes in the rainfall regime, through its influence on episodes and physical scouring at high flow.

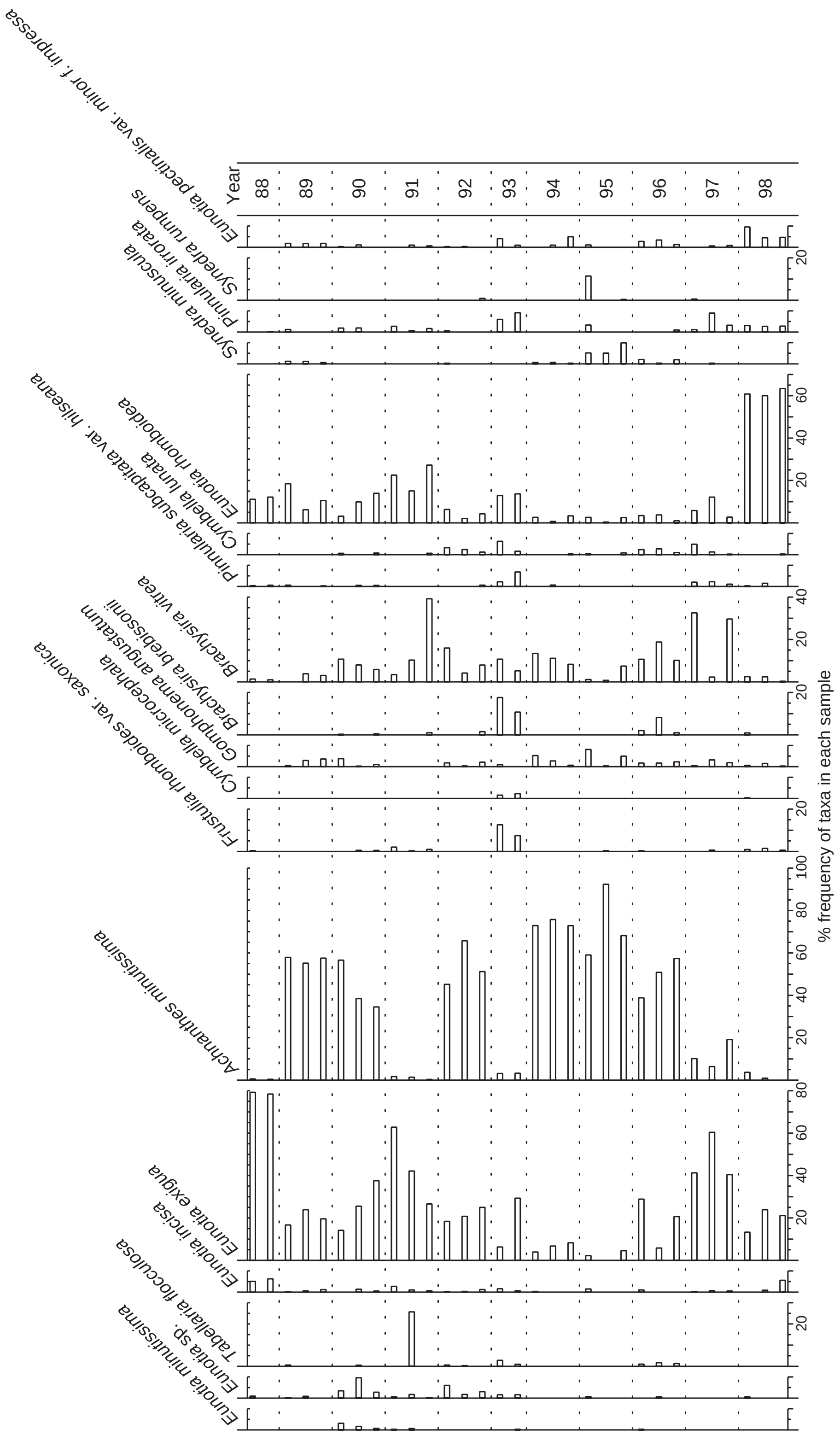


Figure 4.12.3

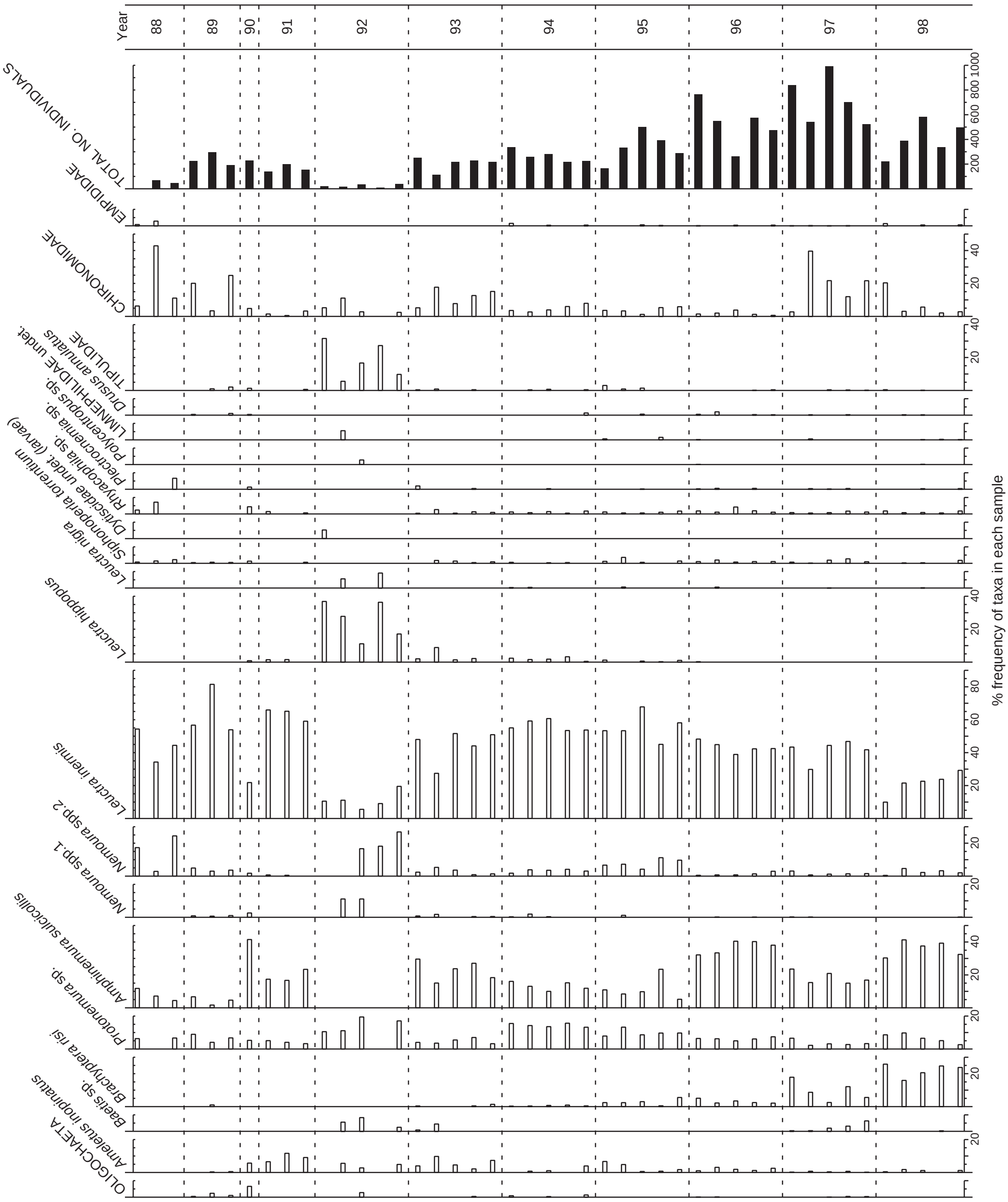
River Etherow: summary of epilithic diatom data (1988 - 1998)

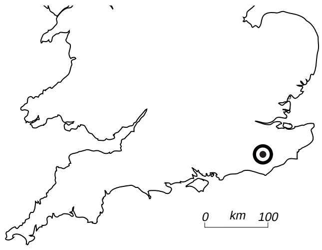
Percentage frequency of all taxa occurring at >2% abundance in any one sample

Figure 4.12.4

River Etherow: summary of macroinvertebrate data (1988 - 1998)

Percentage frequency of taxa in individual samples





4.13 Old Lodge

Site Review

Situated on the Ashdown sands, within the Ashdown Forest, the Old Lodge catchment is the only UKAWMN site in southeast England. The survey sections are prone to occasional wind-blow of large beech trees, and while fallen timber is generally removed in the course of Reserve maintenance, physical changes have resulted from the accumulation of old wood and other debris in some reaches and from changes in the extent of shading. Otherwise there has been no major physical disruption within the catchment over the course of the last decade.

Water Chemistry

(Figure 4.13.2, Table 4.13.2-3)

Old Lodge is the most chronically acidic site in the UKAWMN, with a mean pH of 4.59, a mean alkalinity of -30 μeq l^{-1}, and a mean labile Al

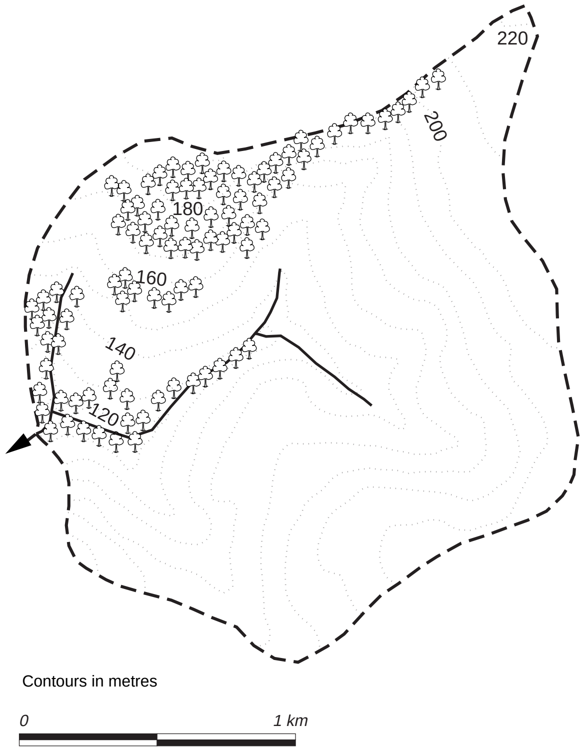


Figure 4.13.1

Old Lodge: catchment

Table 4.13.1

Old Lodge: site characteristics

Grid reference	*TQ 456294*
Catchment area	*240 ha*
Minimum catchment altitude	*94 m*
Maximum catchment altitude	*198 m*
Catchment Geology	*Ashdown sands*
Catchment Soils	*podsols*
Catchment vegetation	*heathland 80%*
	deciduous woodland 15%
	conifers15%
Mean annual rainfall	*872 mm*
1996 deposition	
Total S	*14 kg ha^{-1} yr^{-1}*
non-marine S	*11 kg ha^{-1} yr^{-1}*
Oxidised N	*5 kg ha^{-1} yr^{-1}*
Reduced N	*9 kg ha^{-1} yr^{-1}*

Table 4.13.2

Old Lodge: summary of chemical determinands, July 1988 - March 1998

Determinand		Mean	Max	Min
pH		*4.59*	*4.95*	*4.10*
Alkalinity	μeq l^{-1}	*-30.0*	*-9.0*	*-86.0*
Ca	μeq l^{-1}	*152.0*	*354.5*	*91.5*
Mg	μeq l^{-1}	*144.2*	*358.3*	*66.7*
Na	μeq l^{-1}	*463.0*	*813.0*	*269.6*
K	μeq l^{-1}	*20.0*	*110.3*	*7.7*
SO_4	μeq l^{-1}	*252.7*	*818.8*	*64.6*
xSO_4	μeq l^{-1}	*192.7*	*731.5*	*-17.5*
NO_3	μeq l^{-1}	*7.1*	*25.0*	*< 1.4*
Cl	μeq l^{-1}	*571.0*	*1036.6*	*304.2*
Soluble Al	μg l^{-1}	*239.9*	*533*	*36.2*
Labile Al	μg l^{-1}	*194.7*	*530.5*	*22.4*
Non-labile Al	μg l^{-1}	*45.0*	*310.0*	*< 2.5*
DOC	mg l^{-1}	*5.0*	*15.0*	*1.7*
Conductivity	μS cm^{-1}	*105.9*	*202.0*	*63.0*

concentration of 195 μeq l^{-1} (maximum 531 μeq l^{-1}). Alkalinity has remained negative, and pH below 5.0, throughout the monitoring period, and several large episodic decreases have been recorded for both determinands (Figure 4.13.2a,b). Major ion concentrations are generally high at this site, with mean Cl, Na, Mg, Ca and K concentrations the highest in the Network, and xSO_4 second only to the Etherow. These high concentrations result partly from the warmer and drier climate, and hence higher evaporation, at this southeast England site compared to the rest of the Network. They are also a function of high marine ion deposition from the nearby English Channel, and high pollutant inputs from upwind emission sources, relative to the low rainfall. DOC concentrations are also high, with large episodic increases, but NO_3 concentrations are low (mean 7 μeq l^{-1}), indicating that the catchment retains the capacity to immobilise large N inputs.

Trend analyses at Old Lodge are hindered by analytical problems prior to a laboratory change in April 1991 (Section 3.1.1), and data for the first three years are missing for pH, alkalinity and NO_3. Absence of significant trends in pH and alkalinity is therefore unsurprising, although there appears to have been a peak in 1994 and 1995 (Figure 4.13.2a,b). Regression analysis does however indicate that NO_3 has risen significantly since 1991, by approximately 7 μeq l^{-1}, although the relatively short period analysed must be taken into consideration. Also identified by regression are declining trends in SO_4, xSO_4, Na, Mg and Ca, and an increase in DOC. The DOC change, of around 3 mg l^{-1} over the decade, is also identified by SKT, and appears to represent a fairly steady increase. The other regression trends are not observed using SKT, however, and are therefore less certain. Inspection of time series in Figure 4.13.2 suggests that changes have occurred erratically for these determinands over time. It is therefore possible that climatic factors have influenced changes over the decade, and apparently cyclical variations in Cl and Na (Figures 4.13.2f,h) support this hypothesis. In fact, despite the difference in geographical location, there are striking similarities between marine ion variations at Old Lodge and those at west coast sites, with a pronounced peak around 1990. Nevertheless, some underlying decline in SO_4, xSO_4 and Ca is suggested by time series (Figure 4.13.2c,d,g), perhaps indicating a catchment response to deposition reductions.

Table 4.13.3

Significant trends in chemical determinands (July1988 - March 1998)

Determinand	Units	Annual trend (Regression)	Annual trend (Seasonal Kendall)
SO_4	*μeq 1^{-1}*	*-10.12***	-
xSO_4	*μeq 1^{-1}*	*-8.81**	-
Na	*μeq 1^{-1}*	*-9.30***	-
Mg	*μeq 1^{-1}*	*-4.42***	-
Ca	*μeq 1^{-1}*	*-4.90****	-
NO_3	*μeq 1^{-1}*	*+0.71**	-
DOC	*mg 1^{-1}*	*+0.35****	*+0.28***
labile Al	*μg 1^{-1}*	*-5.98**	-

** Trend significant at $p < 0.05$; ** trend significant at $p < 0.01$; *** trend significant at $p < 0.001$. Trend for nitrate based on 1991-1998 only*

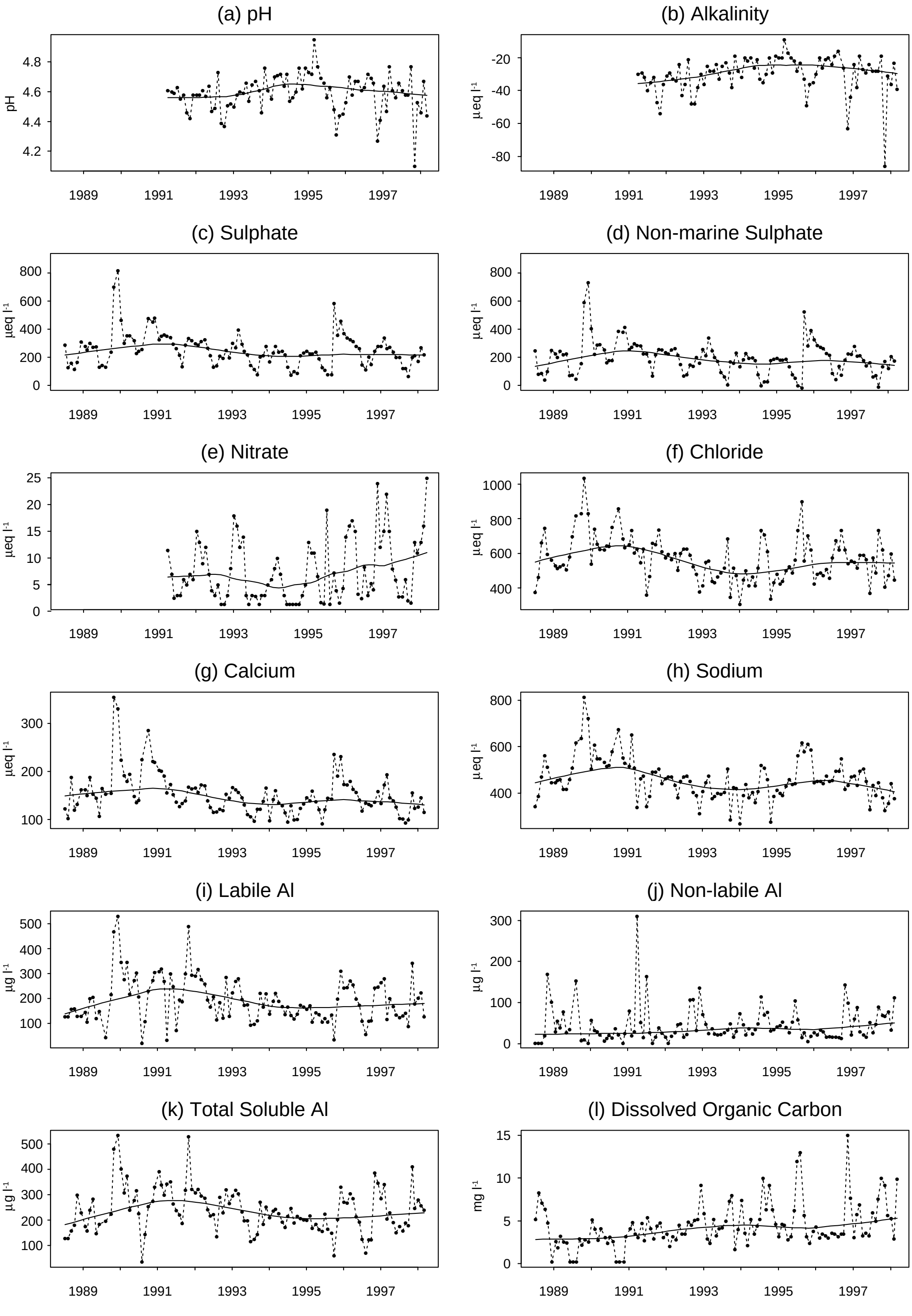


Figure 4.13.2

Old Lodge: summary of major chemical determinands (July 1988 - March 1998)

Smoothed line represents LOESS curve (Section 3.1.2)

Table 4.13.4

Old Lodge: trend statistics for epilithic diatom, macrophyte and macroinvertebrate summary data (1988 - 1998)

	Total sum of squares	Number of taxa	Mean N_2 diversity	λ_1RDA/l_2RDA	λ_1RDA/λ_1PCA
Epilithic diatoms	*176.0*	*87*	*2.5*	*0.30*	*0.28*
Macrophytes	*1.1*	*3*	*1.3*	*0.14*	*0.12*
Invertebrates	*351.0*	*23*	*3.3*	*0.50*	*0.41*

Variance explained (%)	within year	between years	linear trend	p unrestricted	p restricted
Epilithic diatoms	*42.2*	*57.8*	*8.4*	*0.01*	*0.13*
Macrophytes	-	-	*11.6*	*0.38*	*0.52*
Invertebrates	*26.9*	*73.1*	*12.6*	*<0.01*	*0.08*

Table 4.13.5

Old Lodge: relative abundance of aquatic macrophyte flora (1988 - 1997) (see Section 3.2.3 for key to indicator values)

(% cover of 50 m survey stretch)

Year	88	89	90	91	92	93	95	96	97
SUBMERGED SPECIES									
Filamentous green algae	*9.4*	*63.0*	*<0.1*	*1.3*	*22.8*	*0.0*	*0.0*	*<0.1*	*<0.1*
Scapania undulata	*0.6*	*2.0*	*3.2*	*2.6*	*2.4*	*1.9*	*1.1*	*0.5*	*1.3*
Glyceria fluitans	*<0.1*	*<0.1*	*0.1*	*<0.1*	*0.0*	*0.2*	*<0.1*	*0.0*	*0.0*
Juncus bulbosus var. *fluitans*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*0.3*	*0.1*	*<0.1*	*<0.1*
EMERGENT SPECIES									
Juncus effusus	*0.0*	*0.0*	*<0.1*	*0.0*	*0.0*	*0.1*	*0.1*	*<0.1*	*<0.1*
total macrophyte cover excluding filamentous algae	*0.6*	*2.0*	*3.3*	*2.6*	*2.4*	*2.4*	*1.3*	*0.5*	*1.3*
TOTAL NUMBER OF SPECIES		*3*	*3*	*4*	*3*	*2*	*4*	*4*	*3*

■ Epilithic diatoms

(Figure 4.13.3, Table 4.13.4)

As at several other stream sites, the epilithon of Old Lodge has varied markedly from year to year, although the relatively narrow range of pH optima of the dominant species emphasises the restricted, permanently strongly acid pH fluctuations of this site. The acidophilous *Eunotia* species, *E. exigua*, *E. incisa* and *E. rhomboidea*, are the three most abundant taxa and the former was dominant in most years, with the exception of 1993 when *E.incisa* was relatively common. *Achnanthes minutissima*, which has a higher pH optima (6.3) was relatively abundant in 1989, appearing to reflect a period of relatively elevated pH in the summer of this year. However, unlike the majority of stream sites there is no relationship between the diatom inferred pH, using weighted averaging, and summer rainfall. RDA and associated restricted permutation test shows that “sampling year” is not significant at the 0.01 level.

■ Macroinvertebrates

(Figure 4.13.4, Table 4.13.4)

The impoverished macroinvertebrate fauna of Old Lodge is typical of an acid stream, characterised by acid tolerant detritivorous stoneflies and the predatory caddisfly *Plectrocnemia* spp. Of the stoneflies, *Nemoura* spp. and *Leuctra nigra* dominate. *Leuctra hippopus* occurred in high densities in 1992 only, while *Nemurella pictetii* was present intermittently in low numbers during the first half of the study period, but has shown increasing abundance during the last three years. *Siphonoperla torrentium* was present in low numbers in the second half of the monitoring period. Other characteristic fauna include the freshwater Bivalve *Pisidium* spp., the acid tolerant Amphipod *Niphargus aquilex*, and the alderfly *Sialis fuliginosa*. *Baetis* spp. occurred intermittently in low numbers, the highest density being recorded in 1993. Inter-annual variation in species richness is similar to that observed at several other UKAWMN stream sites. This suggests that climatic factors, particularly as they relate to the flow regime, may have an important influence (Section 7.4.2). RDA and associated permutation test show no significant time trend in the species assemblage at the 0.01 level.

■ Fish

(Figure 4.13.5)

Old Lodge has been electrofished since 1989. For the first three years samples were characterised by the absence of any 0+ trout and extremely low numbers of >0+ trout. However, in 1992 a significant increase in density occured with an influx of 0+ trout. Since then recruitment has occurred in all years except 1996. Mean condition factor of 0+ fish was highest in both the high recruitment year of 1992 and the low recruitment year of 1994. Length frequency graphs show clearly the recruitment peak in 1992. They also show that this was not accompanied by a strong cohort of fish progressing through the population in subsequent years. It is interesting to note that the first three years of monitoring, during which there was no recrutiment, were also characterised by particularly elevated concentrations of soluble labile alumium. These data are therefore consistent with a response to declining levels of acidity.

■ Aquatic macrophytes

(Tables 4.13.4-5)

The aquatic macrophyte flora of Old Lodge is dominated by the ubiquitous and acid tolerant liverwort, *Scapania undulata*, although occasionally this has been covered by a considerable growth of filamentous algae. The rush *Juncus bulbosus* var. *fluitans* and the grass *Glyceria fluitans*, both relatively opportunistic, have occurred sporadically over the decade in silty locations. The macrophyte survey stretch has undergone considerable physical change during the monitoring period as the result of wind-blown trees which have caused temporary damming and siltation. In addition, canopy shading has reduced substantially in places. Despite these changes there is no evidence of any trend in cover or species representation over the monitoring period and time is insignificant as a linear trend according to RDA and restricted permutation test.

■ Summary

Old Lodge is severely acidified, with a continuously negative alkalinity. Major ion concentrations are generally higher than at other UKAWMN sites, due to a combination of high pollutant and marine deposition and higher evaporation, although most incoming NO_3 continues to be retained. Shortened data series for some determinands makes trend analysis difficult, but it appears that xSO_4 and Ca may have declined, and NO_3 and DOC risen. Marine ions have exhibited large fluctuations over the monitoring period, possibly having a significant impact on stream acidity. Trout data indicate a general improvement in conditions, but this is not apparent for other biological groups and suggestions of signs of "biological recovery" are perhaps premature at this stage.

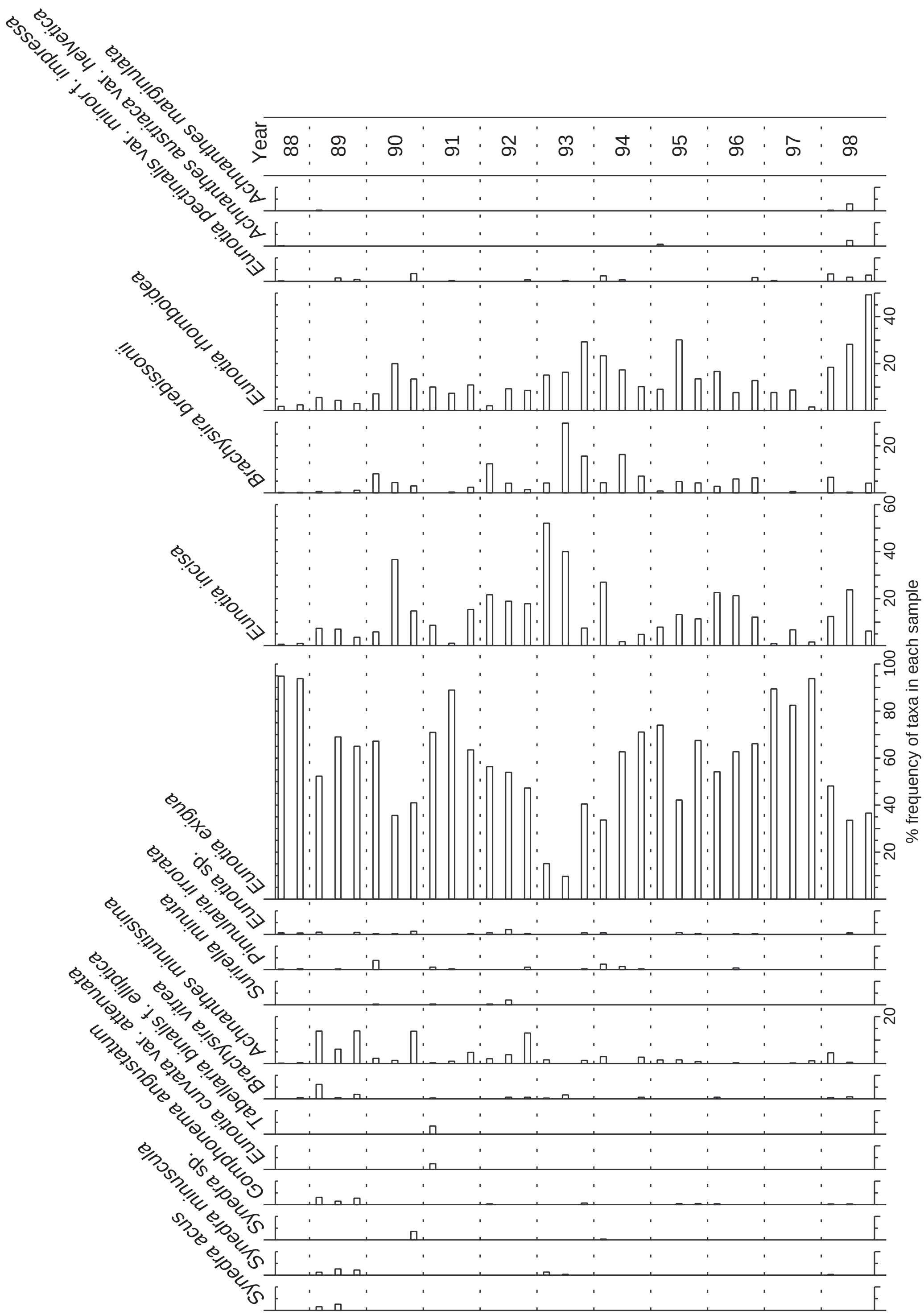


Figure 4.13.3

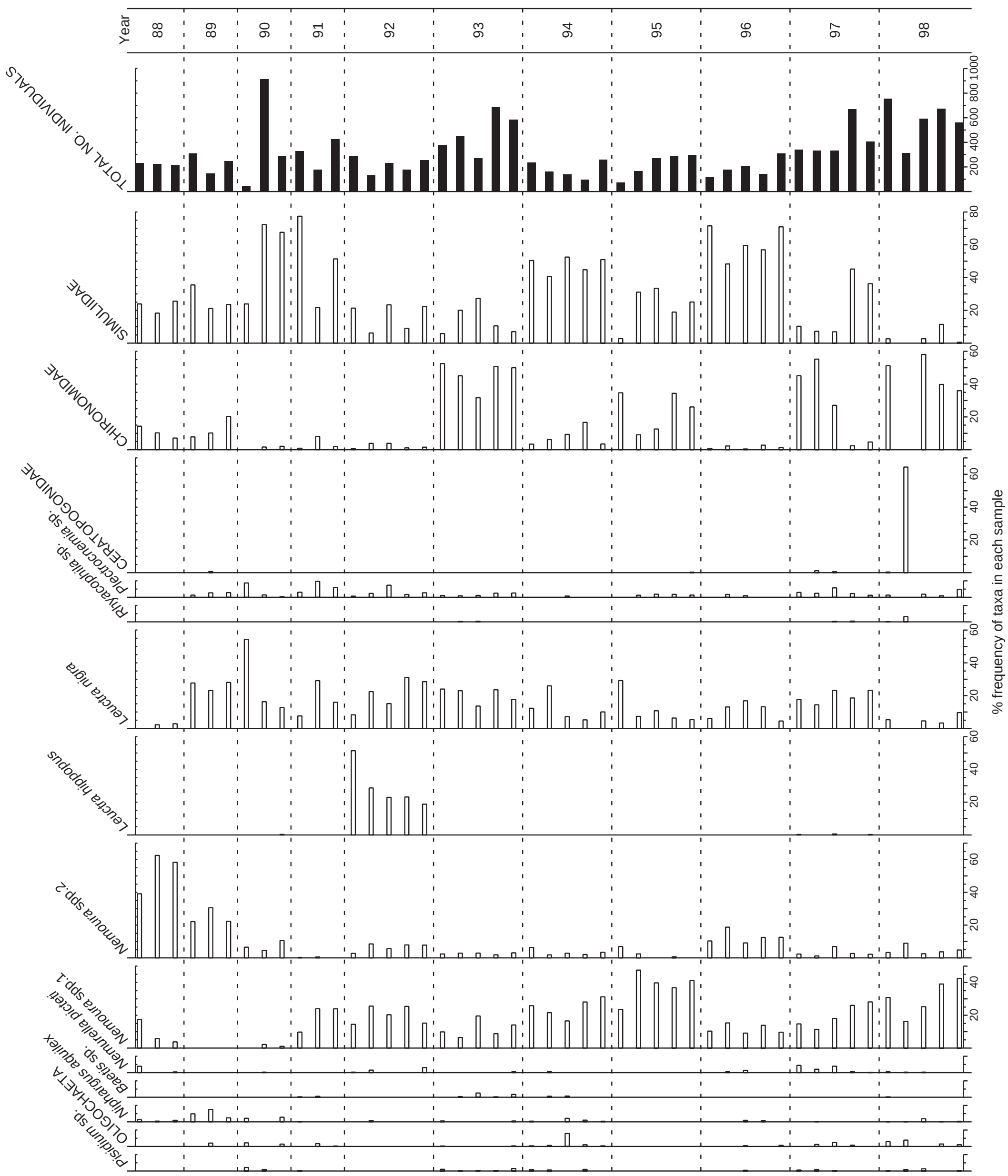
Old Lodge: summary of epilithic diatom data (1988 - 1998)

Percentage frequency of all taxa occurring at >2% abundance in any one sample

Figure 4.13.4

Old Lodge: summary of macroinvertebrate data (1988 - 1998)

Percentage frequency of taxa in individual samples



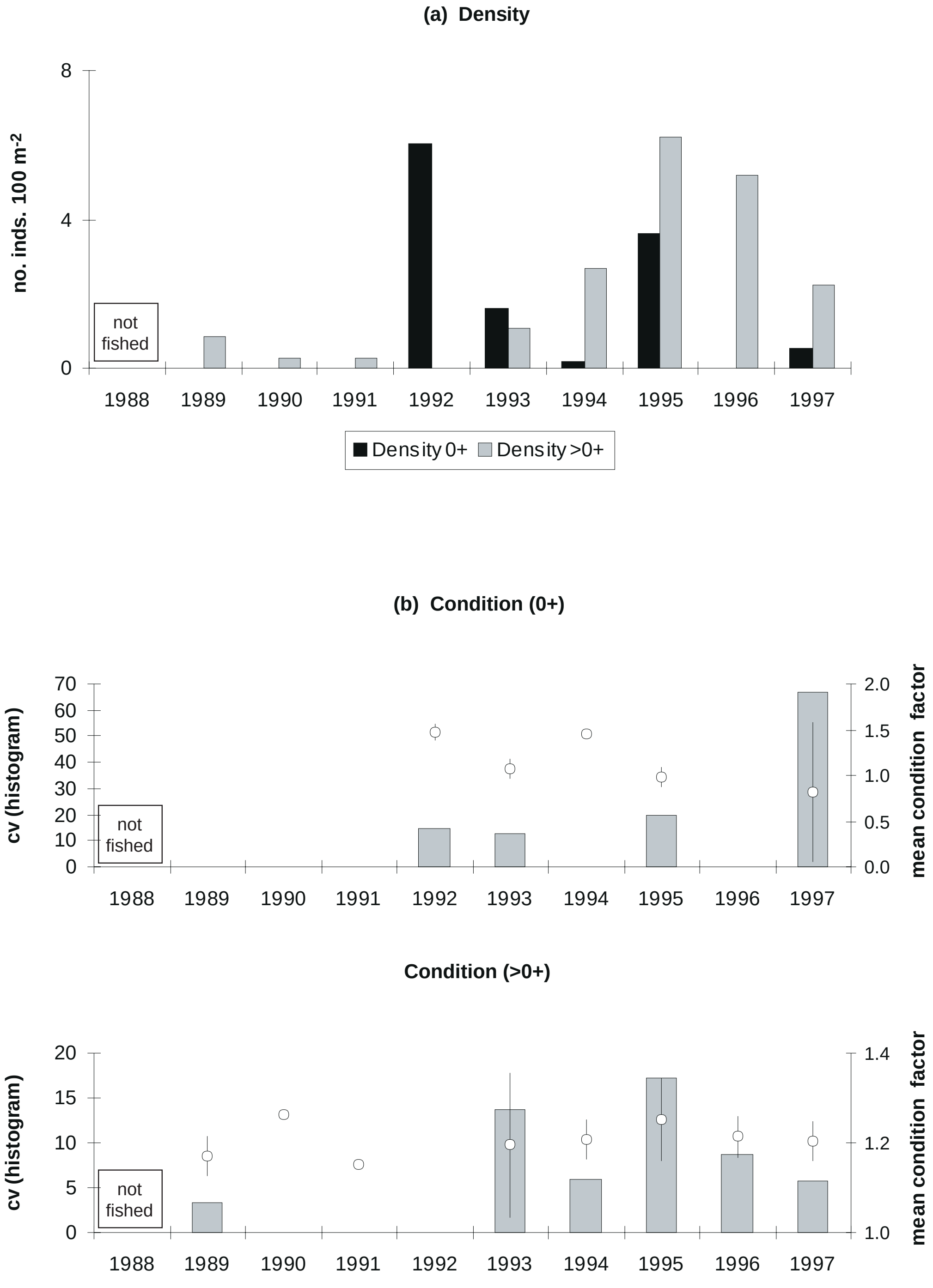
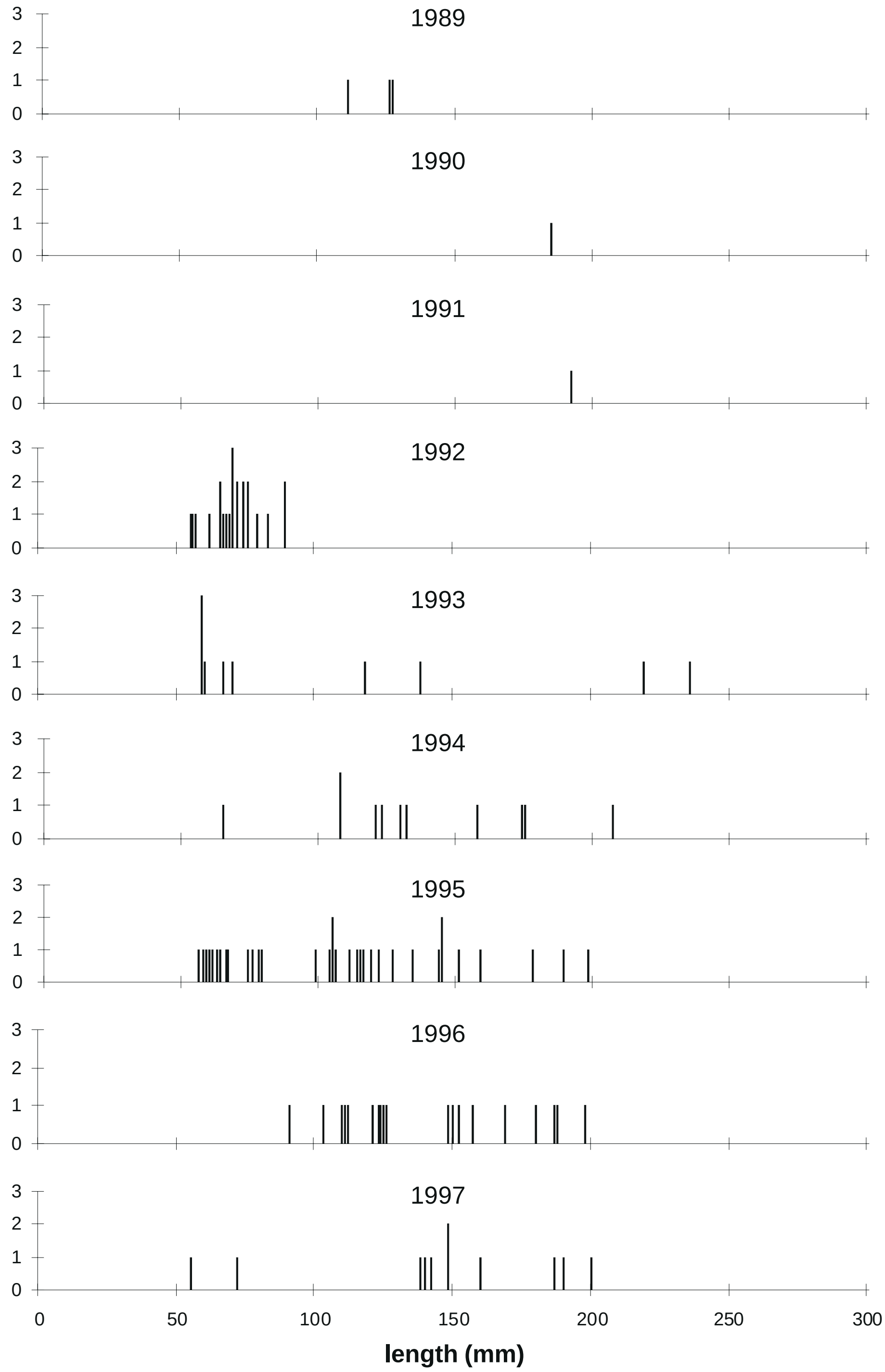


Figure 4.13.5

Old Lodge: summary of fish data (1989 - 1997)
(a) Trout population density for 0+ and >0+ age classes (individuals 100 m^{-2})
(b) Mean condition factor (with standard deviation) of the trout population and its coefficient of variation (histogram)

Figure 4.13.5

Old Lodge: summary of fish data (1989 - 1997) (c) Trout length frequency summaries



4.14 Narrator Brook

Site Review

Narrator Brook, which feeds the Burrator Reservoir within the Dartmoor National Park, is the only representative site for southwest England. The water chemistry sampling point was moved upstream in 1991 following a period of felling in the lower part of the catchment. This has led to a step change in the concentration of some chemical determinands and as a result trend analysis has only been carried out on the last 7 years of data. Low intensity grazing around the 50 m long macrophyte survey stretch has recently been restricted following the introduction of new fencing. However, this has had little impact on the bank-side vegetation to date. Otherwise, there are no indications of physical changes within the catchment over the past decade.

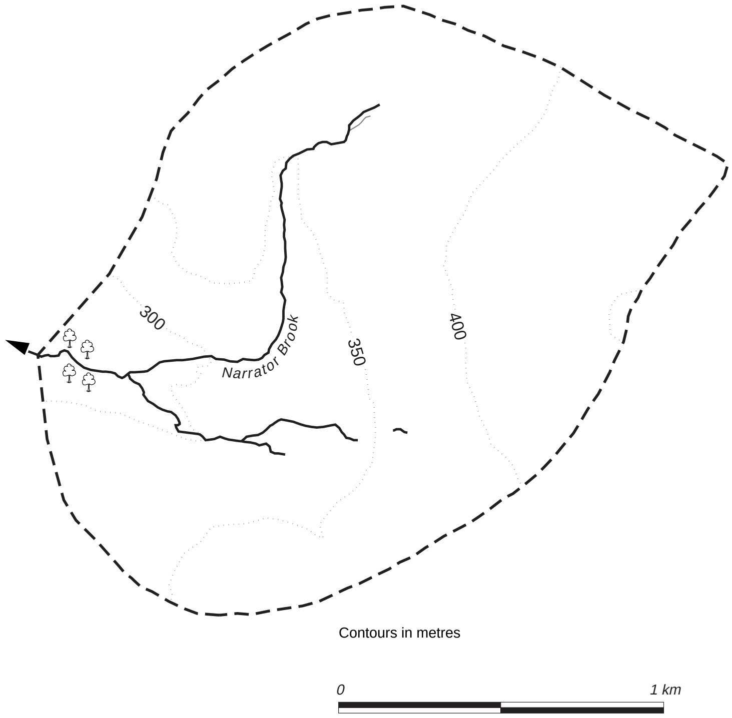


Figure 4.14.1

Narrator Brook: catchment

Table 4.14.1

Narrator Brook: site characteristics

Grid reference	*SX 568692*
Catchment area	*253 ha*
Minimum catchment altitude	*225 m*
Maximum catchment altitude	*456 m*
Catchment Geology	*granite*
Catchment Soils	*iron pan stagnopodsols, brown podsols*
Catchment vegetation	*moorland and acid grassland 98%, deciduous woodland 2%*
Mean annual rainfall	*1819 mm*
1996 deposition	
Total S	*22 kg ha^{-1} yr^{-1}*
non-marine S	*15 kg ha^{-1} yr^{-1}*
Oxidised N	*9 kg ha^{-1} yr^{-1}*
Reduced N	*20 kg ha^{-1} yr^{-1}*

Table 4.14.2

Narrator Brook: summary of chemical determinands, July 1988 - March 1998

Determinand		Mean	Max	Min
pH		*5.77*	*6.37*	*4.93*
Alkalinity	µeq l^{-1}	*15.6*	*58.4*	*-11.0*
Ca	µeq l^{-1}	*34.5*	*69.5*	*17.5*
Mg	µeq l^{-1}	*65.0*	*100.0*	*50.0*
Na	µeq l^{-1}	*253.5*	*334.8*	*208.7*
K	µeq l^{-1}	*20.0*	*28.2*	*15.4*
SO4	µeq l^{-1}	*73.8*	*85.4*	*62.5*
xSO4	µeq l^{-1}	*45.0*	*57.7*	*22.7*
NO3	µeq l^{-1}	*6.4*	*15.7*	*<1.4*
Cl	µeq l^{-1}	*273.8*	*478.9*	*219.7*
Soluble Al	µg l^{-1}	*60.0*	*236.0*	*11.0*
Labile Al	µg l^{-1}	*26.6*	*166.0*	*<2.5*
Non-labile Al	µg l^{-1}	*33.6*	*156.0*	*<2.5*
DOC	mg l^{-1}	*1.4*	*5.8*	*0.3*
Conductivity	µS cm^{-1}	*42.9*	*58.0*	*29.0*

Water Chemistry

(Figure 4.14.2, Tables 4.14.2-3)

Narrator Brook has a mean pH of 5.77, and a mean alkalinity of 16 μeq l^{-1}. Al concentrations are low, and divided equally between labile and non-labile forms. Low Ca concentrations (mean 35 μeq l^{-1}) suggest that this is a sensitive catchment, and it becomes acidic (pH <5.0, alkalinity <0 μeq l^{-1}) during episodes. NO_3 concentrations are low, with a mean of 6 μeq l^{-1}, whilst marine ion concentrations are high owing to the near-coastal location.

The change of sampling point in April 1991 led to a step change in a number of determinands (Patrick *et al.* 1995). Data collected prior to this are not included in trend analyses. The 1991-1998 dataset exhibits a number of significant trends (Table 4.14.3). Cl has declined significantly since 1991 according to both analytical methods, and this is clearly observable in the time series (Figure 4.14.2f). It is thought that this represents part of a similar cyclical Cl variation to that observed at many other sites across the UK, and this is supported by pre-1991 data at Narrator Brook. Although not comparable to post-1991 data in absolute terms, Cl levels clearly rose during the first three years of sampling to a peak in winter 1990-1991. Given high marine cation concentrations and the subsequent sea-salt effect during the early 1990s, pH and alkalinity may have been depressed at this time. This would explain the subsequent increases in these determinands identified by regression analysis, rather than a recovery due to reduced acid deposition reduction. This conclusion is supported by the fact that SO_4 and xSO_4 appear actually to have risen since 1991. Reasons for this increase are uncertain; it is possible that xSO_4 deposition has also risen in this region over the last decade (Vincent *et al.*, 1998), but an alternative cause may be the variation in marine inputs. It has been proposed by Evans *et al.* (in press) that during periods of high sea-salt deposition, higher SO_4 concentration in soil water leads to increased SO_4 adsorption on to the soil, which in turn leads to an effective reduction in xSO_4 (ie. a reduction in the ratio of total SO_4 to Cl). This mechanism is discussed in more detail in Section 5.3.3. The rise in xSO_4 from 1991 onwards may therefore represent the desorption of this stored SO_4.

Although Narrator Brook exhibits limited episodicity, two major episodes were sampled in the latter part of the record. The first, in November 1996, appears to have been a standard base cation dilution event, with Ca falling to its lowest recorded level. In contrast, the January 1998 event was the result of a major sea-salt storm, and led to the highest observed Cl and Na concentrations. The resulting sea-salt effect generated a severe acidic episode, with the

Table 4.14.3

Significant trends in chemical determinands (July 1988 - March 1998)

Determinand	Units	Annual trend (Regression)	Annual trend (Seasonal Kendall)
pH		*+0.053***	-
Alkalinity	μeq l^{-1}	*+1.86***	-
SO_4	μeq l^{-1}	*+0.65***	*+0.52**
xSO_4	μeq l^{-1}	*+1.02****	*+1.08**
Cl	μeq l^{-1}	*-3.55**	*-5.63**
Labile Al	μg l^{-1}	*+2.92**	-

** Trend significant at $p < 0.05$; ** trend significant at $p < 0.01$; *** trend significant at $p < 0.001$*

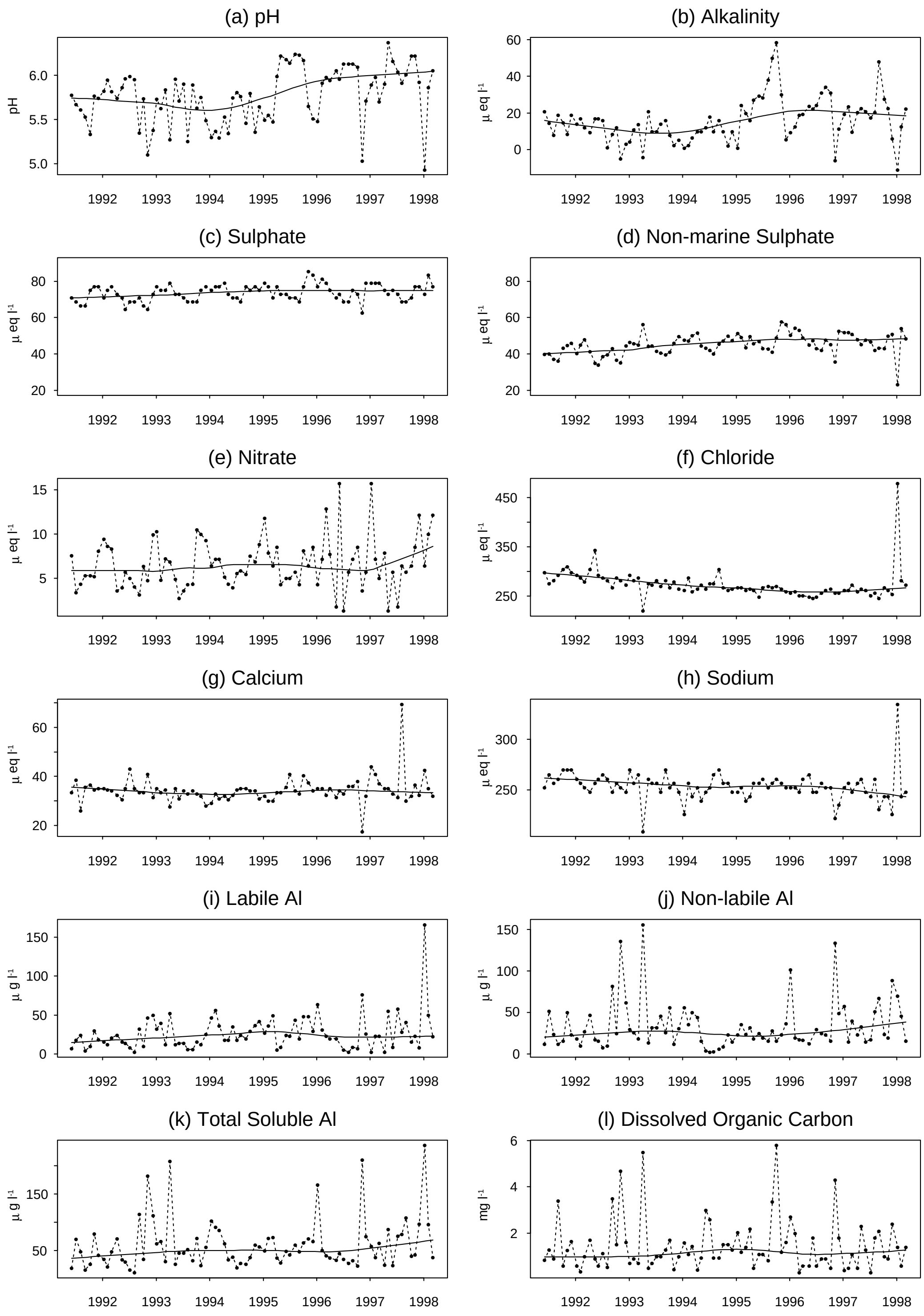


Figure 4.14.2

Narrator Brook: summary of major chemical determinands (September 1988 - March 1998)

Smoothed line represents LOESS curve (Section 3.1.2)

Table 4.14.4

Narrator Brook: trend statistics for epilithic diatom, macrophyte and macroinvertebrate summary data (1988 - 1998)

	Total sum of squares	Number of Taxa	Mean N_2 diversity	λ_1RDA/λ_2RDA	λ_1RDA/λ_1PCA
Epilithic diatoms	*333*	*88*	*3.1*	*0.20*	*0.20*
Macrophytes	*5*	*13*	*2.1*	*0.84*	*0.57*
Invertebrates	*436*	*46*	*5.6*	*0.30*	*0.29*

Variance explained (%)	within year	between years	linear trend	p unrestricted	p restricted
Epilithic diatoms	*44.4*	*55.6*	*4.3*	*0.17*	*0.64*
Macrophytes	*	*	*30.3*	*0.04*	*0.06*
Invertebrates	*54.1*	*45.9*	*6.1*	*<0.01*	*0.09*

lowest pH and alkalinity, and highest labile Al, observed during the monitoring period. Additionally, there was a sharp decline in xSO_4, supporting the hypothesis of marine SO_4 retention described above.

Epilithic diatoms

(Figure 4.14.3, Table 4.14.4)

Although the epilithon of Narrator Brook is dominated by *Achnanthes minutissima* and *Fragilaria vaucheriae,* species typical of mildly acid streams, samples in some years have also contained taxa with lower pH preferences. *Eunotia vanheurckii* var. *intermedia* (pH optima 5.3) was particularly abundant in 1991 and 1993, while Eunotia [sp. 10 (minima)] (pH optima 4.9) occurred at >5% frequency in 1997 and 1998. Increases in both taxa appear to be balanced by a reduction in *A. minutissima*, suggesting more acid conditions during these periods. These findings are consistent with changes in the water chemistry for this site. For example, *A. minutissima* was particularly abundant in 1992 and 1995 when pH of samples was consistently elevated during the spring and summer, probably as a result of low rainfall (as recorded by the nearby Princetown Meteorological Station) and base-flow dominance of the stream hydrology. As with several other UKAWMN stream sites, diatom inferred pH (derived from weighted averaging), is inversely correlated with June-July rainfall over the period (Section 7.4.1). RDA and associated permutation test show that time is not a significant variable at the 0.01 level.

Macroinvertebrates

(Figure 4.14.4, Table 4.14.4)

This is the most diverse stream in the Network. After the Chironomidae, the fauna is dominated by a diverse community of stoneflies, characterised by *Leuctra inermis* and the predators *Isoperla grammatica* and *Siphonoperla torrentium*. Other abundant stoneflies include *Protonemura* spp., which had its highest density in 1998 and *Brachyptera risi*. Several species intolerant of low pH have been recorded (e.g. *Baetis* spp., *Hydropsyche siltalai* and *Limnius volckmari*). Caddisfly species are also numerous, although several have appeared in the last 5 years (notably *Lepidostoma hirtum*, *Drusus annulatus* and *Adicella reducta)*. The first five years were rather impoverished in abundance, with 1992 being a particularly poor year. Since 1993 there has been an increase in both species richness and

Table 4.14.5

Narrator Brook: relative abundance of aquatic macrophyte flora (1988 - 1997)
(see Section 3.2.3 for key to indicator values)

Abundance Taxon Year	88	89	90	91	92	93	95	96	97
INDICATOR SPECIES									
Lemanaea sp.[1]	0.0	0.0	0.0	<0.1	0.0	0.0	0.0	0.3	0.0
Brachythecium plumosum[2]	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Fontinalis squamosa[2]	3.9	5.2	2.4	2.5	2.8	1.5	2.5	2.6	0.4
Hyocomium armoricum[2]	4.9	4.6	2.4	2.9	1.3	1.5	2.8	3.8	1.9
Rhyncostegium riparioides[1]	19.2	14.1	18.3	13.9	9.4	7.5	18.3	12.6	7.3
Nardia compressa[3]	<0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
OTHER SUBMERGED SPECIES									
Filamentous green algae	0.0	0.3	<0.1	0.7	<1.0	0.0	0.0	0.0	0.0
Juncus bulbosus var. *fluitans*	0.0	0.1	<0.1	0.1	0.2	<0.1	0.0	0.0	0.0
Polytrichum commune	0.0	<0.1	0.0	0.0	0.0	<0.1	<0.1	1.4	<0.1
Scapania undulata	<0.1	0.9	0.5	0.7	0.5	0.2	0.6	1.0	0.8
Sphagnum sp.	0.0	0.0	0.0	0.0	0.7	0.0	0.0	<0.1	0.0
EMERGENT SPECIES									
Glyceria fluitans	<0.1	0.3	<0.1	0.0	0.0	<0.1	0.1	0.0	0.0
Juncus effusus	0.0	<0.1	<0.1	0.0	0.0	<0.1	0.0	0.0	0.1
Ranunculus flammula	0.0	<0.1	<0.1	0.1	<0.1	0.0	0.1	0.1	<0.1
Ranunculus omiophyllus	<0.1	0.1	<0.1	0.0	<0.1	0.0	0.3	0.0	0.1
total macrophyte cover excluding filamentous algae	28.8	25.3	23.6	20.2	14.9	10.7	24.7	21.8	10.6
TOTAL NUMBER OF SPECIES	8	11	10	8	9	8	8	8	8

abundance. This may reflect an improvement in conditions, although similar temporal patterns have been observed in macroinvertebrate diversity at several other stream sites and it seems likely that climatic factors, particularly those relating to spring flow conditions have an important influence (Section 7.4.2). Time as a linear trend is not significant in explaining changes in species composition using RDA and associated permutation test at the 0.01 level.

Fish

(Figure 4.14.5)

Narrator Brook has been electrofished since 1988. Mean trout densities are the second highest found in the Network and reflect the relatively high water quality of this site. Population density of both 0+ and >0+ fish show no trends over the ten years, although the density of >0-group fish was lower between 1991 and 1994 than in other years. Similarly, no time trends are apparent for condition factor statistics for either age class, although they do show remarkably smooth and synchronous oscillatory patterns which appear independent of density. The length frequency histograms indicate a healthy population structure at the site although a somewhat higher proportion of 0+ fish might have been expected.

Aquatic macrophytes

(Tables 4.14.4-5)

The particularly diverse aquatic macrophyte flora of the Narrator Brook survey stretch appears to reflect the relatively alkaline water chemistry, and the incised nature of the channel which provides a habitat for a number of emergent species. Throughout the decade the stretch has been dominated by the acid sensitive moss *Rhyncostegium ripariodes*, while two other moss species, *Fontinalis squamosa* and *Hyocomium armoricum* have also been relatively abundant. There has been a general reduction in overall cover over the decade. However, as this has not been accompanied by relative changes in species representation, it most likely represents effects of physical disturbance, or possibly an increase in shading of the survey stretch by bank-side vegetation, rather than any response to changing water chemistry. RDA and associated permutation test show that the change in species cover with time is insignificant at the 0.01 level.

■ Summary

Narrator Brook is moderately acidic, with occasional dilution or sea-salt driven episodes causing alkalinity to fall below zero. Trend analysis is only possible on data for 1991-1998, during which time chemical changes have been dominated by recovery from a marine ion peak in 1990-1991. Apparently contradictory increases in xSO_4 and pH/alkalinity may both be due to the effects of marine ions, while inter-annual variation in the macroinvertebrate and epilithic diatom communities may both be linked to variations in flow at particular times of the year.

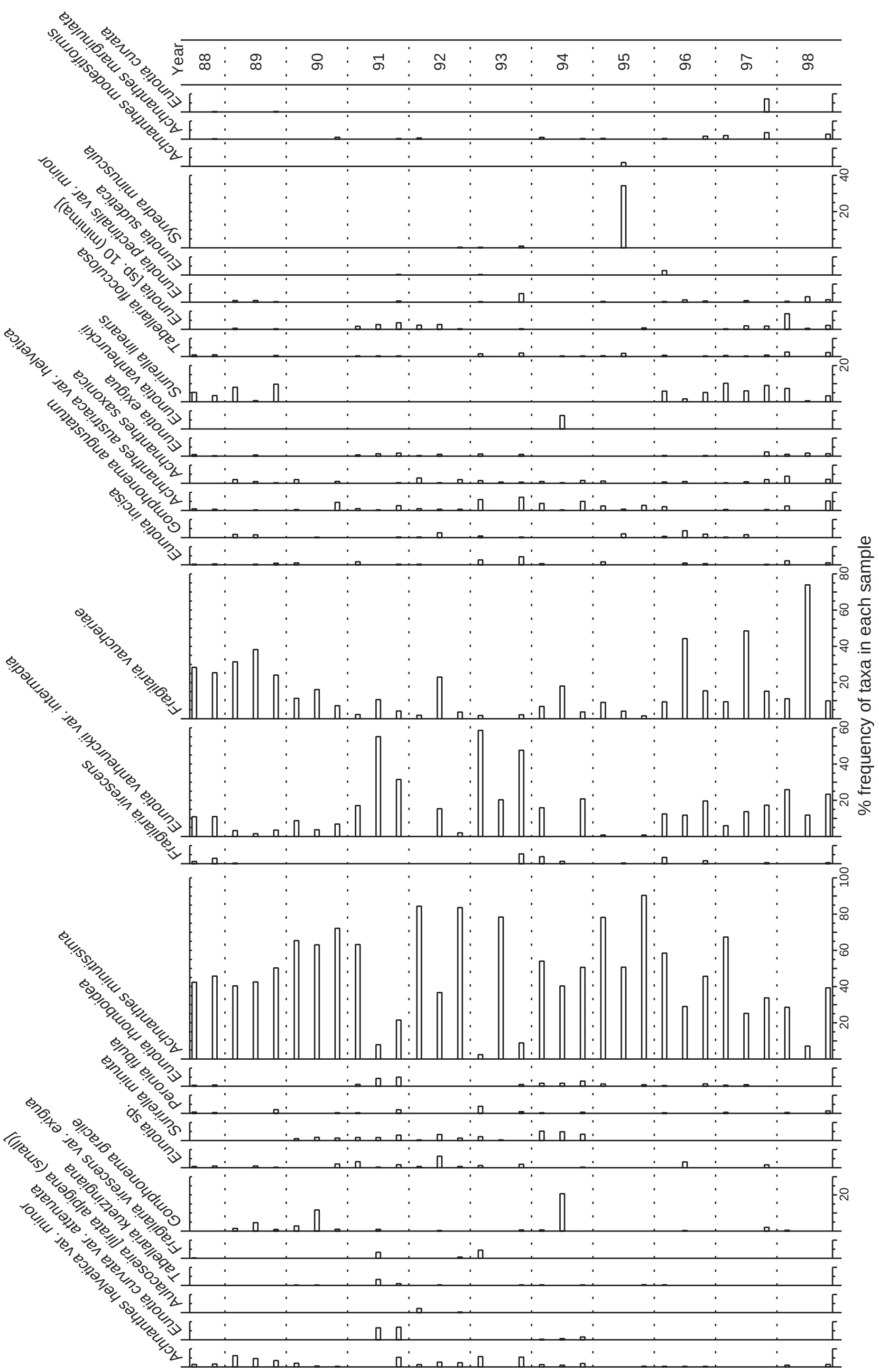


Figure 4.14.3

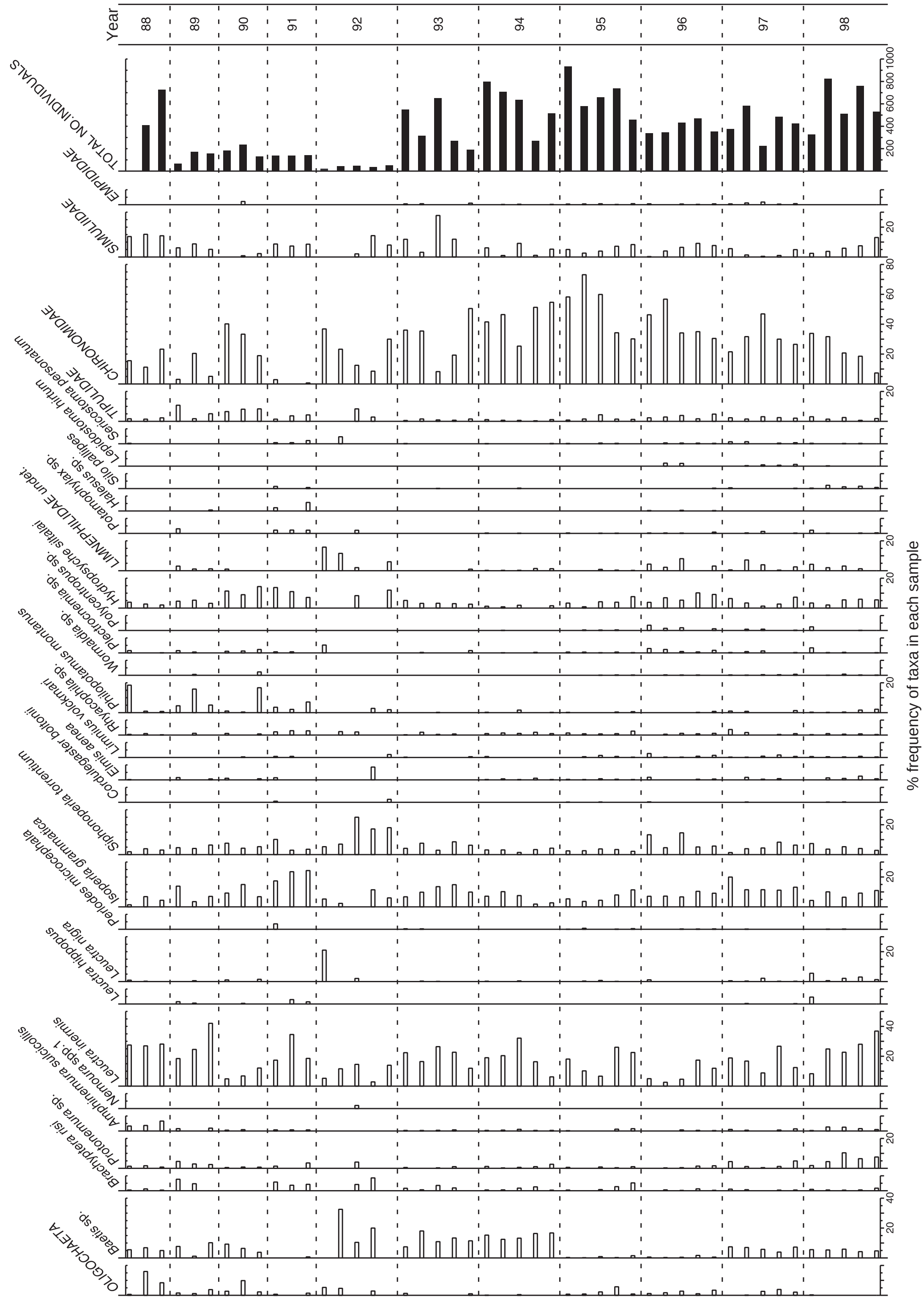
Narrator Brook: summary of epilithic diatom data (1988 - 1998)

Percentage frequency of all taxa occurring at >2% abundance in any one sample

Figure 4.14.4

Narrator Brook: summary of macroinvertebrate data (1988 - 1998)

Percentage frequency of taxa in individual samples



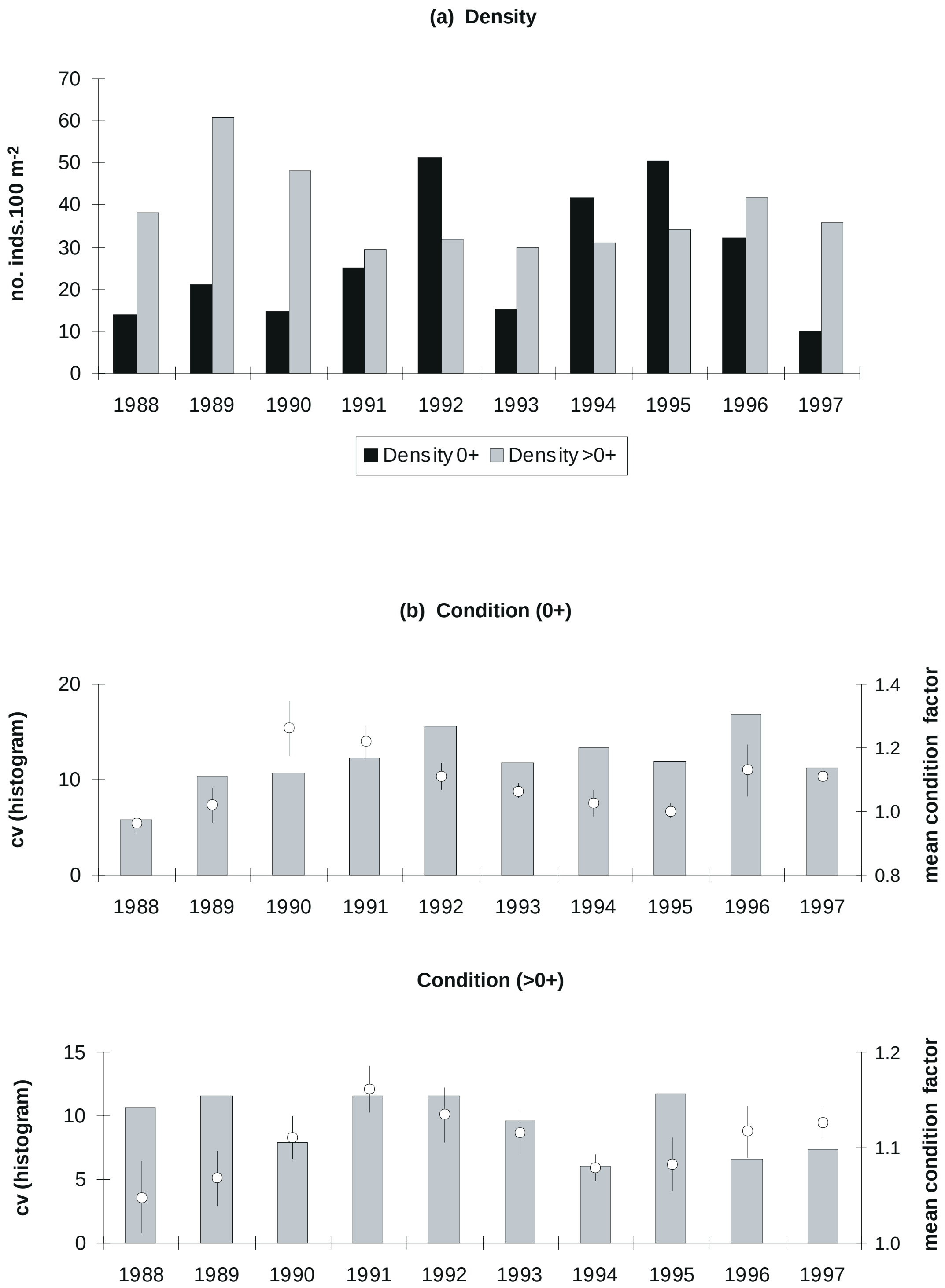
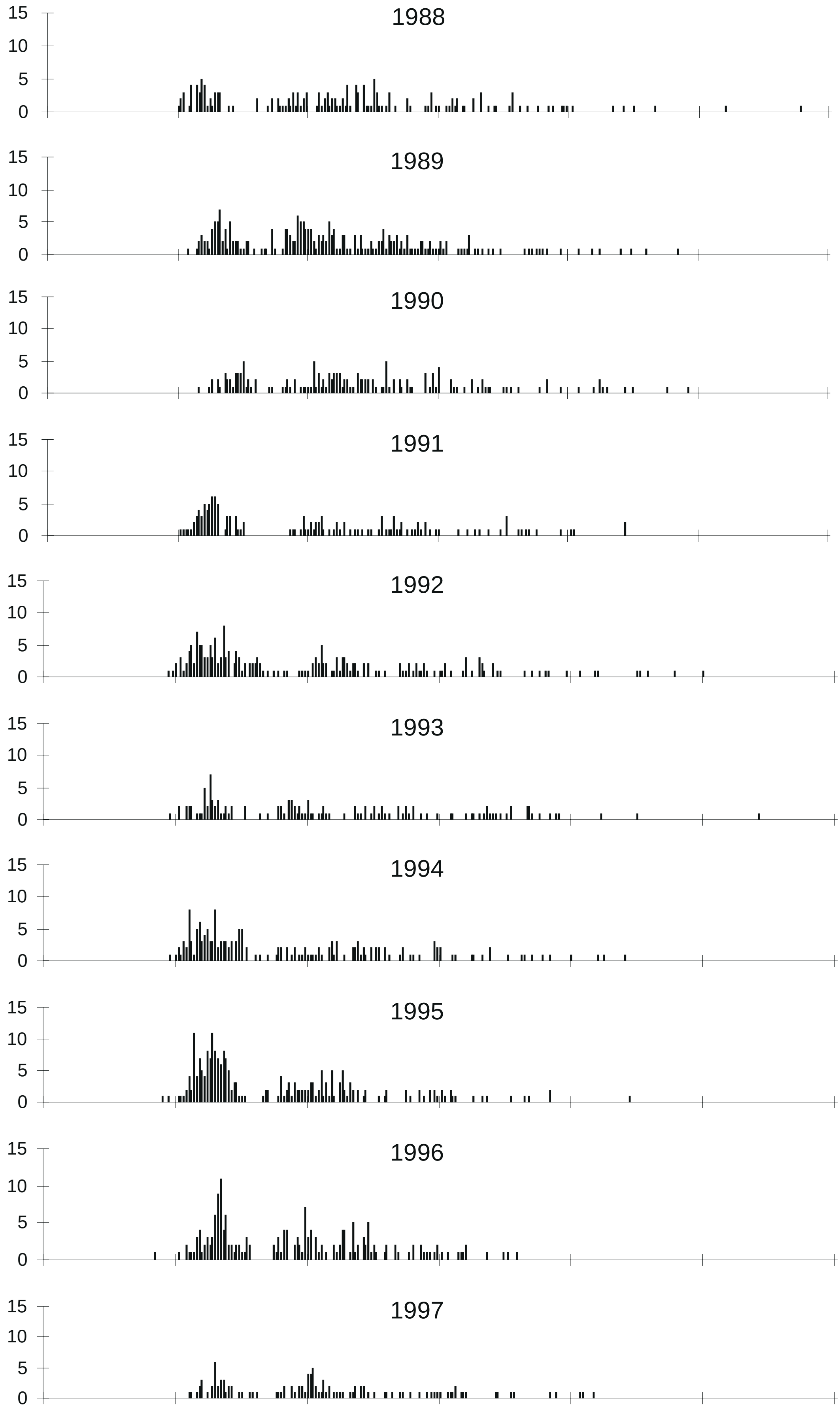


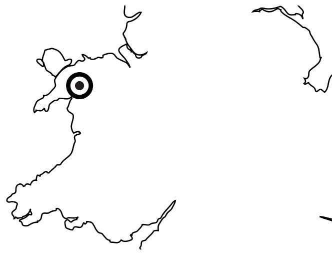
Figure 4.14.5

Narrator Brook: summary of fish data (1988 - 1997)
(a) Trout population density for 0+ and >0+ age classes (individuals 100 m^{-2})
(b) Mean condition factor (with standard deviation) of the trout population and its coefficient of variation (histogram)

Figure 4.14.6

Narrator Brook: summary of fish data (1988 - 1997)
(c) Trout length frequency summaries





4.15 Llyn Llagi

Site Review

Llyn Llagi lies at an altitude of 380 m in the Snowdonia National Park. Changes in the fossil diatom assemblage of a sediment core from the site indicate that the lake has acidified progressively from at least the mid-nineteenth century (diatom inferred pH 6.0) to around pH 4.6 by the mid 1980s (Patrick *et al.*, 1995). The uppermost levels of the sediment core suggested a slight improvement (i.e. recovery) from this time to the top of the core (1990). There has been no physical disturbance or change in the land management regime (low intensity sheep grazing) in the catchment over the last decade. Recently the site has been included in the UK Acid Deposition Monitoring Network, and

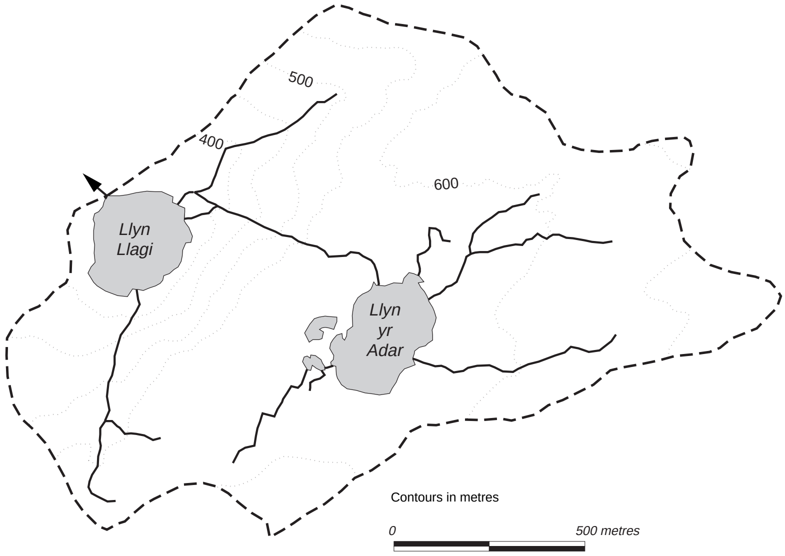


Figure 4.15.1

Llyn Llagi: catchment

Table 4.15.1

Llyn Llagi: site characteristics

Grid reference	*SH 649483*
Lake altitude	*380 m*
Maximum depth	*16.5 m*
Mean depth	*5.8 m*
Volume	*3.3 x 10^5 m^3*
Lake area	*5.67 ha*
Catchment area (excl. lake)	*157 ha*
Catchment: Lake area ratio	*27.7*
Catchment Geology	*ordivcian slates and shales, dolerite and volcanic intrusions*
Catchment Soils	*stagnopodsols, stagnohumic gleys, blanket peat*
Catchment vegetation	*moorland 100%*
Net relief	*298 m*
Mean annual rainfall	*2941 mm*
1996 deposition	
Total S	*24 kg ha^{-1} yr^{-1}*
non-marine S	*18 kg ha^{-1} yr^{-1}*
Oxidised N	*9 kg ha^{-1} yr^{-1}*
Reduced N	*18 kg ha^{-1} yr^{-1}*

Table 4.15.2

Llyn Llagi: summary of chemical determinands, July 1988 - March 1998

Determinand		Mean	Max	Min
pH		*5.34*	*6.30*	*4.78*
Alkalinity	µeq l^{-1}	*5.6*	*33.4*	*-8.0*
Ca	µeq l^{-1}	*52.5*	*94.0*	*31.0*
Mg	µeq l^{-1}	*46.7*	*75.0*	*25.0*
Na	µeq l^{-1}	*168.7*	*291.3*	*100.0*
K	µeq l^{-1}	*6.2*	*19.2*	*2.6*
SO_4	µeq l^{-1}	*61.0*	*81.3*	*39.6*
xSO_4	µeq l^{-1}	*40.6*	*67.9*	*17.1*
NO_3	µeq l^{-1}	*10.0*	*38.6*	*2.1*
Cl	µeq l^{-1}	*193.8*	*377.5*	*98.6*
Soluble Al	µg l^{-1}	*74.1*	*193.0*	*5.0*
Labile Al	µg l^{-1}	*39.7*	*159.0*	*<2.5*
Non-labile Al	µg l^{-1}	*35.6*	*80.0*	*<2.5*
DOC	mg l^{-1}	*2.4*	*5.50*	*<0.10*
Conductivity	µS cm^{-1}	*31.2*	*58.0*	*13.0*

this should allow a more thorough comparison of the temporal relationship between deposition and surface water chemistry in the catchment in future years.

Water Chemistry

(Tables 4.15.2-3, Figure 4.15.2)

Llyn Llagi is a moderately acidic site with a mean pH of 5.34 and a mean alkalinity of 6 µeq l^{-1}. Al concentrations are fairly low, with approximately equal concentrations of labile and non-labile forms. Large seasonal variations are observed for a number of determinands, with alkalinity generally becoming negative during winter. Although mean NO_3 levels are low (mean 10 µeq l^{-1}), large winter peaks have been recorded, at which times concentrations have approached those of xSO_4 (mean 41 µeq l^{-1}).

Trend analyses show that little net change has occurred in lake chemistry at this site since 1988. A trend is identified in pH, using SKT (Table 4.15.3), but as this is not accompanied by significant changes in either alkalinity or acid anions it is difficult to attribute to genuine chemical recovery. Peaks in Cl and Na during 1990-1991 are remarkably similar to those observed in the Galloway and the Lake District, supporting the hypothesis of a wide-ranging climatic influence. On the chemical evidence alone it is therefore more likely that the pH trend and cyclical variation in Ca, primarily result from climatic effects (Figure 4.15.2g) (however, see epilithic diatom Section). Non-marine sulphate rose during the early part of the record but may now have begun to decline, as in Galloway and the Lake District.

Epilithic diatoms

(Figure 4.15.3, Table 4.15.4)

The epilithic diatom assemblage of Llyn Llagi has undergone highly significant linear change, according to RDA and associated permutation test. “Sample year” can account for 17.6 % of all variance between samples while the maximum variance which can be explained by one axis in PCA is only 22.9%. The most striking change observed is the dramatic reduction in acidophilous *Tabellaria quadriseptata* (pH optima 4.9) between 1995-1996. As at Loch Grannoch there has been an abrupt change in the relative abundance of this species, although at Loch Grannoch it has become more abundant. Its decline appears to be reciprocally related to increases in species with higher pH optima including *Nitzschia perminuta* (pH optima 5.7), *Peronia fibula* (pH optima 5.3) and *Brachysira vitrea* (pH optima 5.9). Diatom inferred pH (derived from weighted averaging) shows that the species assemblage is indicative of gradually increasing pH during the decade (Figure 7.3a). Similar species changes are apparent in the sediment trap samples (Figure 4.15.6) although in these there is a steadier increase in *E.incisa.* Generally therefore, changes in both the epilithon and sediment traps are consistent with an increase in pH observed in the more recent years of monitoring and also appear to follow the

Table 4.15.3

Significant trends in chemical determinands (July 1988 -1998)

Determinand	Units	Annual trend (Regression)	Annual trend (Seasonal Kendall)
pH		*+0.049**	-

** Trend significant at $p < 0.05$; ** trend significant at $p < 0.01$; *** trend significant at $p < 0.001$*

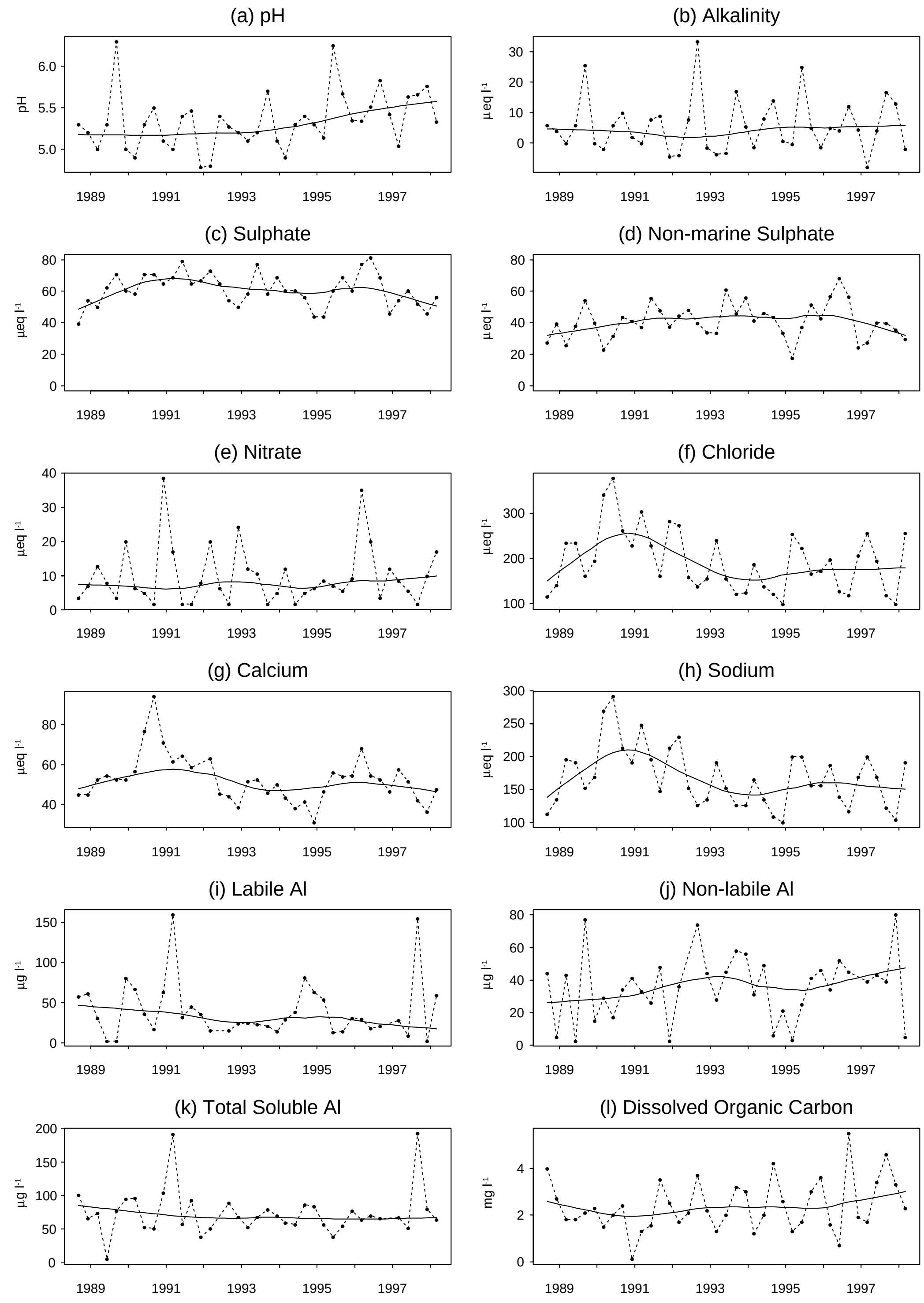


Figure 4.15.2

Llyn Llagi: summary of major chemical determinands (September 1988 - March 1998)

Smoothed line represents LOESS curve (Section 3.1.2)

Table 4.15.4

Llyn Llagi: trend statistics for epilithic diatom, macrophyte and macroinvertebrate summary data (1988 - 1998)

	Total sum of squares	Number of Taxa	Mean N_2 diversity	λ_1RDA/λ_2RDA	λ_1RDA/λ_1PCA
Epilithic diatoms	*376*	*135*	*8.0*	*1.28*	*0.77*
Macrophytes	*39.8*	*21*	*11.9*	*1.01*	*0.70*
Invertebrates	*771*	*36*	*3.0*	*0.69*	*0.46*

Variance explained (%)	within year	between years	linear trend	p unrestricted	p restricted
Epilithic diatoms	*43.4*	*56.6*	*17.6*	*<0.01*	*<0.01*
Macrophytes	*	*	*27.6*	*0.02*	*0.12*
Invertebrates	*42.0*	*58.0*	*11.5*	*<0.01*	*<0.01*

apparent recovery trend identified in the uppermost levels of the sediment core taken in 1990 (Patrick *et al.*, 1995) (Section 7.2.5). These observations provide the most convincing evidence of real biological "recovery" seen at any UKAWMN site. However, due to the clear sensitivity of the chemistry of Llyn Llagi to climatic effects, further monitoring is essential to ascertain whether these changes are sustained.

■ Macroinvertebrates

(Figure 4.15.4, Table 4.15.4)

Llyn Llagi is dominated by chironomids and the acid tolerant mayfly family, the Leptophlebiidae. The first few years were characterised by acid tolerant stoneflies (*Nemoura* spp.) and caddisflies (*Plectrocnemia* spp., *Limnephilus* spp.). The second half of the survey showed an increase in the number of Coleopterans, particularly *Oulimnius tuberculatus*. Of the Polycentropodid caddisflies, *Polycentropus* spp. was the most abundant and ocurred in all years except 1990, *Plectrocnemia* spp. was recorded in low numbers and was absent in 1998, while *Holocentropus* spp. and *Cyrnus* spp. were both recorded intermittently. The Hydroptilid caddisfly, *Oxyethira* spp. was first recorded in 1993 and was present in very high numbers in 1995. Time as a linear trend is significant at the 0.01 level according to RDA and restricted permutation test. There seems to have been a change in species composition from a community characterised by acid tolerant stoneflies in the early years to one with fewer stoneflies and some moderately acid sensitive beetles and caddisflies.

■ Fish

(Figure 4.15.5)

The outflow stream from Llyn Llagi has been electrofished since 1989. Mean trout densities are in the middle range of those found in the Network sites. Densities of 0+ trout have fluctuated over the years and overall show a pattern of decline although there is not a statistically significant linear relationship with time. Densities of >0+ fish and the mean condition factor for both age groups show no pattern over the years. The coefficient of variation of the condition factor for the >0 group is particularly elevated in 1990. The length frequency graphs show the variation in recruitment together with the subsequent impact upon the numbers of >0+ fish present in the following year.

Table 4.15.5

Llyn Llagi: relative abundance of aquatic macrophyte flora (1988 - 1997)
(see Section 3.2.3 for key to indicator values)

Abundance Taxon Year	88	89	90	91	92	93	95	97
INDICATOR SPECIES								
Myriophyllum alterniflorum[2]	1	1	1	1	1	2	1	1
Sphagnum auriculatum[4]	1	2	2	3	3	3	3	3
Juncus bulbosus[4]	0	1	1	1	1	1	2	2
OTHER SUBMERGED SPECIES								
Batrachospermum sp.	2	2	2	2	2	3	2	2
Filamentous green algae	4	5	5	5	5	5	5	5
Amblystegium sp.	1	2	0	1	2	2	2	1
Drepanocladus sp.	1	1	0	0	0	0	0	1
Fontinalis sp.	1	1	2	2	2	2	2	1
Polytrichum sp.	0	0	1	0	0	0	0	0
Rhytidiadelphus squarrosus	0	1	0	0	1	0	1	1
Marsupella emarginata	0	1	1	1	1	1	1	1
Nardia compressa	0	1	2	2	1	0	1	1
Plectocolea obovata	1	1	1	1	0	0	0	0
Scapania undulata	1	2	2	2	0	1	0	1
Isoetes echinospora	1	1	2	2	2	1	2	2
Isoetes lacustris	5	5	5	5	5	5	5	5
Littorella uniflora	2	2	3	3	3	3	3	3
Lobelia dortmanna	4	4	4	4	4	4	4	4
Subularia aquatica	0	0	0	0	0	1	0	0
Potamogeton polygonifolius	0	0	1	1	1	2	1	1
Sparganium angustifolium	1	2	2	2	2	2	2	2
EMERGENT SPECIES								
Juncus effusus	2	2	2	2	2	2	2	2
Juncus acutifloris/articulatus	5	5	5	5	5	5	5	5
TOTAL NUMBER OF SPECIES	16	20	19	19	18	18	18	20

■ Aquatic macrophytes

(Tables 4.15.4-5)

Llyn Llagi is characterised by an aquatic macroflora typical of moderately acid lakes. The submerged flora is dominated by the isoetid species, *Lobelia dortmanna*, in the shallows, and *Isoetes lacustris*, which forms a dense sward in deeper water. At the time of summer sampling, *I. lacustris* plants support a thick bloom of filamentous algae. *Littorella uniflora* occurs in association with these species but at a lower frequency. The relatively acid sensitive species *Myriophyllum alterniflorum* is limited to two locations close to stream inflows. According to survey maps, the cover of the acidophilous species *Juncus bulbosus* var. *fluitans*, which was not recorded until 1989, has since gradually increased in several littoral areas. This is surprising, given the gradual amelioration in acidity observed for Llyn Llagi, and requires further attention. *Callitriche hamulata*, which was recorded at the site by Wade in 1980 (Wade

1980), has not been seen over the monitoring period. With the exception of the increase in *J.bulbosus* var. *fluitans* there is no other evidence of floristic change over the decade and "sample year" is insignificant as a linear variable according to RDA and restricted permutation test.

Summary

Llyn Llagi has an intermediate pH, alkalinity and xSO_4 concentration, and a relatively low NO_3 concentration. Linear regression shows pH to have increased over the decade although there is no accompanying downward trend in acid anion concentration. Pronounced cyclical variations have been observed in marine ion concentrations which could account for cyclical change in Ca, and climatic effects may also have influenced the pH trend. However, changes in the relative abundance of diatom species, both in epilithon and sediment trap samples appear to follow the apparent "recovery" trend identified in the uppermost layers of a sediment core taken in 1990. These provide strong evidence that long term chemical and biological recovery from acidification is underway. Improvements have also been observed in the macroinvertebrate community. It is therefore possible that the last decade of data for Llyn Llagi demonstrate the effects of climatic variation superimposed on a longer term recovery trend. It is essential that monitoring is maintained at this site, first to determine whether recent chemical and biological improvements are sustained, and second, to see whether this apparent response at a low trophic level will eventually be accompanied by improvements further up the food chain.

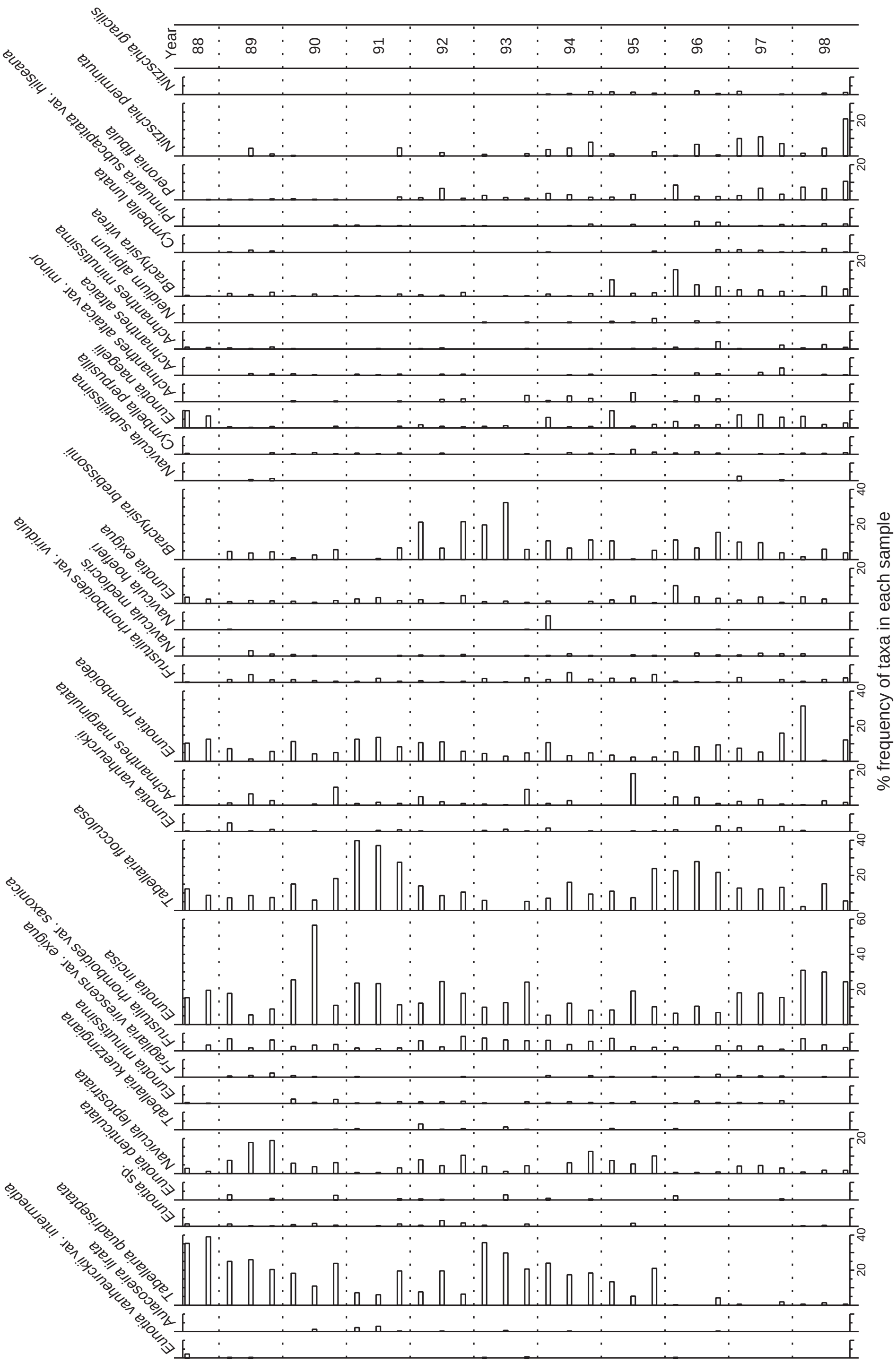


Figure 4.15.3

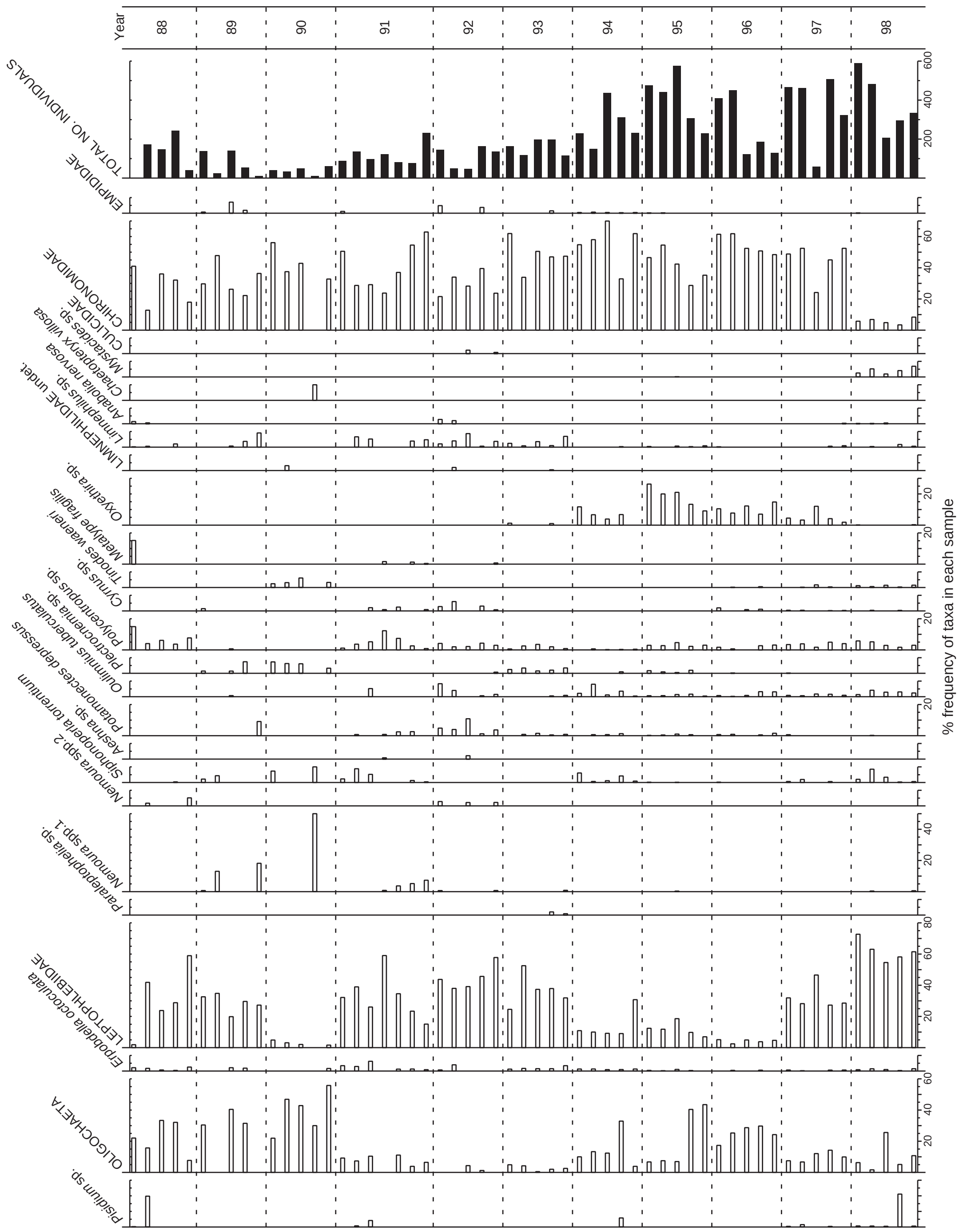
Llyn Llagi: summary of epilithic diatom data (1988 - 1998)

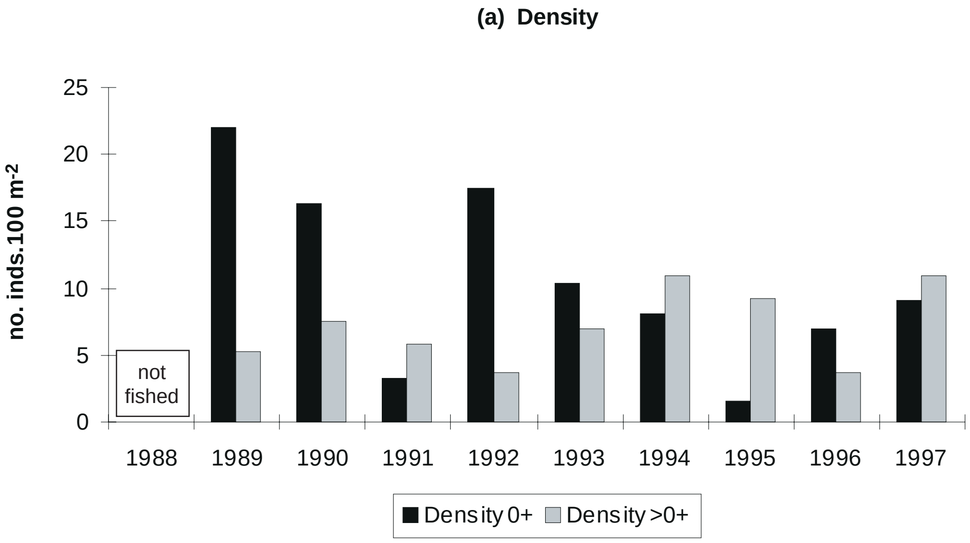
Percentage frequency of all taxa occurring at >2% abundance in any one sample

Figure 4.15.4

Llyn Llagi: summary of macroinvertebrate data (1988 - 1998)

Percentage frequency of taxa in individual samples





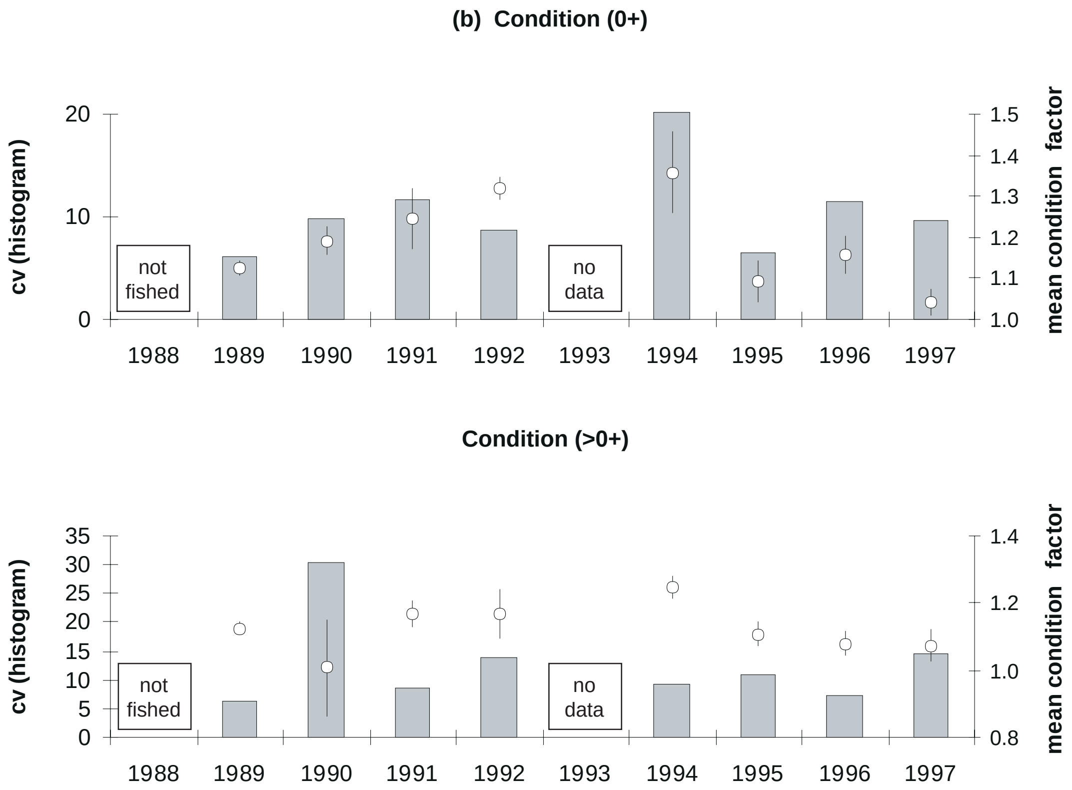


Figure 4.15.5

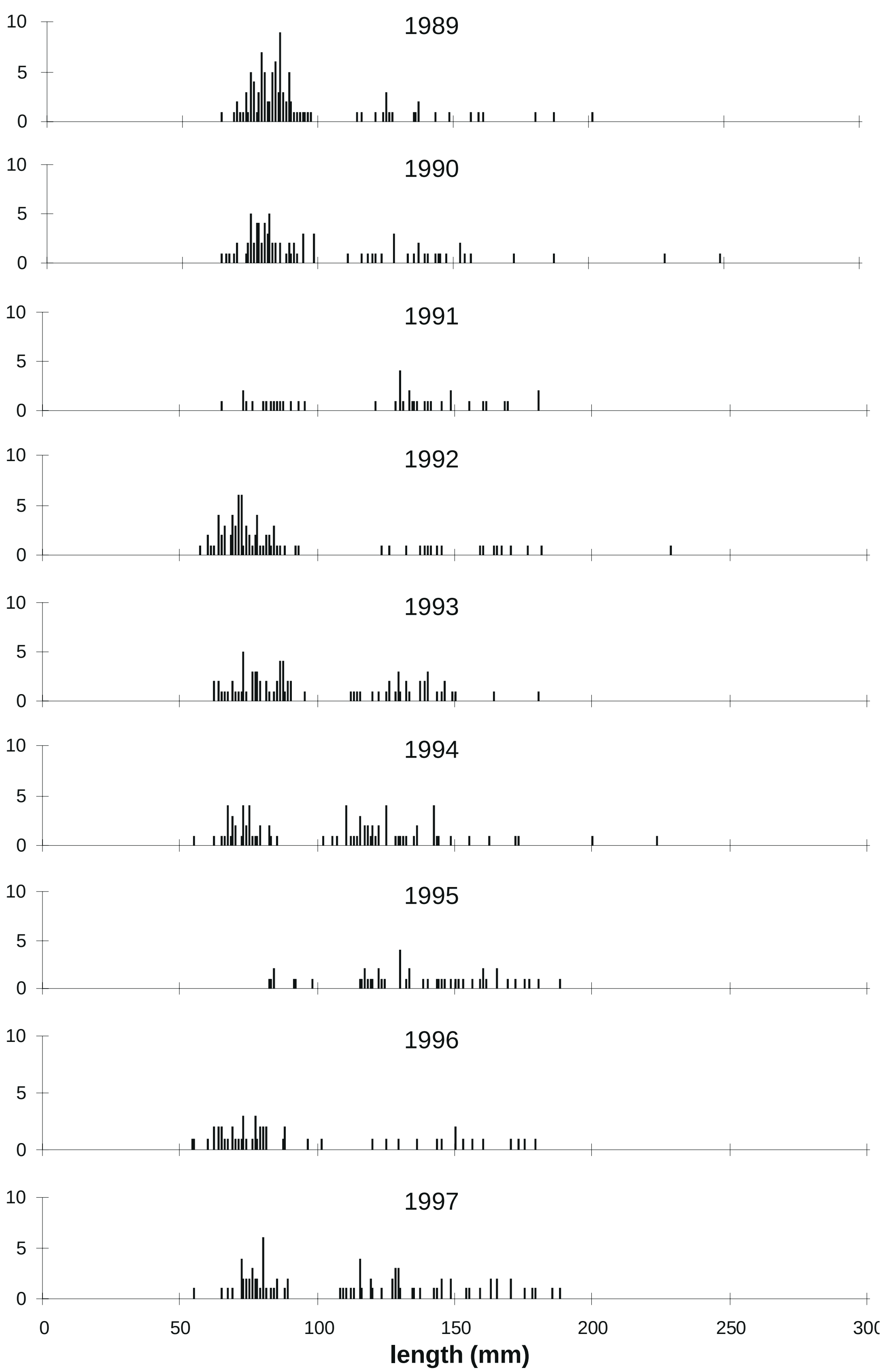
Llyn Llagi: summary of fish data (1988 - 1997)

(a) Trout population density for 0+ and >0+ age classes (individuals 100 m^{-2})

(b) Mean condition factor (with standard deviation) of the trout population and its coefficient of variation (histogram)

Figure 4.15.5

Llyn Llagi: summary of fish data (1989 - 1997)
(c) Trout length frequency summaries



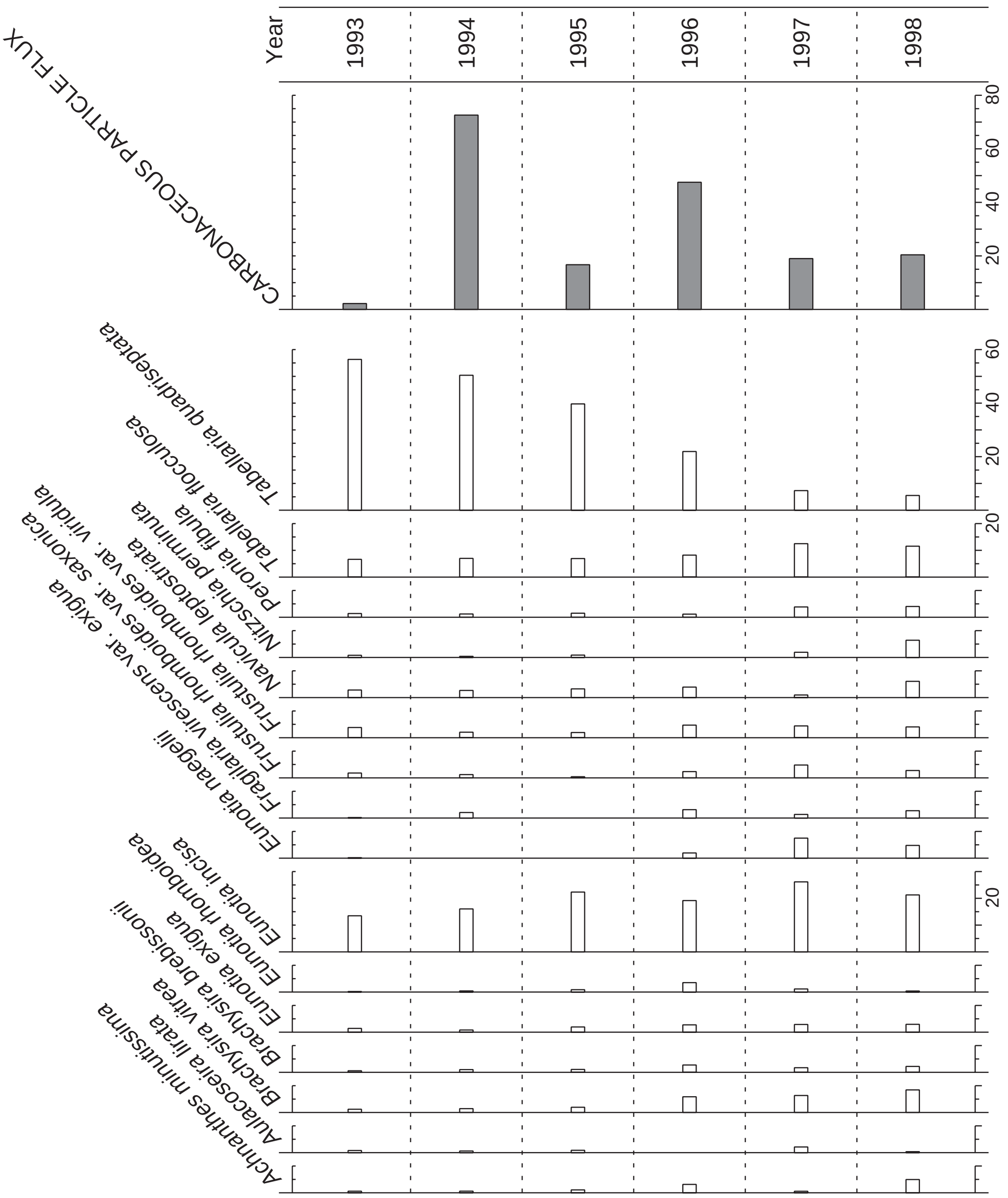
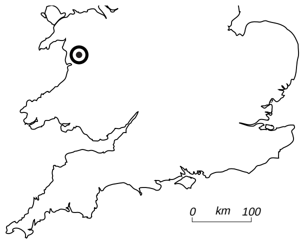


Figure 4.15.6

Llyn Llagi: summary of sediment trap data for diatoms and carbonaceous particles

Relative frequency of diatom taxa (>2% in at least one sample) at time of trap retrieval and estimated carbonaceous particle flux (no. $trap^{-1}$ day^{-1}) for preceding year



4.16 Llyn Cwm Mynach

Site Review

The catchment of Llyn Cym Mynach, in the Rhinog mountains of north Wales, includes a substantial proportion of mature forest. According to diatom based pH reconstruction, using a sediment core taken in 1990, Llyn Cwm Mynach has undergone relatively recent acidification, with pH declining from 5.8 at the turn of the century to 5.4 by the onset of the monitoring period. Over the past four years some thinning of the forest has been carried out but the overall land cover has remained unchanged. The main lake basin has been affected by the blue-green alga *Plectonema* which has blanketed large areas and out-competed submerged vascular aquatic macrophytes. As a result, the littoral strand-line has become increasingly choked

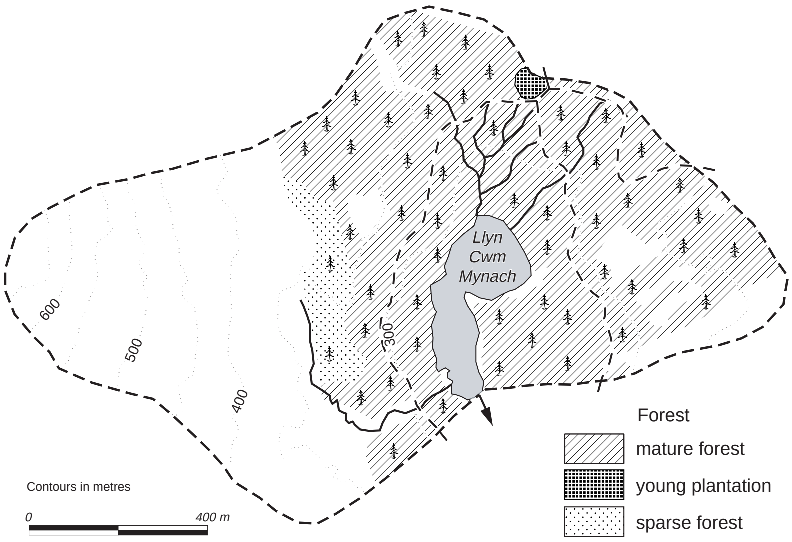


Figure 4.16.1

Llyn Cwm Mynach: catchment

Table 4.16.1

Llyn Cwm Mynach: site characteristics

Grid reference	*SH 678238*
Lake altitude	*285 m*
Maximum depth	*11.0 m*
Mean depth	*0.9 m*
Volume	*5 x 10^4 m^3*
Lake area	*5.9 ha*
Catchment area (excl. lake)	*152.5 ha*
Catchment: lake area ratio	*25.9*
Catchment Geology	*Cambrian sedimentary*
Catchment Soils	*blanket peats, acid rankers*
Catchment vegetation	*conifers 55%, moorland 45%*
Net relief	*395 m*
Mean annual rainfall	*2197 mm*
1996 deposition	
Total S	*19 kg ha^{-1} yr^{-1}*
non-marine S	*14 kg ha^{-1} yr^{-1}*
Oxidised N	*7 kg ha^{-1} yr^{-1}*
Reduced N	*13 kg ha^{-1} yr^{-1}*

Table 4.16.2

Llyn Cwm Mynach: summary of chemical determinands, July 1988 - March 1998

Determinand		Mean	Max	Min
pH		*5.37*	*6.30*	*4.70*
Alkalinity	μeq l^{-1}	*4.6*	*34.4*	*-21.0*
Ca	μeq l^{-1}	*70.0*	*128.0*	*21.5*
Mg	μeq l^{-1}	*63.3*	*100.0*	*33.3*
Na	μeq l^{-1}	*268.3*	*404.3*	*173.9*
K	μeq l^{-1}	*5.6*	*9.7*	*2.6*
SO_4	μeq l^{-1}	*86.0*	*154.2*	*58.3*
xSO_4	μeq l^{-1}	*54.2*	*110.4*	*32.9*
NO_3	μeq l^{-1}	*10.0*	*30.7*	*2.1*
Cl	μeq l^{-1}	*304.2*	*518.3*	*143.7*
Soluble Al	μg l^{-1}	*117.3*	*378.0*	*5.0*
Labile Al	μg l^{-1}	*65.2*	*291.0*	*<2.5*
Non-labile Al	μg l^{-1}	*52.3*	*158.0*	*<2.5*
DOC	mg l^{-1}	*2.6*	*10.7*	*<0.1*
Conductivity	μS cm^{-1}	*46.0*	*72.0*	*24.0*

by dead vegetation and the availability of macroinvertebrate littoral habitats may have been affected.

Water Chemistry

(Figure 4.16.2, Tables 4.16.2-3)

This is a moderately acidic site, with a mean pH and alkalinity of 5.37 and 5 μeq l^{-1} respectively. Alkalinity frequently becomes negative during winter, and soluble Al concentrations are relatively high (mean 117 μg l^{-1}, maximum 348 μg l^{-1}), with the labile fraction on average slightly exceeding the non-labile fraction. Mean xSO_4 is 54 μeq l^{-1}, significantly higher than at Llyn Llagi in the same region, and this possibly results from the enhancement of deposition by forestry. Despite these differences the acidity of the two sites is very similar, since Ca concentrations are also higher at Cwm Mynach, implying that this catchment has a greater base cation weathering supply. NO_3 concentrations are low, with a mean of 10 μeq l^{-1}, although concentrations are higher during the acidic winter period.

As at Llyn Llagi, this site exhibits few clear trends over the last ten years (Table 4.16.3). The most notable feature of the time series (Figure 4.16.2) is again a very strong cyclical variation in Cl, Na and perhaps also Ca. An apparent decrease in Cl identified by regression analysis is certainly a consequence of this variation. Non-marine SO_4 appears to have risen to a peak in the mid-1990s, and subsequently to have declined (Figure 4.16.2d). An increasing trend is identified by both regression and SKT for non-labile Al, which is consistent with increases observed elsewhere, although it is not matched by a rising trend in DOC. The LOESS curve for DOC (Figure 4.16.2l) does suggest a small increase over the decade, but this is masked to some extent by a very high, and possibly anomalous, DOC value early in the record.

Epilithic diatoms

(Figure 4.16.3, Table 4.16.4)

Epilithic diatom species representation has been relatively stable at Llyn Cwm Mynach compared to other sites in the Network. However, subtle shifts in the proportions of some species have occurred and a time trend is significant at the 0.01 level according to RDA and associated permutation test. The clearest changes have been a decline in *Eunotia incisa* (pH optima 5.1) from maximum abundances in the early 1990s, and increases in *Navicula leptostriata* (pH optima 5.1), *N. tenuicephala* (pH optima 5.3) and *Brachysira vitrea* (pH optima 5.9). These changes are indicative of a small increase in pH at this site and although not strongly supported by water chemistry data, there is evidence for a general increase in pH since 1993. Diatom inferred pH (derived from weighted averaging) illustrates the gradual shift to species with higher pH optima (Figure 7.3a).

Table 4.16.3

Significant trends in chemical determinands (July 1988 - March 1998)

Determinand	Units	Annual trend (Regression)	Annual trend (Seasonal Kendall)
Cl	μeq l^{-1}	*-10.1**	-
Na	μeq l^{-1}	*-7.0**	-
Ca	μeq l^{-1}	*-2.45**	-
Non-labile Al	μg l^{-1}	*+4.77**	*+5.25***

** Trend significant at $p < 0.05$; ** trend significant at $p < 0.01$; *** trend significant at $p < 0.001$*

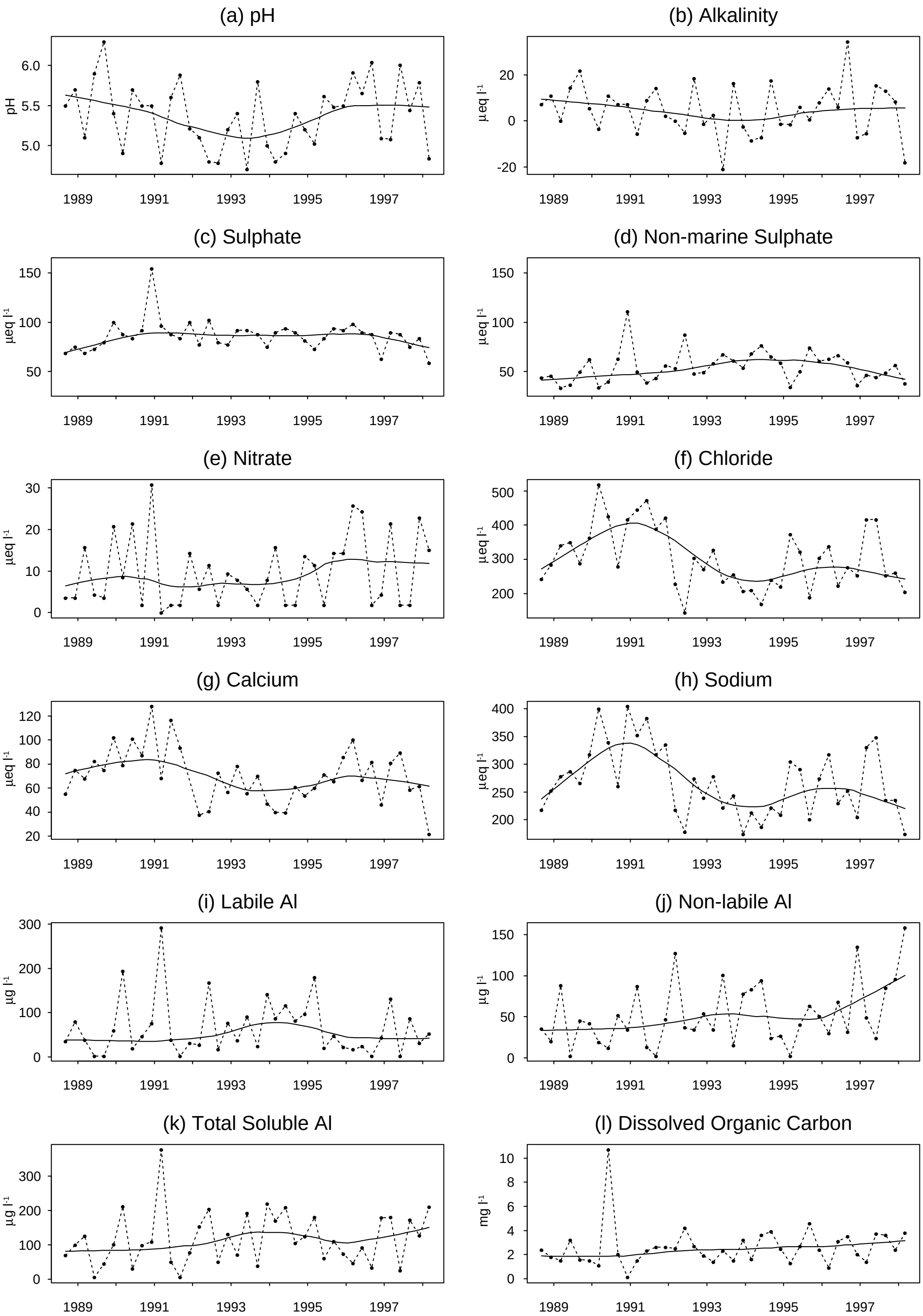


Figure 4.16.2

Llyn Cwm Mynach: summary of major chemical determinands (September 1988 - March 1998)

Smoothed line represents LOESS curve (Section 3.1.2)

Table 4.16.4

Llyn Cwm Mynach: trend statistics for epilithic diatom, macrophyte and macroinvertebrate summary data (1988 - 1998)

	Total sum of squares	Number of Taxa	Mean N_2 diversity	λ_1RDA/λ_2RDA	λ_1RDA/λ_1PCA
Epilithic diatoms	*418*	*123*	*10.1*	*0.68*	*0.53*
Macrophytes	*43*	*28*	*17.7*	*1.02*	*0.74*
Invertebrates	*832*	*40*	*2.5*	*0.86*	*0.55*

Variance explained (%)	within year	between years	linear trend	p unrestricted	p restricted
Epilithic diatoms	*55.2*	*44.8*	*13.0*	*<0.01*	*<0.01*
Macrophytes	*	*	*32.2*	*0.03*	*0.07*
Invertebrates	*57.1*	*42.9*	*12.1*	*<0.01*	*<0.01*

■ Macroinvertebrates

(Figure 4.16.4, Table 4.16.4)

Llyn Cwm Mynach has a relatively species poor fauna dominated by acid tolerant mayflies (Leptophlebiidae) and chironomids. Leptophlebid numbers have declined over the monitoring period, while chironomid numbers appear to have increased. The stonefly community, which is composed of acid tolerant detritivores (*Nemoura* spp.), has become impoverished in recent years. Of the caddisflies, *Plectrocnemia* spp. and *Polycentropus* spp. were both numerous in the first half of the survey but declined after 1993. *Holocentropus* spp. appeared in 1995. Other characteristic species include several corixids, of which *Sigara scotti* is the most numerous, and the relatively acid tolerant alderfly *Sialis lutaria*, which was most abundant in 1997. Time as a linear trend is significant at the 0.01 level using RDA and associated permutation test. The time trend appears to be driven by the decrease in Leptophlebid mayflies and disappearance of some other acid tolerant species. These species however have not been replaced by acid sensitive ones and it should be noted that this site is one of only three in the Network where species richness has declined over the decade. At the other two (Loch Grannoch and Lochnagar), there is evidence for a recent increase in acidity, but similar chemical change has not been experienced here. However, parts of the littoral zone of Llyn Cwm Mynach have become progressively inundated with decaying plant matter (see aquatic macrophyte section). These alterations in littoral habitat and, possibly, food supply, could account for some of the observed changes.

■ Fish

(Figure 4.16.5)

The outflow stream from Llyn Cwm Mynach has been electrofished since 1989. Mean trout densities are the fifth highest found in the Network. Mean population levels of 0+ trout declined between 1989 to 1994, peaked in 1995 and 1996 and were again reduced in 1997 when recruitment was the lowest observed in the nine years of monitoring. Densities of >0+ group have shown a general increase since 1990. Due to problems with weighing fish in 1989 and 1993 insufficient data are available for condition factor trend analysis. Mean condition factor of both age groups was highly variable in the early years of monitoring but has remained relatively constant for the past three years.

Table 4.16.5

Llyn Cwm Mynach: relative abundance of aquatic macrophyte flora (1988 - 1997)
(see Section 3.2.3 for key to indicator values)

Abundance Taxon Year	88	89	90	91	92	93	95	97
INDICATOR SPECIES								
Nitella flexilis[1]	1	0	0	0	0	0	0	0
Myriophyllum alterniflorum[2]	3	3	3	3	3	3	2	2
Utricularia sp.[2]	3	3	4	4	4	4	4	4
Plectonema sp.[4]	2	2	3	3	3	4	4	4
Drepanocladus fluitans[4]	0	1	0	0	0	0	0	1
Sphagnum auriculatum[4]	2	3	3	3	3	3	3	3
Juncus bulbosus var. *fluitans*[4]	5	5	5	5	5	5	4	4
OTHER SUBMERGED SPECIES								
Batrachospermum sp.	1	1	2	3	3	3	3	2
Filamentous green algae	3	4	4	4	4	3	4	2
Amblystegium sp.	1	0	0	0	0	0	0	0
Fontinalis sp.	1	0	0	0	0	0	0	0
Marsupella emarginata	1	0	0	0	0	0	0	0
Nardia compressa	0	0	0	0	0	2	1	0
Scapania undulata	0	0	0	0	0		1	0
Littorella uniflora	2	2	2	2	2	2	2	2
Lobelia dortmanna	2	2	3	3	3	3	2	2
Nuphar lutea	3	3	3	3	3	2	3	2
Nymphaea alba	3	3	3	3	3	2	3	2
Glyceria fluitans	1	1	1	1	1	0	0	1
Potamogeton berchtoldii	1	1	0	0	0	0	0	1
Potamogeton natans	2	2	2	2	2	3	2	2
Potamogeton polygonifolius	1	2	2	2	2	1	1	1
EMERGENT SPECIES								
Equisetum fluviatile	4	4	4	4	4	4	4	4
Hydrocotyle vulgaris	1	1	2	2	2	2	2	2
Menyanthes trifoliata	2	2	2	2	2	2	2	2
Ranunculus flammula	2	2	2	2	2	2	2	2
Carex rostrata	2	2	3	3	3	3	3	3
Eleocharis palustris	1	1	1	1	1	0	1	1
Juncus effusus	2	2	4	4	4	4	4	4
Juncus acutifloris/articulatus	3	3	3	3	3	3	3	3
Scirpus lacustris ssp. *lacustris*	1	1	1	1	1	1	1	1
TOTAL NUMBER OF SPECIES	28	25	23	23	23	22	24	23

Aquatic macrophytes

(Tables 4.16.4-5)

The oligotrophic macrophyte flora of the main basin of Llyn Cwm Mynach has been affected by the increase in the cover of the mat forming blue-green alga, *Plectonema* sp., described in the site review, although no species seems to have been lost completely as a result. The development of blue-green algal mats in acidifying lakes has been described for Scandinavia and the United States (e.g. Hendrey & Vertucci, 1980) but there is no evidence for this in other UKAWMN lakes, and the reasons for its recent expansion in Llyn Cwm Mynach are not understood. Plants which grow in deeper water locations, such as *Juncus bulbosus* var. *fluitans* and *Myriophyllum alterniflorum* appear to have been directly out-competed by the alga, while the littoral habitat of *L. dortmanna* has been reduced as a result of the accumulation of decaying plant material (mainly composed of *J. bulbosus*) originating from the deeper water. A small specimen of the acid sensitive charophyte *Nitella flexilis* was recovered from the site in the first year of monitoring but this species has not been recorded since, and this suggests that the lake was still in the process of acidifying around the onset of monitoring in 1988. *Potamogeton berchtoldii*, which was considered to have been lost after the first five years, has more recently been recorded again. There is no evidence of floristic changes in the shallow basin which leads to the outflow and overall RDA shows “sample year” to be insignificant as a linear variable in explaining changes in the DAFOR abundance data.

Summary

Llyn Cwm Mynach is a moderately acidic site, at which likely enhancement of acid deposition by forestry (Section 5.5) is partly ameliorated by a relatively high internal base cation supply. Few clear changes in lake chemistry have taken place during the last ten years. Fluctuations in marine ion concentrations have been the major cause of chemical variation. This is possibly the main influence on the linear change in the epilithic diatom community which is indicative of gradually improving pH. Vascular aquatic macrophyte cover has been reduced as a result of an increase in a mat forming blue-green alga, and the subsequent increase in dead plant material along the shoreline may have influenced the habitat and food supply of macroinvertebrate species.

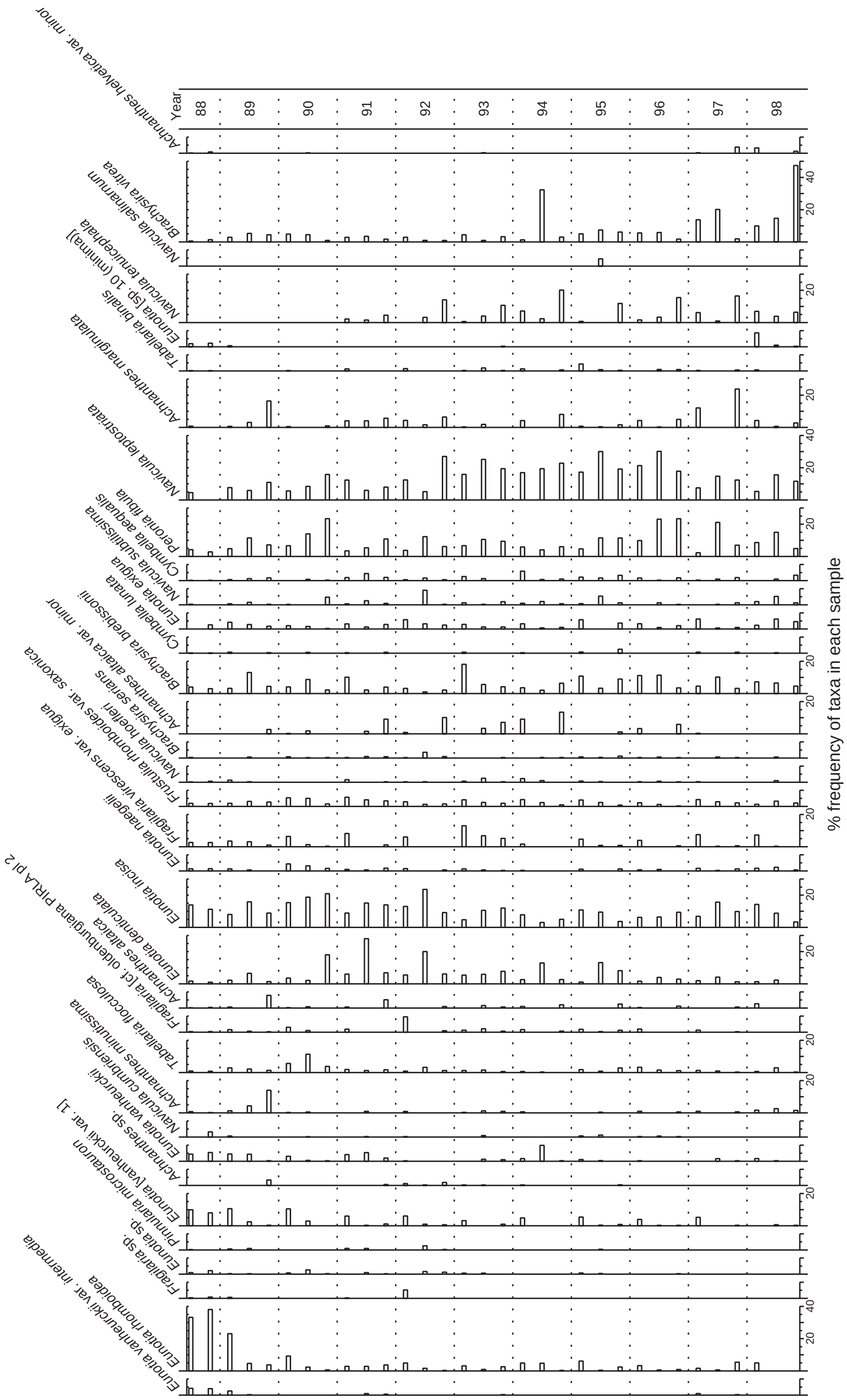


Figure 4.16.3

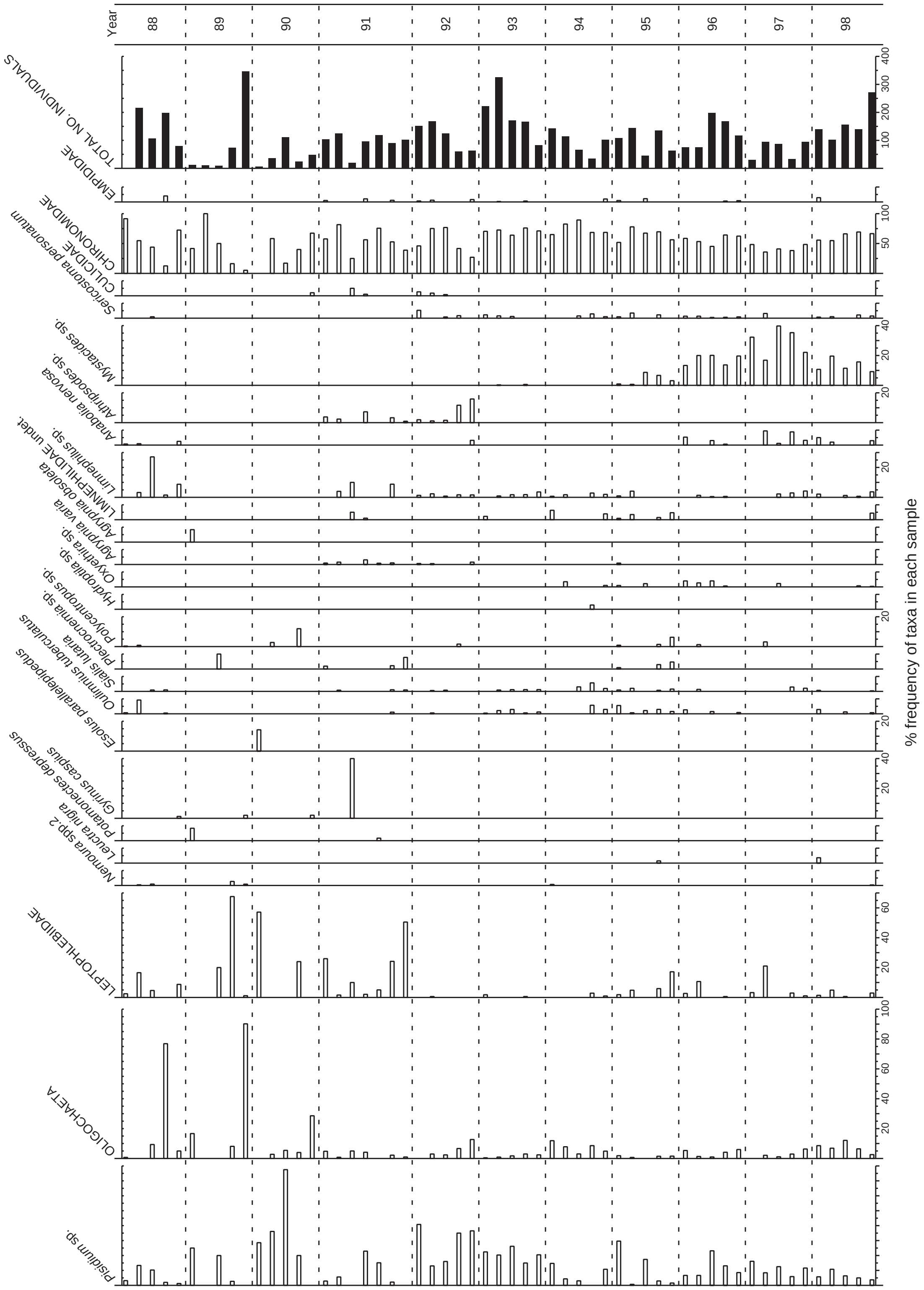
Llyn Cwm Mynach: summary of epilithic diatom data (1988 - 1998)

Percentage frequency of all taxa occurring at >2% abundance in any one sample

Figure 4.16.4

Llyn Cwm Mynach: summary of macroinvertebrate data (1988 - 1998)

Percentage frequency of taxa in individual samples



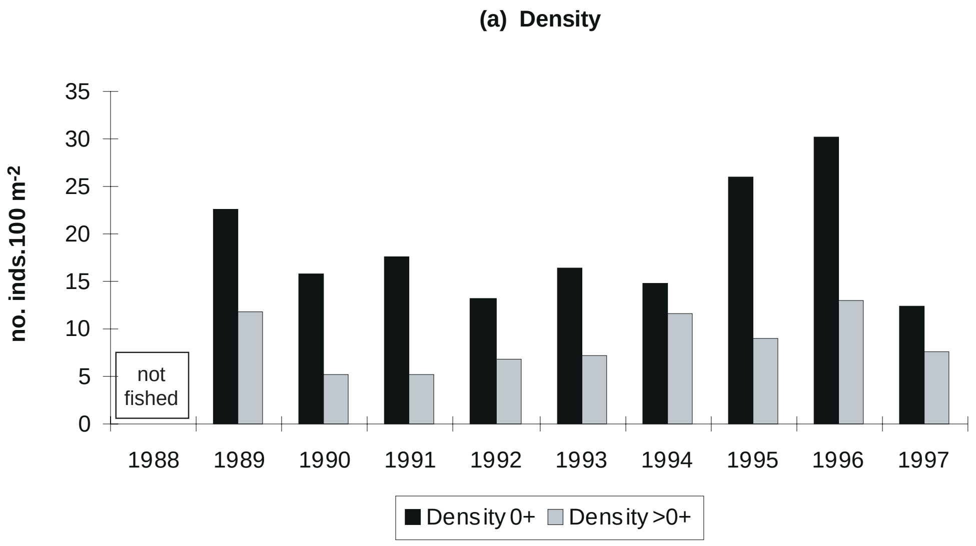


Figure 4.16.5

Llyn Cwm Mynach: summary of fish data (1989 - 1997)

(a) Trout population density for 0+ and >0+ age classes (individuals 100 m^{-2})

(b) Mean condition factor (with standard deviation) of the trout population and its coefficient of variation (histogram)

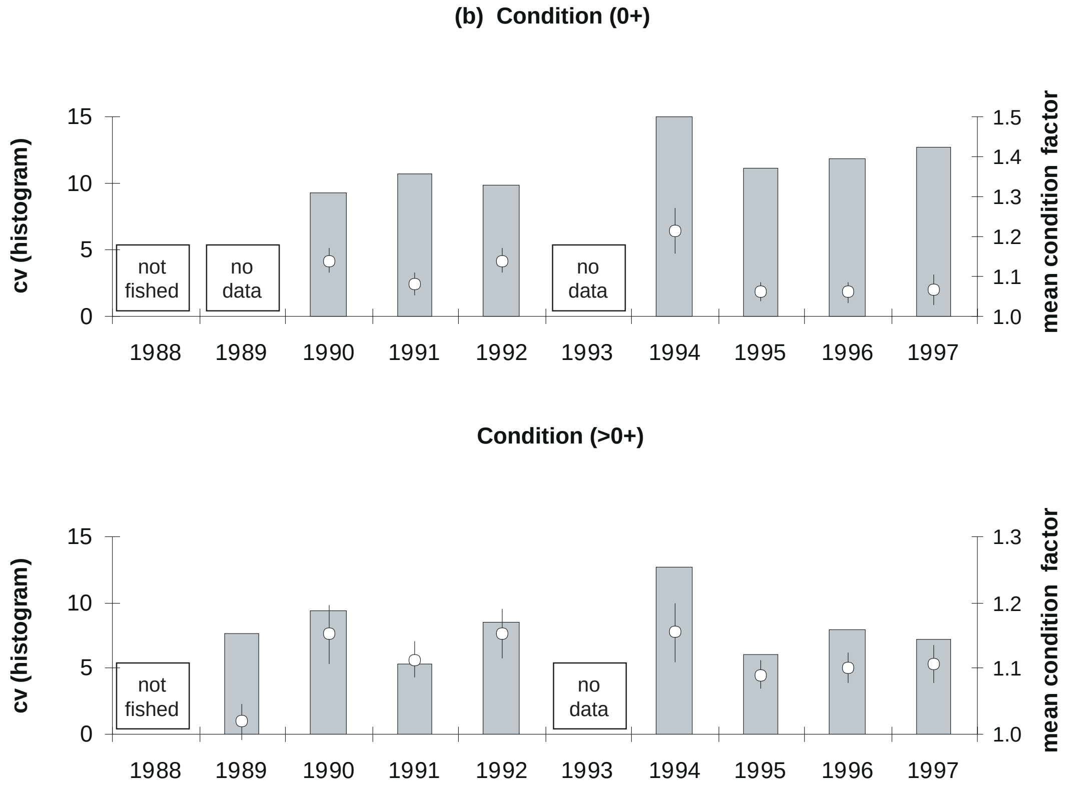
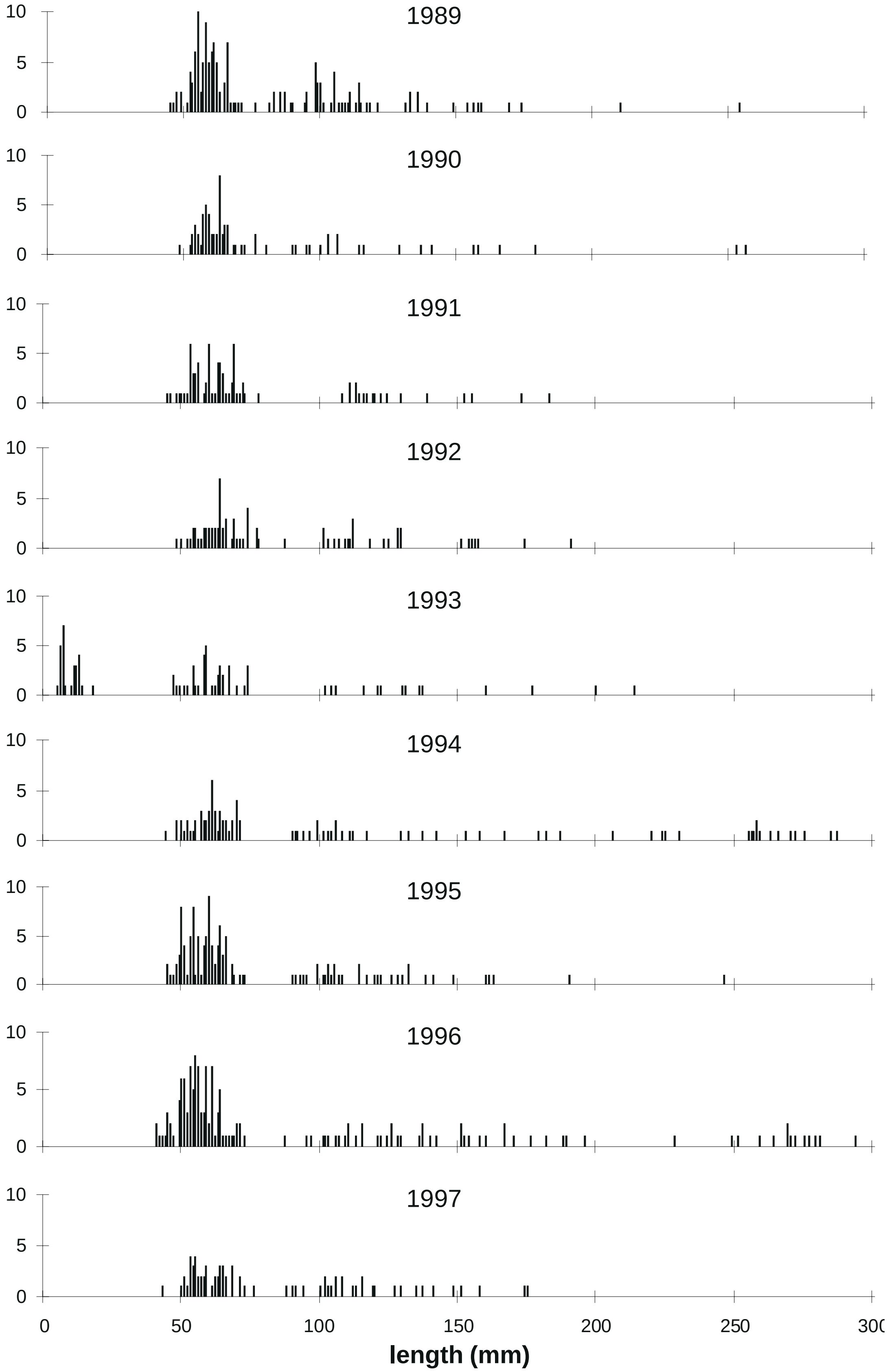


Figure 4.16.5

Llyn Cwm Mynach: summary of fish data (1989 - 1997)
(c) Trout length frequency summaries



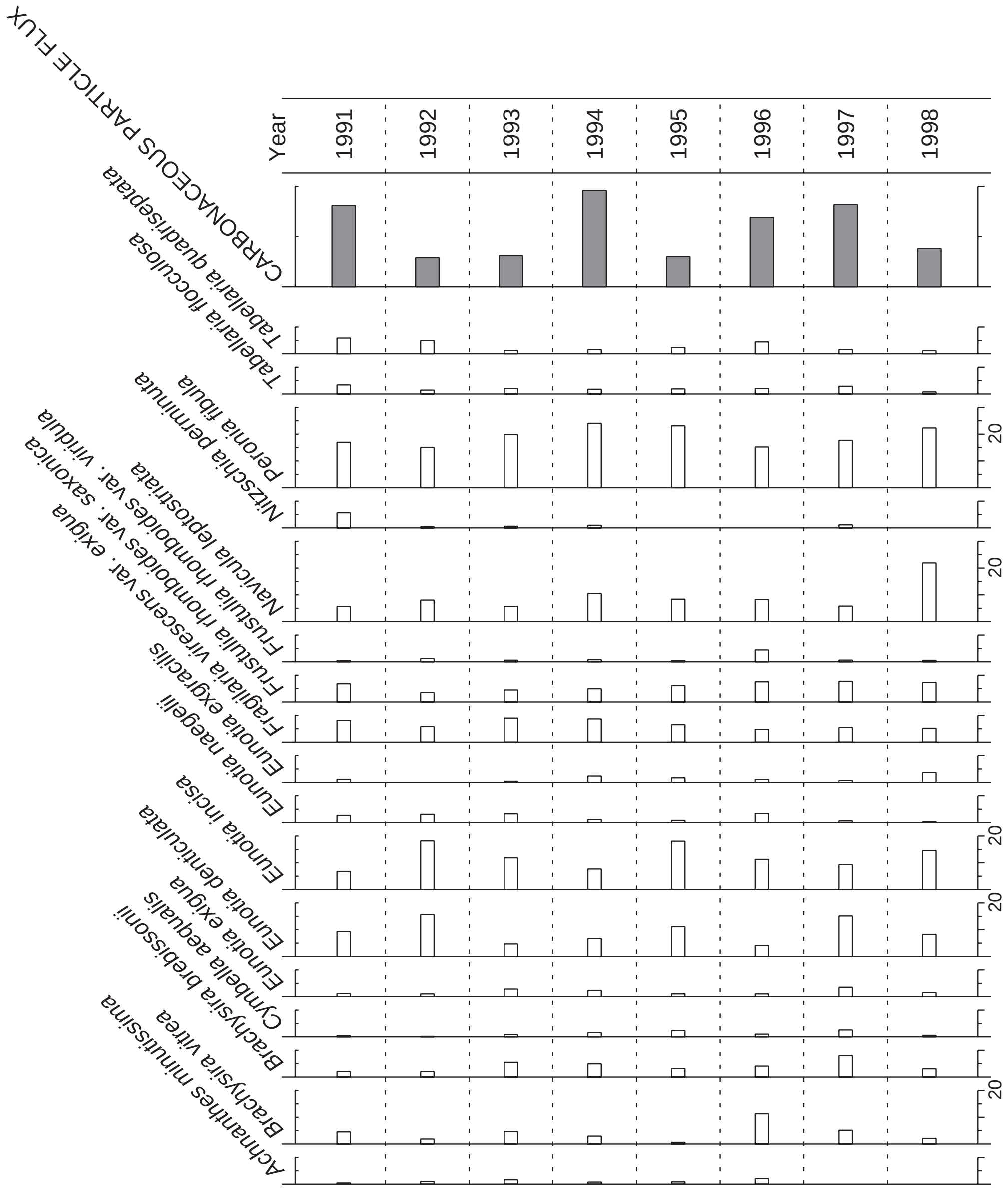
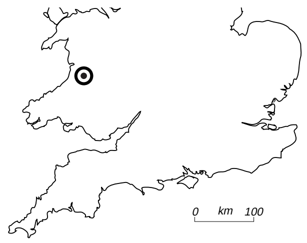


Figure 4.16.5

Llyn Cwm Mynach: summary of sediment trap data for diatoms and carbonaceous particles

Relative frequency of diatom taxa (>2% in at least one sample) at time of trap retrieval and estimated carbonaceous particle flux (no. trap^{-1} day^{-1}) for preceding year



4.17 Afon Hafren

Site Review

The hydrology and ecology of the Afon Hafren, a headwater of the River Severn at Plynlimon, has received considerable scientific attention since the early 1980s due to its inclusion in Plynlimon catchment studies (e.g. Neal *et al*. 1997, Gee & Smith, 1997). Over the course of the last decade the coniferous forest within the catchment has been thinned, but clear-felling, which is now underway, had not been instigated within the period of analysis covered by this report.

Water Chemistry

(Figure 4.17.2, Tables 4.17.2-3)

The Afon Hafren has a mean pH of 5.37 and a mean alkalinity of 6 µeq l^{-1}. Mean xSO_4 (60 µeq l^{-1}) is high for the region, probably due to forest

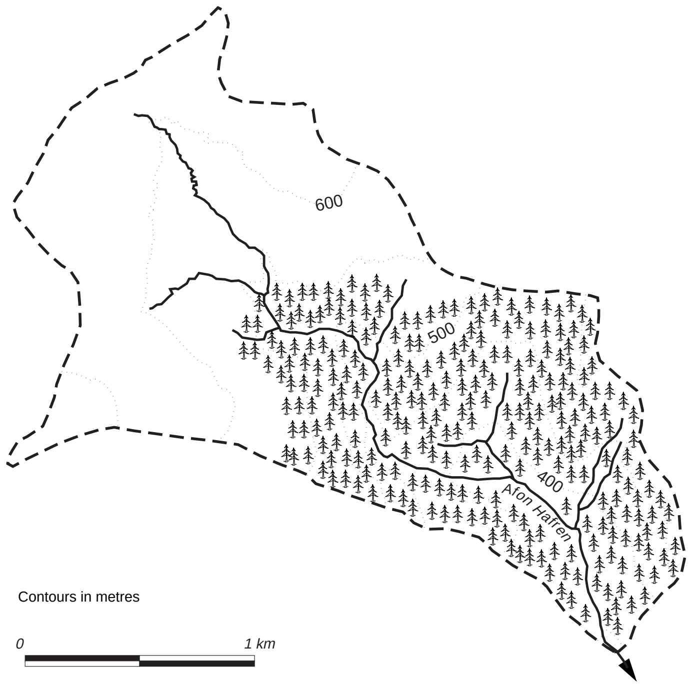


Figure 4.17.1

Afon Hafren: catchment

Table 4.17.1

Afon Hafren: site characteristics

Grid reference	*SH 844876*
Catchment area	*358 ha*
Minimum Catchment altitude	*355 m*
Maximum Catchment altitude	*690 m*
Catchment Geology	*Ordovician and silurian sedimentary*
Catchment Soils	*Podsols and organic peats*
Catchment vegetation	*conifers 50%, moorland 50%*
Mean annual rainfall	*2468 mm*
1996 deposition	
Total S	*30 kg ha^{-1} yr^{-1}*
non-marine S	*20 kg ha^{-1} yr^{-1}*
Oxidised N	*10 kg ha^{-1} yr^{-1}*
Reduced N	*17 kg ha^{-1} yr^{-1}*

Table 4.17.2

Afon Hafren: summary of chemical determinands, July 1988 - March 1998

Determinand		Mean	Max	Min
pH		*5.37*	*6.60*	*4.31*
Alkalinity	µeq l^{-1}	*6.0*	*75.6*	*-42.0*
Ca	µeq l^{-1}	*45.0*	*102.5*	*7.0*
Mg	µeq l^{-1}	*65.8*	*91.7*	*41.7*
Na	µeq l^{-1}	*191.7*	*304.3*	*134.8*
K	µeq l^{-1}	*5.9*	*15.4*	*2.6*
SO_4	µeq l^{-1}	*81.9*	*139.6*	*58.3*
xSO_4	µeq l^{-1}	*60.0*	*113.3*	*35.0*
NO_3	µeq l^{-1}	*20.7*	*62.9*	*<1.4*
Cl	µeq l^{-1}	*209.3*	*349.3*	*152.1*
Soluble Al	µg l^{-1}	*172.5*	*550.0*	*5.0*
Labile Al	µg l^{-1}	*99.1*	*372.0*	*<2.5*
Non-labile Al	µg l^{-1}	*74.7*	*245.0*	*<2.5*
DOC	mg l^{-1}	*1.9*	*8.1*	*<0.1*
Conductivity	µS cm^{-1}	*38.1*	*112.0*	*20.0*

deposition enhancement, and NO_3 concentrations (mean 21 μeq l^{-1}) are also the highest among the Welsh UKAWMN sites. The site has a low buffering capacity, with a mean Ca concentration of 45 μeq l^{-1}, and experiences severe episodic acidification with recorded pH and alkalinity minima of 4.31 and -42 μeq l^{-1} respectively.

Significant declining trends are observed using linear regression, for Cl, Na, Mg and Ca (Table 4.17.3). However, inspection of time series (Figure 4.17.2) suggests that these can all be linked to the same marine ion cycles that have already been described at many other sites. The 1991 peak appears more subdued than at the north Wales lakes, although this is partly due to the large episodic fluctuations superimposed on the longer term variation. There are no clear trends in pH, alkalinity or NO_3, but as at the north Wales lakes xSO_4 appears to have decreased following a peak in the mid-1990s (Figure 4.17.2d). A significant upward trend is identified for DOC using SKT, although this does not appear particularly strong (Figure 4.17.2l). The estimated increase of 0.67 mg l^{-1} over the ten years is less than at most other sites in the Network where DOC is rising.

A previous trend analysis for the Hafren, for the period 1983-1993, has been presented by Robson & Neal (1996). They also found few significant trends, with no clear changes in acidity, xSO_4 or NO_3. However, DOC was found to have increased by an estimated 0.7 mg l^{-1} over the ten years, which is extremely close to the value obtained in the present analysis. Longer term data for the Hafren are discussed in Chapter 6.

Epilithic diatoms

(Figure 4.17.3, Table 4.17.4)

Typically, for stream sites in the Network, epilithic diatom species relative abundance varies substantially between years. *Eunotia exigua* (pH optima 5.1) is dominant in nearly all samples, reflecting the extremely acidic conditions of this site. However, in 1990 *Achnanthes helvetica* var. *minor* (pH optima 5.4) was more abundant. Since 1990 the relative frequency of *E. exigua* has increased, and recent years have also seen a small increase in *Tabellaria flocculosa* (pH optima 5.4). These changes with time are significant at the 0.01 level according to RDA and associated restricted permutation test. Interesting parallels are apparent between the diatom flora and its observed inter-annual variation at this site and that of the Afon Gwy (see section 4.18). Unlike the majority of stream sites, variation in summer rainfall and the associated flow regime does not appear to have had a strong influence on species composition.

Table 4.17.3

Significant trends in chemical determinands (July 1988 - March 1998)

Determinand	Units	Annual trend (Regression)	Annual trend (Seasonal Kendall)
Cl	μeq l^{-1}	*-2.93**	-
Na	μeq l^{-1}	*-2.87****	*-2.91**
Mg	μeq l^{-1}	*-0.58**	-
Ca	μeq l^{-1}	*-1.05***	-
DOC	mg l^{-1}	*+0.07**	-

** Trend significant at $p < 0.05$; ** trend significant at $p < 0.01$; *** trend significant at $p < 0.001$*

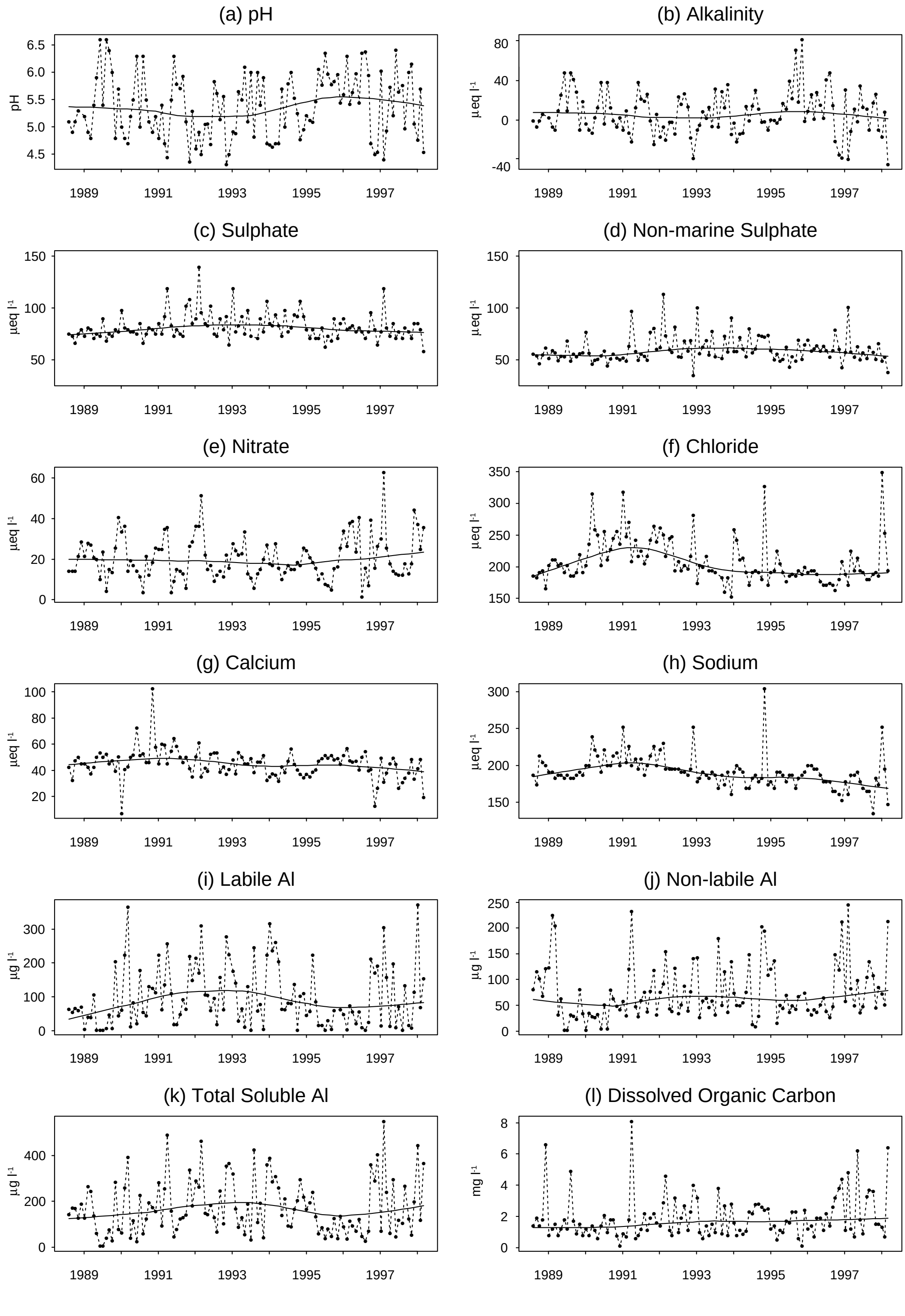


Figure 4.17.2

Afon Hafren: summary of major chemical determinands (September 1989 - March 1997)

Smoothed line represents LOESS curve (Section 3.1.2)

Table 4.17.4

Afon Hafren: trend statistics for epilithic diatom, macrophyte and macroinvertebrate summary data (1988 - 1998)

	Total sum of squares	Number of Taxa	Mean N_2 diversity	λ_1RDA/λ_2RDA	λ_1RDA/λ_1PCA
Epilithic diatoms	154	59	1.8	1.13	0.62
Macrophytes	1.8	7	1.2	0.51	0.34
Invertebrates	191	270	2.9	0.26	0.25

Variance explained (%)	within year	between years	linear trend	p unrestricted	p restricted
Epilithic diatoms	35.7	64.3	6.2	<0.01	<0.01
Macrophytes	*	*	33.0	0.09	<0.01
Invertebrates	45.1	54.9	7.7	<0.01	0.09

■ Macroinvertebrates

(Figure 4.17.4, Table 4.17.4)

The macroinvertebrate fauna is characterised by acid tolerant detritivorous stoneflies typical of acid waters. Two species of stonefly, *Brachyptera risi* and *Leuctra inermis* dominated the fauna, with *Amphinemura sulcicollis*, *Siphonoperla torrentium* and *Protonemura* spp. occurring at lower densities. Of the caddisflies, *Rhyacophila* spp. and *Plectrocnemia* spp. were present throughout the monitoring period, while one individual of the genus Polycentropus was recorded in 1993. Only the most acid tolerant mayfly family, the Leptophlebiidae, have been found at this site, and then only two individuals recorded in 1996. Other characteristic fauna include the Dipterans, Chironomidae and Simulidae. There are no apparent changes in species abundance and diversity over the monitoring period and there is no significant time trend.

■ Fish

(Figure 4.17.5)

No fish were caught in surveys conducted during the first few years of monitoring. However, following recent reports that a small population of trout were known to be present nearby (Crisp & Beaumont 1996), the electrofishing survey stretch was changed in 1995 to cover the lower end of this reach (Beaumont pers. comm). Small numbers of fish were caught on this and subsequent surveys. The three years of data available are insufficient for detailed analysis.

■ Aquatic macrophytes

(Tables 4.17.4-5)

In common with the other most acid streams in the Network, the aquatic macrophyte flora of the Afon Hafren is comprised almost exclusively of the ubiquitous and acid tolerant liverwort *Scapania undulata*. The cover of this species has remained at a consistent level over the decade. In contrast however, cover of filamentous algae has varied markedly between years, and since this is included in the estimate of the overall cover score for each survey stretch, may have led to bias in the liverwort cover estimate in some years. The total number of species, most of which have only ever occured at very low cover, has declined over the monitoring period. These temporal changes are deemed significant by RDA and associated permutation test, but can not be attributed to changes in water chemistry.

Table 4.17.5

Afon Hafren: relative abundance of aquatic macrophyte flora (1988 - 1997)
(see Section 3.2.3 for key to indicator values)

Abundance Taxon Year	88	89	90	91	92	93	95	96	97
INDICATOR SPECIES									
Nardia compressa[3]	*0.0*	*<0.1*	*<0.1*	*<0.1*	*0.0*	*<0.1*	*0.0*	*0.0*	*0.0*
OTHER SUBMERGED SPECIES									
Atrichum sp.	*<0.1*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*
Filamentous green algae	*0.3*	*36.7*	*<0.1*	*<0.1*	*0.3*	*<0.1*	*0.4*	*6.9*	*1.4*
Juncus bulbosus var. fluitans	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*0.0*	*0.0*	*<0.1*	*0.0*	*0.0*
Juncus effusus	*<0.1*	*<0.1*	*<0.1*	*0.0*	*0.0*	*<0.1*	*0.0*	*<0.1*	*<0.1*
Polytrichum commune	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*
Racomitrium aciculare	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*0.0*	*<0.1*	*0.0*
Ranunculus omiophyllus	*<0.1*	*<0.1*	*<0.1*	*0.1*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*
Scapania undulata	*3.1*	*12.8*	*3.5*	*2.5*	*2.7*	*3.2*	*3.0*	*2.7*	*1.5*
total macrophyte cover excluding filamentous algae	*3.1*	*12.8*	*3.5*	*2.5*	*2.7*	*3.2*	*3.0*	*2.7*	*1.5*
TOTAL NUMBER OF SPECIES	*8*	*8*	*8*	*7*	*4*	*6*	*4*	*5*	*4*

■ Summary

The Afon Hafren is a moderately acidic site, which has seemingly been adversely affected by forestry (Section 5.5). Variations in marine ions match those observed at other sites, but apart from this stream chemistry has exhibited few significant changes over the last decade. There have been few changes in water chemistry apart from a possible increase in DOC. Linear changes in the composition of the epilithic diatom flora and the reduction in rare macrophyte species are difficult to explain at this stage, while the macro-invertebrate assemblage remains fairly stable, although in an impoverished state. Trout density is low, but since the survey stretch has only recently been moved it is not possible to comment on trends.

Figure 4.17.3

Afon Hafren: summary of epilithic diatom data (1988 - 1998)

Percentage frequency of all taxa occurring at >2% abundance in any one sample

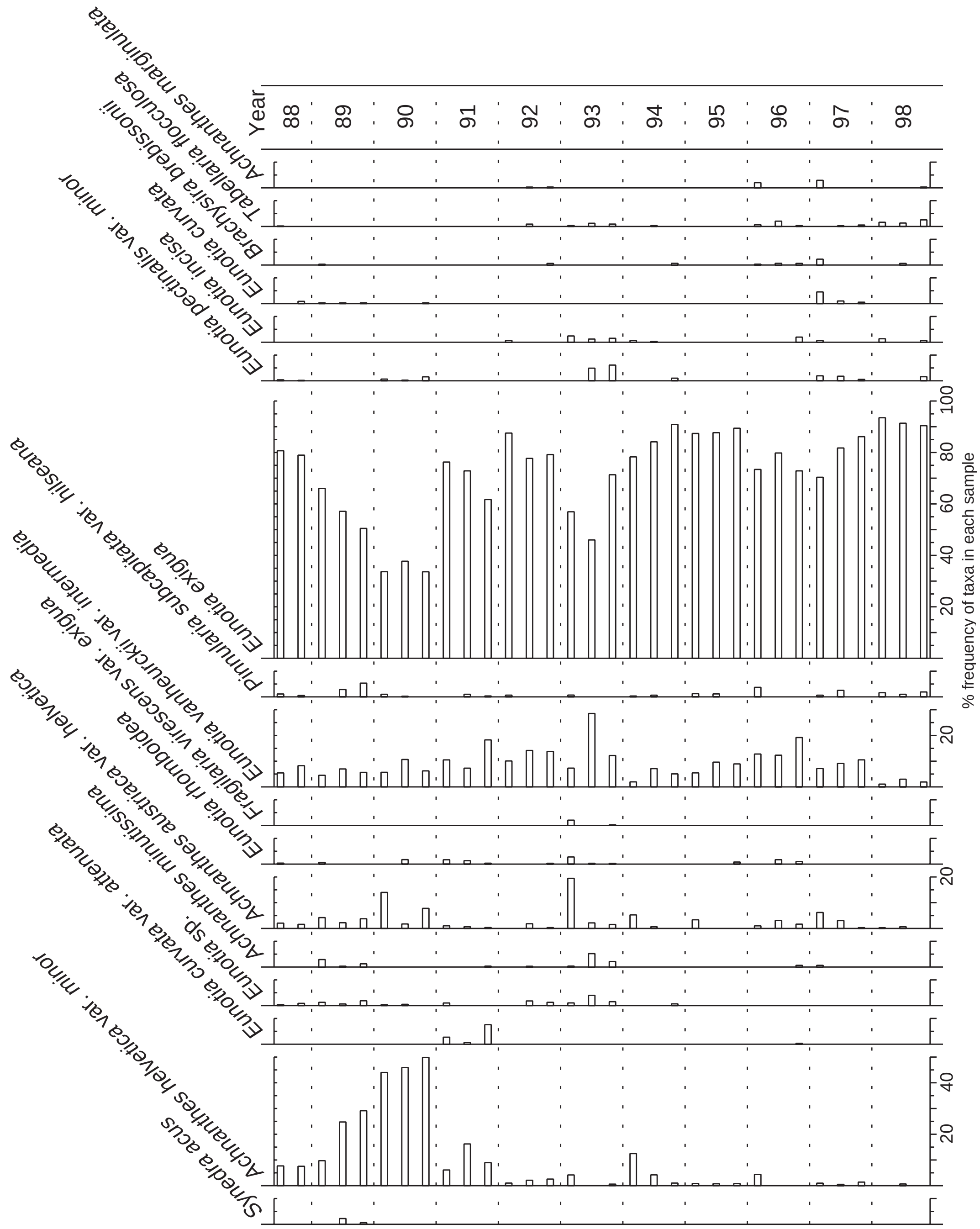


Figure 4.17.4

Afon Hafren: summary of macroinvertebrate data (1988 - 1998)

Percentage frequency of taxa in individual samples

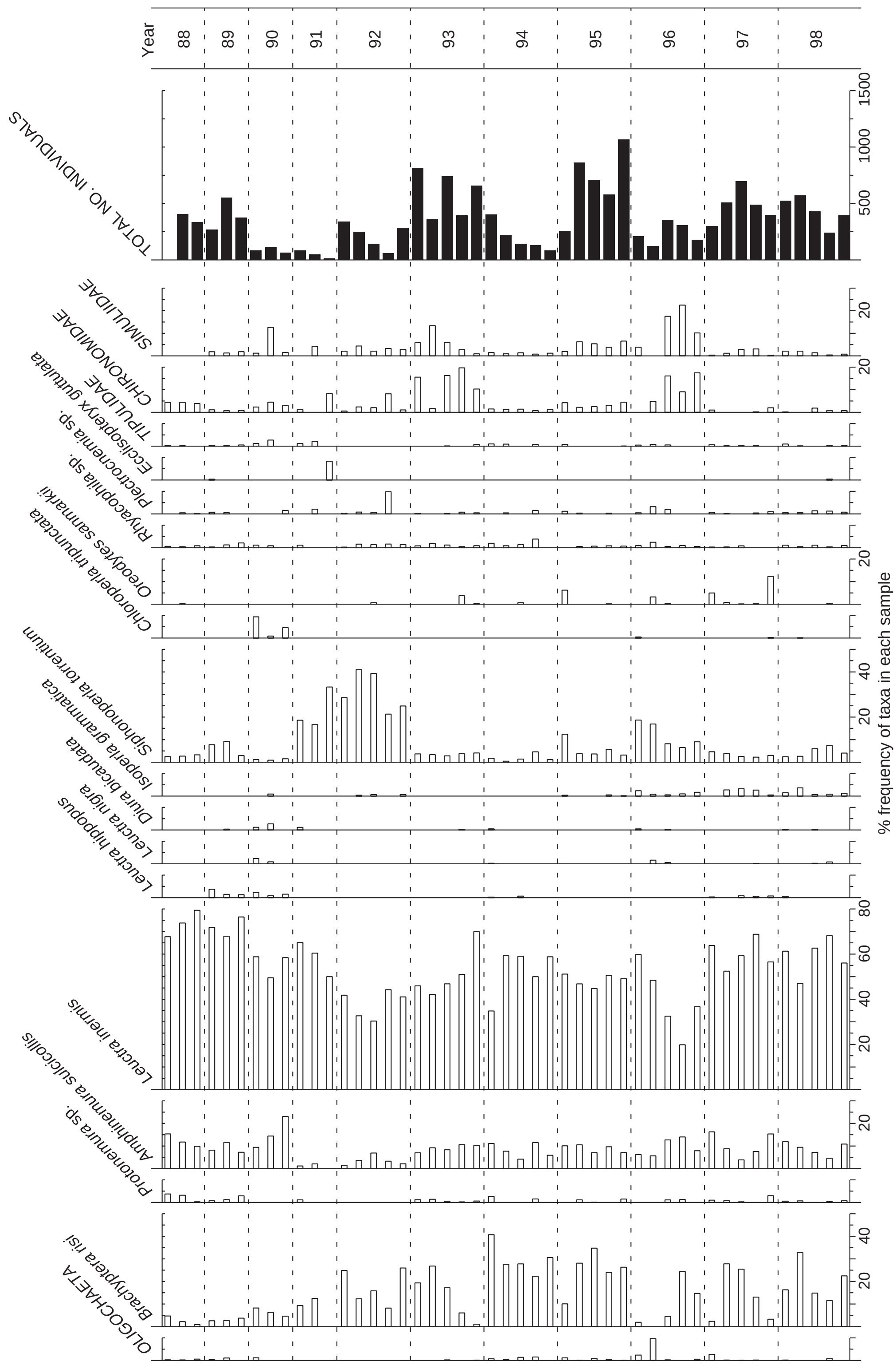
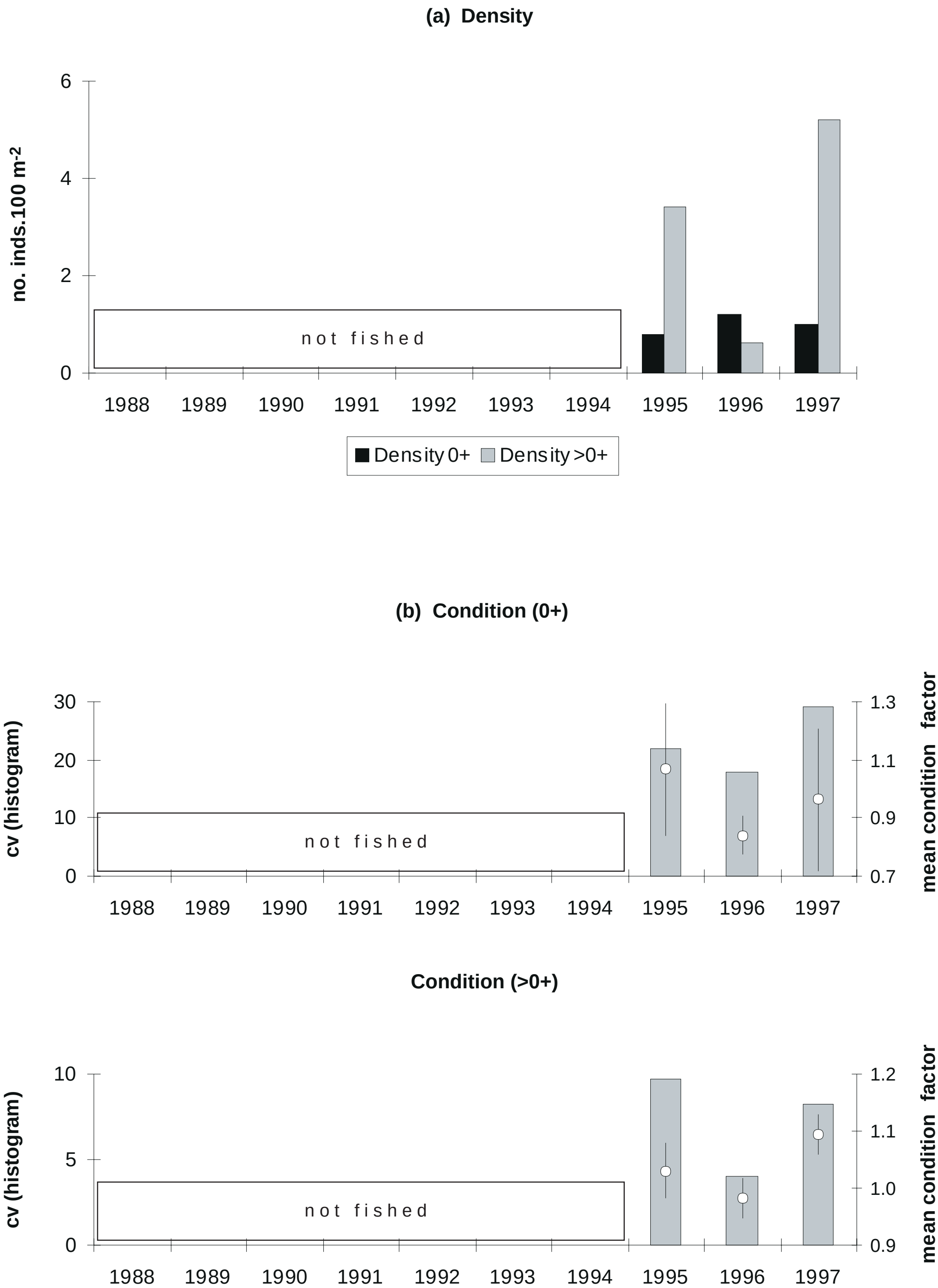
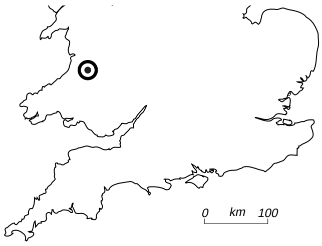


Figure 4.17.5

Afon Hafren: summary of fish data (1995 - 1997)
(a) Trout population density for 0+ and >0+ age classes (individuals 100 m^{-2})
(b) Mean condition factor (with standard deviation) of the trout population and its coefficient of variation (histogram)





4.18 Afon Gwy

Site Review

Monitoring of the moorland Afon Gwy within the UKAWMN only began in 1991, although like the neighbouring site, the Afon Hafren, longer chemical time series records exist due to its inclusion in the Plylimon catchment studies which commenced in 1983 (Section 6.5). In close proximity to the Afon Hafren, these two sites provide an excellent forested/control pair (Section 5.5). There is no evidence of disturbance within the catchment of the Afon Gwy since the onset of monitoring.

Water Chemistry

(Figure 4.18.2, Tables 4.18.2-3)

The Afon Gwy is less acidic than the adjacent forested catchment, the Afon Hafren, with a mean pH of 5.55 and a mean alkalinity of 12 μeq l^{-1}.

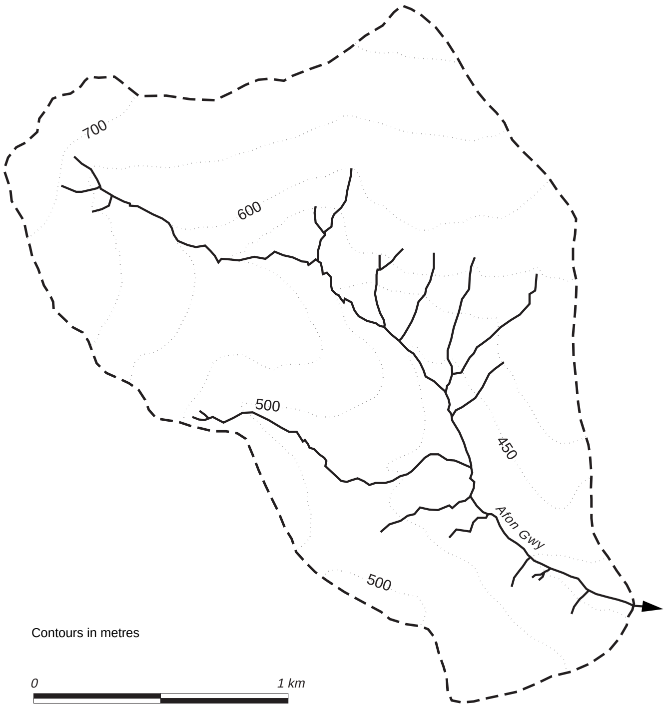


Figure 4.18.1

Afon Gwy: catchment

Table 4.18.1

Afon Gwy: site characteristics

Grid reference	*SN 842854*
Catchment area	*389 ha*
Minimum Catchment altitude	*440 m*
Maximum Catchment altitude	*730 m*
Catchment Geology	*lower palaeozoic sedimentary*
Catchment Soils	*peats, peaty podsols*
Catchment vegetation	*moorland 100%*
Mean annual rainfall	*2599 mm*
1996 deposition	
Total S	*30 kg ha^{-1} yr^{-1}*
non-marine S	*20 kg ha^{-1} yr^{-1}*
Oxidised N	*10 kg ha^{-1} yr^{-1}*
Reduced N	*17 kg ha^{-1} yr^{-1}*

Table 4.18.2

Afon Gwy: summary of chemical determinands, July 1988 - March 1998

Determinand		Mean	Max	Min
pH		*5.55*	*6.40*	*4.50*
Alkalinity	μeq l^{-1}	*11.8*	*65.4*	*-22.6*
Ca	μeq l^{-1}	*39.5*	*63.5*	*8.5*
Mg	μeq l^{-1}	*54.2*	*91.7*	*25.0*
Na	μeq l^{-1}	*146.1*	*239.1*	*113.0*
K	μeq l^{-1}	*4.6*	*16.2*	*2.6*
SO_4	μeq l^{-1}	*64.4*	*106.3*	*37.5*
xSO_4	μeq l^{-1}	*47.7*	*90.0*	*22.9*
NO_3	μeq l^{-1}	*10.7*	*71.4*	*<1.4*
Cl	μeq l^{-1}	*158.6*	*338.0*	*104.2*
Soluble Al	μg l^{-1}	*112.2*	*336.0*	*5.0*
Labile Al	μg l^{-1}	*56.2*	*249.0*	*<2.5*
Non-labile Al	μg l^{-1}	*57.1*	*170.0*	*<2.5*
DOC	mg l^{-1}	*2.12*	*6.30*	*<0.10*
Conductivity	μS cm^{-1}	*27.5*	*44.0*	*16.0*

Although internal base cation supply appears to be similar, xSO_4 is significantly lower, with a mean of 48 µeq l^{-1}. NO_3 concentrations are also lower (mean 11 µeq l^{-1}) and fall below detection limits during summer. Acidic episodes are observed during winter high flows, with alkalinity frequently falling below zero and pH below 5.0. Aluminium levels are moderate (mean 112 µg l^{-1}) and divided approximately equally between labile and non-labile fractions.

The Afon Gwy was not included in the UKAWMN until April 1991, and trend analyses at this site are therefore of limited value. The rising pH trend identified by regression (Table 4.18.3) could be spurious, since it is not supported by the LOESS fit to the data (Figure 4.18.2a), or by changes in any other ions. The DOC increase (1 mg l^{-1} per decade) identified by SKT must also be treated with caution, although it does appear to have occurred steadily over the study period (Figure 4.18.2l), and corresponds to that observed at the Afon Hafren and at other UKAWMN sites. Given the shorter dataset it is also difficult to assess changes in marine ions, but it seems likely that variations are similar to those at the Afon Hafren, and this is supported by apparently higher Cl, Na and Ca concentrations at the Gwy in 1991-1992 (Figure 4.18.2f-h). A pulse of very high Cl and Na at the end of the record corresponds to the sea-salt episode identified at Narrator Brook, and this also appears in the Hafren data (Figure 4.18.2f and h). Unlike at Narrator Brook, however, this large sea-salt input did not generate a major acidic episode at either of the Plynlimon streams. Finally, although xSO_4 has not shown any overall trend during the seven years of monitoring, concentrations appear to have declined sharply since 1996. Additional monitoring will be required to establish whether this is part of a sustained, deposition-driven decrease.

Trends in data collected at the Afon Gwy between 1980 and 1996 were analysed by Reynolds *et al.* (1997). Using SKT they observed a decline in SO_4 by an estimated 0.3 µeq l^{-1} yr^{-1}, and a rise in pH by 0.025 pH units yr^{-1}. These trends are consistent with recovery at the site, but accompanying time series indicate that most of the overall change took place prior to the onset of UKAWMN sampling in 1991. A rising trend in DOC was also observed over the longer time period, with a rate of increase identical to that identified in the present study. (Section 6.5).

Epilithic diatoms

(Figure 4.18.3, Table 4.18.4)

The epilithic diatom flora of the Afon Gwy has similar characteristics to that of the Afon Hafren, reflecting its similar acidic nature. *Eunotia exigua* was again dominant in nearly all samples. Greater diversity is apparent in samples from 1993, 1996 and 1998, when *Tabellaria flocculosa* and *Eunotia incisa* were relatively abundant. Interestingly, *T. flocculosa* also reached higher abundances in the Afon Hafren assemblages during these years, suggesting that both sites are sensitive to the same environmental influences. Rainfall data from the nearby Cymystyth Meteorological Station suggests that flows would have been relatively high and

Table 4.18.3

Significant trends in chemical determinands (July 1988 - March 1998)

Determinand	Units	Annual trend (Regression)	Annual trend (Seasonal Kendall)
pH	-	*+0.05**	-
DOC	mg l^{-1}	-	*+0.10**

** Trend significant at $p < 0.05$; ** trend significant at $p < 0.01$; *** trend significant at $p < 0.001$*

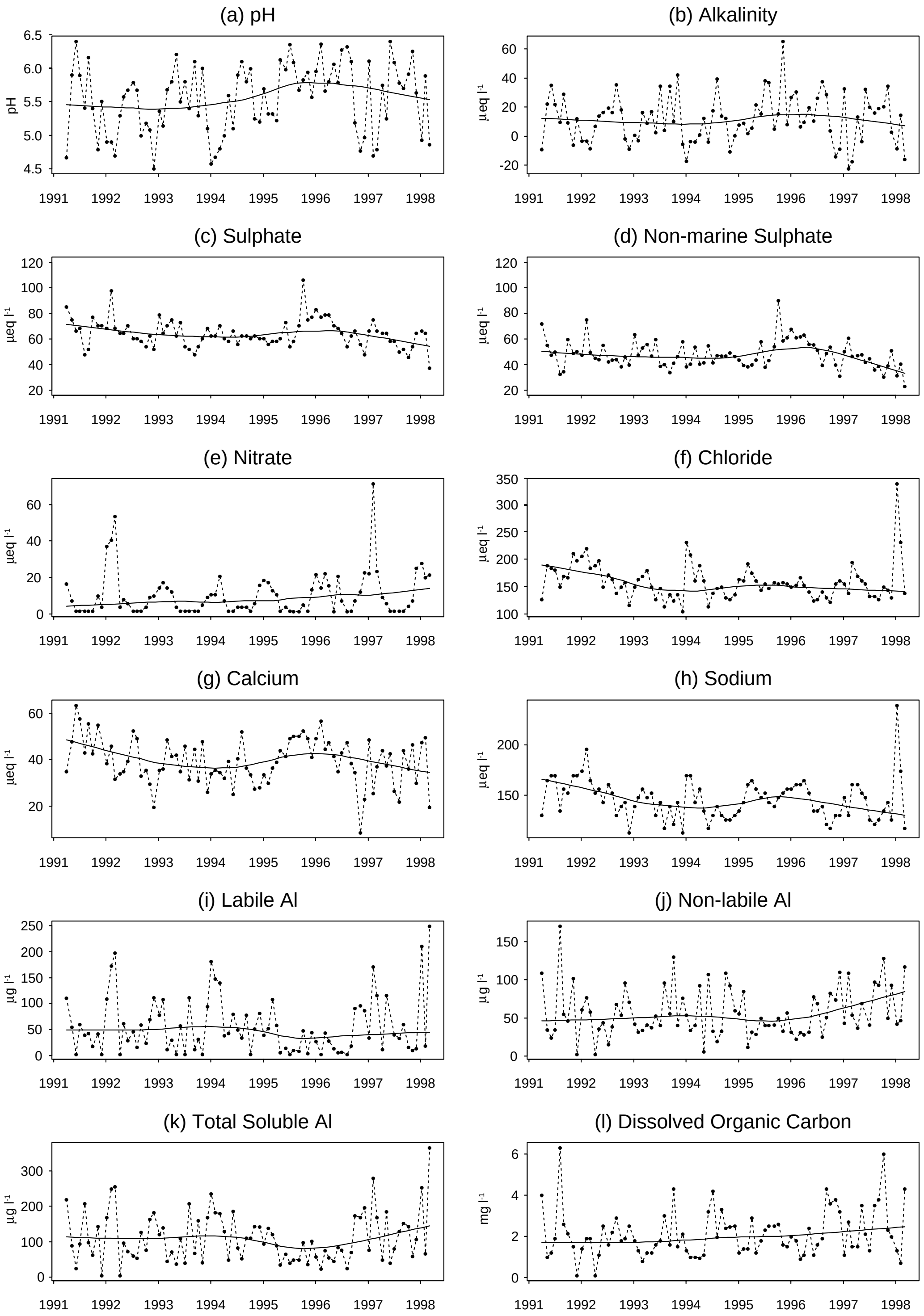


Figure 4.18.2

Afon Gwy: summary of major chemical determinands (September 1991 - March 1998)

Smoothed line represents LOESS curve (Section 3.1.2)

Table 4.18.4

Afon Gwy: trend statistics for epilithic diatom, macrophyte and macroinvertebrate summary data (1988 - 1998)

	Total sum of squares	Number of Taxa	Mean N_2 diversity	λ_1RDA/λ_2RDA	λ_1RDA/λ_1PCA
Epilithic diatoms	*135*	*57*	*4.6*	*0.45*	*0.44*
Macrophytes	*3*	*4*	*1.9*	*1.11*	*0.57*
Invertebrates	*369*	*26*	*3.9*	*0.39*	*0.32*

Variance explained (%)	within year	between years	linear trend	p unrestricted	p restricted
Epilithic diatoms	*	*	*12.0*	*<0.01*	*0.12*
Macrophytes	*	*	*37.9*	*0.13*	*0.16*
Invertebrates	*55.7*	*44.3*	*8.8*	*<0.01*	*0.04*

probably more episodic during the summer of these years and this could account for the inter-annual variation, through effects of flow on pH depression. RDA and associated restricted permutation test show that “sample year” is not significant at the 0.01 level for this relatively short time series (1991-1998). Given the possible sensitivity to the flow regime and the time restricted dataset it is not possible to infer signs of recovery in the Afon Gwy to date.

Macroinvertebrates

(Figure 4.18.4, Table 4.18.4)

This site is very similar to the Afon Hafren in species composition. Chironomids and a diverse community of acid tolerant stoneflies characterise the benthic fauna. The predatory stonefly *Siphonoperla torrentium* is the most abundant, while the detritivores *Leuctra inermis* and *Amphinemura sulcicollis* are also common. *Leuctra hippopus* was abundant in the early years but numbers have declined more recently. Of the caddisflies, *Plectrocnemia* spp. was present throughout the monitoring period with the exception of 1997; *Polycentropus* spp. was only recorded in the last three years and *Rhyacophila* spp. occurred intermittently in low numbers. The Coleopterans *Oreodytes sanmarkii* and *Limnius volckmari* both appeared after 1995. Only four individual mayflies have been recorded in the eight year monitoring period, *Ameletus inopinatus*, *Baetis* spp. and a member of the Leptophlebidae. Time as a linear trend was not significant at the 0.01 level according to RDA and associated restricted permutation test.

Fish

(Figure 4.18.5)

The Afon Gwy has been electrofished since 1991. With only seven years of data available to date there are no significant linear trends in population or condition factor statistics. Population levels of $>0^+$ fish are generally low, although 1993 and 1995 were years of good recruitment. The two highest densities of $>0^+$ fish (associated with relatively low condition factors) have occured within the last three years. Length frequency graphs clearly show the sparseness of the fish population at this site.

Aquatic macrophytes

(Tables 4.18.4-5)

The Afon Gwy survey stretch is dominated by two acid tolerant liverwort species, *Scapania undulata* and *Nardia compressa*. The moss *Racomitrium aciculare* is present in patches

Table 4.18.5

Afon Gwy: relative abundance of aquatic macrophyte flora (1991 - 1998)
(see Section 3.2.3 for key to indicator values)

Abundance Taxon Year	91	92	93	95	96	97
INDICATOR SPECIES						
Nardia compressa[3]	*5.4*	*1.5*	*0.7*	*<0.1*	*0.7*	*0.5*
OTHER SUBMERGED SPECIES						
Filamentous green algae	*10.4*	*0.7*	*9.8*	*0.3*	*19.7*	*2.0*
Polytrichum sp.	*1.0*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*
Racomitrium aciculare	*0.3*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*0.2*
Scapania undulata	*0.9*	*1.7*	*2.0*	*1.0*	*5.8*	*0.9*
EMERGENT SPECIES						
Juncus effusus	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*<0.1*
total macrophyte cover excluding filamentous algae	*7.6*	*3.2*	*2.7*	*1.0*	*6.5*	*1.6*
TOTAL NUMBER OF SPECIES	*5*	*5*	*5*	*5*	*5*	*6*

above the normal water level. There is no evidence of any trend in species cover since the onset of monitoring in 1991 and "sample year" is insignificant as a linear variable according to RDA and associated restricted permutation test.

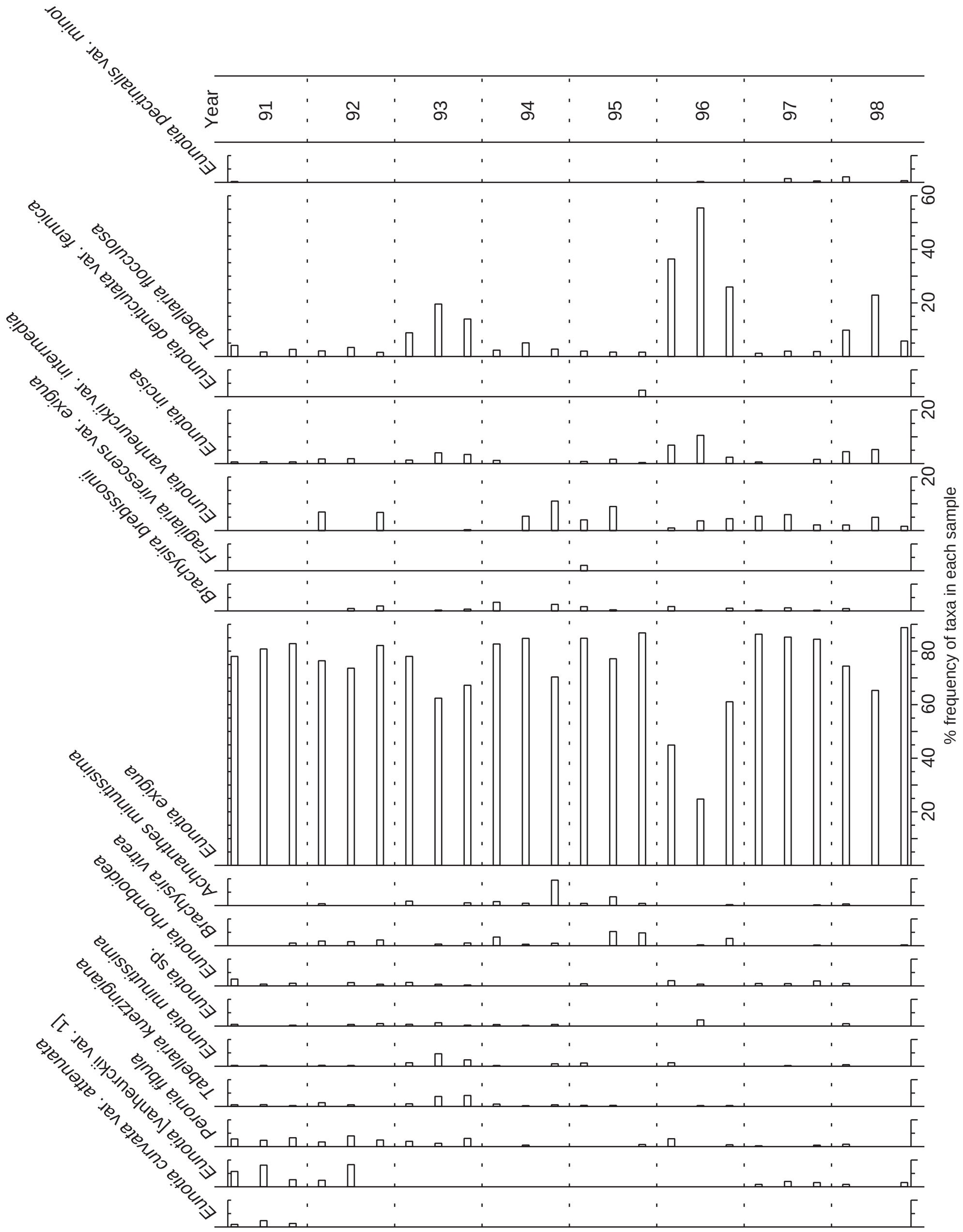
■ Summary

The Afon Gwy is the least acidic of the Welsh UKAWMN sites, although differences between sites are small, and the stream is subject to acid episodes during high flows. NO_3 and xSO_4 concentrations are lower than at the nearby Afon Hafren, and this is likely to reflect the impact of forestry at the latter. The two Welsh stream sites also demonstrate similarities in their aquatic flora and fauna. Trend analyses for the Gwy are limited by the absence of data for the first three years, but there appears to have been an increase in DOC since 1991. There has been a sharp decline in xSO_4 since 1996, but it remains to be seen whether this represents a sustained recovery at the site.

Figure 4.18.3

Afon Gwy: summary of epilithic diatom data (1991 - 1998)

Percentage frequency of all taxa occurring at >2% abundance in any one sample



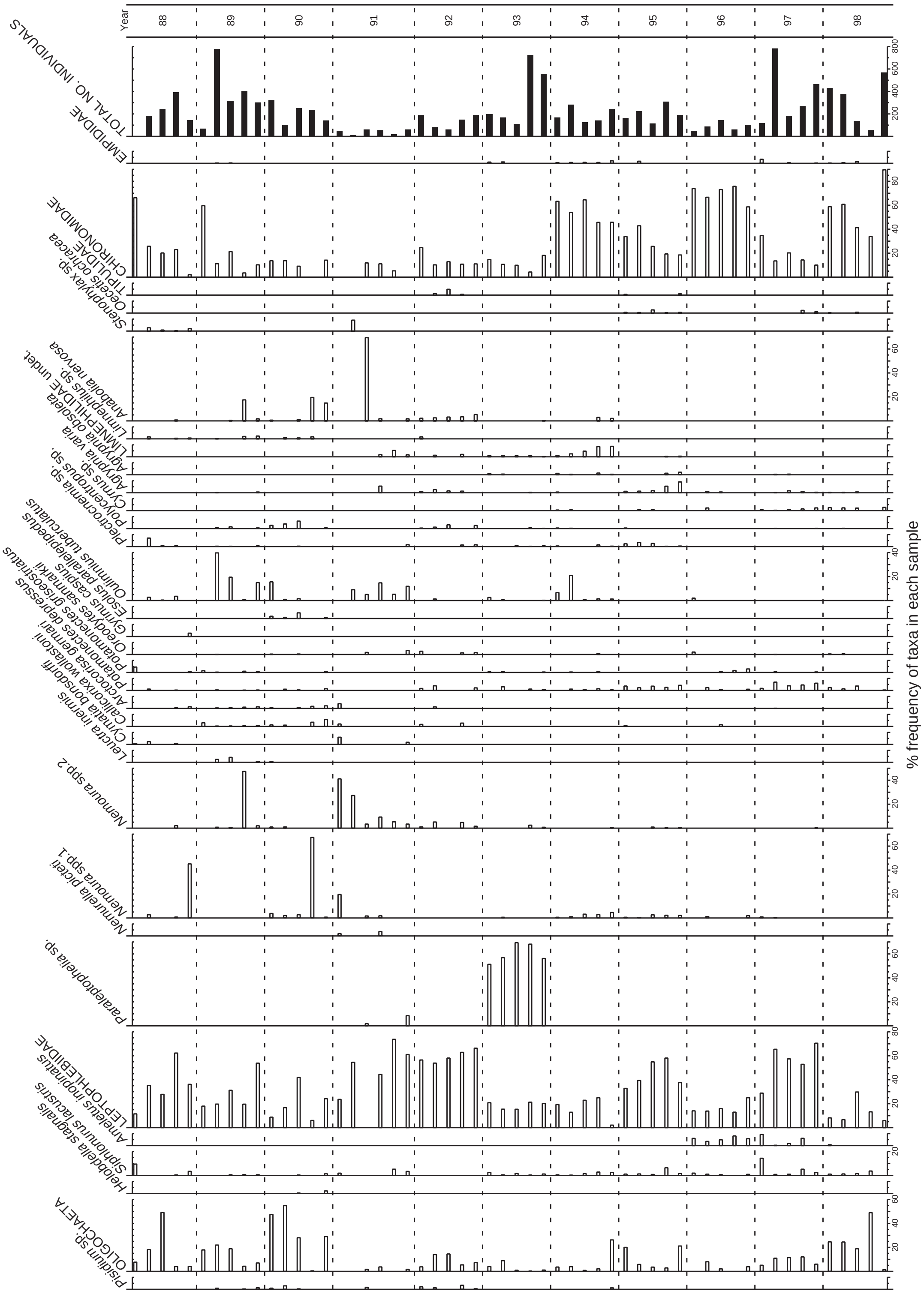


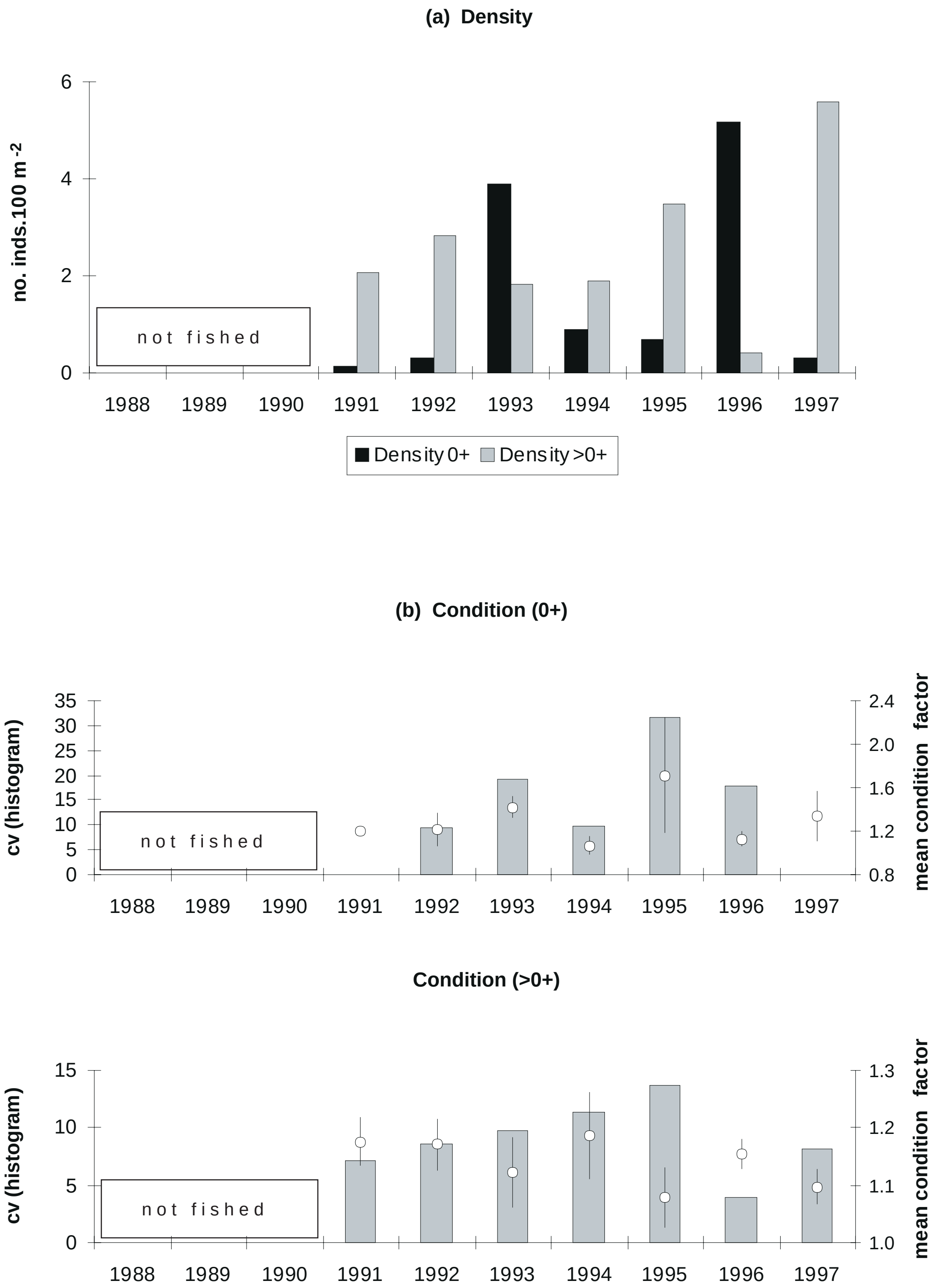
Figure 4.18.4

Afon Gwy: summary of macroinvertebrate data (1988 - 1998)

Percentage frequency of taxa in individual samples

Figure 4.18.5

Afon Gwy: summary of fish data (1991 - 1997)
(a) Trout population density for 0+ and >0+ age classes (individuals 100 m^{-2})
(b) Mean condition factor (with standard deviation) of the trout population and its coefficient of variation (histogram)



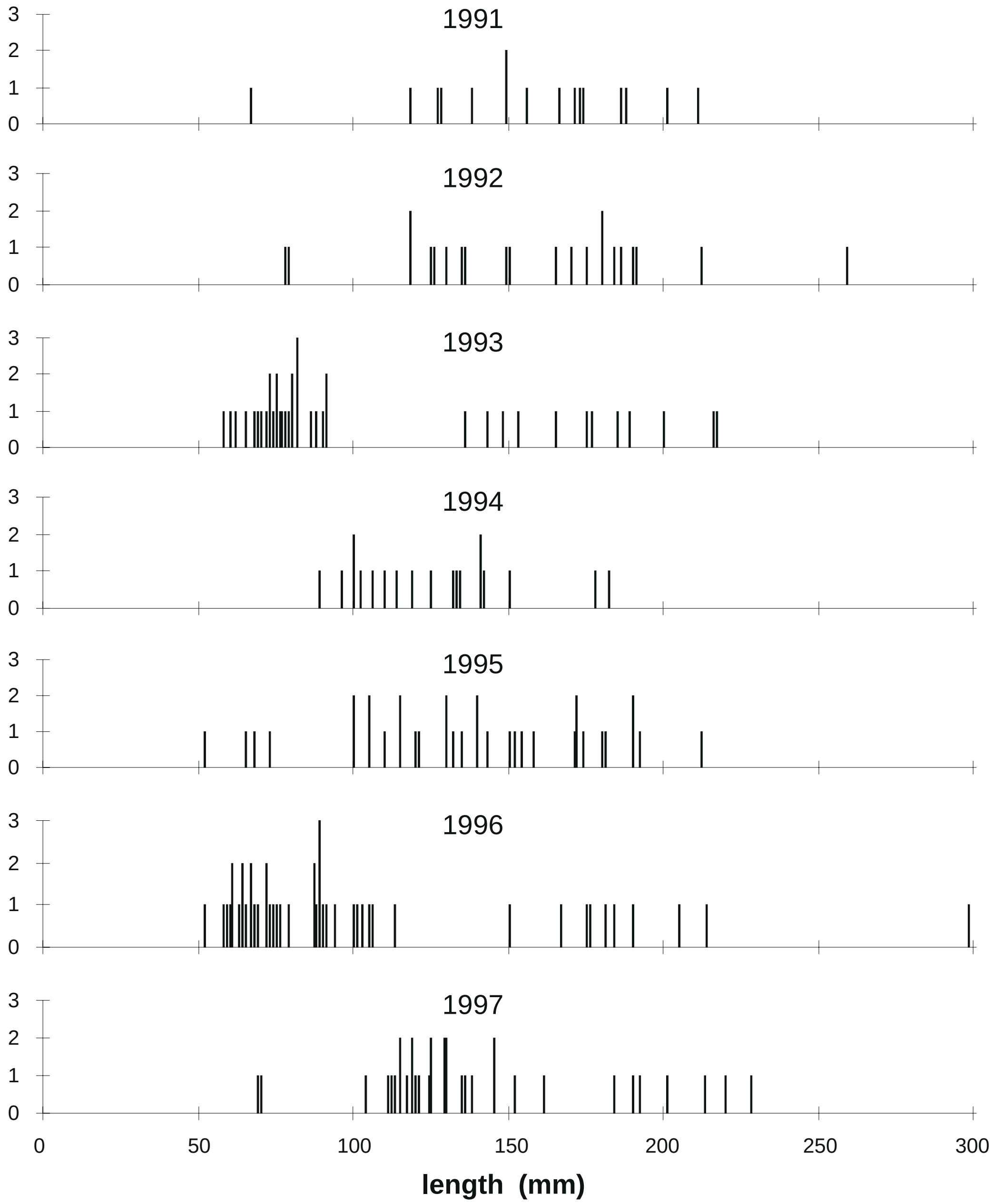


Figure 4.18.5

Afon Gwy: summary of fish data (1991 - 1997)
(c) Trout length frequency summaries

4.19 Beagh's Burn

Site Review

Beagh's Burn lies in the Glens of Antrim in north east Northern Ireland. The site was subject to a major storm event during 1991 which redistributed substrate and sharply reduced the bryophyte cover of the stream bed. Recent work carried out by a local farm, involving improvements to a wall and sheep pen, are all beneath the water sample point and biological survey stretches. There is no evidence of any physical disturbance within the catchment over the survey period.

Water Chemistry

(Tables 4.19.2-3, Figure 4.19.2)

Beagh's Burn is not strongly acidic, having a mean alkalinity of 44 µeq l^{-1}. However, the range of

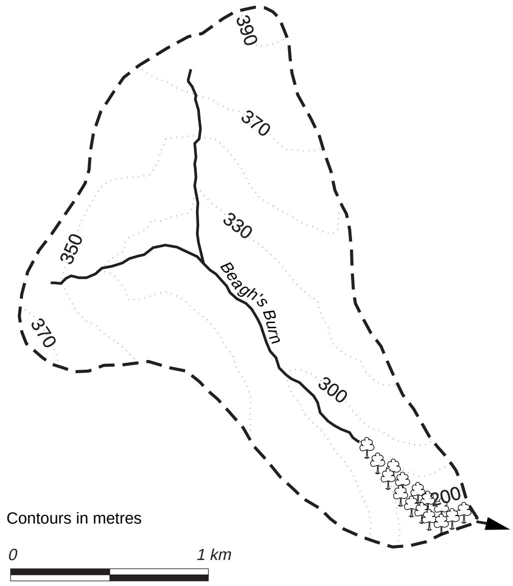


Figure 4.19.1

Beagh's Burn: catchment

Table 4.19.1

Beagh's Burn: site characteristics

Grid reference	*D 173297*
Catchment area	*303 ha*
Minimum Catchment altitude	*150 m*
Maximum Catchment altitude	*397 m*
Catchment Geology	*schists*
Catchment Soils	*blanket peats*
Catchment vegetation	*moorland >99%, deciduous trees <1%*
Mean annual rainfall	*1608 mm*
1996 deposition	
Total S	*16 kg ha^{-1} yr^{-1}*
non-marine S	*13 kg ha^{-1} yr^{-1}*
Oxidised N	*6 kg ha^{-1} yr^{-1}*
Reduced N	*14 kg ha^{-1} yr^{-1}*

Table 4.19.2

Beagh's Burn: summary of chemical determinands, July 1988 - March 1998

Determinand		Mean	Max	Min
pH		*5.76*	*7.18*	*4.31*
Alkalinity	µeq l^{-1}	*44.4*	*240.0*	*-58.0*
Ca	µeq l^{-1}	*102.5*	*218.5*	*35.5*
Mg	µeq l^{-1}	*111.7*	*183.3*	*50.0*
Na	µeq l^{-1}	*302.2*	*443.5*	*204.3*
K	µeq l^{-1}	*10.5*	*23.1*	*2.6*
SO_4	µeq l^{-1}	*72.5*	*275.0*	*27.1*
xSO_4	µeq l^{-1}	*37.5*	*243.1*	*0.0*
NO_3	µeq l^{-1}	*3.6*	*15.7*	*<1.4*
Cl	µeq l^{-1}	*336.6*	*619.7*	*191.5*
Soluble Al	µg l^{-1}	*55.6*	*106.0*	*<2.5*
Labile Al	µg l^{-1}	*10.2*	*60.0*	*<2.5*
Non-labile Al	µg l^{-1}	*45.9*	*92.0*	*<2.5*
DOC	mg l^{-1}	*11.1*	*30.0*	*3.1*
Conductivity	µS cm^{-1}	*59.4*	*96.0*	*39.0*

observed values is high, from –58 to 240 µeq l^{-1}. Mean pH (5.76) is low relative to alkalinity, probably due to high levels of weak organic acidity; Beagh's Burn has the highest mean DOC concentrations in the Network. Na and Cl concentrations are also extremely high, whereas xSO_4 and NO_3 concentrations are both low (means 38 µeq l^{-1} and 4 µeq l^{-1} respectively). In general these characteristics resemble those of the coastal north and central Scotland UKAWMN sites, with very high marine ion deposition and low pollutant deposition. Beagh's Burn also has a relatively high Ca concentration (mean 102 µeq l^{-1}) and therefore a low sensitivity to acid deposition.

A strong correlation between Ca and alkalinity ($R^2 = 0.57$, $p< 0.0001$, Figure 4.19.2b,g) suggests a simple hydrological control on stream acidity, with low flows dominated by Ca-rich, alkaline groundwater, and dilution generating acidic episodes at high flows. Marine ion inputs also generate some acid episodes through the "sea-salt effect". Both processes can be considered natural, although neither would be expected to cause negative alkalinity in the absence of anthropogenic SO_4 and NO_3. However, a small number of SO_4 and NO_3 pulses are also observed at this stream, and the January 1996 NO_3 peak in particular (Figure 4.19.2e) appears to have caused significant episodic acidification. A concurrent and more pronounced peak observed at Coneyglen Burn (Site 22) is discussed in greater detail below.

Trend analyses for Beagh's Burn show few changes in stream chemistry during the last decade (Table 4.19.3). A decreasing trend in labile Al obtained using regression can be linked to a small, possibly anomalous group of high values during 1990-1991, and no changes were observed in alkalinity, pH, xSO_4 or NO_3. LOESS curves suggest some inter-annual variability in Na and Cl, but this is small relative to UK mainland sites. The only major change in stream chemistry appears to have been an increase in DOC, highly significant using both analytical methods, of around 6 mg l^{-1} over the decade. Most of this increase appears to have occurred since 1993, with both spring minima and autumn maxima having risen.

■ Epilithic diatoms

(Figure 4.19.3, Table 4.19.4)

The composition of the epilithic diatom assemblage of Beagh's Burn has fluctuated markedly beween years and no species has been consistently dominant. The earlier years are characterised by relatively diverse samples, dominated by species with relatively acid preferences including *Eunotia exigua* (pH optima 5.1), *Gomphonema angustatum* [agg.](pH optima 5.8) and *Pinnularia subcapitata* var. *hilseana* (pH optima 5.0). *Achnanthes minutissima* (pH optima 6.3) and *Synedra minuscula* (pH optima 6.0) comprised >80% of the assemblage of all samples in 1994 and 1995 respectively since when *G. angustatum*, and *P. subcapitata* var. *hilseana* have again been abundant. The substantial differences between years in the pH preference of the dominant taxa are likely to relate to the varying hydrological regime. Summer rainfall

Table 4.19.3

Significant trends in chemical trends (July 1988 - March 1998)

Determinand	Units	Annual trend (Regression)	Annual trend (Seasonal Kendall)
DOC	mg l^{-1}	*+0.65****	*+0.60***
labile Al	µg l^{-1}	*-0.93**	-

** Trend significant at p < 0.05; ** trend significant at p < 0.01; *** trend significant at p < 0.001*

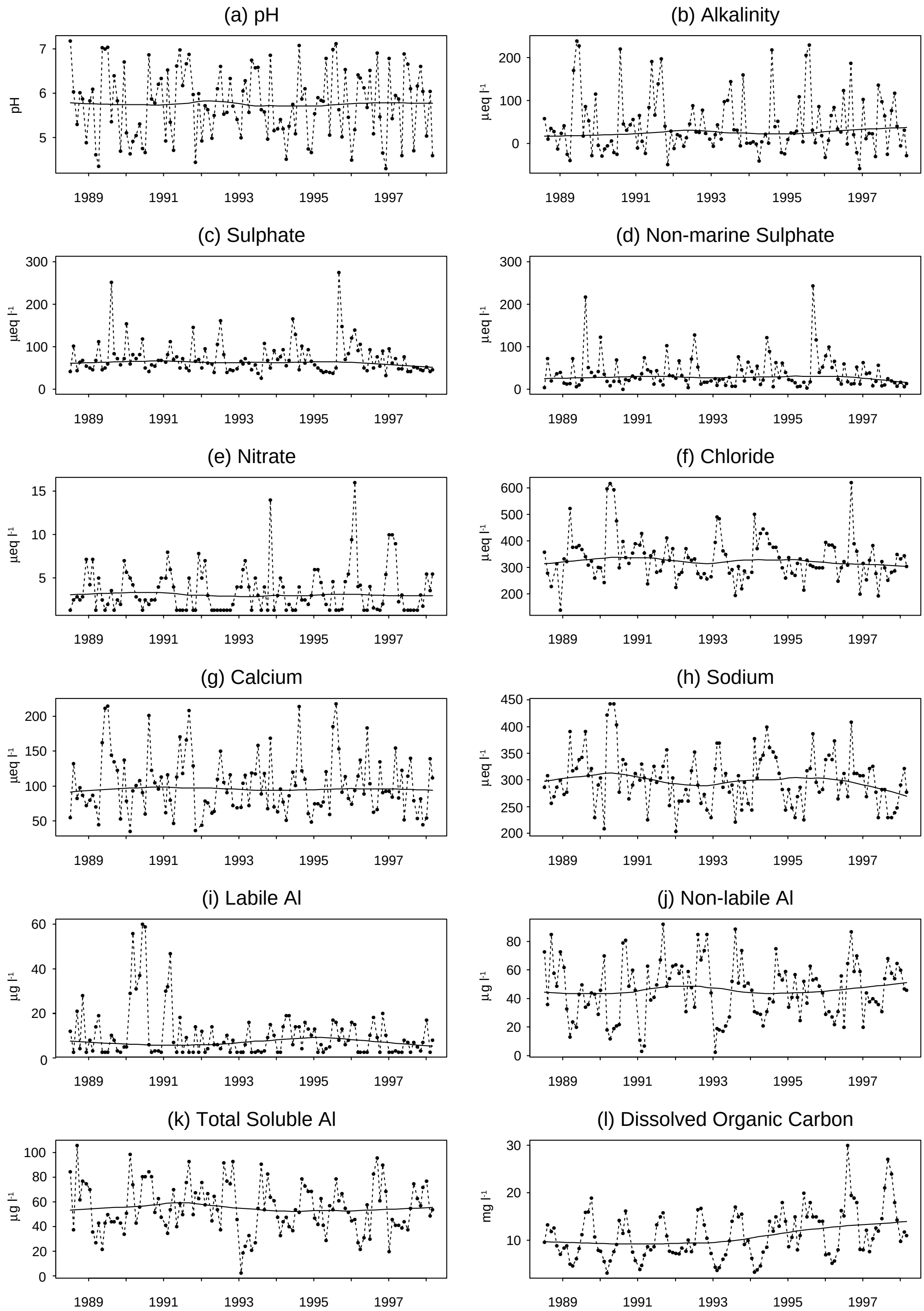


Figure 4.19.2

Beagh's Burn: summary of major chemical determinands (July 1988 - March 1998)

Smoothed line represents LOESS curve (Section 3.1.2)

Table 4.19.4

Beagh's Burn: trend statistics for epilithic diatom, macrophyte and macroinvertebrate summary data (1988 - 1998)

	Total sum of squares	Number of Taxa	Mean N_2 diversity	λ_1RDA/λ_2RDA	λ_1RDA/λ_1PCA
Epilithic diatoms	530	87	4.4	0.46	0.46
Macrophytes	9	5	1.7	0.26	0.21
Invertebrates	449	28	2.7	0.43	0.41

Variance explained (%)	within year	between years	linear trend	p unrestricted	p restricted
Epilithic diatoms	25.2	74.8	12.3	<0.01	0.07
Macrophytes	*	*	19.5	0.25	0.50
Invertebrates	51.7	48.3	8.6	<0.01	0.02

(June-August) was particularly low in 1994 and 1995 at the nearby Ballypatrick Meteorological station and this is likely to have resulted in fewer and less intense flow related acid episodes. As at the majority of UKAWMN stream sites, diatom inferred pH, using weighted averaging, is significantly and inversely correlated with total June-July rainfall (Section 7.4.1). RDA and associated restricted permutation test shows that a time trend is insignificant at the 0.01 level.

■ Macroinvertebrates

(Figure 4.19.4, Table 4.19.4)

The macroinvertebrate community is characterised by very large numbers of Simuliidae, which in some years make up to 80% of the total species composition. Acid tolerant stoneflies form the largest part of the remaining benthic composition. *Siphonoperla torrentium* dominated most years and was accompanied by *Leuctra inermis*, *Protonemura* spp., *Amphinemura sulcicollis* and *Brachyptera risi*. 1998 saw a marked increase in stonefly abundance. The caddisflies *Rhyacophila* spp. and *Plectrocnemia* spp. were both common, the latter species being absent the years 1991-1993. Several species of the moderately acid sensitive family Hydropsychidae (mainly *Hydropsyche siltalai* and *Hydropsyche pellucidula*) have been recorded, with highest densities occurring after 1994. 1991 was the poorest year both in number of species and abundance, while 1995 was the richest. While acid tolerant stoneflies have been present throughout the monitoring period, some species which are intolerant of very acid conditions have only been recorded in more recent years, during which time minimum species richness has also increased (see Figure 7.11b). Despite this, time as a linear trend is not significant at the 0.01 level according to RDA and associated permutation test.

■ Fish

(Figure 4.19.5)

A full ten years of data are available for Beagh's Burn. Mean trout densities are low and 0+ trout recruitment is extremely sporadic with presence only recorded in three years (1989, 1990 and 1997). Population densities of >0+ trout are relatively stable, with a minimum recorded in 1992 and a maximum in 1996. The mean condition factor of >0+ trout has also remained relatively stable between years although the coefficient of variation of the condition factor has shown wide fluctuations. The lowest condition factor recorded was associated with the highest coefficient of variation (1988). Length frequency

Table 4.19.5

Beagh's Burn: relative abundance of aquatic macrophyte flora (1988 - 1997)
(see Section 3.2.3 for key to indicator values)

Abundance Taxon Year	88	89	90	91	92	93	95	96	97
SUBMERGED SPECIES									
Filamentous green algae	*6.9*	*5.9*	*1.5*	*0.5*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*
Hyocomium armoricum	*0.0*	*0.0*	*0.0*	*0.0*	*<0.1*	*0.0*	*0.0*	*0.1*	*0.0*
Marsupella emarginata	*<0.1*	*0.0*	*0.0*	*<0.1*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*
Racomitrium aciculare	*1.4*	*2.2*	*0.1*	*0.1*	*<0.1*	*<0.1*	*<0.1*	*0.4*	*<0.1*
Rhytidiadelphus squarrosus	*0.0*	*0.0*	*0.0*	*<0.1*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*
Scapania undulata	*11.2*	*10.5*	*7.6*	*0.1*	*0.6*	*<0.1*	*0.8*	*3.2*	*3.7*
total macrophyte cover excluding filamentous algae	*12.6*	*12.7*	*7.7*	*0.2*	*0.6*	*<0.1*	*0.8*	*3.7*	*3.7*
TOTAL NUMBER OF SPECIES	*4*	*3*	*3*	*5*	*4*	*3*	*3*	*4*	*3*

graphs illustrate the sparse population, even in the three recruitment years, and the absence of all medium sized (c.150 mm) fish in 1992.

■ Aquatic macrophytes

(Tables 4.19.4-5)

The impoverished aquatic macrophyte flora of Beagh's Burn, which is limited almost entirely to the acid tolerant liverwort, *Scapania undulata,* reflects the more acid characteristics of the site during high flows, rather than mean conditions. *S.undulata* is the only species which has been consistently recorded in fully submerged locations, although the moss *Racomitrium aciculare* is present in patches above the normal water level. The cover of *S.undulata* was substantially reduced in 1991, probably as a result of a major storm event earlier in the year, and consequent physical scouring effects. Since then the abundance of this species has gradually increased again. Time is insignificant as a linear variable according to RDA and restricted permutation test.

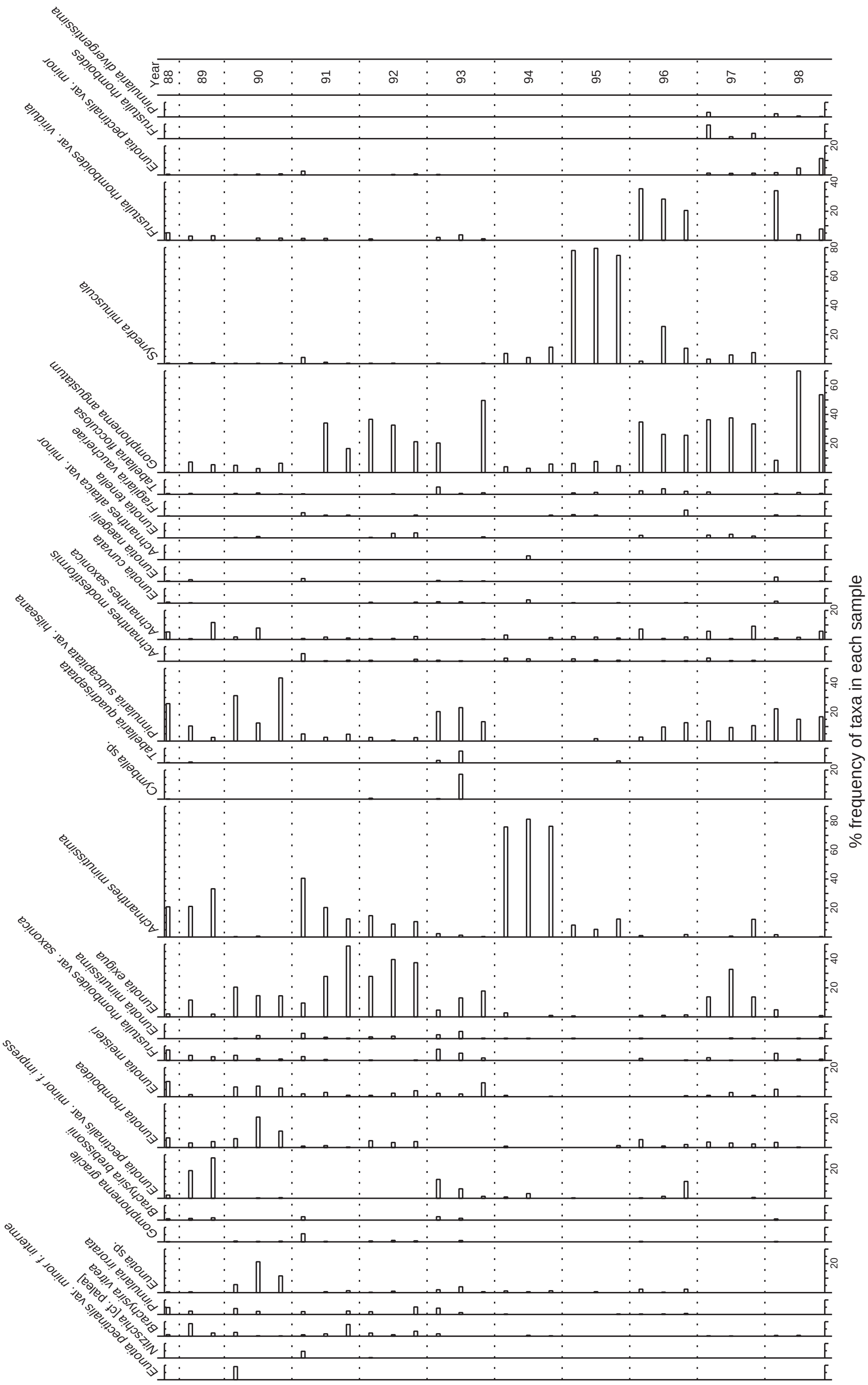
■ Summary

Beagh's Burn is a relatively unimpacted site, upwind of major emission sources, and is not severely acidified. The stream does however experience acidic episodes, driven by dilution of weathering-derived Ca during high flows, and by sea-salt cation exchange processes, and these, rather than mean conditions, appear to determine the nature of the aquatic biota. All biological groups demonstrate considerable inter-annual variability but there is no evidence of time trends in species composition. There has not been any change in major ion composition over the monitoring period, but DOC levels appear to have risen substantially from an already high baseline.

Figure 4.19.3

Beagh's Burn: summary of epilithic diatom data (1988 - 1998)

Percentage frequency of all taxa occurring at >2% abundance in any one sample



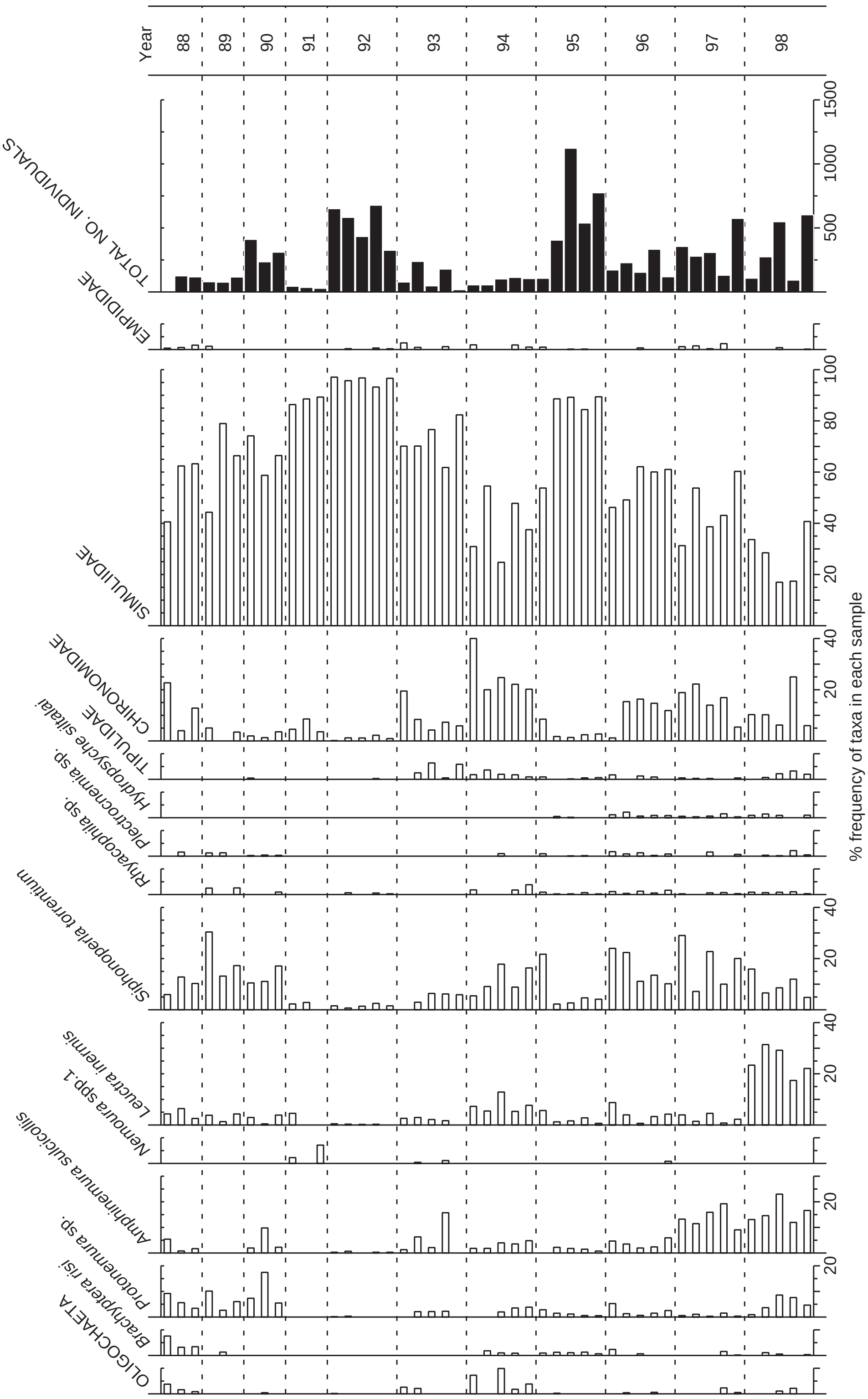


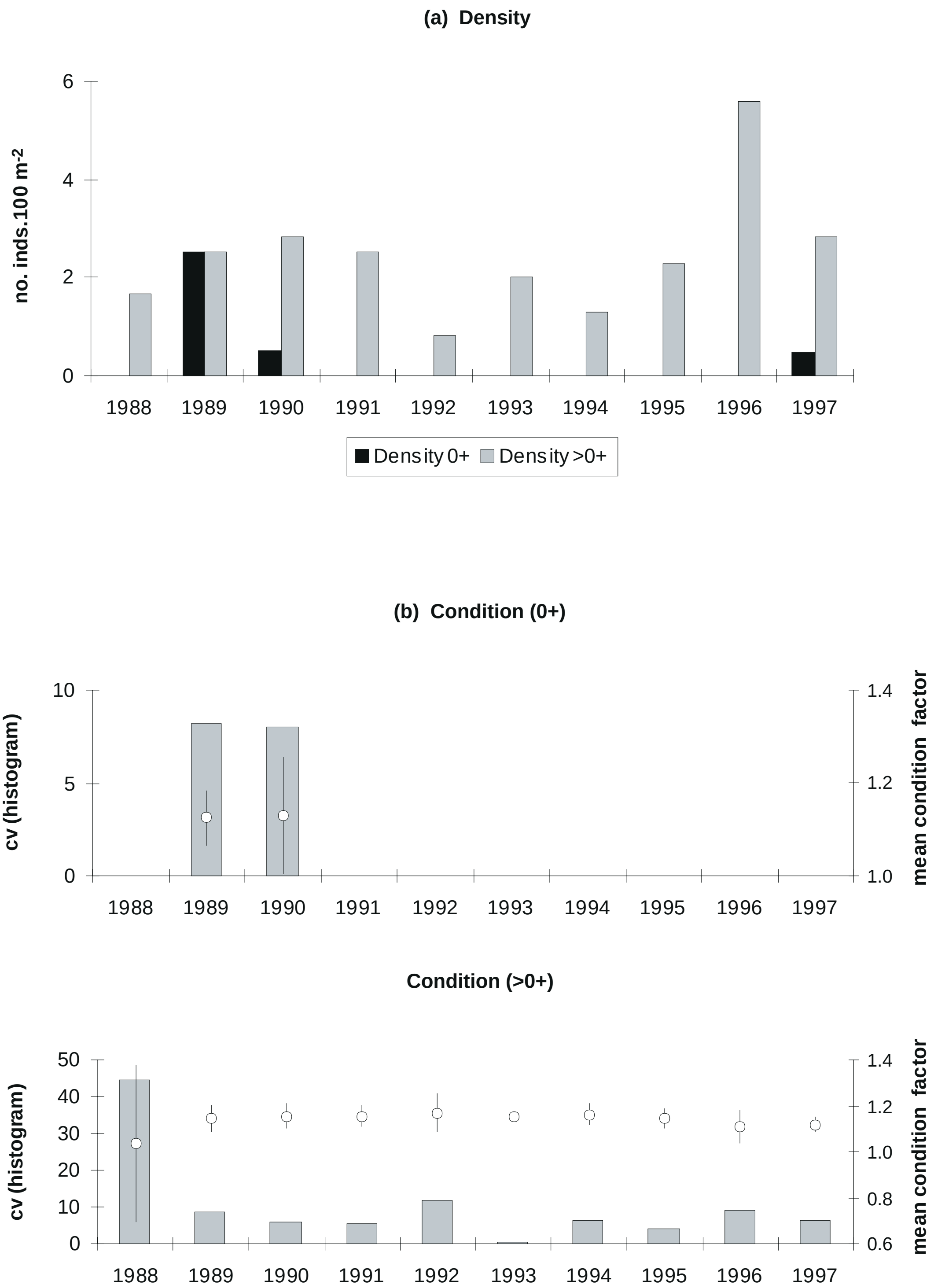
Figure 4.19.4

Beagh's Burn: summary of macroinvertebrate data (1988 - 1998)

Percentage frequency of taxa in individual samples

Figure 4.19.5

Beagh's Burn: summary of fish data (1988 - 1997)
(a) Trout population density for 0+ and >0+ age classes (individuals 100 m^{-2})
(b) Mean condition factor (with standard deviation) of the trout population and its coefficient of variation (histogram)



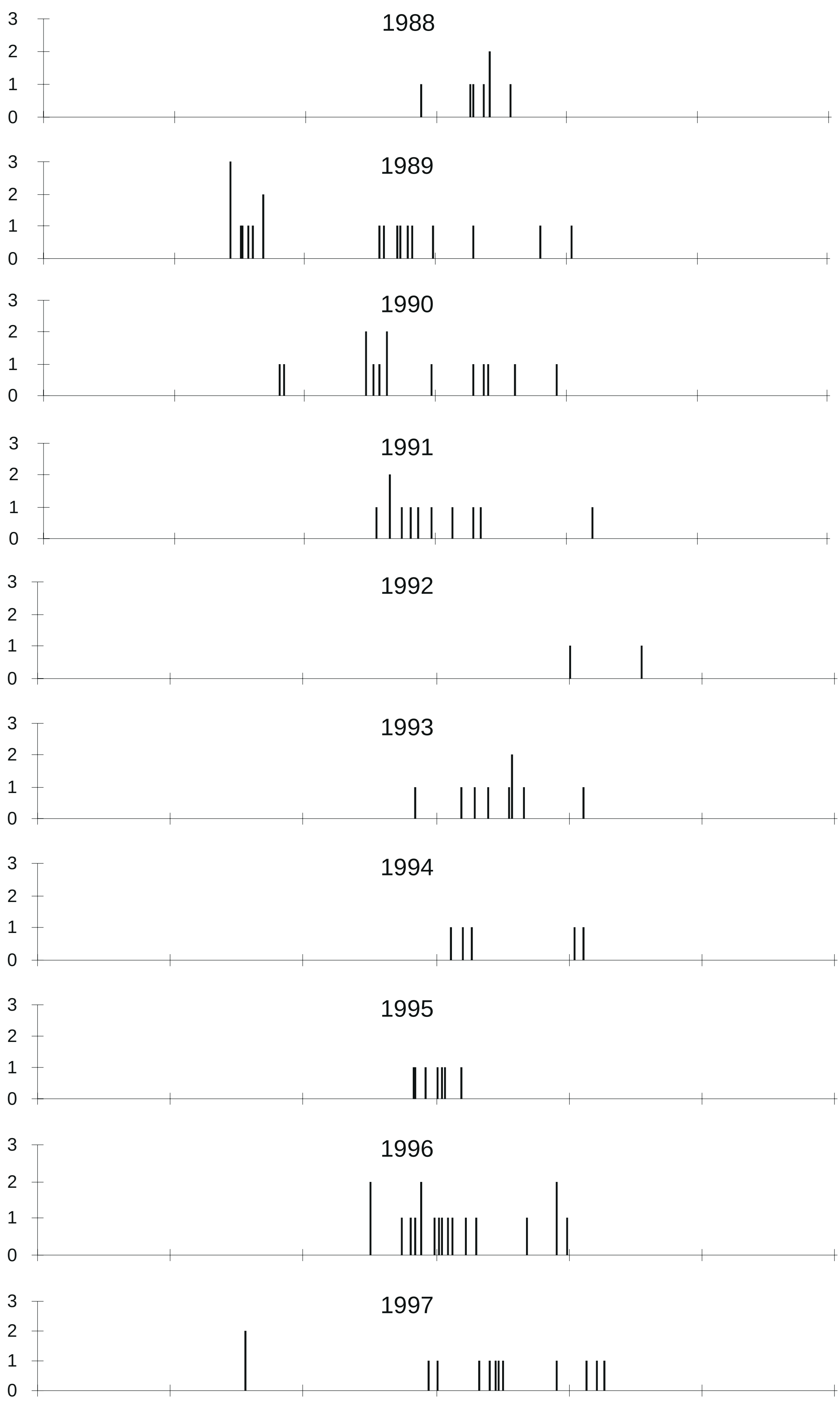


Figure 4.19.5

Beagh's Burn: summary of fish data (1988 - 1997)
(c) Trout length frequency summaries

4.20 Bencrom River

Site Review

The Bencrom River drains into the Silent Valley Reservoir in the Mourne Mountains of south eastern Northern Ireland. There has been no physical disturbance within the catchment since the onset of monitoring in 1988.

Water Chemistry

(Figure 4.20.2, Tables 4.20.2-3)

The Bencrom River is chronically acidic, with a mean alkalinity of –5 µeq l^{-1} and a mean pH of 5.19. Ca concentrations are low (mean 53 µeq l^{-1}), whilst Al concentrations are high and dominated by the labile fraction. The acidity of this stream can be attributed to high levels of xSO_4 (mean 67 µeq l^{-1}) and also to the second highest NO_3 concentrations in the UKAWMN (mean 29 µeq l^{-1}). NO_3 remained above detection limits throughout the monitoring

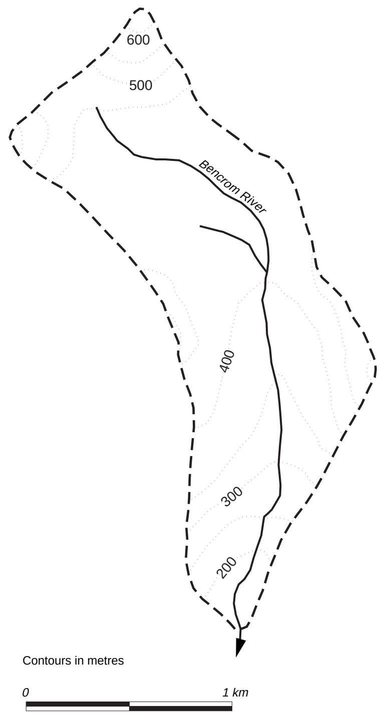


Figure 4.20.1

Bencrom River: catchment

Table 4.20.1

Bencrom River: site characteristics

Grid reference	*J 304250*
Catchment area	*216 ha*
Minimum Catchment altitude	*140 m*
Maximum Catchment altitude	*700 m*
Catchment Geology	*granite*
Catchment Soils	*blanket peat*
Catchment vegetation	*moorland 100%,*
Mean annual rainfall	*1768 mm*
1996 deposition	
Total S	*17 kg ha^{-1} yr^{-1}*
non-marine S	*15 kg ha^{-1} yr^{-1}*
Oxidised N	*7 kg ha^{-1} yr^{-1}*
Reduced N	*14 kg ha^{-1} yr^{-1}*

Table 4.20.2

Bencrom River: summary of chemical determinands, July 1988 - March 1998

Determinand		Mean	Max	Min
pH		*5.19*	*6.27*	*4.38*
Alkalinity	µeq l^{-1}	*-5.4*	*37.0*	*-45.0*
Ca	µeq l^{-1}	*52.5*	*81.5*	*29.5*
Mg	µeq l^{-1}	*61.7*	*108.3*	*33.3*
Na	µeq l^{-1}	*263.5*	*352.2*	*178.3*
K	µeq l^{-1}	*11.0*	*25.4*	*5.1*
SO_4	µeq l^{-1}	*93.5*	*187.5*	*52.1*
xSO_4	µeq l^{-1}	*66.7*	*161.5*	*28.5*
NO_3	µeq l^{-1}	*28.6*	*77.1*	*5.7*
Cl	µeq l^{-1}	*255.5*	*371.8*	*138.0*
Soluble Al	µg l^{-1}	*202.1*	*400.0*	*9.0*
Labile Al	µg l^{-1}	*125.3*	*308.0*	*<2.5*
Non-labile Al	µg l^{-1}	*76.9*	*237.0*	*2.5*
DOC	mg l^{-1}	*4.1*	*15.5*	*1.2*
Conductivity	µS cm^{-1}	*50.4*	*80.0*	*36.0*

period, with some seasonal cyclicity evident, and peak concentrations exceeded 60 μeq l^{-1} during four separate winter/spring periods. In early 1996, NO_3 exceeded xSO_4 on an equivalent basis in two samples, and was thus the dominant acidifying anion at this time. It appears that NO_3 pulses, base cation dilution and sea-salt cation exchange all contribute to large episodic alkalinity and pH depressions at this site.

Rising trends have been observed at the Bencrom River for DOC using SKT and regression, and for NO_3 using regression only. (Table 4.20.3). The increase in NO_3 appears to be the result of climatically driven fluctuations, with higher concentrations at the beginning and end of the record (Figure 4.20.2e). No clear changes have taken place in pH, alkalinity or xSO_4, but there appears to be some cyclicity in Cl, Na and Ca (Figures 4.20.2f,h) with 1990-1991 and 1995-1996 peaks comparable to those at many UK mainland sites. However, in contrast to most other sites, the 1995-1996 peak was the larger at the Bencrom River. The DOC increase, which is highly significant using both methods, appears to have occurred linearly over the monitoring period (Figure 4.20.2l), with the overall change estimated between 1.4 at 2.1 mg l^{-1}.

Epilithic diatoms

(Figure 4.20.3, Table 4.20.4)

The epilithic diatom flora of the Bencrom River is typical for a permanently very acid stream and shows relative stability between years. The bulk of the assemblage was represented by *Eunotia naegelii* (pH optima 5.0) and *Brachysira brebissonii* (pH optima 5.3). The former was dominant in most samples and showed a general increase with time, although the latter was more frequent in 1990 and 1995. *Tabellaria quadriseptata*, which has a preference for particularly acid conditions (pH optima 4.9), commonly comprised over 5% of samples until 1994, since when it declined. The general increase in *E.naegelii* and reduction in *T. quadriseptata* is indicative of slight improvement in pH in recent years, and this is supported by LOESS plots for water chemistry data. However, as for the majority of UKAWMN stream sites, summer rainfall appears to be important in influencing species composition, and total June-July rainfall for the nearby Meteorological Station (Silent Valley) is inversely related to diatom infered pH using weighted averaging (Section 7.3.1). “Sample year” is not significant according to RDA and associated restricted permutation test.

Macroinvertebrates

(Figure 4.20.4, Table 4.20.4)

The Bencrom River is the most impoverished stream site of the Network. Species composition has remained relatively persistent through time although there is high within-year variation due to habitat patchiness. The fauna is dominated by two detritivorous stonefly species (*Amphinemura sulcicollis* and *Leuctra inermis*). Only one individual acid sensitive *Baetis* spp. was recorded in 1990. Other mayfly species, *Ameletus inopinatus* and *Siphlonurus lacustris*

Table 4.20.3

Significant trends in chemical determinands (July 1988 - March 1998)

Determinand	Units	Annual trend (Regression)	Annual trend (Seasonal Kendall)
NO_3	μeq l^{-1}	*+1.00**	-
DOC	mg l^{-1}	*+0.21***	*+0.14**

** Trend significant at $p < 0.05$; ** trend significant at $p < 0.01$; *** trend significant at $p < 0.001$*

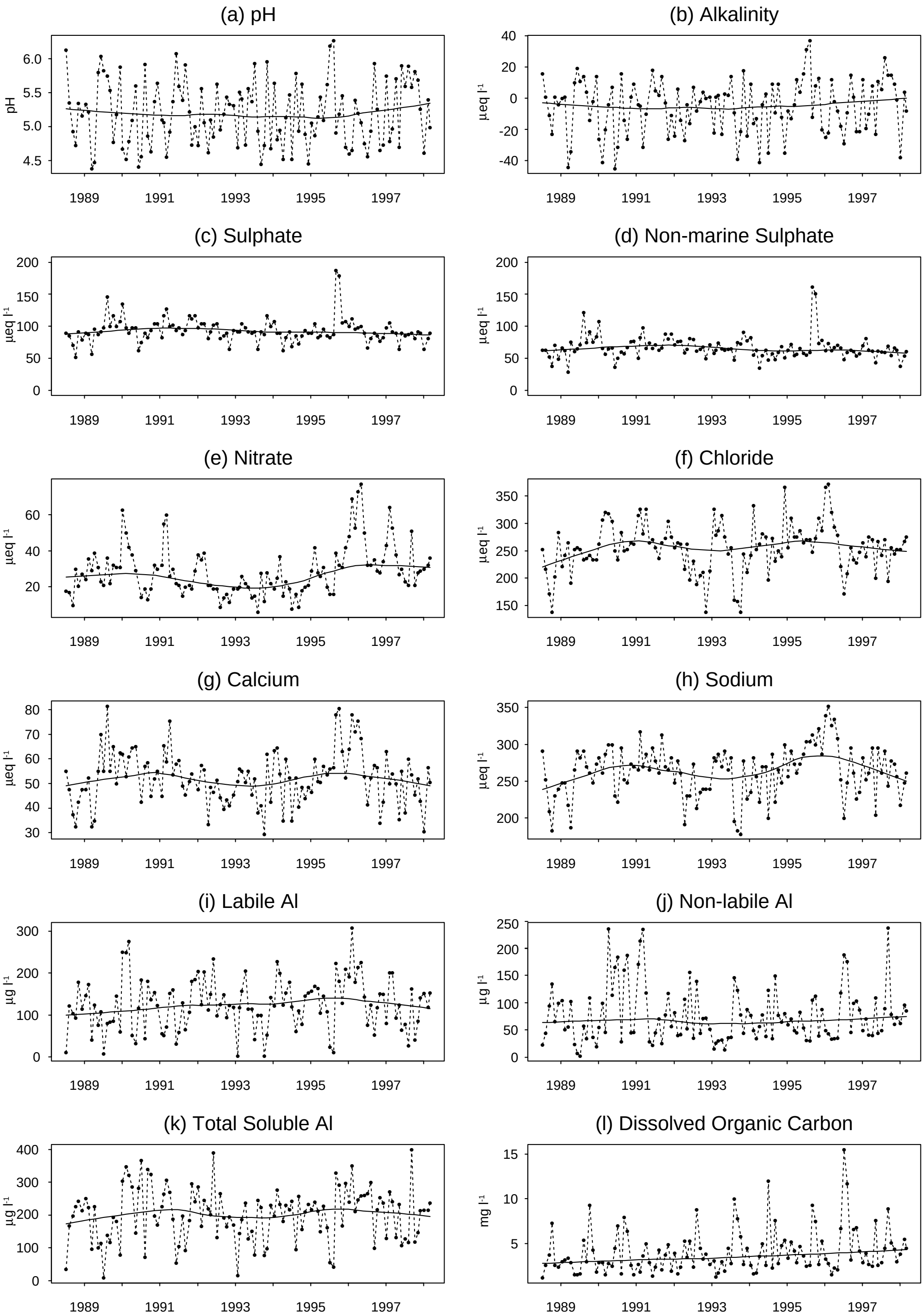


Figure 4.20.2

Bencrom River: summary of major chemical determinands (July 1988 - March 1998)

Smoothed line represents LOESS curve (Section 3.1.2)

Table 4.20.4

Bencrom River: trend statistics for epilithic diatom, macrophyte and macroinvertebrate summary data (1988 - 1998)

	Total sum of squares	Number of Taxa	Mean N_2 diversity	λ_1RDA/λ_2RDA	λ_1RDA/λ_1PCA
Epilithic diatoms	*101*	*56*	*3.1*	*0.44*	*0.40*
Macrophytes	*3*	*5*	*1.1*	*0.67*	*0.40*
Invertebrates	*471*	*18*	*3.9*	*0.18*	*0.17*

Variance explained (%)	within year	between years	linear trend	p unrestricted	p restricted
Epilithic diatoms	*44.6*	*55.4*	*9.3*	*<0.01*	*0.03*
Macrophytes	*	*	*38.0*	*0.06*	*0.23*
Invertebrates	*67.5*	*32.5*	*4.1*	*0.05*	*0.16*

were recorded intermittently in low numbers. Of the caddisflies, *Plectrocnemia* spp. was present in all years apart from 1989 and 1991, *Polycentropus* spp. appeared in 1997 and *Rhyacophila* spp. has been recorded on every survey since 1993. In common with other UKAWMN stream sites there has been a gradual increase in minimum species richness in more recent years (Section 7.3.2). However, RDA and associated permutation test show no significant linear trend between years.

Fish

(Figure 4.20.5)

This site has been electrofished since 1988 and trout densities have remained low. Mean population density of 0+ trout show some variation but no linear change over the ten years. Population density of >0+ trout seemed to show a decline between 1989 to 1995 but in 1996 and 1997 densities had returned to 1990 levels. Gaps in the data for fish weight make interpretation of the condition factor data difficult. However there has been a significant decline in condition factor of the >0+ fish ($p=<0.05$ df = 6) over the ten years indicative of a general worsening of conditions. No trend is apparent in the condition factor of the 0+ population.

Aquatic macrophytes

(Tables 4.20.4-5)

As for the other more acid UKAWMN stream sites, the permanently submerged flora of Bencrom River is largely restricted to a single liverwort species, in this case the acid tolerant, *Nardia compressa*. The abundance of filamentous algae and the red alga *Batrachospermum* sp. have varied considerably between years. Time is insignificant as a linear trend according to RDA and restricted permutation test.

Summary

The Bencrom River is severely acidified by a combination of high xSO_4 and NO_3 concentrations and this is reflected in its impoverished aquatic biology. NO_3 makes up a substantial part of the acid anion total, reaching levels comparpable to those of xSO_4 during the winter, when biological uptake within the catchment is minimal. The significant upward trend identified for NO_3 probably reflects differences in climate between the beginning and end of the monitoring period. Marine ions and NO_3 have both exhibited inter-annual variability during the monitoring period, but the only overall

Table 4.20.5

Bencrom River: relative abundance of aquatic macrophyte flora (1988 - 1997)
(see Section 3.2.3 for key to indicator values)

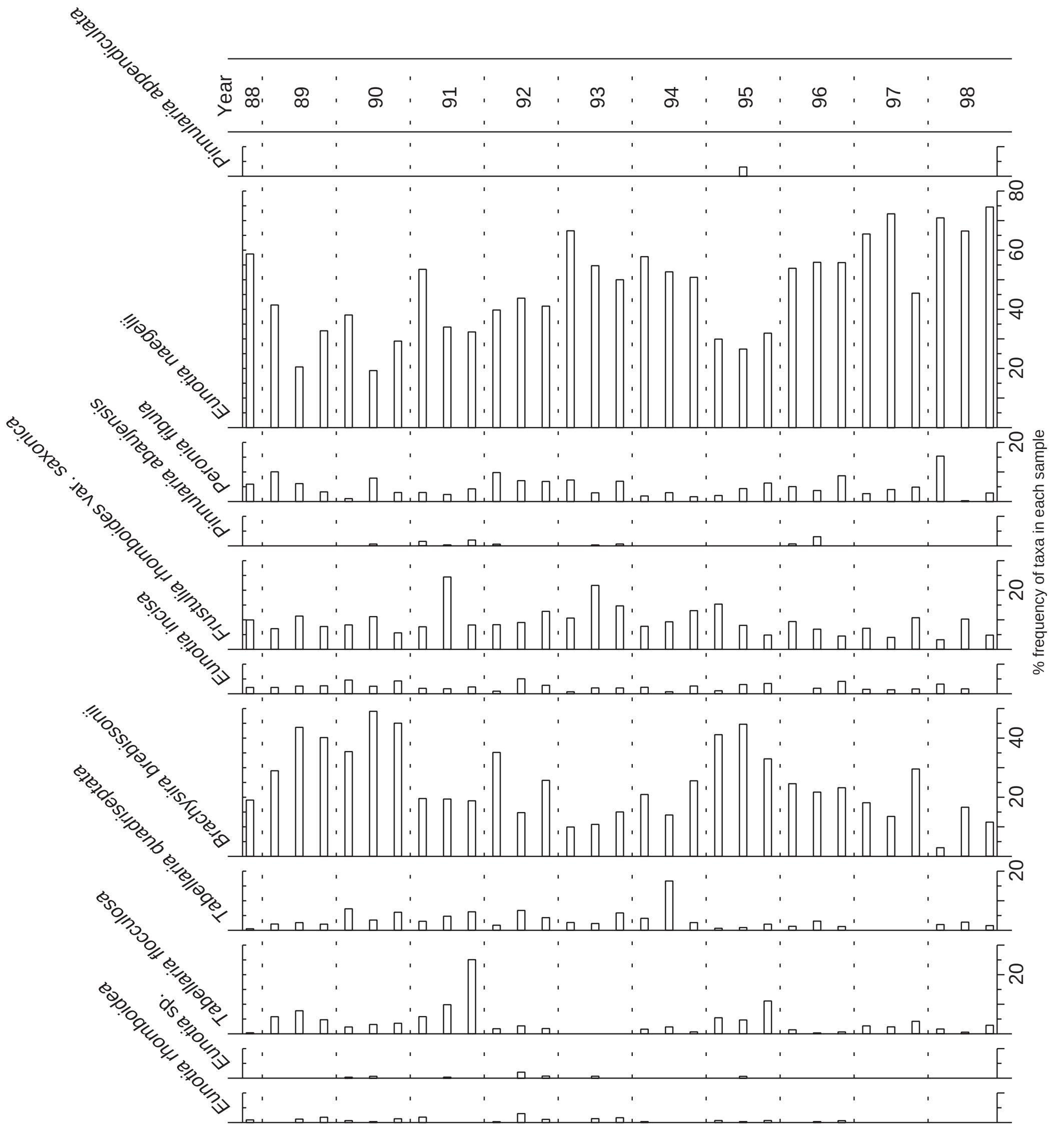
Abundance Taxon Year	88	89	90	91	92	93	95	96	97
INDICATOR SPECIES									
*Nardia compressa*3	2.2	6.2	10.6	8.6	3.7	2.5	2.9	1.3	1.3
OTHER SUBMERGED SPECIES									
Batrachospermum sp.	0.0	0.0	<0.1	<0.1	<0.1	0.5	0.0	0.0	<0.1
Filamentous green algae	7.8	9.7	3.0	3.9	3.1	2.2	30.1	1.4	1.7
Juncus bulbosus var. fluitans	0.0	0.0	<0.1	<0.1	0.0	0.0	<0.1	0.0	0.0
Pellia sp.	0.0	<0.1	<0.1	0.0	0.0	0.0	0.0	0.0	0.0
Scapania undulata	0.0	0.1	<0.1	<0.1	0.0	<0.1	0.0	0.0	0.0
total macrophyte cover excluding filamentous algae	2.2	6.3	10.6	8.6	3.7	2.5	2.9	1.3	1.3
TOTAL NUMBER OF SPECIES	2	4	6	5	3	4	3	2	3

change during this time appears to have been an increase in DOC. Variation between years in the epilithic diatom and macroinvertebrate communities appear to be strongly influenced by flow conditions, and no linear trends were detected in the biological datasets.

Figure 4.20.3

Bencrom River: summary of epilithic diatom data (1988 - 1998)

Percentage frequency of all taxa occurring at >2% abundance in any one sample



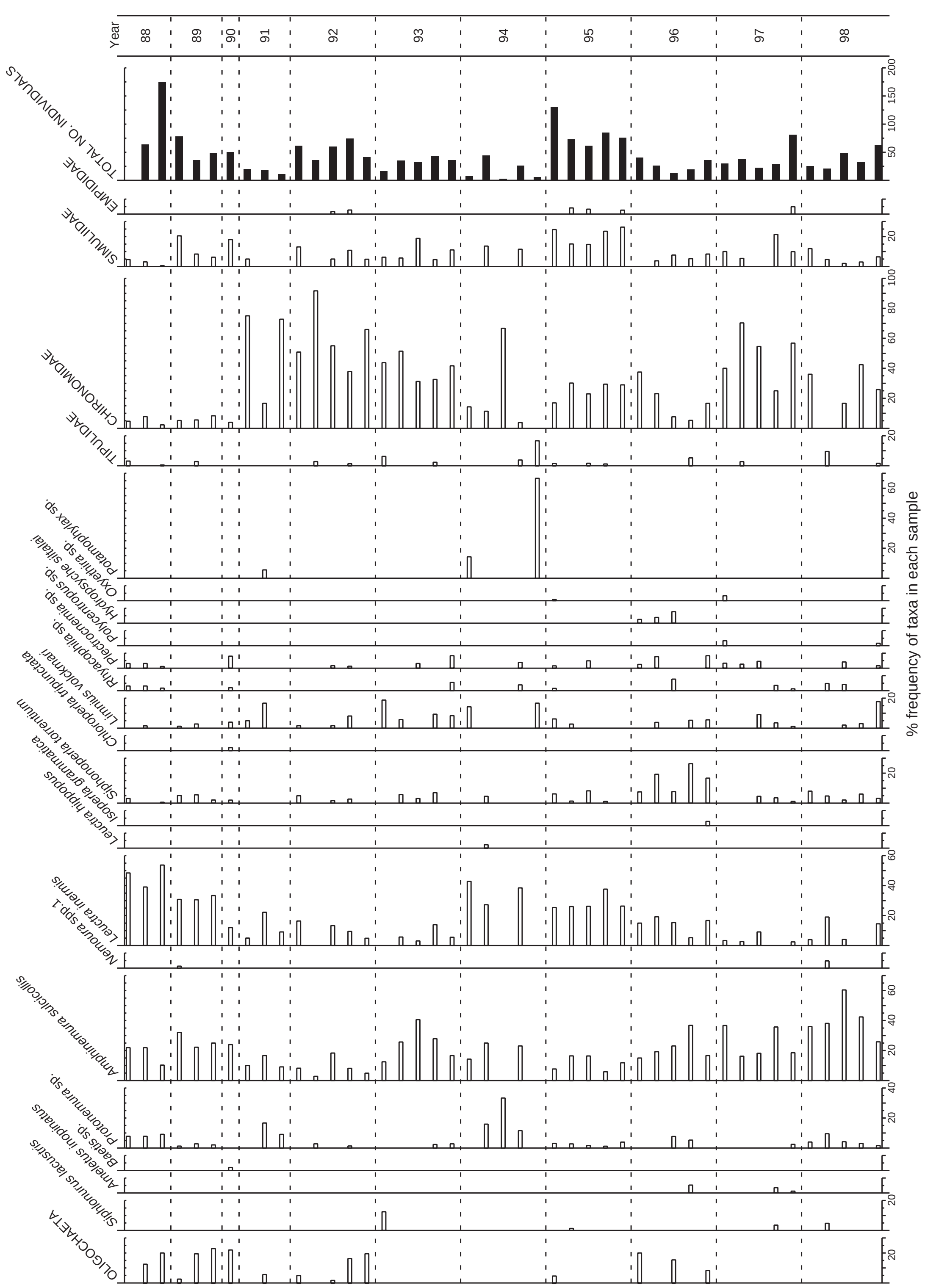


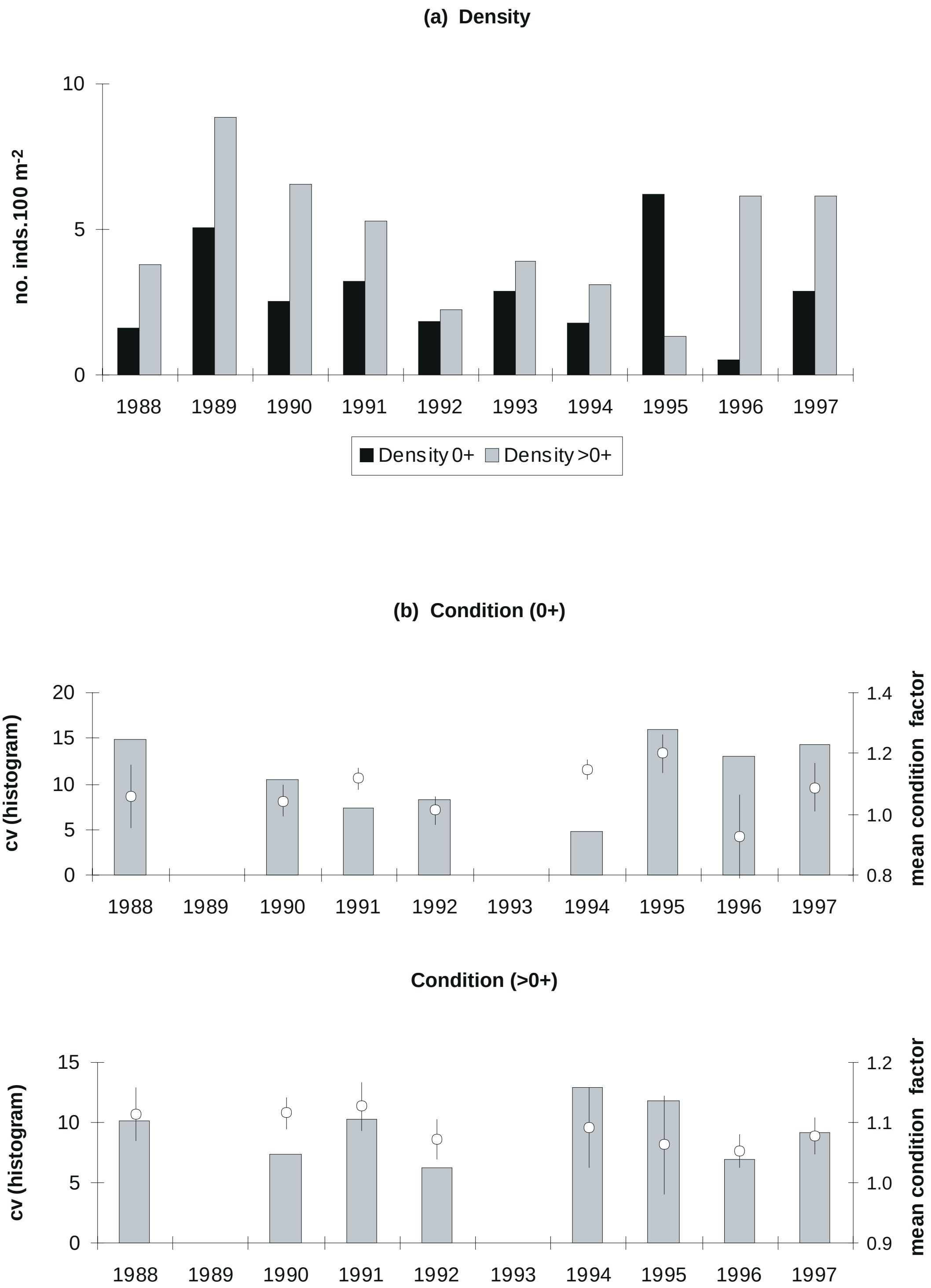
Figure 4.20.4

Bencrom River: summary of macroinvertebrate data (1988 - 1998)

Percentage frequency of taxa in individual samples

Figure 4.20.5

Bencrom River: summary of fish data (1988 - 1997)
(a) Trout population density for 0+ and >0+ age classes (individuals 100 m^{-2})
(b) Mean condition factor (with standard deviation) of the trout population and its coefficient of variation (histogram)



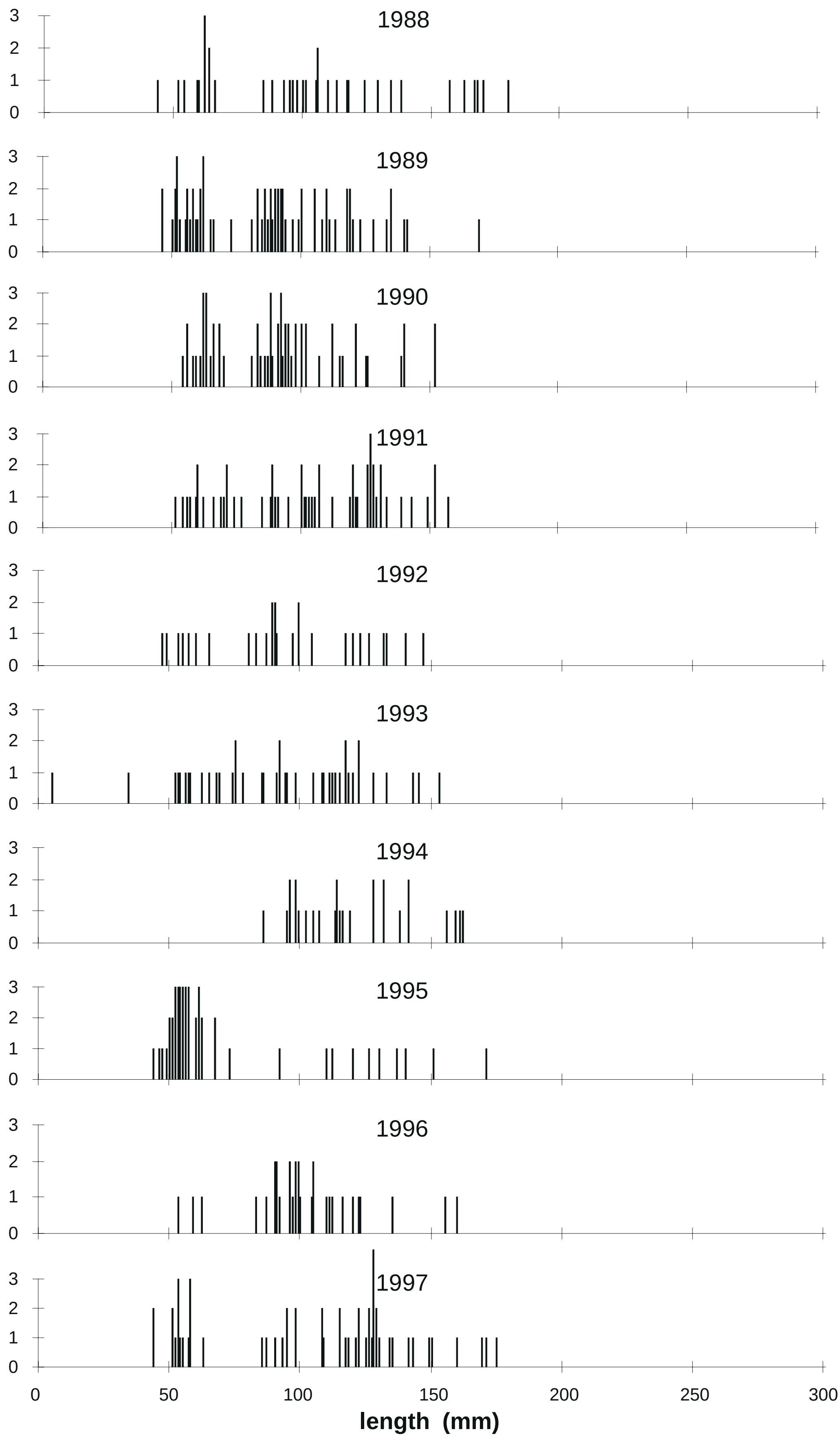


Figure 4.20.5

Bencrom River: summary of fish data (1988 - 1997)
(c) Trout length frequency summaries

4.21 Blue Lough

Site Review

Blue Lough lies in a col between the Silent Valley and the Annalong Valley in the Mourne Mountains, southeastern Northern Ireland. Diatom based pH reconstruction of a sediment core taken in 1992 suggest that the Lough has been acidic since at least the mid-nineteenth century (represented by the base of the core), but has acidified still further (i.e. pH 4.8 to 4.4) over the last one hundred years (Patrick *et al.* 1995). There is no evidence of land use change or any physical disruption within the catchment since the onset of monitoring in 1989.

Water Chemistry

(Figure 4.21.2, Tables 4.21.2-3)

Blue Lough is located just 2.3 km from the Bencrom River, and despite differences in catchment characteristics the two have remarkably

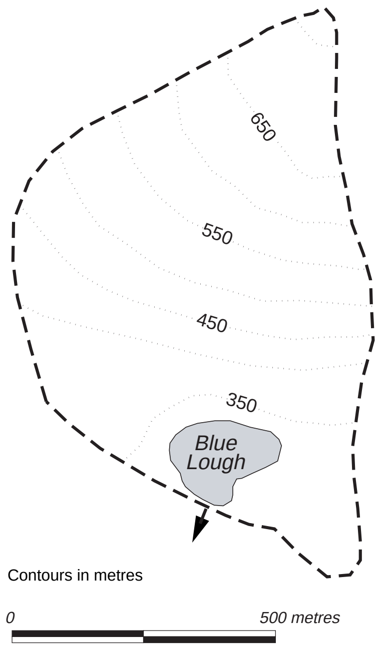


Figure 4.21.1

Blue Lough: catchment

Table 4.21.1

Blue Lough: site characteristics

Grid reference	*J 327252*
Lake altitude	*340 m*
Maximum depth	*5.0 m*
Mean depth	*1.7 m*
Volume	*3.6 x 10^4 m^3*
Lake area	*2.1 ha*
Catchment area (excl. lake)	*47.9 ha*
Catchment: lake area ratio	*19.9*
Catchment Geology	*granite*
Catchment Soils	*blanket peats*
Catchment vegetation	*moorland 100%,*
Net relief	*363 m*
Mean annual rainfall	*1629 mm*
1996 deposition	
Total S	*17 kg ha^{-1} yr^{-1}*
non-marine S	*15 kg ha^{-1} yr^{-1}*
Oxidised N	*7 kg ha^{-1} yr^{-1}*
Reduced N	*14 kg ha^{-1} yr^{-1}*

Table 4.21.2

Blue Lough: summary of chemical determinands, July 1990 - March 1998

Determinand		Mean	Max	Min
pH		*4.69*	*5.11*	*4.51*
Alkalinity	μeq l^{-1}	*-22.8*	*-4.0*	*-33.0*
Ca	μeq l^{-1}	*40.0*	*98.0*	*16.5*
Mg	μeq l^{-1}	*60.0*	*91.7*	*33.3*
Na	μeq l^{-1}	*257.0*	*369.6*	*121.7*
K	μeq l^{-1}	*12.8*	*25.4*	*7.7*
SO_4	μeq l^{-1}	*94.8*	*118.8*	*35.4*
xSO_4	μeq l^{-1}	*66.3*	*87.3*	*19.4*
NO_3	μeq l^{-1}	*28.6*	*72.9*	*10.0*
Cl	μeq l^{-1}	*275.8*	*400.0*	*152.1*
Soluble Al	μg l^{-1}	*377.2*	*520.0*	*280.0*
Labile Al	μg l^{-1}	*286.9*	*470.0*	*72.0*
Non-labile Al	μg l^{-1}	*90.2*	*394.0*	*18.0*
DOC	mg l^{-1}	*3.5*	*6.8*	*1.4*
Conductivity	μS cm^{-1}	*55.9*	*73.0*	*36.0*

similar chemistry. Mean xSO_4 and NO_3 values at Blue Lough (66 meq l^{-1} and 29 meq l^{-1} respectively) are virtually identical to those at Bencrom, and marine ion concentrations are also very similar. Blue Lough is more acidic, however, with a mean alkalinity of –23 μeq l^{-1}, a mean pH of 4.69, and the highest mean labile Al concentrations in the Network. It appears that these more severe conditions can be attributed to differences in Ca concentrations, which are on average 13 μeq l^{-1} lower at Blue Lough. This may reflect the Lough's higher elevation (340 m compared to 140 m at the Bencrom River sampling point), with thinner, high-altitude soils and perhaps less weatherable geology generating a smaller internal supply of base cations.

Monitoring of Blue Lough only began in 1990, and the data are therefore of limited value for trend determination. Regression analyses suggest that pH and alkalinity have risen over the eight years of monitoring, although time series (Figures 4.21.2a,b) show that much of this increase may result from two unusually high values in 1997. Neither trend is identified using SKT. No accompanying trends are observed in SO_4 or xSO_4, but visual inspection of the LOESS curve for xSO_4 (Figure 4.21.2d) suggests that concentrations have been falling fairly steadily since 1992. This is consistent with data from the nearby Hillsborough Forest deposition monitoring site (Campbell *et al.* 1998), which shows a steady decline in wet deposited xSO_4 since the beginning of the decade. A number of determinands show evidence of cyclical concentration changes over the study period, including NO_3, Cl, Na, Ca, labile and total Al. These variations appear to coincide with those at the Bencrom River, with peaks in 1995-1996 and perhaps also 1990-1991. Similar climatic controls are therefore likely. The only determinand exhibiting a clear and apparently linear rising trend, as at the other Northern Ireland sites, is DOC.

■ Epilithic diatoms

(Figure 4.21.3, Table 4.21.4)

The dominance of *Tabellaria quadriseptata* (pH optima 4.9) in the epilithon of Blue Lough emphasises the extremely acidic nature of the site. However, there is evidence of an increase in the representation of species with higher pH optima, including *Frustulia rhomboides* var. *saxonica* (pH optima 5.2) and *Brachysira brebissonii* (pH optima 5.3) since 1993, while *Navicula hoefleri* (pH optima 4.9) has decreased, and "sample year" is significant as a linear trend according to RDA and associated restricted permutation test. These changes point to a recent increase in pH and alkalinity and are consistent with evidence from LOESS plots for pH and alkalinity. As these changes are accompanied by a long term reduction in xSO_4, it is possible that they represent early stages of biological recovery in response to reducing acid deposition. However, given the strong cyclicity in marine ions, further years of monitoring are required to verify whether this trend of improvement is sustainable. The diatom assemblage of sediment trap samples collected since 1992 do not show

Table 4.21.3

Significant trends in chemical determinands (July 1990 - March 1998)

Determinand	Units	Annual trend (Regression)	Annual trend (Seasonal Kendall)
pH	-	*+0.018**	-
Alkalinity	μeq l^{-1}	*+1.18***	-
DOC	mg l^{-1}	*+0.18**	*+0.19**

** Trend significant at $p < 0.05$; ** trend significant at $p < 0.01$; *** trend significant at $p < 0.001$*

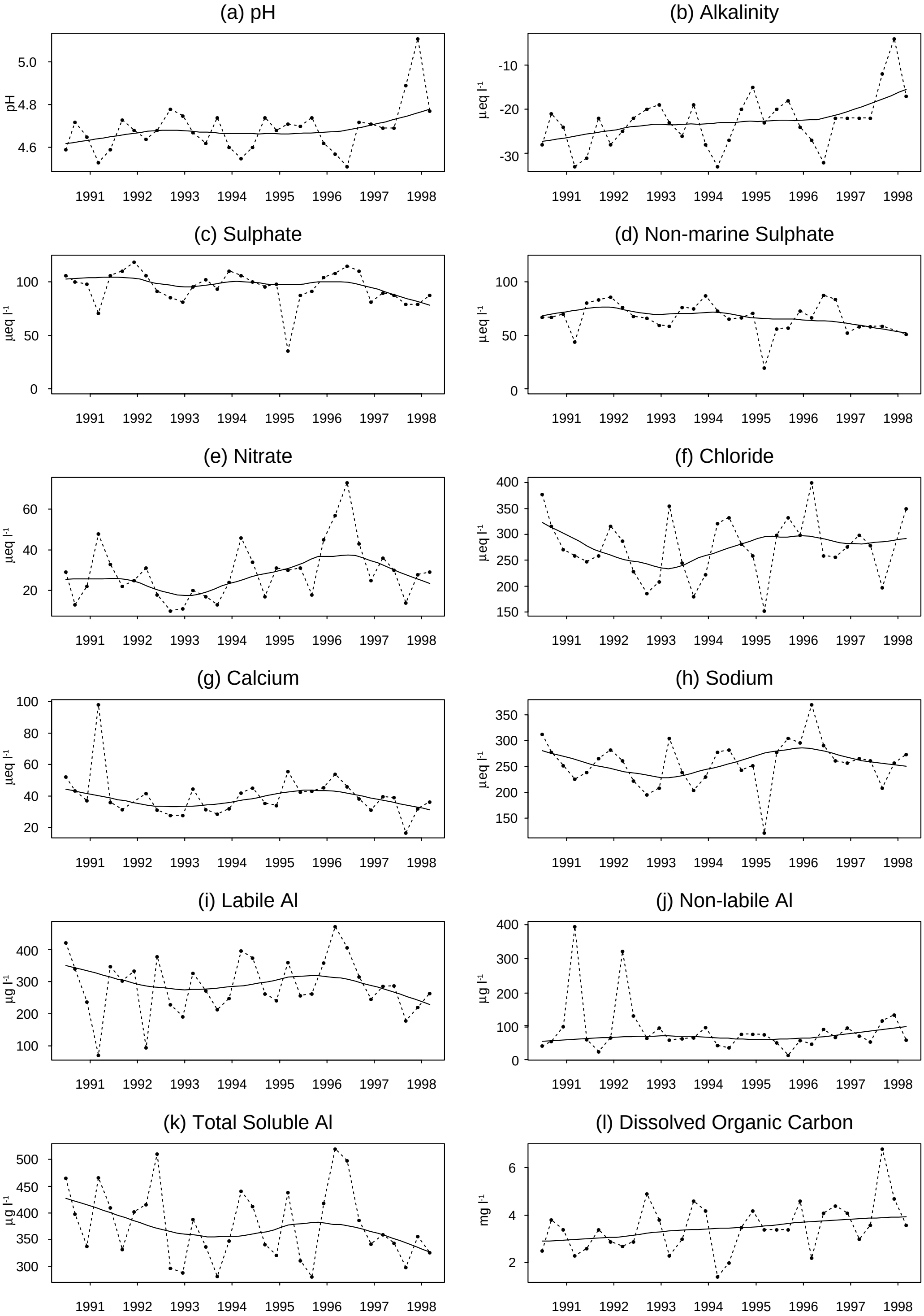


Figure 4.21.2

Blue Lough: summary of major chemical determinands (July 1990 - March 1998)

Smoothed line represents LOESS curve (Section 3.1.2)

Table 4.21.4

Blue Lough: trend statistics for epilithic diatom, macrophyte and macroinvertebrate summary data (1990 - 1998)

	Total sum of squares	Number of Taxa	Mean N_2 diversity	λ_1RDA/λ_2RDA	λ_1RDA/λ_1PCA
Epilithic diatoms	*192*	*87*	*3.7*	*0.53*	*0.50*
Macrophytes	*6*	*11*	*6.4*	*0.41*	*0.34*
Invertebrates	*813*	*17*	*2.4*	*0.68*	*0.52*

Variance explained (%)	within year	between years	linear trend	p unrestricted	p restricted
Epilithic diatoms	*52.5*	*47.5*	*10.8*	*<0.01*	*<0.01*
Macrophytes	*	*	*14.7*	*0.55*	*0.51*
Invertebrates	*47.2*	*52.8*	*14.4*	*<0.01*	*<0.01*

such clear trends with time (Figure 4.21.6).

Macroinvertebrates

(Figure 4.21.4, Table 4.21.4)

The impoverished fauna of Blue Lough is typical of an acid lake. Only the most acid tolerant mayfly family, the Leptophlebiidae are represented. Acid tolerant caddisflies *Plectrocnemia* spp. and *Polycentropus* spp. occurred in most years and the latter has increased in abundance over the last three years. The remaining benthos is composed of several species of Corixidae and water beetles, mainly *Arctocorisa germari*, *Callicorixa wollostoni* and *Potamonectes griseostriatus*. The Corixid *Glaenocorisa propinqua* was very abundant in 1997. Only one individual stonefly, *Leuctra hippopus* was recorded in 1994. There is a high turnover of species at this site, mainly driven by the highly mobile Corixidae and water beetles, which are aquatic both as adults and nymphs. “Sample year”, as a linear variable, accounts for 14% of the variance in the macroinvertebrate data according to RDA and is significant at the 0.01 level using the restricted permutation test. Despite recent small improvements in pH and alkalinity, the change in species composition cannot be attributed to changes in water chemistry.

Fish

(Figure 4.21.5)

Only three fish have been caught in the outflow of Blue Lough in the period monitored (1990-1997). It is not possible to ascertain the population status or any pattern in the data from these results. However, fears that the population had become extinct have been countered by the presence of one fish in the site in 1997. HABSCORE HQS values indicate that the site could potentially carry a reasonable density of fish.

Aquatic macrophytes

(Tables 4.21.4-5)

Blue Lough is characterised by a small number of acid tolerant species. *Isoetes lacustris* dominates the deeper water habitats, where the acidophilous moss *Sphagnum auriculatum* is also common. *Lobelia dortmanna* and *Juncus bulbosus* var. *fluitans* are the most abundant vascular species in shallow water, occuring in association with a

Table 4.21.5

Blue Lough: relative abundance of aquatic macrophyte flora (1989 - 1997)
(see Section 3.2.3 for key to indicator values)

Abundance Taxon Year	89	90	91	92	93	95	97
INDICATOR SPECIES							
Sphagnum auriculatum[4]	3	3	3	3	3	3	3
Juncus bulbosus var. *fluitans*[4]	2	2	2	2	2	2	2
OTHER SUBMERGED SPECIES							
Batrachospermum sp.	1	1	1	1	1	0	1
Filamentous green algae	3	3	2	3	3	2	2
Cephalozia bicuspidata	0	1	1	1	1	1	1
Cladopodiella fluitans	1	0	0	0	0	0	0
Diplophyllum albicans	0	1	0	0	0	0	0
Jungermannia/Nardia sp.	2	2	2	2	2	2	2
Isoetes lacustris	4	4	4	4	4	4	4
Littorella uniflora	0	0	0	1	1	0	0
Lobelia dortmanna	3	3	3	3	3	3	3
Sparganium angustifolium	0	1	1	1	0	1	1
TOTAL NUMBER OF SPECIES	8	10	9	10	9	8	9

number of liverwort species. There is no evidence of any change in species presence/absence or abundance over the last decade and time is insignificant as a linear variable according to RDA and associated permutation test.

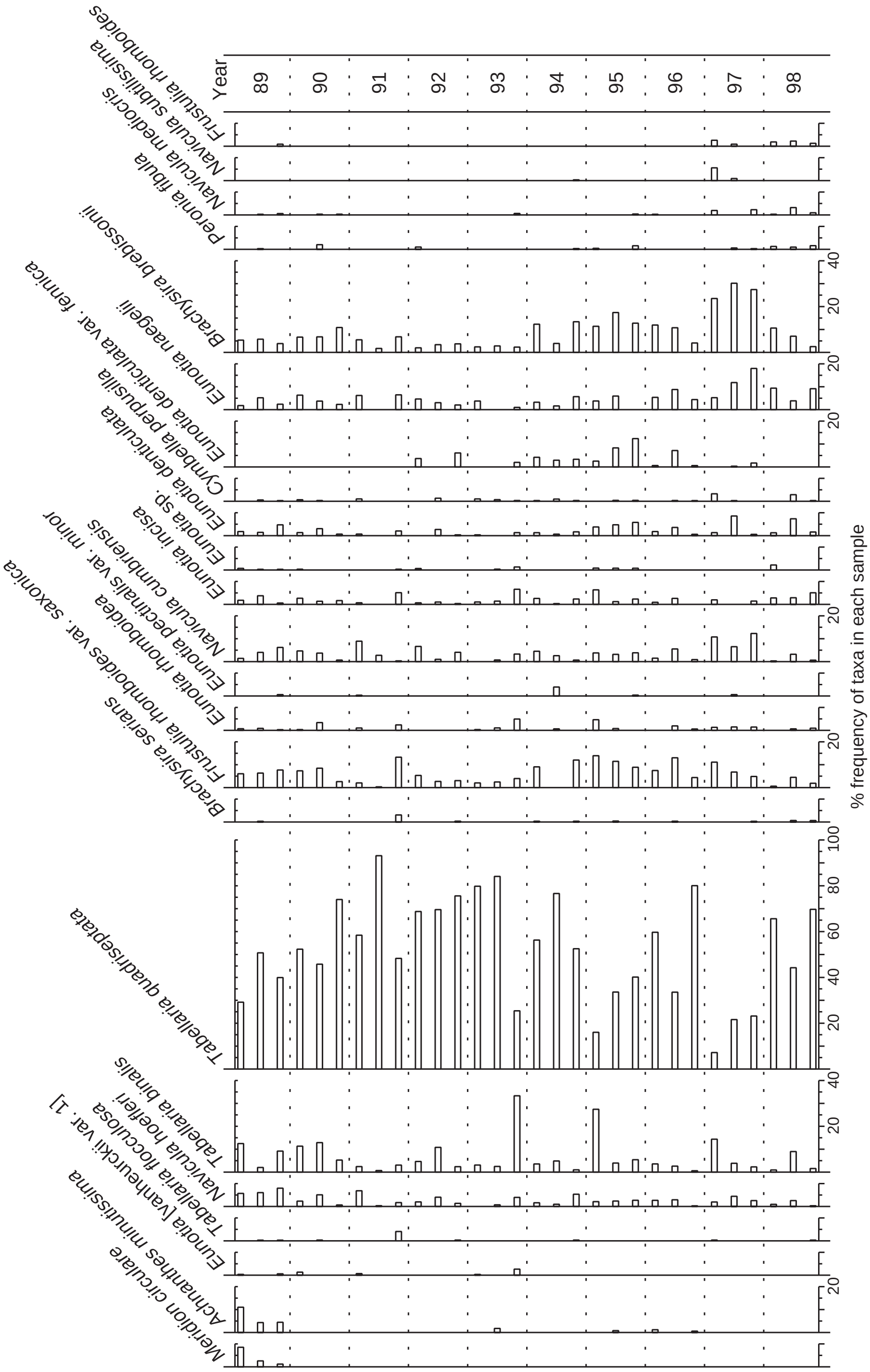
Summary

Blue Lough is highly acidic, with pollutant anion concentrations very similar to the nearby Bencrom River. NO_3 concentrations are high, and contribute significantly to the acidity of the Lough. Low pH and alkalinity relative to the Bencrom River can be attributed to a lower supply of base cations, in particular Ca, from internal sources. The only clear trend observed over eight years of monitoring is a rise in DOC, but there are some indications of falling xSO_4 and increasing pH and alkalinity in recent years, which could explain changes in the epilithic diatom community. The extent to which trends in the epilithic diatom and macroinvertebrate communities may represent sustainable recovery from acidification, as opposed to part of a climatic cycle, requires further monitoring for validation.

Figure 4.21.3

Blue Lough: summary of epilithic diatom data (1989 - 1998)

Percentage frequency of all taxa occurring at >2% abundance in any one sample



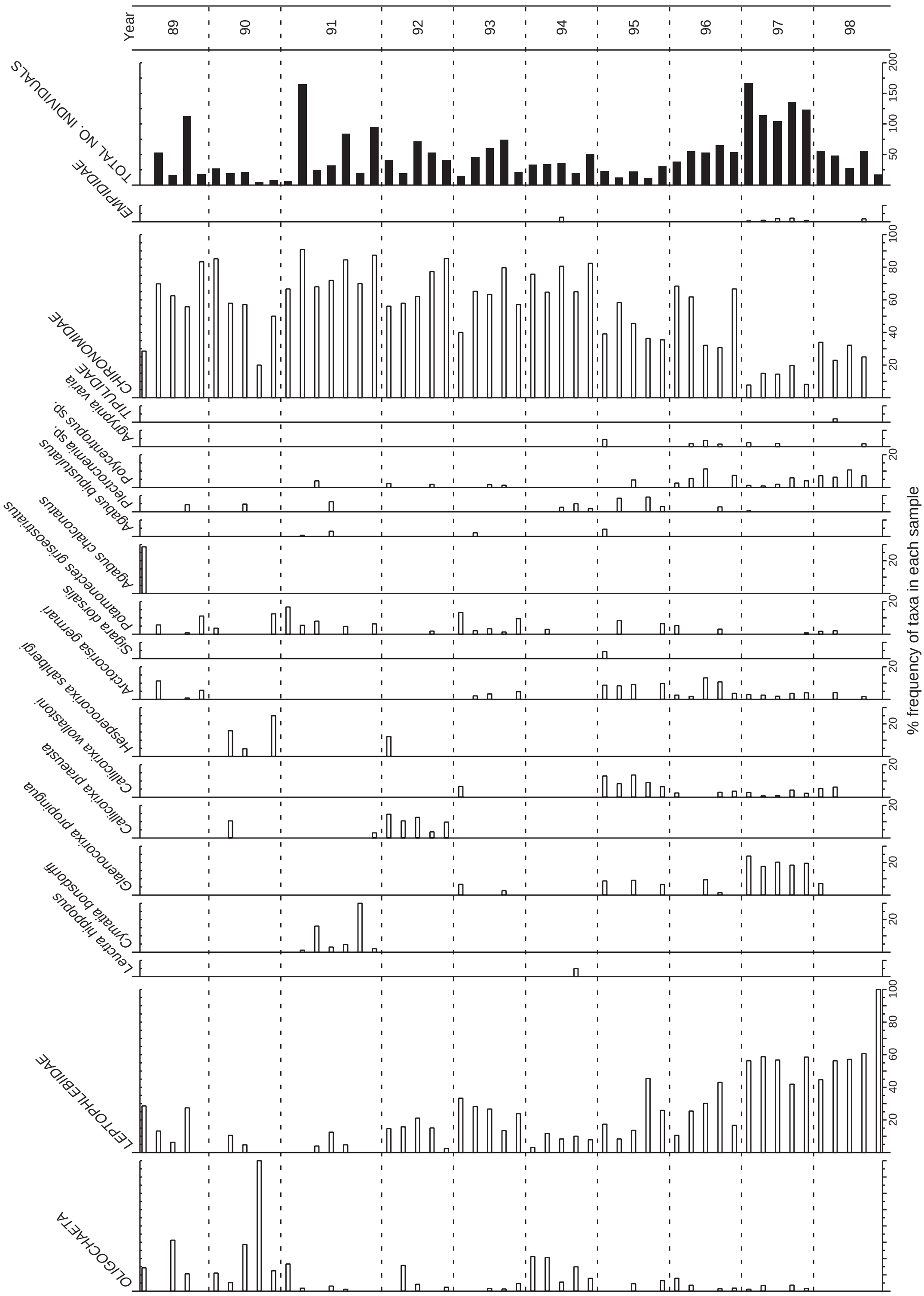


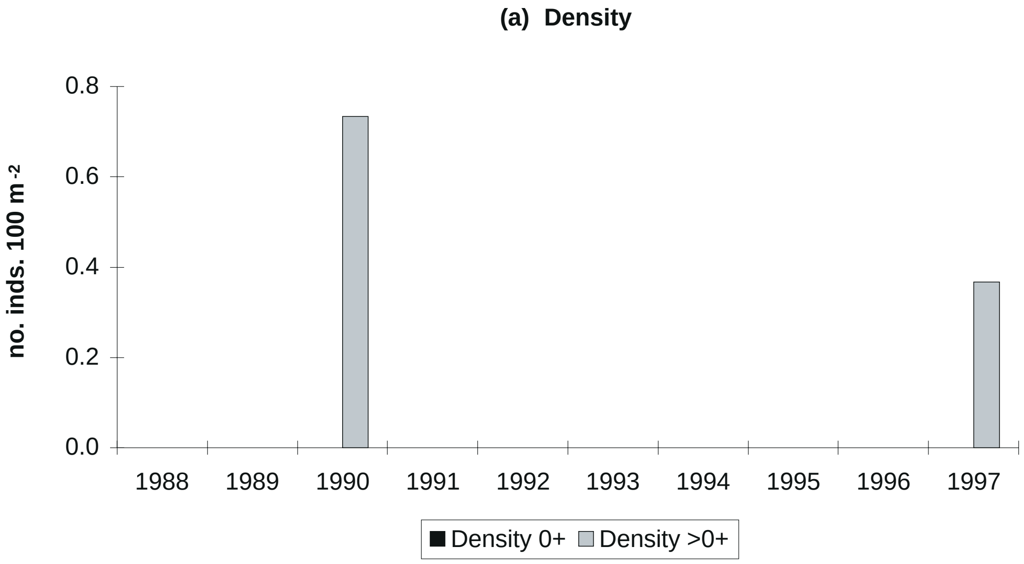
Figure 4.21.4

Blue Lough: summary of macroinvertebrate data (1989 - 1998)

Percentage frequency of taxa in individual samples

Figure 4.21.5

Blue Lough: summary of fish data (1990 - 1997)
(a) Trout population density for 0+ and >0+ age classes (individuals 100 m^{-2})
(b) Mean condition factor (with standard deviation) of the trout population and its coefficient of variation (histogram)



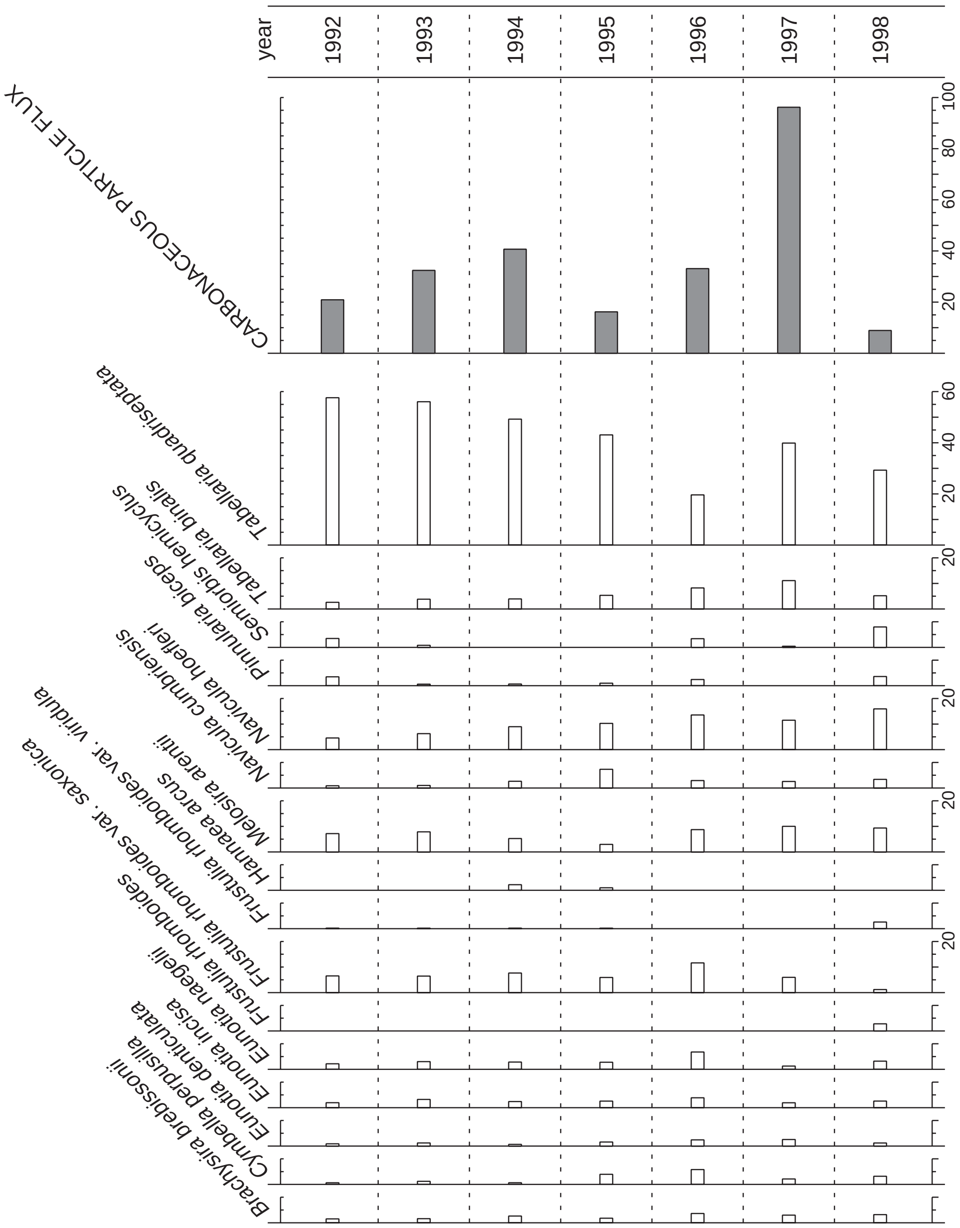
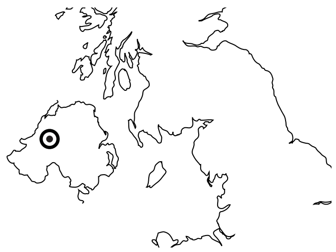


Figure 4.21.6

Blue Lough: summary of sediment trap data for diatoms and carbonaceous particles

Relative frequency of diatom taxa (>2% in at least one sample) at time of trap retrieval and estimated carbonaceous particle flux (no. trap^{-1} day^{-1}) for preceding year



4.22 Coneyglen Burn

Site Review

Coneyglen Burn, in the Sperrin Hills of Northern Ireland, drains a large area of moorland, although it is flanked by a relatively small area of coniferous forestry immediately upstream of the sampling stretches. The forest is approaching maturity but no felling has been carried out, and there is no other evidence of catchment disturbance since the onset of monitoring in 1989.

Water Chemistry

(Figure 4.22.2, Tables 4.22.2-3)

Coneyglen Burn has the highest mean pH and alkalinity of any UKAWMN site (6.51 and 161 µeq l^{-1} respectively). This is the result both of low levels of xSO_4 and NO_3 (means 30 µeq l^{-1} and 3 µeq l^{-1} respectively), consistent with the location of the catchment upwind of emission sources, and of

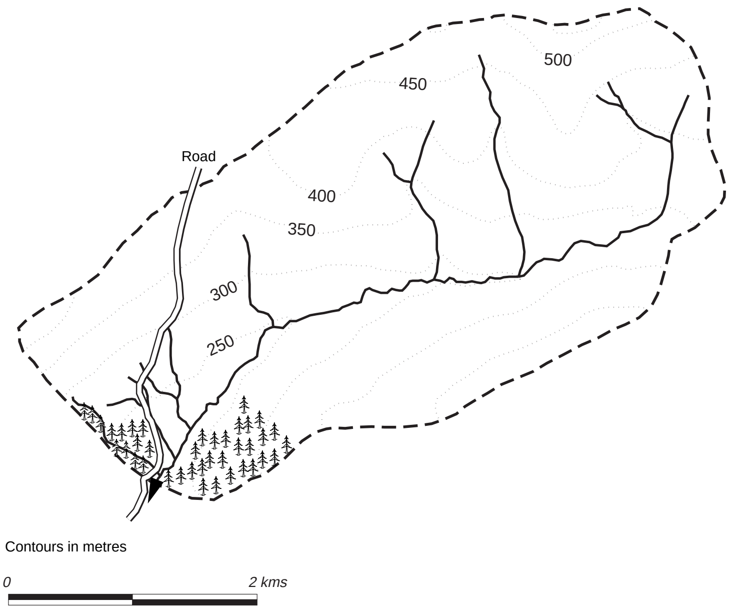


Figure 4.22.1

Coneyglen Burn: catchment

Table 4.22.1

Coneyglen Burn: site characteristics

Grid reference	*H 641884*
Catchment area	*1311 ha*
Minimum Catchment altitude	*230 m*
Maximum Catchment altitude	*562 m*
Catchment Geology	*schists*
Catchment Soils	*blanket peat*
Catchment vegetation	*moorland 95%, conifers 5%*
Mean annual rainfall	*1536 mm*
1996 deposition	
Total S	*15 kg ha^{-1} yr^{-1}*
non-marine S	*11 kg ha^{-1} yr^{-1}*
Oxidised N	*5 kg ha^{-1} yr^{-1}*
Reduced N	*13 kg ha^{-1} yr^{-1}*

Table 4.22.2

Coneyglen Burn: summary of chemical determinands, August 1990 - March 1998

Determinand		Mean	Max	Min
pH		*6.51*	*7.44*	*4.60*
Alkalinity	µeq l^{-1}	*160.6*	*461.0*	*-26.0*
Ca	µeq l^{-1}	*149.0*	*308.5*	*27.0*
Mg	µeq l^{-1}	*120.8*	*208.3*	*41.7*
Na	µeq l^{-1}	*239.1*	*373.9*	*139.1*
K	µeq l^{-1}	*10.3*	*23.1*	*5.1*
SO_4	µeq l^{-1}	*57.1*	*237.5*	*20.8*
xSO_4	µeq l^{-1}	*30.4*	*206.3*	*-0.8*
NO_3	µeq l^{-1}	*2.9*	*52.1*	*<1.4*
Cl	µeq l^{-1}	*255.5*	*495.8*	*104.2*
Soluble Al	µg l^{-1}	*40.5*	*264.0*	*6.0*
Labile Al	µg l^{-1}	*8.0*	*211.0*	*<2.5*
Non-labile Al	µg l^{-1}	*33.3*	*82.0*	*<2.5*
DOC	mg l^{-1}	*8.3*	*26.9*	*1.7*
Conductivity	µS cm^{-1}	*55.2*	*83.0*	*31.0*

buffering by relatively large internal base cation sources (mean Ca = 149 µeq l^{-1}, mean Mg = 121 µeq l^{-1}).

Stream chemistry at Coneyglen Burn is however subject to major episodic fluctuations, and alkalinity fell below zero on six occasions during the monitoring period. Most episodes appear to have been caused by base cation dilution, but in addition, an extremely large xSO_4 pulse was recorded in October 1995, followed by a similarly large NO_3 pulse in Febuary 1996 (Figure 4.22.2d,e). In the first pulse, xSO_4 rose from 25 to 206 µeq l^{-1}, after which concentrations took around a year to return to normal levels. The initial increase did not generate a major acidic episode, however, because base cation levels remained high. In contrast the increase in NO_3, from below detection limits to 52 µeq l^{-1}, concided with a large dilution of Ca. Alkalinity fell to –26 µeq l^{-1} and pH to 4.62, and the labile Al peak of 211 µg l^{-1} compares to a maximum of 28 µg l^{-1} for the remainder of the study period.

It is thought that the xSO_4 pulse at Coneyglen Burn was the result of a severe drought during the summer of 1995 (Marsh, 1996), at which time river flows in the area fell to their lowest levels in ten years (National River Flow Archive, Institute of Hydrology). De-saturation of peats at this time is likely to have allowed re-oxidation of stored reduced S, with the resulting SO_4 flushed to the stream as the soil re-wetted during autumn (Bayley *et al.*, 1986). Similar, albeit less pronounced xSO_4 peaks can also be detected in time series for Beagh's Burn and the Bencrom River, suggesting that this climatic effect covered a wide area. The NO_3 pulse is believed to result from a combination of drought and, subsequently, an unsually cold winter, both of which are likely to have reduced uptake, and increased the supply of dead biomass for mineralisation and nitrification (Reynolds *et al.* 1992; Monteith *et al.*, in press). Very high NO_3 peaks were observed throughout the UKAWMN in Spring 1996, and possible mechanisms are discussed in Section 5.4.

Regression trend analysis suggests an increase in NO_3 over the monitoring period (Table 4.22.3). This is partly a function of the 1996 peak, but NO_3 concentrations also rose above detection limits during the following two winters (Figure 4.22.2e). This could indicate a transition from Stage 0 to Stage 1 N saturation according to the classification of Stoddard (1994), but it is also possible that winter maxima are slowly returning to pre-1996 levels. A similar recovery over several years was observed at the C2 catchment at Plynlimon following a drought in 1984 (Reynolds *et al.* 1992). This issue should be resolved by further sampling. No trends are observed in other major ions, but an extremely large linear increase in DOC (approximately 8 mg l^{-1} over 10 years) and an accompanying rise in non-labile Al are identified by both SKT and regression (Table 4.22.3, Figures 4.22.2j,l).

Epilithic diatoms

(Figure 4.22.3, Table 4.22.4)

The epilithic diatom assemblage of samples from Coneyglen Burn has varied markedly between years. *Synedra minuscula* (pH optima 6.0) is the

Table 4.22.3

Significant trends in chemical determinands (August 1990 - March 1998)

Determinand	Units	Annual trend (Regression)	Annual trend (Seasonal Kendall)
NO_3	µeq l^{-1}	*+0.64***	-
DOC	mg l^{-1}	*+0.80****	*+0.78*
Non-labile Al	µg l^{-1}	*+1.86***	*+2.42**

** Trend significant at $p < 0.05$; ** trend significant at $p < 0.01$; *** trend significant at $p < 0.001$*

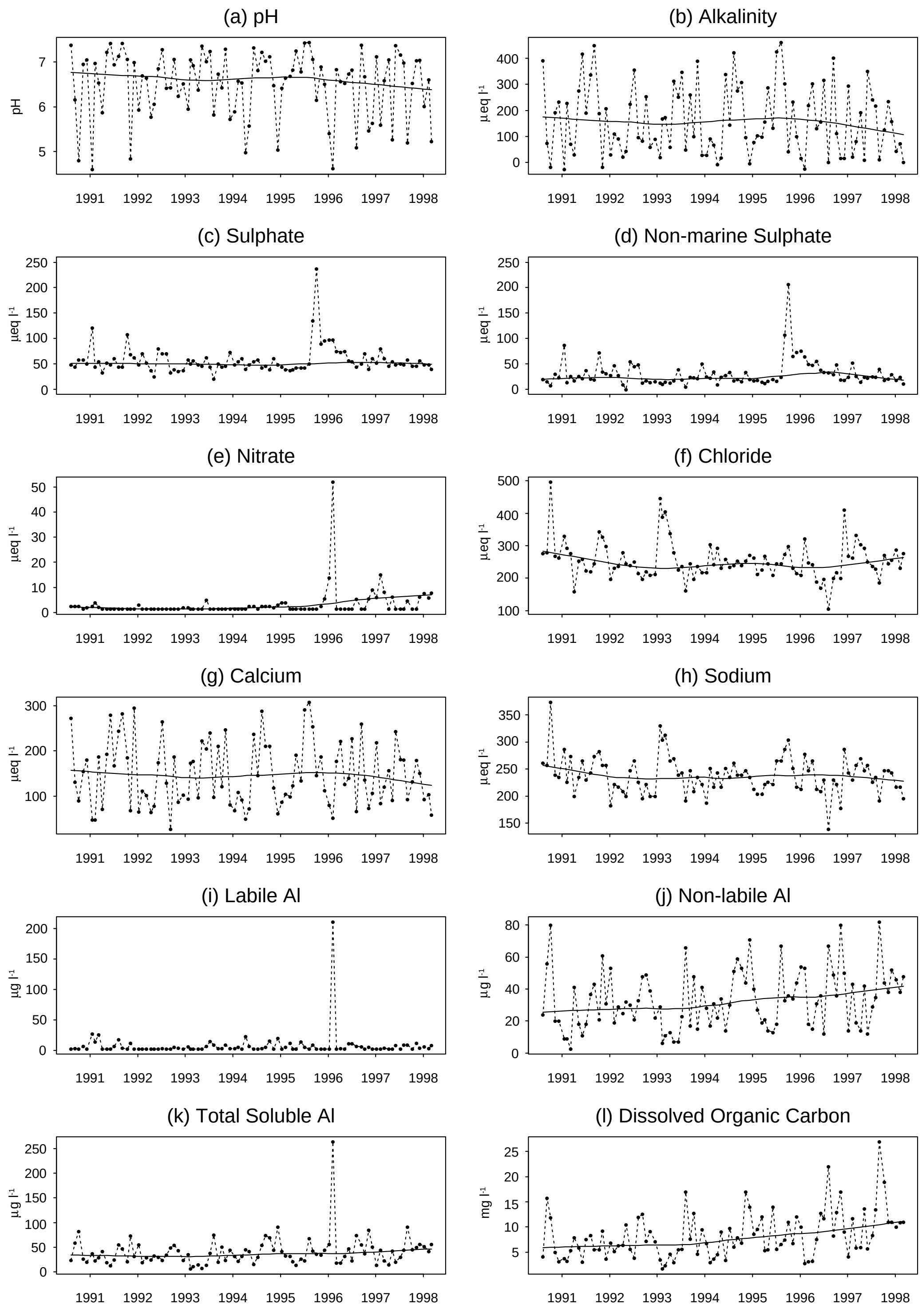


Figure 4.22.2

Coneyglen Burn: summary of major chemical determinands (August 1980 - March 1998)

Smoothed line represents LOESS curve (Section 3.1.2)

Table 4.22.4

Coneyglen Burn: trend statistics for epilithic diatom, macrophyte and macroinvertebrate summary data (1989 - 1998)

	Total sum of squares	Number of Taxa	Mean N_2 diversity	λ_1RDA/λ_2RDA	λ_1RDA/λ_1PCA
Epilithic diatoms	*448*	*110*	*5.1*	*0.60*	*0.49*
Macrophytes	*4*	*5*	*2.1*	*0.12*	*0.11*
Invertebrates	*357*	*32*	*2.6*	*0.68*	*0.49*

Variance explained (%)	within year	between years	linear trend	p unrestricted	p restricted
Epilithic diatoms	*29.5*	*70.5*	*13.4*	*<0.01*	*<0.01*
Macrophytes	*	*	*7.8*	*0.68*	*0.48*
Invertebrates	*44.9*	*55.1*	*13.9*	*<0.01*	*<0.01*

most abundant species in most samples. However, it was relatively scarce in 1992 and 1993, when several *Eunotia* taxa, and particularly *E.exigua* (pH optima 5.1), indicative of more acid conditions, were more abundant. Water chemistry data for Coneyglen Burn suggest that the summer months of 1992 and 1993 were unusually episodic. Rainfall data for the nearby Meteorological Station (Lough Fea) is incomplete for the summer of 1993 but demonstrates that July and August in 1992 were unusually wet. It is therefore possible that the hydrological regime has had a significant effect on the diatom flora of this site through the effect of variations in surface run-off relative to base-flow on pH. Over the nine year period (1989-1997) there has been a general decline in the relative abundance of *Achnanthes minutissima* (pH optima 6.3) and an increase in *Tabellaria flocculosa* (pH optima 5.4), which suggests the stream is becoming gradually more acidic. This is supported by LOESS plots which suggest a recent decline in pH. RDA and associated restricted permutation test show the time trend to be significant at the 0.01 level

Macroinvertebrates

(Figure 4.22.4, Table 4.22.4)

The fauna is dominated by the predatory stonefly *Siphonoperla torrentium* which was present in high densities throughout the study. Much of the benthos is characterised by detritivorous stoneflies (*Leuctra inermis*, *Brachyptera risi* and *Amphinemura sulcicollis*) and a relatively diverse community of water beetles. Three years, 1992, 1993 and 1997 had very large populations of Simuliidae larvae. 1994 was a poor year both in terms of number of species and abundance due to adverse sampling conditions. The caddisfly, *Hydropsyche siltalai*, which had been present in the first few years was absent during 1994 and 1995, and then reappeared in 1996. The acid sensitive mayfly *Baetis* spp. was first abundant in 1992 and 1993 then declined and has since reappeared in 1997. The mayfly *Heptagenia lateralis* also disappeared during the middle of the monitoring period then reappeared in 1998. The recent change in species composition is supported by a significant linear time trend at the 0.01 level according to RDA and associated permutation test and may indicate a general improvement in conditions.

Fish

(Figure 4.22.5)

Coneyglen Burn has been electrofished since 1990. Trout densities are in the middle range of those found in the Network sites. The population density of 0+ fish shows a general increase which is accompanied by a general decrease in

Table 4.22.5

Coneyglen Burn: relative abundance of aquatic macrophyte flora (1989 - 1997)
(see Section 3.2.3 for key to indicator values)

Abundance Taxon Year	89	90	91	92	93	95	96	97
INDICATOR SPECIES								
Hygrohypnum ochracheum[1]	22.2	21.1	4.3	14.9	18.1	15.4	8.8	18.6
Fontinalis squamosa[2]	13.1	6.8	7.1	10.1	7.6	7.3	13.8	7.8
OTHER SUBMERGED SPECIES								
Filamentous green algae	13.5	<0.1	17.6	<0.1	<0.1	11.9	6.3	3.7
Racomitrium aciculare	<0.1	<0.1	<0.1	0.2	<0.1	<0.1	0.8	0.2
Scapania undulata	1.8	3.7	0.5	4.3	4.0	0.5	0.9	1.4
Juncus bulbosus var. *fluitans*	0.0	<0.1	0.0	0.0	0.0	0.0	0.0	0.0
EMERGENT SPECIES								
Juncus acutifloris	0.0	<0.1	0.0	<0.1	<0.1	0.0	0.0	<0.1
Juncus effusus	0.0	<0.1	0.0	0.0	0.0	0.0	0.0	0.0
total macrophyte cover excluding filamentous algae	37.1	31.6	11.9	29.5	29.7	23.2	24.3	28.0
TOTAL NUMBER OF SPECIES	5	8	5	6	6	5	5	6

condition factor, although neither are statistically significant as linear trends over the eight years. The density of >0+ trout shows no notable trends over the sampling period but their mean condition factor shows a linear decline which in this case is statistically significant ($p = 0.05$ df = 6). The length frequency histograms show very poor recruitment in 1991 and 1992 but this did improve considerably in 1993 and there is evidence of this high recruitment following on in subsequent years. Unsurprisingly 1993 was a very poor year for >0+ trout.

Aquatic macrophytes

(Tables 4.22.4-5)

The composition and relatively high cover of the submerged aquatic macrophyte flora of Coneyglen Burn is indicative of the well buffered water chemistry of the site. The acid sensitive moss species, *Hygrohypnum ochraceum* and *Fontinalis squamosa* dominated the survey stretch, although the acid tolerant liverwort *Scapania undulata* was also abundant in patches. Considerable cover of filamentous green algae was also recorded in some years. Overall cover and relative species representation have remained very stable over the last eight years and time is insignificant as a linear variable using RDA and restricted permutation test.

Summary

Coneyglen Burn is not chronically acidified, with relatively low pollutant anion and high base cation concentrations, but can become acidic during high flows. Time series are dominated by very large pulses of xSO_4 and NO_3 in 1995-1996 following a major drought and subsequent cold winter, the effects of which lasted for at least a year. The NO_3 peak in particular generated a severe acidic episode. The only overall changes in stream chemistry during the monitoring period have been increases in DOC and labile Al. The interpretation of the significant trends in epilithic diatoms and macroinvertebrate communities appear to conflict, with the former suggesting deterioration and the latter if anything, suggesting an ammelioration of acid conditions.

Figure 4.22.3

Coneyglen Burn: summary of epilithic diatom data (1989 - 1998)

Percentage frequency of all taxa occurring at >2% abundance in any one sample

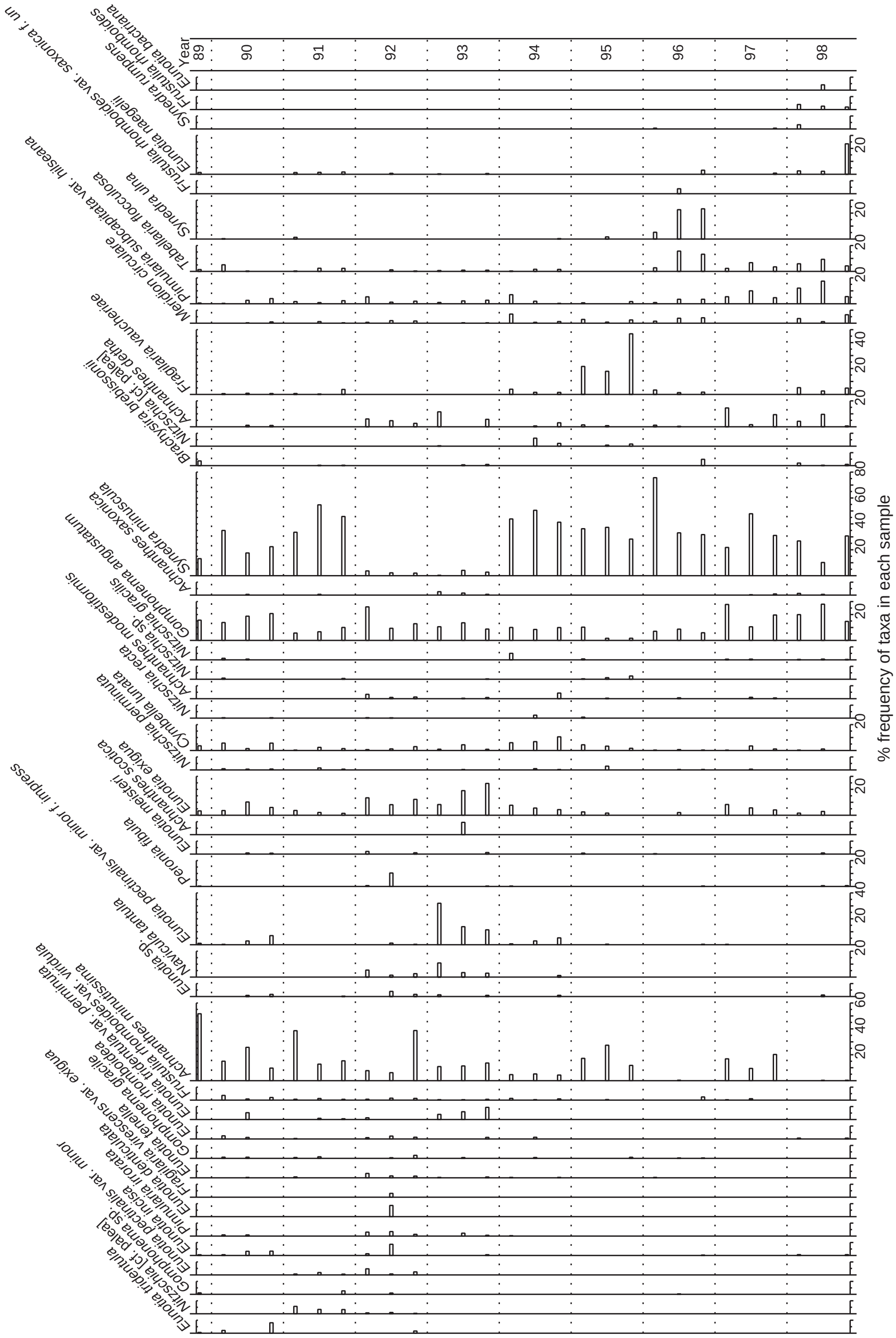


Figure 4.22.4

Coneyglen Burn: summary of macroinvertebrate data (1989 - 1998)

Percentage frequency of taxa in individual samples

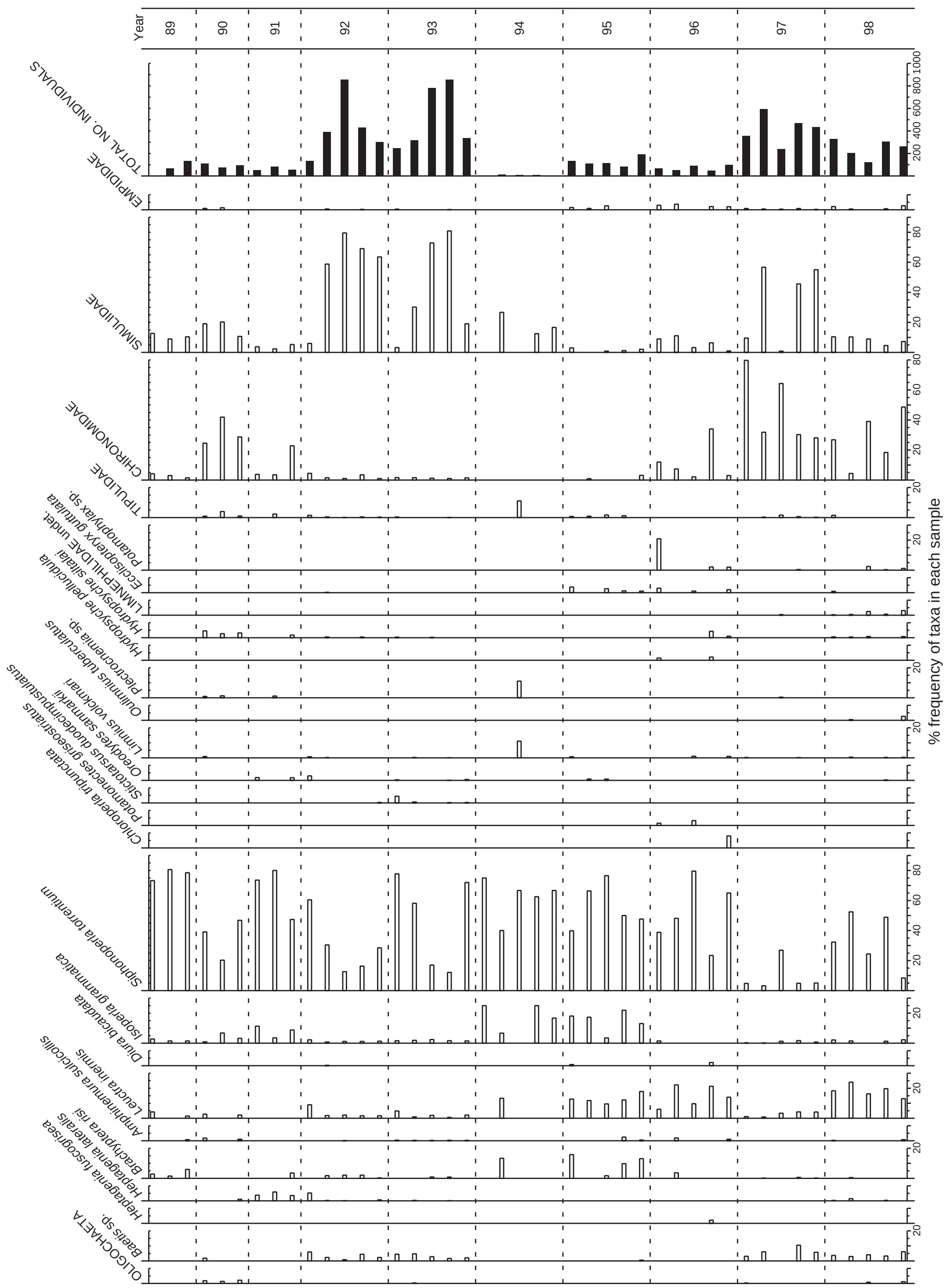
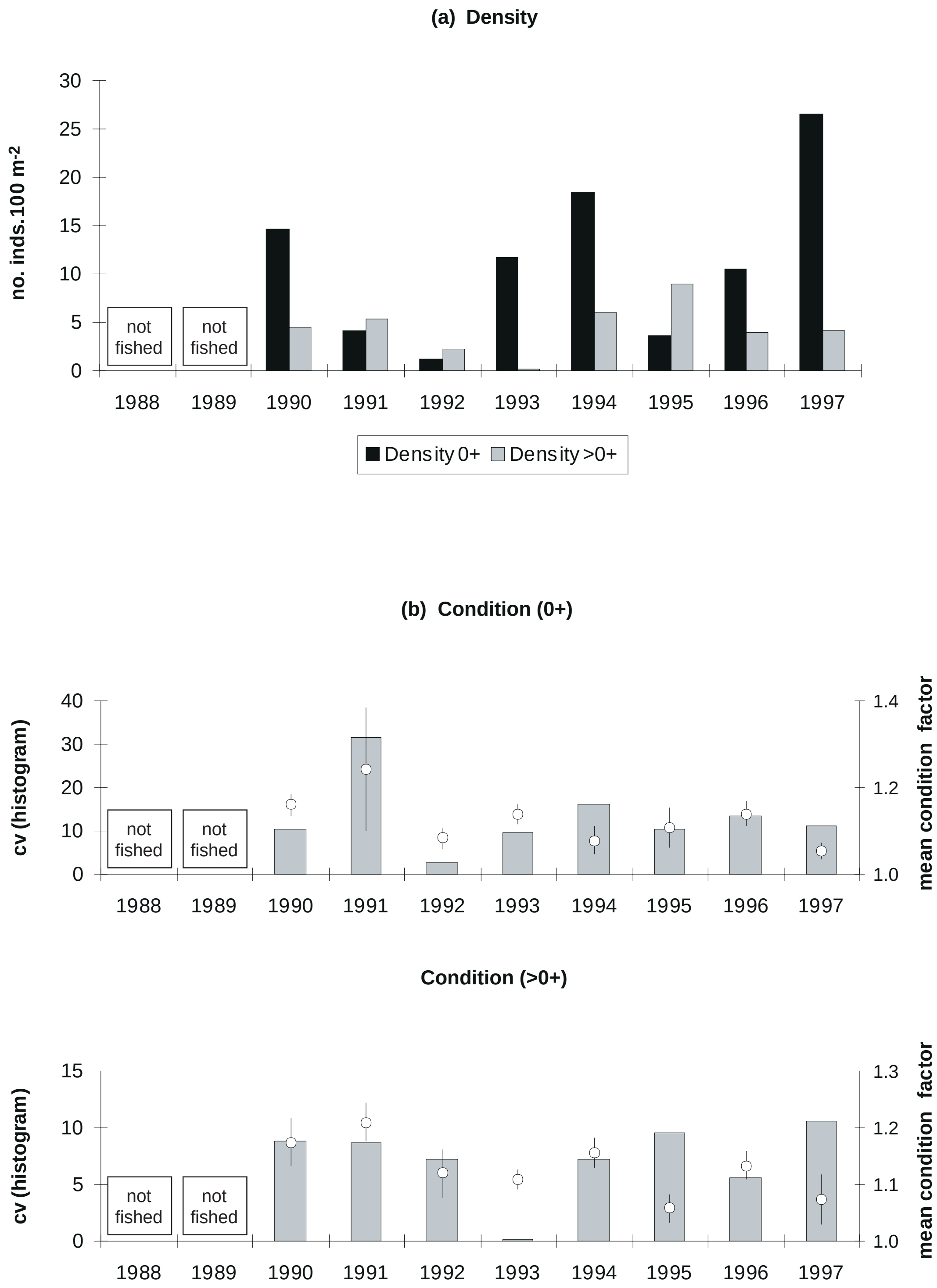


Figure 4.22.5

Coneyglen Burn: summary of fish data (1990 - 1997)
(a) Trout population density for 0+ and >0+ age classes (individuals 100 m^{-2})
(b) Mean condition factor (with standard deviation) of the trout population and its coefficient of variation (histogram)



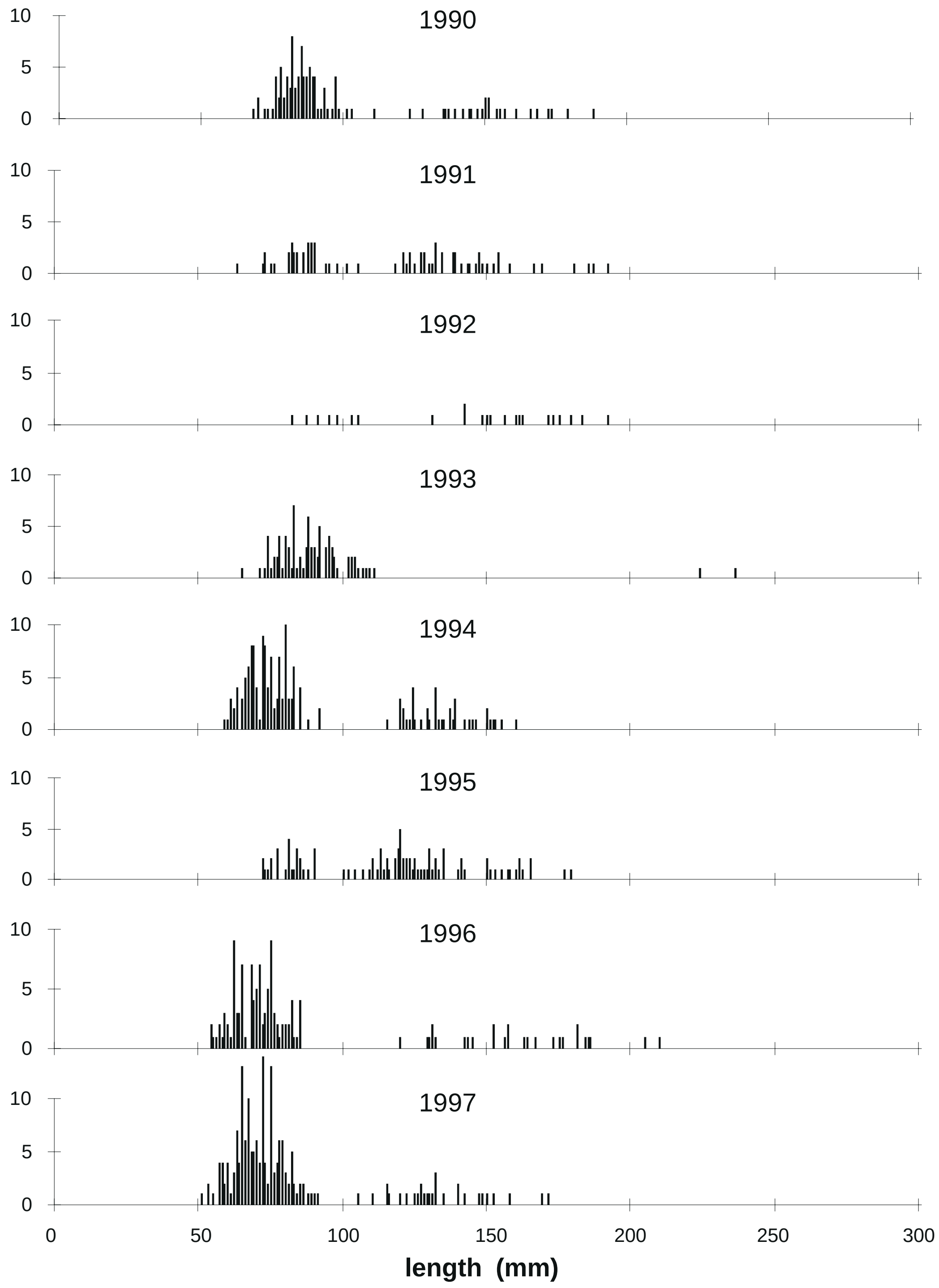


Figure 4.22.5

Coneyglen Burn summary of fish data (1990 - 1997)
(c) Trout length frequency summaries