7 Biology Discussion

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Introduction

Palaeoecological records and bio-monitoring provide convincing evidence that freshwater acidification has resulted in detrimental change to aquatic biota through the loss of sensitive taxa and a general reduction in diversity (e.g. Battarbee *et al*., 1990; Schindler *et al*., 1989; Rutt *et al*., 1990; Muniz, 1991; Jeffries, 1997). Emissions reduction policy is aimed at reversing the chemical effects of acidification, in order to improve biological status and perhaps even to restore ecosystems to a pre-impacted condition. However, evidence for chemical and biological recovery from acidification, even at the international scale, is still fairly limited and it is far from clear how aquatic biota in acidified upland waters in the UK might respond to improving conditions.

Some of the strongest evidence for a biological response to chemical recovery comes from lakes in the heavily impacted Sudbury area of Ontario, Canada, where marked chemical improvements followed major reductions in local smelter emissions (Gunn & Keller, 1990). Here, acid sensitive species of phytoplankton, zooplankton, and macroinvertebrates have re-invaded or increased in abundance as lake pH has increased (Gunn & Keller, 1990; Nicholls *et al*., 1992; Locke *et al*., 1994; Griffiths & Keller, 1992). Experimental studies have also demonstrated that an increase in pH is usually followed by colonisation of more acid sensitive species. However, time lags are usually observed, and there is some evidence that biota of more acidified systems take longer to respond, while the new community may not resemble the pre-acidified one (Jeffries, 1997).

There is rarely any inventory available to tell us what has been lost from acidified freshwaters. Fossil remains in lake sediments do however provide an excellent record of biological change through time for certain lake biota, and in particular the diatom community. Diatoms and other fossil organisms can also be used to set pre-industrial 'base-lines' which provide hypothetical biological restoration targets. However, there are several groups of freshwater organisms which do not leave strong fossil evidence and stream systems do not possess any sediment record. Historical and palaeoecological evidence alone is therefore insufficient to directly infer how sensitive freshwater ecosystems, as a whole, have been impacted by acidification. Consequently it is also unclear how these systems might respond biologically if and when their environments begin to recover chemically.

7.1 Spatial acidity-biology relationships

An alternative approach to understanding acidification impacts at the ecosystem level, is to use monitoring data to make biological comparisons of sites across an acidity gradient. Clear spatial correlations have been demonstrated between freshwater fauna and flora and acidity in many studies (e.g. Harriman and Morrison, 1982; Townsend *et al*., 1983; Roberts *et al*., 1985; Flower, 1986; Ormerod *et al*., 1987). In the following Sections (7.1.1-2) we present a descriptive overview of the relationship between monitored biological characteristics and acidity for UKAWMN sites only. It is important to note that although acidified, palaeoecological records demonstrate that some UKAWMN lakes are naturally moderately acid. In addition, the sites differ in many attributes other than acidity such as: other aspects of chemistry, substrate, altitude, and in the case of lakes, size, depth and exposure to wind, and these are also important in determining biological properties. The ecosystems of the less acid sites, therefore, do not necessarily provide good analogues for the pre-industrial condition of the more acid sites. Analysis of integrated physio-chemical and biological datasets for a considerably larger number of sites than those represented by the UKAWMN would be necessary for this issue to be adequately addressed.

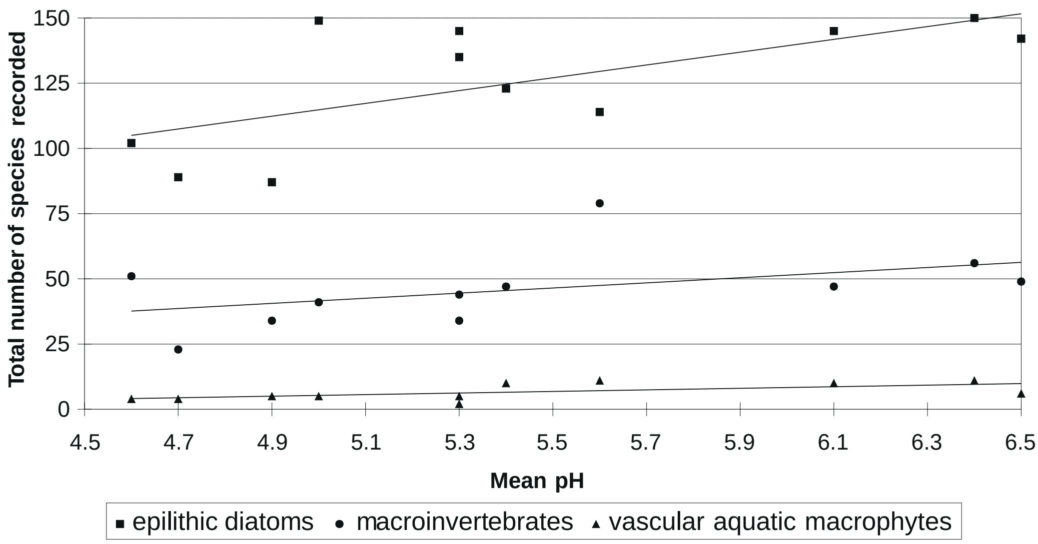


Figure 7.1
Relationship between the total number of species recorded (1988 - 1997) for epilithic diatoms, macroinvertebrates and vascular aquatic macrophytes (submerged or floating leaves) and the mean pH of UKAWMN lakes for the same period

Lines for each biological group fitted by linear regression

7.1.1 Biological characteristics of UKAWMN lakes in relation to acidity

Total species numbers for the biological groups monitored at UKAWMN lakes are generally positively correlated with pH (Figure 7.1), and this is consistent with findings from other studies (e.g. Schindler *et al*., 1989; Stewart & Freedman, 1989; Gunn & Keller, 1990; Jefferies, 1997). These measures of bio-diversity are derived from various methods of survey and analysis and are therefore not directly comparable. Consequently they should not be taken to represent differences in total community diversity between sites. For example, diatoms are sampled from only one habitat, i.e., the epilithon, and at only one time of year. Only 300 individual valves are identified from each microscope slide, and less common taxa may never be recorded even if they were collected within the original sample. Aquatic macrophyte data, on the other hand, should provide a relatively accurate inventory of higher plant species for each site.

The four strongly acid lakes with a ten year mean pH of 5.0 or less (Loch Grannoch, Blue Lough, Round Loch of Glenhead and Scoat Tarn) are generally species-poor. Their submerged vascular flora is mainly restricted to isoetid species which are adapted to low nutrient concentrations and a CO_2-only carbon source, i.e. *Isoetes lacustris* L. (Quillwort), *Lobelia dortmanna* L. (Water Lobelia), *Littorella uniflora* (L.) Asch. (Shoreweed). The Bulbous Rush *Juncus bulbosus* var *fluitans* L. is also abundant at these sites. These four species occur across the entire UKAWMN acidity gradient. The total number of epilithic diatom species counted in samples from Loch Grannoch, Blue Lough and Round Loch of Glenhead is low. Assemblages are dominated by the acidobiontic *Tabellaria quadriseptata* Knudson but are also well represented by *Eunotia*, *Navicula* and *Frustulia* species. Scoat Tarn is an exception, exhibiting a larger number of diatom species (predominantly *Eunotia* spp.), a common feature of other higher altitude oligotrophic lakes (Cameron pers. comm.). With the exception of Loch Grannoch, species representation of macroinvertebrates is also low; the acid tolerant family, the Leptophelbiidae, is the only mayfly representative, and otherwise assemblages are dominated by chironomids and relatively low numbers of acid tolerant beetle, Hemipteran, stonefly and caddisfly species. Loch Grannoch is surprisingly diverse for an acid lake, with several species of acid tolerant mayfly and caddisfly having been recorded. As a large water body, Loch Grannoch is fed by several sub-catchments with varying chemical characteristics. This, in addition to the greater variation in habitat type offered by a larger system, could account for the relatively enhanced site diversity. Trout densities in the outflows of all four lakes are low with those for Blue Lough, Loch Grannoch and Scoat Tarn particularly impoverished.

Llyn Llagi, Llyn Cwm Mynach, Loch Chon and Lochnagar (all with mean pH between 5.0 and 6.0) exhibit a range of biological characteristics. Lochnagar can be considered a statistical outlier, which seems to reflect the extreme altitude of the site (790 m). Here the aquatic macroflora may be restricted by a combination of factors including acidity, low temperatures, low nutrient availability, poor littoral substrate quality, prolonged winter ice cover and high winds. *Isoetes lacustris* and *Juncus bulbosus* var. *fluitans* are the only vascular plants at the site. Loch Chon, Llyn Cwm Mynach and Llyn Llagi all support *Myriophyllum alterniflorum* which is absent from the more acid sites, while the former two have sheltered, silty, littoral zones colonised by water lilies, *Nuphar lutea* (L.) Sm. and *Nymphaea alba* L., and emergent species including *Equisetum fluviatile* L. (Water Horsetail) and *Carex rostrata* Stokes (Bottle Sedge).

The total number of epilithic diatom species recorded for these four sites is intermediate for UKAWMN lakes, with the exception of Lochnagar for which numbers (like the next highest altitude site Scoat Tarn) are relatively high. Macroinvertebrate species richness at Llyn Llagi, Llyn Cwm Mynach and Lochnagar is also intermediate for UKAWMN lakes. These sites are characterised by moderate numbers of mayfly, stonefly, beetle and caddisfly species. Lochnagar is the only UKAWMN lake for which there is no record for Hemipterans. Species richness for Loch Chon is the highest for all UKAWMN lake sites, again possibly reflecting the diversity of habitats and spatial variation in chemistry in this relatively large lake with convoluted shoreline and sheltered bays. The relatively elevated calcium concentration of Loch Chon, compared to most other lakes, is also likely to have a beneficial influence on diversity. Numbers of mayfly and Hemipteran species in particular, greatly exceed those recorded in any other UKAWMN site. The trout populations in the outflows of these sites, all of which have relatively low labile Al concentrations, are generally high, while the density at Llyn Llagi is intermediate. Electro-fishing at Lochnagar is conducted at a distance down-stream of the water chemistry sampling point, and conditions here are likely to be better buffered and therefore less acid, than the reported chemistry for the loch.

The least acid lakes, Burnmoor Tarn, Loch Coire nan Arr and Loch Tinker (all with mean pH of greater than 6.0), exhibit high species richness of aquatic macrophytes, and epilithic diatoms. These sites are the only lakes which contain the acid sensitive charophyte species *Nitella flexilis*, and they also support populations of other relatively acid sensitive species including *Myriophyllum alterniflorum* (Alternate Water-milfoil) and the Bladderwort *Utricularia* sp. L., in addition to the isoetid species named above. The diverse diatom epilithon is dominated by taxa with only slightly acid optima, and particularly *Achnanthes minutissima* Kütz. and *Brachysira vitrea* (Grun.). Samples from Burnmoor Tarn include the normally planktonic *Cyclotella kuetzingiana* var. *minor*, although it is likely that this species is deposited on to the sampled substrate and is not truly epilithic (i.e. growing attached). The macroinvertebrates include numerous mayfly, stonefly, beetle and caddisfly species amongst other groups. The mildly acid conditions are not associated with elevated trout densities. The outflow of Loch Coire nan Arr is the only site to support even a moderate trout density, although it is possible that regulation of flow following the installation of a dam may have had a detrimental effect. It appears that although normally non-acid, occasional highly acid spate events (and associated high labile Al concentrations) (Section 4.11) may be important in limiting the population in the outflow of Burnmoor Tarn, while fish parasites have been identified as a possibly detrimental factor in the outflow of Loch Tinker.

7.1.2 Biological characteristics of UKAWMN streams in relation to acidity

The aquatic macrophyte communities of UKAWMN streams consist almost entirely of bryophytes. However, a general ecological distinction can be made between those relatively diverse sites, which include aquatic mosses, and those populated only by liverworts. Ormerod *et al.* (1987) found a clear relationship between aquatic macroflora and macroinvertebrate composition and acidity in Welsh streams, and similar relationships are apparent here. The identification of links between stream chemistry and the aquatic biota is complicated by the highly flow dependent (i.e. episodic) nature of stream acidity (Section 7.3.1). Sites with acid soils and relatively base-rich sources of groundwater show marked chemical variation, and the use of mean pH to characterise overall conditions is inadequate in representing the potentially limiting factor of acid episodes. The following classification is therefore based on the mean of pH values beneath the lower quartile for each site, in order to represent the more acid conditions experienced.

Those UKAWMN streams with a mean for the lowest 25% of pH values greater than 5.2, i.e., the least acid sites, Allt a'Mharcaidh (5.9), Allt Coire nan Con (5.3), Narrator Brook (5.4) and Coneyglen Burn (5.4), are clearly the most diverse. Their aquatic macrofloras are characterised by mixed communities of mosses and liverworts; truly aquatic (i.e. permanently submerged) mosses are absent from all other stream sites. The moss genus *Hygrohypnum* spp. Lindb. is dominant at three sites, whereas *Rhynchostegium ripariodes* (Hedw.) is the most abundant species at Narrator Brook. The acid sensitive red alga *Lemanaea* sp., has been recorded periodically in both the Allt a'Mharcaidh and Narrator Brook. All four sites have relatively diverse epilithic diatom floras, dominated by *Achnanthes minutissima*, and are often well represented by *Synedra minuscula* Grun., *Fragilaria vaucheriae* (Kütz) and *Gomphonema angustatum* [agg.] (Kütz). Macroinvertebrate species richness is the highest for all streams, with between 40 to 52 species having been recorded over the past decade. Mayfly and caddisfly species are particularly well represented. Total trout density is also higher than for all other streams and the best buffered of these, Allt a'Mharcaidh and Narrator Brook, exhibit significantly higher densities than the two more episodic systems.

Biological characteristics of the remaining seven stream sites are less easily characterised with regard to acidity. The submerged aquatic macroflora is confined to acid tolerant liverwort species, while the most acidic sites are largely monospecific (almost exclusively *Scapania undulata* (L.) Dum. in the River Etherow (< lower quartile mean pH 4.1), Old Lodge (pH 4.4), Beagh's Burn (pH 4.8) and the Afon Hafren (pH 4.8), and almost exclusively *Nardia compressa* (Hook.) in the Bencrom River (pH 4.6)). Dargall Lane, where labile Al concentration is relatively low, supports a moderate trout density, while density at the other sites, all of which have high labile Al concentrations, is very low. The macroinvertebrate assemblages of these sites are all dominated by stoneflies and caddisflies, and there is no obvious within-group relationship between species richness and water chemistry. The total number of epilithic diatoms recorded over the decade is relatively low but varies between sites. Large inter-annual variation in species representation at some sites appears to be primarily dependent on the extent to which variation in flow during summer influences acidity (Section 7.4.1). For example, the River Etherow is characterised by contrasting assemblages in high and low summer rainfall years and consequently the total number of taxa occurring over the last decade is higher than for permanently acid Old Lodge.

7.1.3 UKAWMN trout density and acidity

The trout populations of UKAWMN sites are sampled in streams and lakes outflows, and data are therefore directly comparable. Densities vary from very low (<1 trout per 100 m^2) to high (>20 trout per 100 m^2). The higher densities equate to those found in unpolluted chalk-streams (Beaumont pers. comm.). Most sites have lower densities than those predicted by HABSCORE HQS (Chapter 3, Table 7.1), the main exceptions being sites in northern Scotland, southwest England (Narrator Brook), and northwest Northern Ireland (Coneyglen Burn). These sites also tend to be the least acid deposition impacted

Table 7.1

Relationship between observed trout density and that predicted by HABSCORE HQS for 0+ and >0+ fish over the monitoring period

	0+	*>0+*
Loch Coire nan Arr	=	-
Allt A'Mharcaidh	+	=
Allt na Coire nan Con	-	-
Lochnagar	=	=
Loch Chon	+	=
Loch Tinker	-	-
Round Loch of Glenhead	-	-
Loch Grannoch	-	-
Dargall Lane	-	-
Scoat Tarn	-	-
Burnmoor Tarn	-	-
River Etherow	-	-
Old Lodge	-	-
Narrator Brook	+	=
Llyn Llagi	-	-
Llyn Cwm Mynach	+	-
Afon Hafren	*no data*	*no data*
Afon Gwy	*no data*	*no data*
Beagh's Burn	-	-
Bencrom River	-	-
Blue Lough	-	-
Coneyglen Burn	=	-

-: mean density lower than predicted
+: mean density higher than predicted
=: mean density similar to that predicted

on the Network. The data therefore suggest that factors related to acidification may limit the trout population across much of the remainder of the Network.

Mean trout densities for the complete UKAWMN record can be linked to mean water chemistry over the same period (Figure 7.2). Although there is only a weak relationship between density and pH (Figure 7.2a), Figure 7.2b suggests a link between trout density and labile Al concentration, with a roughly exponential decline in the maximum observed densities with increasing concentration. Densities above 10 fish per 100 m^2 are restricted to sites with mean labile Al concentration below 70 µeq l^{-1}. However, factors other than mean labile Al are clearly important, as four of the fourteen sites above this chemical threshold also have poor populations. The effect of labile Al on trout populations has been widely studied and is suspected of being a major cause of fish kills in acid sensitive waters (Kelso *et al*., 1986; Howells *et al*., 1990; Rosseland *et al*., 1990). Trout exposed to Al at low pH have been shown to undergo respiratory stress as a result of damage to gills (Meuller *et al*., 1991, Wilson *et al*., 1994). Experimental work at sub-lethal exposures (i.e. 30 µg l^{-1} at pH

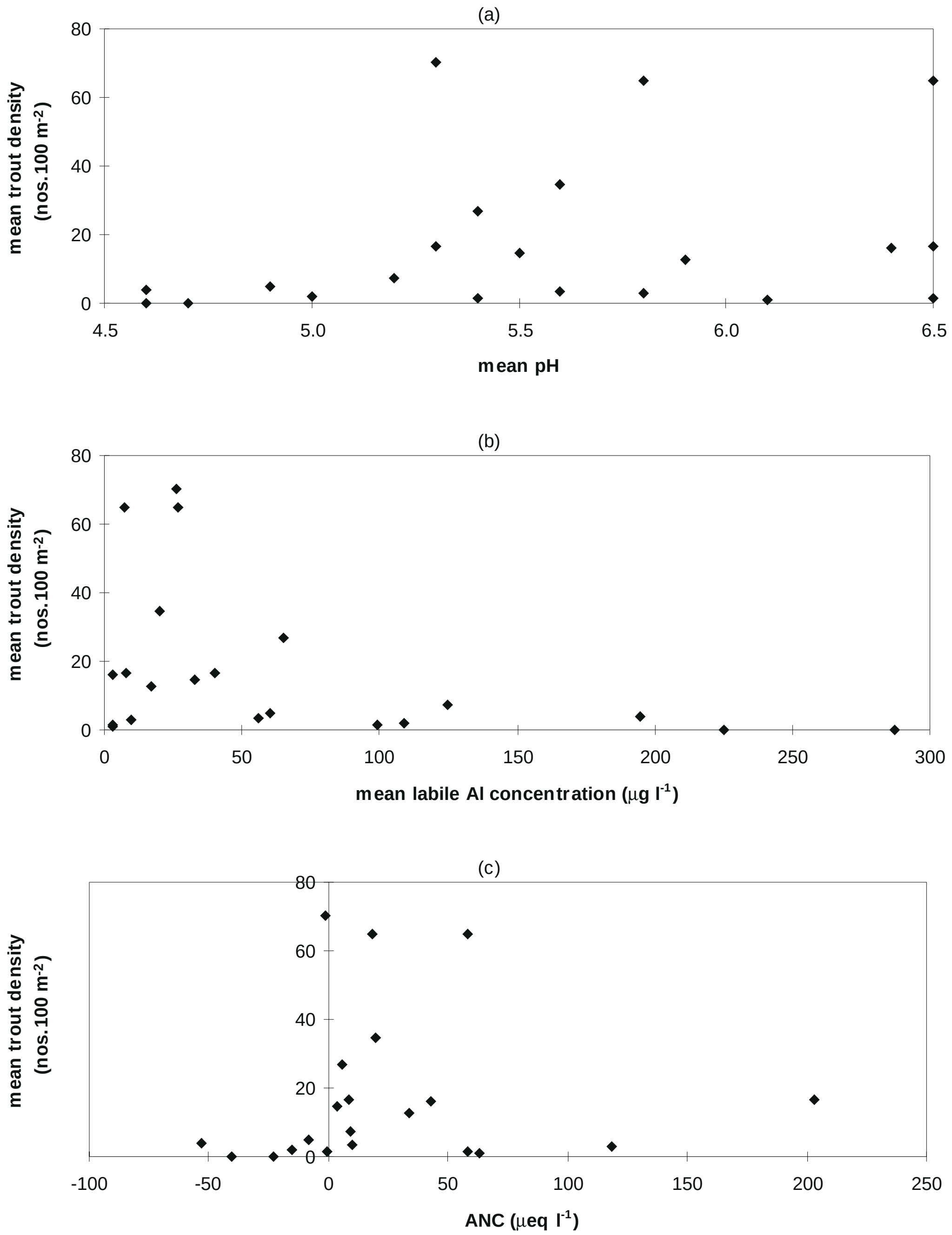


Figure 7.2

Relationship between mean trout density (nos. per 100 m²) at UKAWMN sites and mean water chemistry 1988-1998 (a) pH, (b) labile aluminium, (c) Acid Neutralising Capacity (ANC)

5.2) has shown depressed feeding rates, lowered red blood cell counts and a reduction in overall swimming activity (Wilson *et al*., 1994, Allin & Wilson, 1999).

Lien *et al* (1993) demonstrated a probabilistic relationship between damage to the trout population in Norwegian freshwaters and Acid Neutralising Capacity (ANC, Section 5.1.1). They proposed an ANC threshold of 20 µeq l^{-1} above which damage was unlikely to occur. UK Critical Loads freshwater maps are based on 0 µeq l^{-1} which, according to the same relationship, provides a 50% probability of damage to trout. The mean of 0 µeq l^{-1} ANC appears to represent a critical limit for UKAWMN trout data, with healthy populations present in several sites where mean ANC is only slightly positive (Figure 7.2c). Only very low densities are found at sites with negative mean ANC, and this is consistent with the findings of Harriman *et al*. (1995c). The only exception to this general rule is at Lochnagar, where mean ANC is fractionally negative but trout density is high. However, it is likely that the water chemistry for the Lochnagar fishing reaches is less acid than the outflow chemistry (see Section 4.4 Fish summary). It should be emphasised that this relationship is based on a 10 year average. Considerable inter-annual variation in ANC occurs at most sites (Figure 5.4), yet long time-series such as this dataset are rarely available for the assessment of long term mean conditions. It would therefore seem that, for sites which are vulnerable to marine influences, and for which only limited chemistry data are available, a 20 μeq l^{-1} ANC limit would provide a more suitable margin of protection.

7.2 Temporal trends in biological data

In the five year interpretative exercise (Patrick *et al.*, 1995; Lancaster *et al.*, 1996) statistical time trend analyses were used to detect biological change in UKAWMN data. These methods have been re-employed here (Section 3.2). Biological data have been analysed in isolation from water chemistry data. Strong chemical-biological correlations are not necessarily expected, given the likelihood of non-linear relationships and possible cause-effect time lags. The approaches of linear regression and RDA both test for linear change with time and both over-simplify the anticipated nature of temporal biological recovery. However, for these temporally short datasets, which at most only represent very slight chemical gradients, only small changes in flora or fauna are expected. In addition, results from DCCA (Section 3.2.2) demonstrate that time constrained change in species assemblages is generally low. Linear methods should therefore be the most sensitive to temporal change in the datasets.

The following sections (7.2.1 - 7.2.4**)** summarise the results of trend analysis for each biological group.

7.2.1 Linear time trends in epilithic diatom communities

Linear trends with time in the epilithic diatom assemblage were identified at nine sites (Table 7.2). Interpretation of how these temporal changes might reflect changes in acidity is assisted by our knowledge of the pH preferences of individual species. The interpretation provided here is based partly on subjective observation of relative species changes and partly on the pH inference technique described below.

pH prediction techniques were developed to reconstruct historical lake pH change from fossil diatom remains in sediment cores. The Weighted Averaging (WA) approach (ter Braak, 1987; Birks *et al.*, 1990), based on the weighted average of the optimal pH of all species in a sample, has been the most widely used in recent years. Reconstructions for UK lakes have mostly been based on a calibration set of surface sediments from 167 lakes from the UK and Scandinavia, developed for the Surface Water Acidification Project (SWAP) (Stevenson, *et al*., 1991). For lake sediments, the WA approach has a root mean square error of prediction of 0.32 pH units. Since this training set is based on sediment diatom assemblages (i.e. mid-lake fossil deposits), it is not generally considered appropriate to apply to epilithic diatom assemblages and may not provide the same degree of precision of prediction. However, the diatom composition of surface sediments of acid lakes is well represented by epilithic taxa and it is clear from the assemblage descriptions in Chapter 4, that the dominant taxa at most sites have SWAP pH optima which are close to the mean site pH. Time series plots of pH inferred from the epilithon samples should therefore at least provide an indication of the temporal direction of pH response in the diatom community. Epilithic diatom inferred pH time series for lakes and streams are presented in Figure 7.3 (a) and (b) respectively.

Of those sites showing linear trends, five are indicative of an increase in pH (Loch Chon, Burnmoor Tarn, Llyn Llagi, Llyn Cym Mynach and Blue Lough), and one is indicative of deterioration (Loch Grannoch), while species shifts at the remaining three sites do not suggest

Table 7.2

Summary of statistically significant linear trends in epilithic diatom and macroinvertebrate communities, and trends identified in acidity, at UKAWMN sites

	Linear trends in epilithic diatoms	Linear trends in macroinvertebrates	trends in alkalinity and pH
Loch Coire nan Arr			
Allt A'Mharcaidh			
Allt na Coire nan Con		↑	
Lochnagar		↓	pH↓
Loch Chon	↑	↑	pH↑ ALK↑
Loch Tinker	↔	↔	
Round Loch of Glenhead			
Loch Grannoch	↓	↔	
Dargall Lane			ALK↑
Scoat Tarn		↔	pH↑
Burnmoor Tarn	↑	↔	
River Etherow			
Old Lodge			
Narrator Brook			pH↑ ALK↑
Llyn Llagi	↑	↑	pH↑
Llyn Cwm Mynach	↑	↔	
Afon Hafren	↔		
Afon Gwy			pH↑
Beagh's Burn			
Bencrom River			
Blue Lough	↑	↔	pH↑ ALK↑
Coneyglen Burn	↔	↔	

For biological groups, presence of any symbol represents a significant linear time trend according to RDA and associated restricted permutation test. ↑ = indicative of reduction in acidity; ↓ = indicative of increase acidity; ↔ = not indicative of acidity change according to current understanding of species preferences. For chemistry, presence of symbols represents significant time trend according to Seasonal Kendall Test and or Linear Regression, in alkalinity (ALK) and pH: ↑ = increase; ↓ = decrease.

acidity changes (Loch Tinker, Afon Hafren and Coneyglen Burn).

Species changes at Loch Chon, Llyn Llagi and Blue Lough are consistent with the increases in pH reported for these sites. Furthermore, the changes at Loch Chon and Llyn Llagi are supported by changes in the diatom species assemblages of sediment traps and sediment cores (this is considered in further detail in Section 7.2.5).

Trends indicating amelioration in acidity at Burnmoor Tarn and Llyn Cwm Mynach appear to follow chemical changes which, although statistically non-linear, suggest a recent (i.e. post 1992) increase in pH. At these sites there is less indication of similar temporal change in sediment

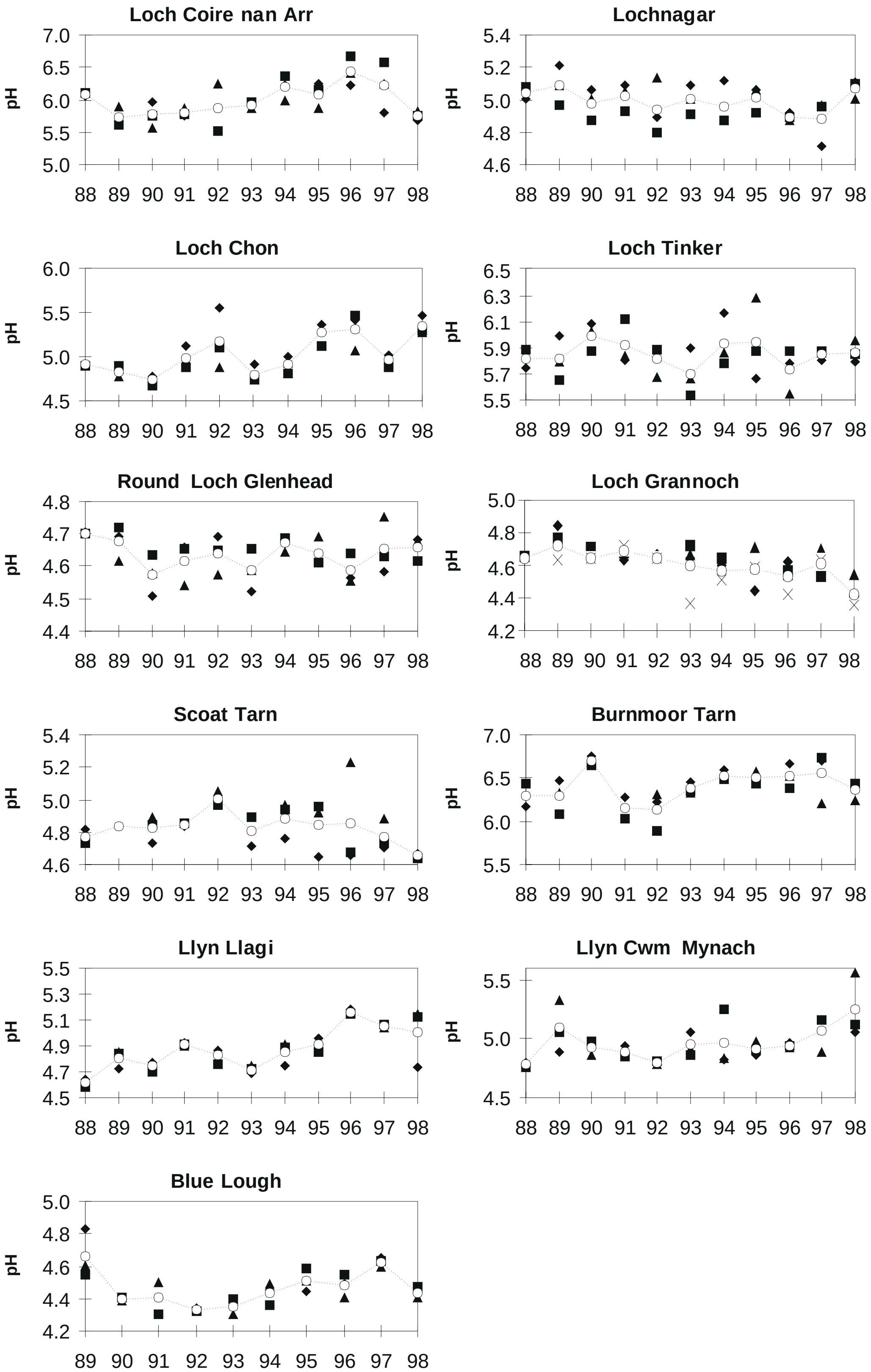


Figure 7.3a

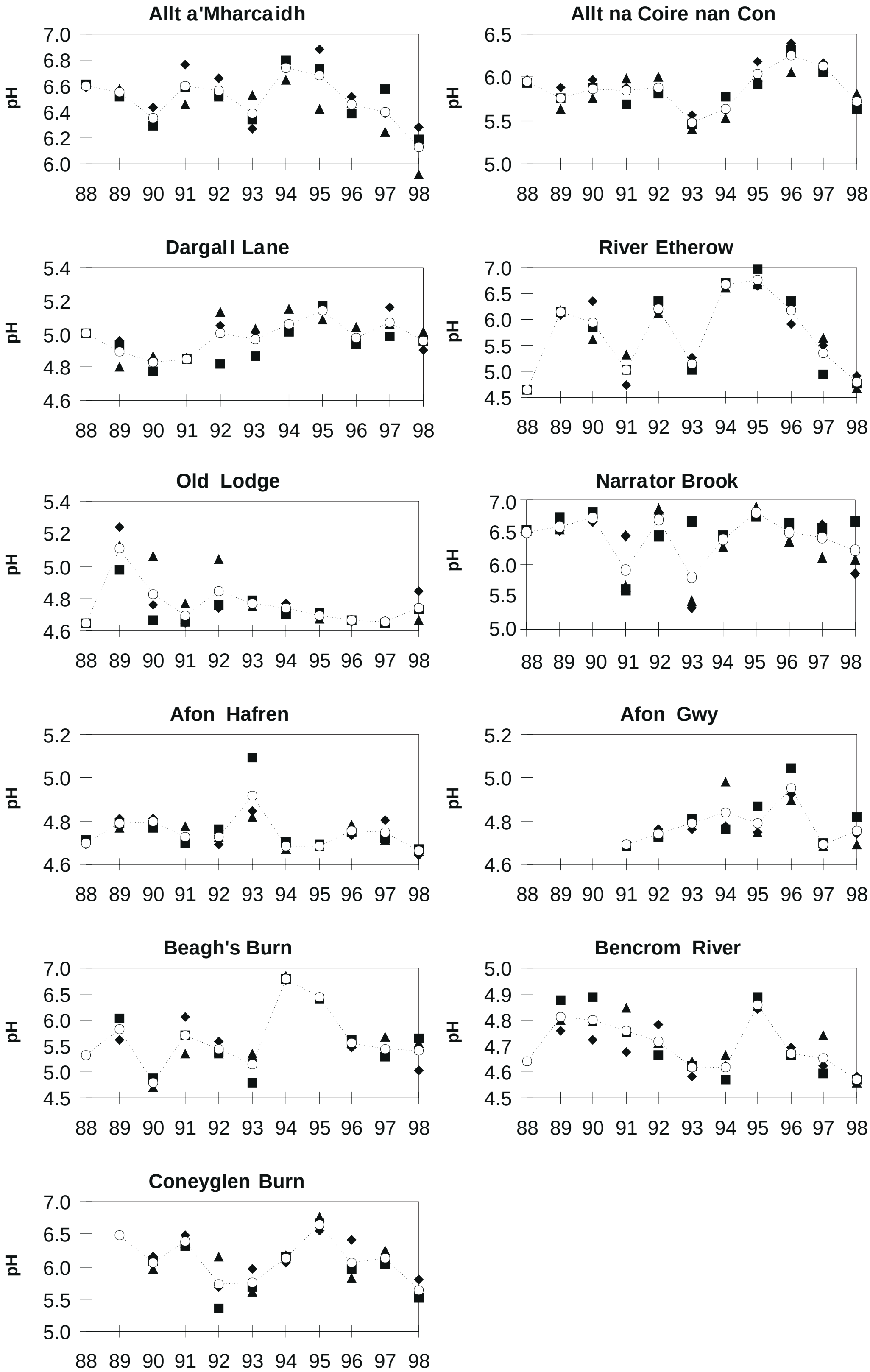
Time series of epilithic diatom inferred pH (all samples) for UKAWMN lake sites (black symbols)

Dotted line indicates variation in annual mean inferred pH (open circle)

Figure 7.3b

Time series of epilithic diatom inferred pH (all samples) for UKAWMN stream sites (black symbols)

Dotted line indicates variation in annual mean inferred pH (open circle)



trap diatom assemblages.

The indication of further acidification in Loch Grannoch is consistent with the LOESS plot for pH (Figure 4.8.2), although no significant trend for pH was found for this site. Likewise, non-linear variation at most other lakes generally appears to reflect their non-linear variation in acidity. Scoat Tarn is the only lake showing linear trends in acidity (improvement), which does not show any clear temporal change in the diatom epilithon. Inter-annual variability in diatom assemblages from stream sites tends to be more marked and is less obviously linked to inter-annual variation in chemistry. However, there is indirect evidence that stream diatoms are primarily influenced by summer acidity. This is considered further in Section 7.4.1.

7.2.2 Linear time trends in macroinvertebrate communities

Eleven sites exhibited statistically significant linear trends in macroinvertebrate data. However, interpretation of these trends is more difficult than for diatom data given the generally wider acidity tolerance of many species and the current lack of information available on species-chemistry relationships for the UK.

Trends at two sites (Loch Chon and Llyn Llagi), are indicative of less acid conditions, while one is indicative of deterioration (Lochnagar) (Table 7.2). As with the epilithic diatoms, the linear trends indicative of improving conditions at Loch Chon and Llyn Llagi (Section 4.5 and 4.15) are consistent with the trends of recovery in water chemistry (however, see Section 7.3), while the trend indicative of deterioration at Lochnagar is consistent with the linear decline identified for pH.

Potential influences on linear change at the remaining eight sites (Allt na Coire nan Con, Loch Tinker, Loch Grannoch, Scoat Tarn, Burnmoor Tarn, Llyn Cym Mynach, Blue Lough and Coneyglen Burn) are less immediately apparent but are considered in more detail in section 7.3.

7.2.3 Linear time trends in trout data

Linear trend analysis was carried out for density and condition factor statistics for the trout population. These data demonstrate considerable inter-annual variability, but few within site time trends have been found, and where they do occur they rarely correspond with changes in water chemistry (see site specific comments in Chapter 4). Fish are highly mobile, relative to other monitored biological groups, and to date it has not been possible to determine to what extent variations in density are driven by mortality and recruitment, as opposed to up- or down-stream migration. Given the large inter-annual variation resulting from the effects of mobility, it is clear that for most sites, the current time series available are of insufficient length for trends to be identified. However, a trend in the density of 0+ trout has been observed at the extremely acid stream, Old Lodge. Here, densities have increased substantially (Figure 4.13.5), and this could represent a general movement of the population upstream from more buffered reaches. The trend is matched by a period of sharply declining labile Al concentration (Figure 4.13.2), accompanied by declining non-marine SO_4 concentration, and may therefore be indicative of biological recovery in response to chemical improvements (Section 4.13). However sea-salt inputs have also reduced over the same period, and further time is therefore required to assess the relative importance of SO_4 decline against climatic influences.

7.2.4 Linear time trends in aquatic macrophyte abundance/cover

Aquatic macrophyte data (consisting of relative abundance measurements for lakes and cover estimates for streams) are the most temporally conservative of all the biological datasets. This is not surprising since: i) aquatic macrophytes tend to be slow growing and perennial, ii) most species have relatively wide tolerance of changes in the chemical and physical environment, and iii) data for lakes is based on a relatively coarse 1-5 scale of relative abundance and this is not particularly sensitive to subtle changes with time. However, spatial studies demonstrate aquatic macrophyte species assemblages do change across broad pH/alkalinity gradients (e.g. Roberts *et al*., 1985; Palmer *et al*., 1992; Allott & Monteith, 1998) and species changes would be expected at UKAWMN sites were substantial improvements in water chemistry to occur.

Temporal trends are apparent at five sites, four of which are streams. At Loch Coire nan Arr there has been a clear reduction in the representation of emergent taxa which almost certainly results from the installation of a dam in 1991 and subsequent water level management. It is unlikely that these species will be able to re-establish around the Loch shoreline unless water level fluctuations cease. Trends at Allt a' Mharcaidh, Allt na Coire nan Con, the River Etherow and the Afon Hafren all appear to result from a reduction in overall cover, rather than any shift in relative species abundance during the interpretative period. Physical scouring during high flow events in the early to middle part of the record, provide the most likely explanation for these changes. Therefore, all linear trends observed in the aquatic macrophyte data most likely result from the effects of physical disturbance, rather than chemical change.

There is no strong evidence for change in aquatic macrophyte composition at those sites showing possible recovery in epilithic diatoms and macroinvertebrates (i.e. Loch Chon and Llyn Llagi). The apparent inertia in species composition at most sites raises the issue of the suitability of aquatic macrophyte monitoring as a tool for detecting biological recovery. However, the relative stability of this group over a period of generally non-directional, or at most very slight, changes in water chemistry can be seen to complement the other more environmentally sensitive but relatively 'noisy' biological datasets. It follows that the appearance, large expansion or disappearance of a species, should these be observed, is likely to be of considerable significance. Furthermore, aquatic macrophytes have a pivotal role in aquatic ecosystems in providing a habitat and food resource. Regular assessment of status therefore provides environmental information which may be important in understanding causes of change in other biological groups.

7.2.5 Supporting evidence for diatom recovery from sediment traps and sediment cores

Evidence for biological recovery from linear trends in epilithic diatom assemblages in Loch Chon and Llyn Llagi is supported by similar floristic trends in sediment trap samples for these sites. Situated in deep water, the contents of these traps should represent the diatom assemblage of the most recently deposited sediment. Comparisons can therefore be made between the historical trend in sediment core diatoms, marking acidification, and the recent annually monitored diatom trend (Figures 7.4 - 7.5).

Sediment core data for Chon11 (taken in 1992) (Patrick *et al*., 1995) shows that the acidification of Loch Chon was marked by a sharp decline in *Achnanthes minutissima* (pH optima 6.3) and *Brachysira vitrea* (pH optima 5.9), and an increase in *Navicula leptostriata* (pH optima 5.1), *Eunotia exigua* (pH optima 5.1) and *Cymbella perpusilla* (pH optima 5.2). Since 1991 the sediment traps show an increase in *B.vitrea* and decreases in *C. perpusilla*, and possibly *E. exigua* and *N.leptostriata*. These changes suggest a small improvement in pH. They also suggest that in its early stages, biological 'recovery' at this site involves a return toward an earlier flora, at least as far as this concerns the dominant taxa. There is no evidence to date of any response in the relatively circumneutral *A. minutissima* and diatom inferred pH (5.2) remains well below that of pre-industrial times (6.3). It should be noted that the change in the diatom inferred pH in epilithon is well correlated, not only with measured March pH, but also negatively with March Cl concentration (Figure 7.8). Floristic changes could therefore primarily represent a response to climatic effects rather than emission reduction induced recovery (Section 7.3).

Evidence of recovery from comparisons of sediment trap and sediment core assemblages is more dramatic and convincing for Llyn Llagi (Figure 7.5). Here, the acidification history involved an early decline in *Achnanthes minutissima* (pH optima 6.3), later decline in *Brachysira vitrea* (pH optima 5.9), temporary dominance by *Eunotia incisa* (pH optima 5.1),

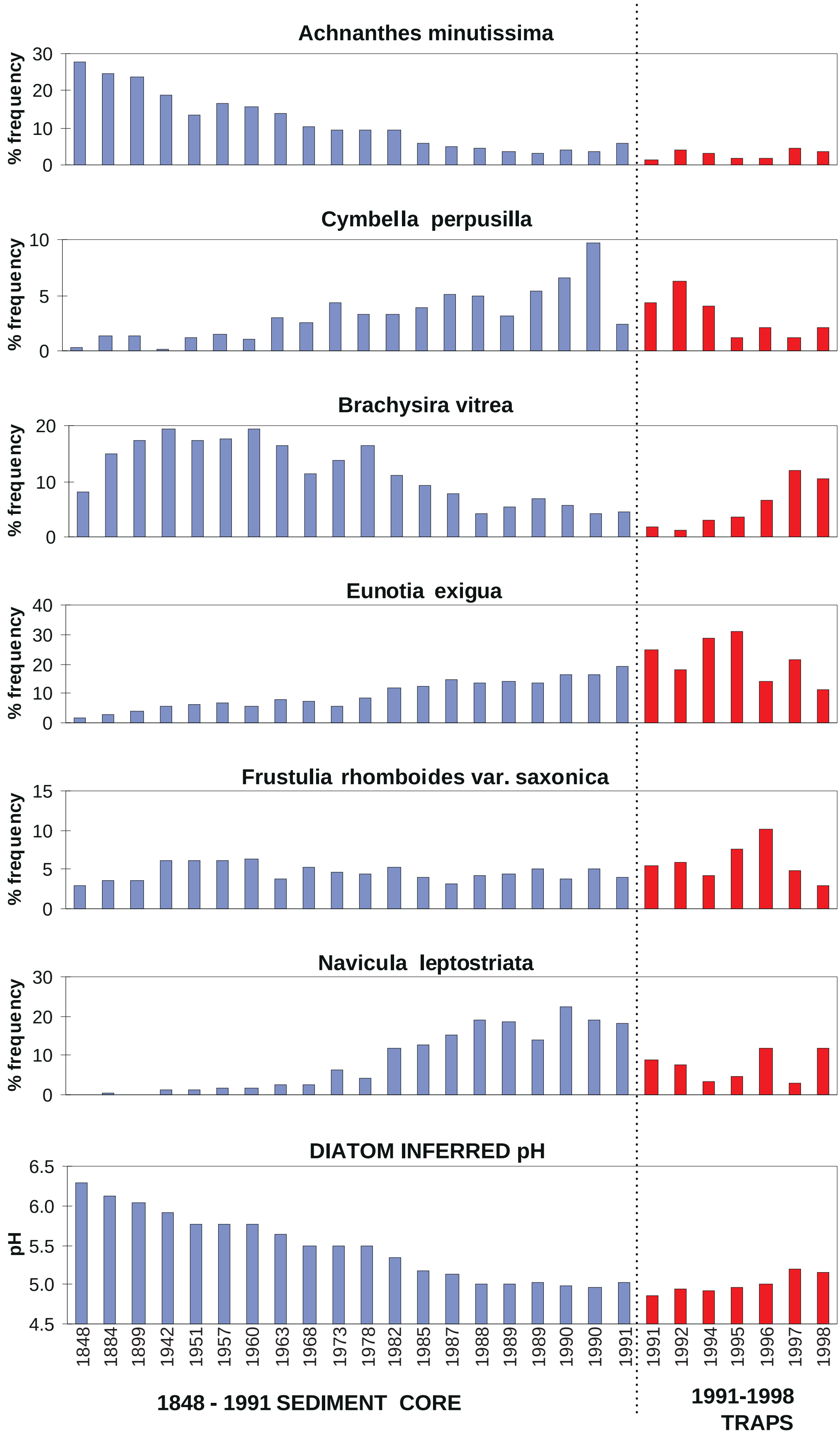


Figure 7.4

Comparison of changes in the representation of dominant diatom taxa in Pb^{210} dated samples from a sediment core sequence (CHON 11) and more recent changes in sediment trap samples from Loch Chon. The bottom graph shows diatom inferred pH (based on weighted averaging) for all samples

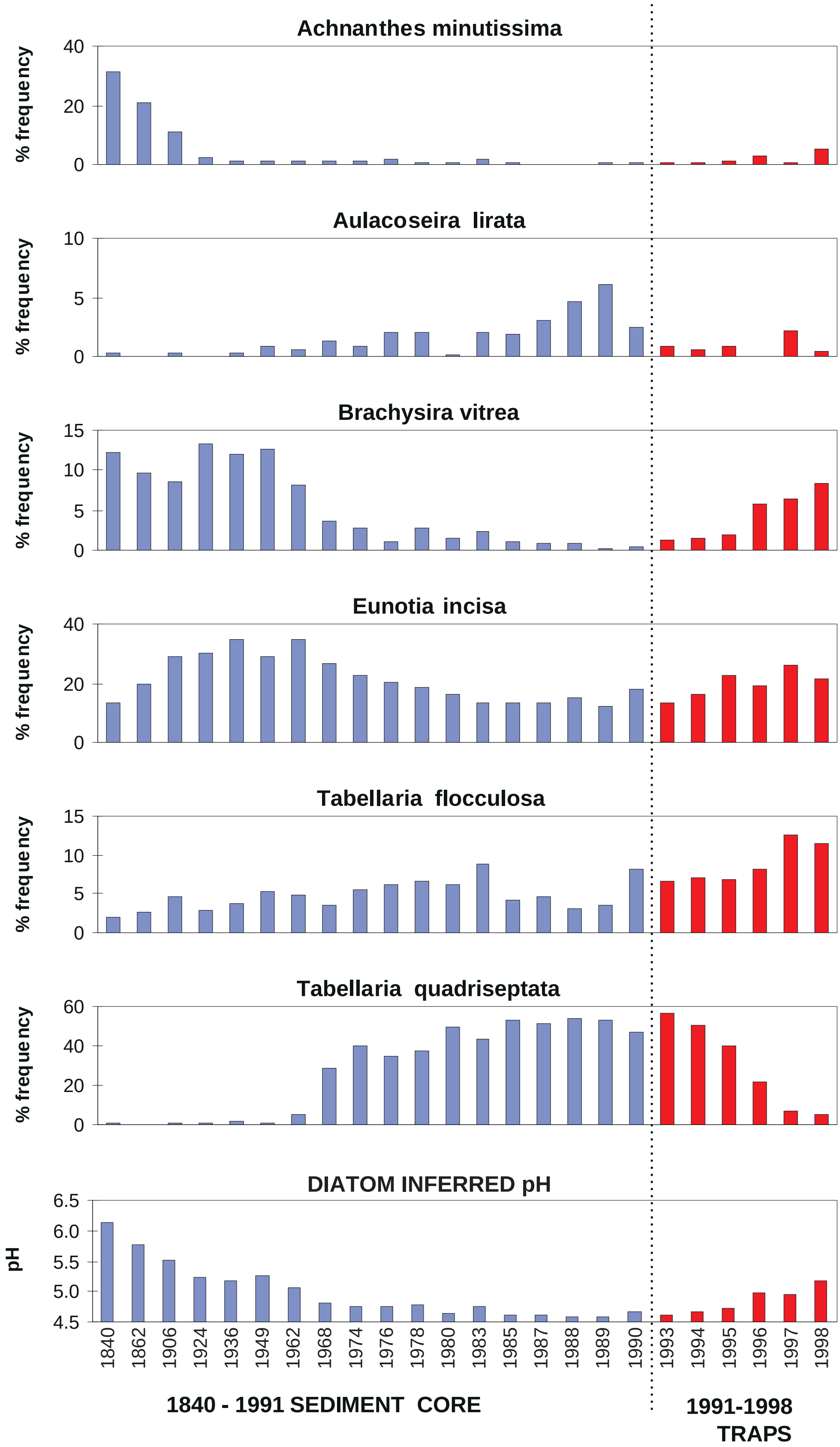


Figure 7.5

Comparison of changes in the representation of dominant diatom taxa in Pb^{210} dated samples from a sediment core sequence (LAG 3) and more recent changes in sediment trap samples from Llyn Llagi. The bottom graph shows diatom inferred pH (based on weighted averaging) for all samples

and then displacement of *E. incisa* by *Tabellaria quadriseptata* (pH optima 4.9) which increased to approximately 50% representation. The floristic assemblage of the contents of the first sediment trap, collected in 1993, matched that at the top of the sediment core taken in 1991. However, since 1991 there has been a progressive decline in *T. quadriseptata* and an increase in *E.incisa* and *B.vitrea* in successive sediment trap samples. There is even evidence for a recent small increase in *A.minutissima*. Again, therefore, the diatom flora appears to be reverting to a former state; however, compared to Loch Chon, the rate of change has been far steeper.

There is a taxonomic exception to the general evidence for a return to a previous flora in Llyn Llagi. *Tabellaria flocculosa* appeared to increase slightly over the course of acidification and has continued to increase in sediment trap samples. It is possible that the current abundance of this species will not persist, but it would seem that it has responded to factors other than acidity, e.g. changes in climate, nutrient availability, etc.. This emphasises the possibility that the physio-chemical environment of a theoretically 'recovered' lake may differ from its pre-industrial state for reasons other than acidity, and may not therefore have the capacity to support an identical flora and fauna to that which was lost.

Unlike Loch Chon, the observed changes in Llyn Llagi do not appear to correlate with chloride concentration or any other climatically related factor. In short, these changes represent the most convincing evidence of real biological recovery, resulting from an amelioration in pH, observed for the whole Network. There is little evidence for linear change in sediment trap species assemblages for other UKAWMN lakes, although these have not been analysed statistically.

7.3. Further consideration of linear trends in macroinvertebrate and epilithic diatom data

Comparisons between the trend results for water chemistry and biology highlight differences between the two datasets (Table 7.2). Linear trends were found at nine and eleven sites for epilithic diatoms and macroinvertebrates respectively, but temporal trends in acidity related variables were only detected at seven sites. At only two sites, Loch Chon and Llyn Llagi, were linear decreases in acidity mirrored by recovery trends in both epilithic diatoms and macroinvertebrates.

For those sites where chemical improvements have not been observed, biological trends could represent responses to one, or a combination, of the following:

- real recovery in response to chemical changes which have not been detected with the methods of analysis employed (e.g. chemical improvements confined to one time of year);
- lagged recovery, e.g. biological responses to chemical improvements which occurred before the onset of monitoring, as for example suggested in the longer term data sets (Chapter 6);
- responses to other changes in the environment (lagged or immediate), such as changes in climate, or catchment effects such as felling or water level change;
- natural population or ecosystem driven oscillations with a cycle of several years.

It is important that the nature of the trends identified in the biological datasets is adequately understood so that:

i) real biological recovery is recognised if, when and where it occurs;

ii) other trends, which may be indicative of improvement but may not be sustained in the longer term, are not incorrectly attributed to emissions reduction policy; and,

iii) major influences which are not related to chemical recovery may eventually be quantified and statistically 'removed', so as to allow more sensitive detection of underlying trends.

<u>Macroinvertebrates</u>

At sites where linear trends have been identified, the inter-annual pattern of variation in assemblages is often very similar. For example, the mean of the annual score of samples on the first axis of PCA (which summarises the component of maximum variation in the species assemblage between samples) tends to be well correlated between those sites which show linear trends but not for most others (see Table 7.3). This suggests that the macroinvertebrate communities of these sites may be influenced by one or more common factor, despite the apparent absence of common trends in water chemistry.

The near west coast location of the sites showing linear trends in macroinvertebrate assemblages may provide a key to understanding the underlying influences (see Figure 7.6). As discussed in Section 5.3.1, sites close to the west coast appear vulnerable to westerly and southwesterly storms, as these influence sea-salt and rainfall enhanced acidity. Since macroinvertebrates are sampled in the spring, and since, for the majority of species captured, the larval stage occurs over the winter-spring period, it is reasonable to hypothesise that the significant time trends in the species assemblages might reflect reductions in winter-spring acidity resulting from the declining influence of these weather conditions over the bulk of the monitoring period.

Water chemistry sampling is inadequate to capture the extent and frequency of acid episodes. Most occur over relatively few days, usually between December and March, but no water samples are collected from lakes between the first week of December and the first week of March. Even monthly samples from streams will not fully represent inter-annual variability in the frequency and intensity of extreme events. In order to test whether winter-spring storminess could explain the observed common variation in the species assemblages we took various monthly combinations of the North Atlantic Oscillation Index (NAOI) (see Section 5.3.5) as surrogate variables for storm activity. These were applied as explanatory variables to the species datasets in Redundancy Analysis (RDA), using the same approach adopted for time-trend analysis (Section 3.2.2).

This analysis showed that the January NAOI can consistently explain a significant proportion of variance in the macroinvertebrate data. Overall the January NAOI is significant for nine sites, all but one of which shows a linear (i.e. time) trend (Table 7.4). Table 7.4 also demonstrates that the correlation coefficients between the mean annual PCA Axis 1 scores, and the January NAOI are high for several sites (i.e. Loch Coire nan Arr, 0.83; Loch Tinker, 0.69; Loch Grannoch, 0.68; and Llyn Cym Mynach 0.80).

Why the weather in the month of January may be of particular importance in influencing inter-annual variability in the macroinvertebrate assemblage is unclear. Westerly storms mostly occur from December to March and are certainly not confined to this one month only. However, chloride concentrations in monthly sampled stream sites often reach their annual peak in samples collected in either January or February, both of which could be influenced by January weather conditions. Furthermore, years in which the January NAOI has been either high or low, have often been characterised by similar extremes in February and March. The January NAOI variable could therefore represent a longer winter-spring period. It is also possible that macroinvertebrate larvae are most vulnerable to acid episodes when at an early stage of development at the beginning of the year.

Perhaps importantly, the January NAOI generally explains a larger proportion of overall variance in sites in mid-west to northwest Scotland, i.e. Loch Chon, Loch Tinker, Allt na Coire nan Con, and Loch Coire nan Arr. At these sites the January NAOI is well correlated with both spring Cl

Table 7.3

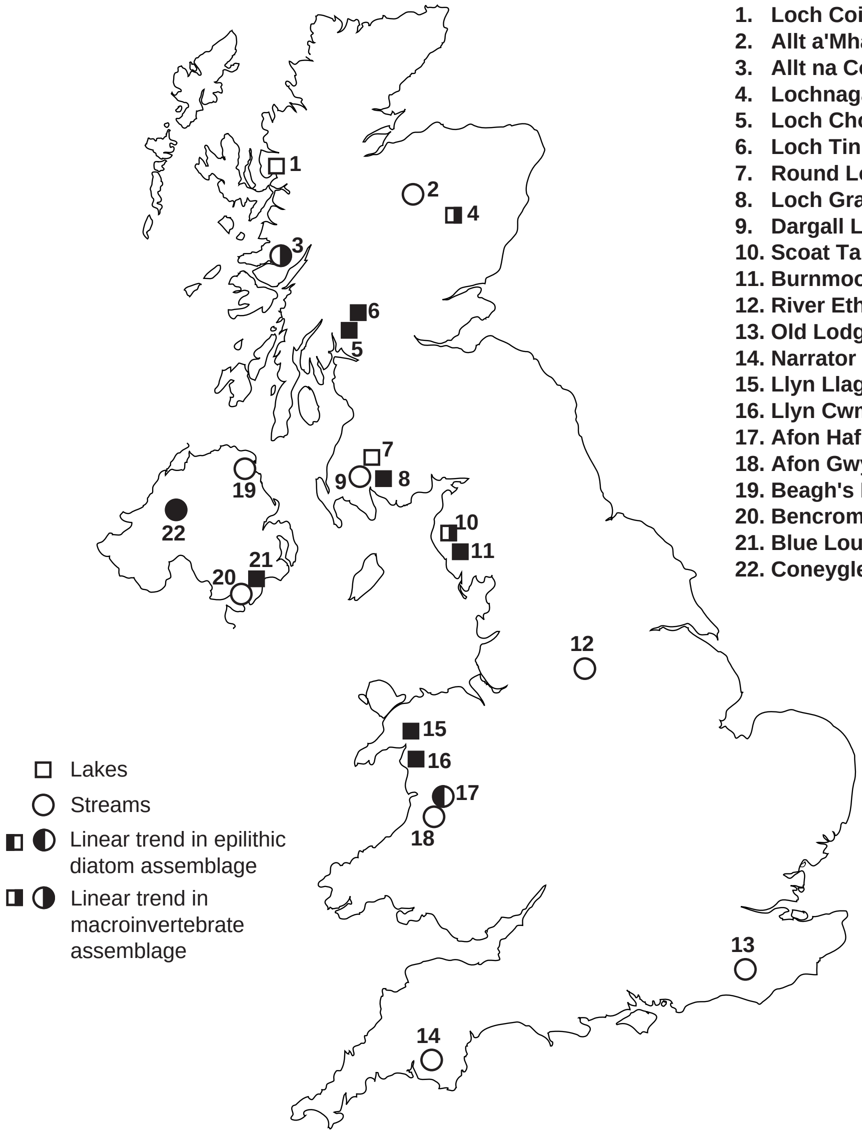
Between-site correlation coefficients (r) for the mean annual score of macroinvertebrate samples on PCA Axis 1

	UKAWMN site number																				
site name and number	3	4	5	6	8	10	11	15	16	21	22	1	2	7	9	12	13	14	17	19	20
Allt na Coire nan Con (3)	1.00	0.44	0.67	0.92	0.90	0.71	0.70	0.62	0.68	0.62	0.79	0.62	0.33	0.17	0.25	0.41	0.38	0.28	0.50	0.67	0.27
Lochnagar (4)	0.44	1.00	0.42	0.39	0.38	0.14	0.70	0.28	0.25	0.27	0.28	0.08	0.24	0.03	0.24	0.19	0.73	0.17	0.48	0.04	0.30
Loch Chon (5)	0.67	0.42	1.00	0.69	0.81	0.77	0.38	0.61	0.84	0.52	0.47	0.77	0.04	0.21	0.50	0.81	0.22	0.01	0.40	0.51	0.10
Loch Tinker (6)	0.92	0.39	0.69	1.00	0.90	0.79	0.76	0.63	0.78	0.67	0.84	0.70	0.37	0.24	0.14	0.40	0.32	0.22	0.39	0.64	0.36
Loch Grannoch (8)	0.90	0.38	0.81	0.90	1.00	0.79	0.59	0.66	0.76	0.68	0.81	0.68	0.13	0.16	0.31	0.50	0.35	0.22	0.31	0.63	0.04
Scoat Tarn (10)	0.71	0.14	0.77	0.79	0.79	1.00	0.51	0.49	0.91	0.41	0.66	0.95	0.36	0.61	0.41	0.69	0.11	0.42	0.00	0.37	0.23
Burnmoor Tarn (11)	0.70	0.70	0.38	0.76	0.59	0.51	1.00	0.44	0.50	0.36	0.68	0.41	0.60	0.30	0.31	0.13	0.74	0.29	0.25	0.14	0.54
Llyn Llagi (15)	0.62	0.28	0.61	0.63	0.66	0.49	0.44	1.00	0.72	0.76	0.22	0.46	0.20	0.03	0.01	0.27	0.40	0.36	0.29	0.32	0.08
Llyn Cwm Mynach (16)	0.68	0.25	0.84	0.78	0.76	0.91	0.50	0.72	1.00	0.63	0.52	0.91	0.19	0.42	0.32	0.67	0.19	0.31	0.19	0.39	0.21
Blue Lough (21)	0.62	0.27	0.52	0.67	0.68	0.41	0.36	0.76	0.63	1.00	0.54	0.38	0.29	0.17	0.04	0.07	0.07	0.07	0.38	0.56	0.01
Coneyglen Burn (22)	0.79	0.28	0.47	0.84	0.81	0.66	0.68	0.22	0.52	0.54	1.00	0.55	0.42	0.16	0.17	0.21	0.13	0.03	0.20	0.63	0.34
Loch Coire nan Arr (1)	0.62	0.08	0.77	0.70	0.68	0.95	0.41	0.46	0.91	0.38	0.55	1.00	0.28	0.52	0.41	0.68	0.02	0.28	0.07	0.36	0.16
Allt a'Mharcaidh (2)	0.33	0.24	0.04	0.37	0.13	0.36	0.60	0.20	0.19	0.29	0.42	0.28	1.00	0.43	0.03	0.19	0.31	0.37	0.00	0.02	0.85
Round Loch Glenhead (7)	0.17	0.03	0.21	0.24	0.16	0.61	0.30	0.03	0.42	0.17	0.16	0.52	0.43	1.00	0.10	0.41	0.03	0.60	0.47	0.32	0.38
Dargall Lane (9)	0.25	0.24	0.50	0.14	0.31	0.41	0.31	0.01	0.32	0.04	0.17	0.41	0.03	0.10	1.00	0.80	0.34	0.08	0.22	0.52	0.13
River Etherow (12)	0.41	0.19	0.81	0.40	0.50	0.69	0.13	0.27	0.67	0.07	0.21	0.68	0.19	0.41	0.80	1.00	0.03	0.17	0.22	0.35	0.08
Old Lodge (13)	0.38	0.73	0.22	0.32	0.35	0.11	0.74	0.40	0.19	0.07	0.13	0.02	0.31	0.03	0.34	0.03	1.00	0.28	0.12	0.17	0.15
Narrator Brook (14)	0.28	0.17	0.01	0.22	0.22	0.42	0.29	0.36	0.31	0.07	0.03	0.28	0.37	0.60	0.08	0.17	0.28	1.00	0.47	0.25	0.21
Afon Hafren (17)	0.50	0.48	0.40	0.39	0.31	0.00	0.25	0.29	0.19	0.38	0.20	0.07	0.00	0.47	0.22	0.22	0.12	0.47	1.00	0.73	0.16
Beaghs Burn (19)	0.67	0.04	0.51	0.64	0.63	0.37	0.14	0.32	0.39	0.56	0.63	0.36	0.02	0.32	0.52	0.35	0.17	0.25	0.73	1.00	0.05
Bencrom River (20)	0.27	0.30	0.10	0.36	0.04	0.23	0.54	0.08	0.21	0.01	0.34	0.16	0.85	0.38	0.13	0.08	0.15	0.21	0.16	0.05	1.00

Sites which have high correlation coefficients will exhibit similar patterns of temporal variation in species composition. The 11 sites shaded are those showing significant linear time-trends according to RDA and associated restricted permutation test. Note that Lochnagar, a non west coast site, and the only site where macroinvertebrate changes appear indicative of deterioration, is relatively poorly correlated with most other sites showing linear trends.

Figure 7.6

UK map showing the location of sites for which linear trends have been identified in epilithic diatom and macroinvertebrate assemblages



concentrations (i.e. March concentrations in lakes and mean January to March concentrations in streams) and January rainfall totals, and as a consequence it is likely to be associated with the frequency and intensity of acid episodes and overall winter-spring acidity for sites in this area (Figure 7.7). For several lakes, macroinvertebrate communities tend to be represented by low numbers of individuals and are dominated by acid tolerant species, such as the mayfly family the Leptophlebiidae, in the early 1990s, while they are relatively diverse, and represented by some acid intolerant taxa in 1996-1997. The former periods correspond with high January NAOI (i.e. stormy conditions), while the NAOI was negative for the latter.

It is interesting to note that the January NAOI is not significant in explaining between-sample variability at Llyn Llagi, for which a time trend has been identified, and where there is convincing evidence of recovery in the diatom community. It is therefore possible that the nature of the temporal trend in macroinvertebrates at this site is different from those observed elsewhere and this increases the possibility that change at this site reflects a longer term response to improving chemistry. However, for the

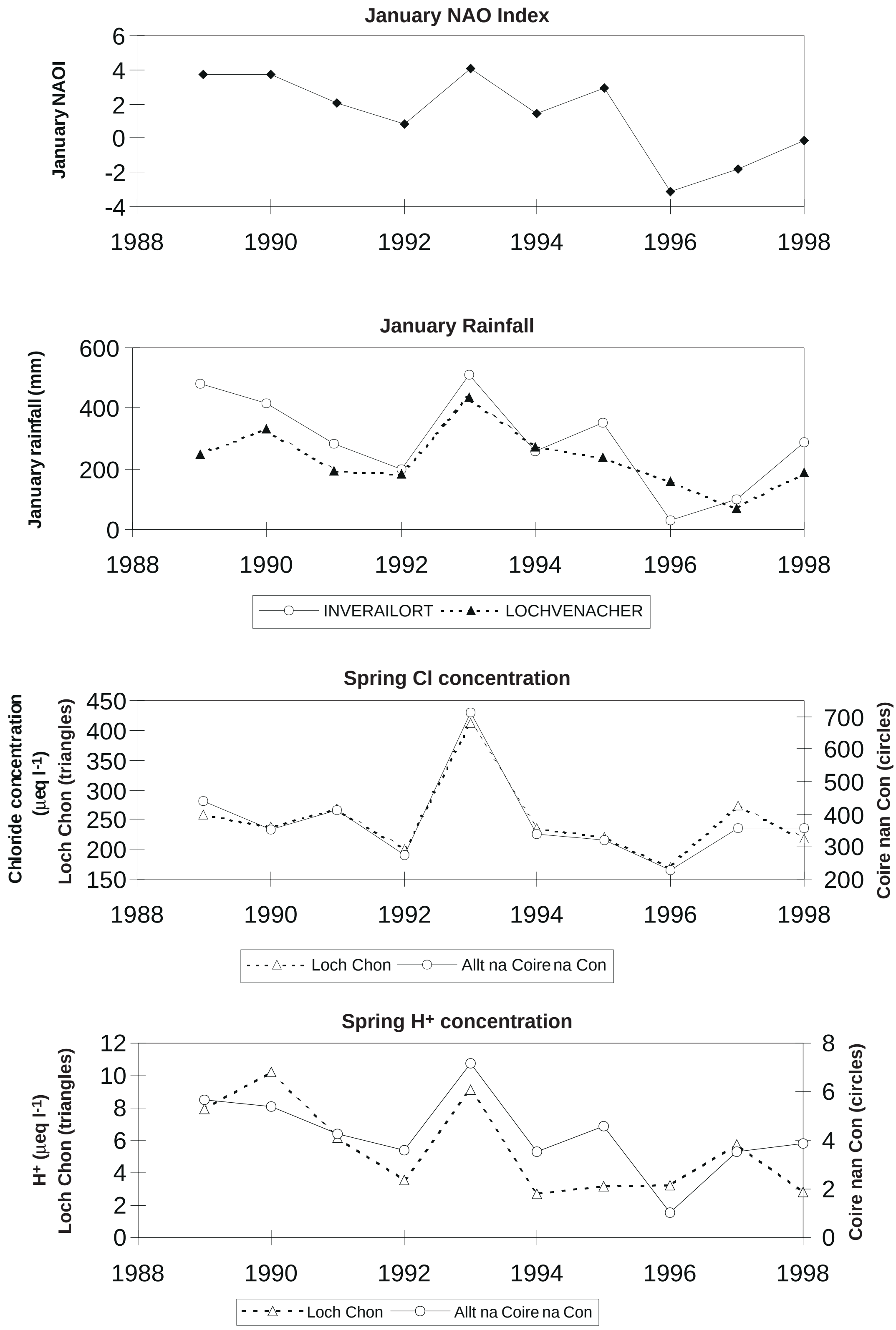


Figure 7.7

Relationship between the January NAO Index, January rainfall, and spring water chemistry for two Scottish sites (mean January to March concentration for Allt na Coire nan Con; March concentration for Loch Chon)

Rainfall data from nearby Meteorological Stations for these sites (Appendix 2)

majority of sites for which linear trends have been identified, it is more likely that changes result primarily from a reduction in winter storm activity. Reductions in intensity and duration of acid episodes provide possible mechanisms. Alternatively, community composition may simply co-vary with acidity. Other effects of inter-annual variations in climate, such as the extent and frequency of water level oscillations, variations in turbulence in the littoral zone or even winter temperatures (winter temperature is positively correlated with the NAO) may also be important. Specific mechanisms are therefore unclear and urgently require further research to ascertain.

These results tentatively suggest that, on an inter-annual scale, macroinvertebrate assemblages may be sensitive to changes in the severity of acid conditions in the winter-spring period. There is evidence from the longer term chemical datasets, described in Chapter 6, that chemical recovery has led to a gradual increase in the pH of the most acid events at some sites. It might therefore be expected that these changes will be tracked by a gradual return of more acid sensitive

Table 7.4

Variance in macroinvertebrate datasets explained by the first axis of PCA (PCA λ_1), and a time trend and the January North Atlantic Oscillation Index (NAOI) when statistically significant. The last column provides the correlation (r) for the relationship between the January NAOI and the mean annual score of samples on the first axis of PCA

site	% variance explained by PCA λ_1	% variance explained by time trend* RDA λ_1	% variance explained by January NAOI* RDA λ_1	correlation coefficient for January NAOI against PCA λ_1
Loch Coire nan Arr	30.6		16.8	0.83
Allt a'Mharcaidh	27.4			0.12
Allt na Coire nan Con	23.6	15.8	10.4	0.52
Lochnagar	26.2	10.4		0.07
Loch Chon	21.4	14.1	10.6	0.59
Loch Tinker	21.1	15.5	11.3	0.69
Round Loch of Glenhead	20.6			0.29
Loch Grannoch	20.6	13.1	10.0	0.68
Dargall Lane	32.8			0.10
Scoat Tarn	19.8	12.0	13.1	0.81
Burnmoor Tarn	23.3	11.6	6.2	0.43
River Etherow	41.4			0.32
Old Lodge	31.1			0.17
Narrator Brook	20.9			0.34
Llyn Llagi	25.0	11.5		0.58
Llyn Cwm Mynach	21.9	12.1	6.9	0.80
Afon Hafren	31.1			0.15
Afon Gwy	27.2			0.16
Beagh's Burn	21.1			0.27
Bencrom River	23.8			0.04
Blue Lough	27.6	14.4		0.50
Coneyglen Burn	28.4	13.9	10.5	0.57

macroinvertebrate taxa. However given the clear importance of inter-annual variability in weather on the chemistry of these sites, it is also likely that the temporal nature of recovery will be far from linear, and more sophisticated statistical techniques may be necessary to more sensitively detect any 'recovery' component within the inter-annual variation.

Epilithic diatoms

Of the nine sites showing temporal trends in epilithic diatom assemblages, only five also show temporal trends in water chemistry (Table 7.2). However, with the exception of the Afon Hafren, all of the sites showing trends in epilithic diatoms also exhibit trends in macroinvertebrates and all have westerly locations (see Figure 7.6). It is therefore possible that climatic controls similar to those proposed above for the freshwater fauna (Section 7.1.1) are important for the diatom flora.

Figure 7.3a demonstrates that for approximately half of UKAWMN lakes, the most acid assemblages occured in the early 1990s (and for several sites 1993) while those in 1996 or 1997 were the least acid. The earlier years were characterised by winters with relatively high winter-spring sea-salt inputs and rainfall, and this may have depressed lake pH well into the growing season. The winter of 1996, on the other hand, was largely free of westerly and south-westerly activity, and most lakes were less acid over this period. Given the west coast location of these lakes, and the temporal patterns in climate discussed above, the trends identified in the epilithon of some sites may therefore again reflect a change in winter-spring storminess over the monitoring period.

The most striking example of how climatic effects may have influenced trends in the epilithic diatom assemblage comes from Loch Chon. For this site the mean annual diatom inferred pH of all samples is exceptionally tightly correlated with measured March chloride concentration and March pH (Figure 7.8). It is therefore possible that the potential recovery discussed earlier for Loch Chon may primarily represent natural variability in response to changes in weather. If this is the case, then the current trend should disappear, once stormy (i.e. high NAOI) winters of the frequency and duration experienced at the onset of monitoring return to the UK.

7.4 Other between-year biological variability

7.4.1 Epilithic diatoms in UKAWMN streams and flow

Site summaries in Chapter 4 indicate that the epilithic diatom assemblages show considerably greater temporal variation in streams than lakes. The most obvious explanation for this is the greater temporal variation in chemistry experienced in most stream systems, resulting from sensitivity to variations in flow.

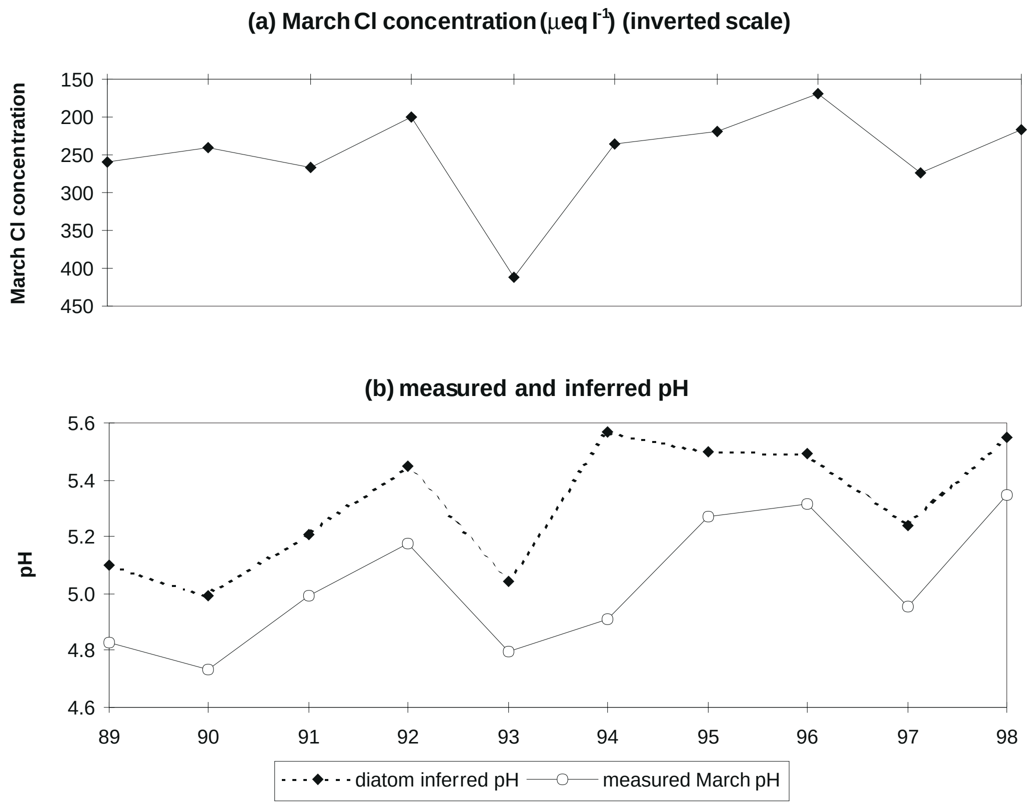
The acidity response of the stream epilithic flora may again be gauged by analysis of the relative change in diatom inferred pH with time. The application of the SWAP dataset to infer pH from stream epilithon should again be viewed with caution, and particularly since the stream environment is very different from the lake environments on which the method is based. However, it is clear from Figure 7.3b that several stream sites show similar temporal patterns in inferred pH, and these are very different from the trends observed for most lakes.

Most UKAWMN stream sites show strong relationships between pH and flow, which results from the changing proportional contributions of various flow paths to the watershed with changing rainfall (Figure 7.9). pH tends to be highest at low flows when the contribution from relatively buffered baseflow is highest. For the majority of stream sites, flow data is only available for the time of sampling, i.e. monthly spot measurements, and it is not possible from this to infer time-integrated flow conditions. We have therefore examined monthly rainfall records for local Meteorological Stations, to see whether flow could explain any of the inter-annual variability observed in diatom inferred pH.

For several sites, negative relationships were apparent between total June-July rainfall and mean annual diatom inferred pH (Figure 7.10).

Figure 7.8

Measured chemistry (pH and Cl concentration) of March water samples and mean annual epilithic diatom inferred pH for Loch Chon 1989-1998



Given the possible limitations in the application of a lake sediment based transfer function, and other potential errors, such as those associated with the representativity of local Meteorological Station rainfall data for the UKAWMN site, the apparent strength of these relationships is surprising. The only statistically significant linear relationship was for the River Etherow ($r^2 = 0.61$ $p<0.01$); however, the consistently negative regression slopes and relatively high r^2 values (four other sites show r^2 values of more than 0.4) suggest that summer flow may have a dominant influence on inter-annual variability at many sites. It is interesting to note that the weakest rainfall-diatom inferred pH relationships are for Old Lodge and the Afon Hafren, and these sites also show poor relationships between flow and measured pH.

The strength of the Etherow diatom-flow relationship could in part reflect the particularly large gradient in pH which is observed between high and low flows. Inter-annually, the diatom assemblage probably varies more than for any other site on the Network and ranges from a *Eunotia incisa* dominated flora indicative of very low pH, to one dominated by the circumneutral species *Achnanthes minutissima*.

The relationships identified suggest that the assemblages of many sites will represent antecedent flow conditions, perhaps for the previous two months, and it is likely that species representation for most sites will be in a process of continuous change over the spring-summer growing season. The summer sampled (mostly July-August) epilithic diatom assemblages may therefore not be particularly representative of the year-round crop.

The apparent sensitivity of the stream diatom assemblage to fluctuations in flow has obvious

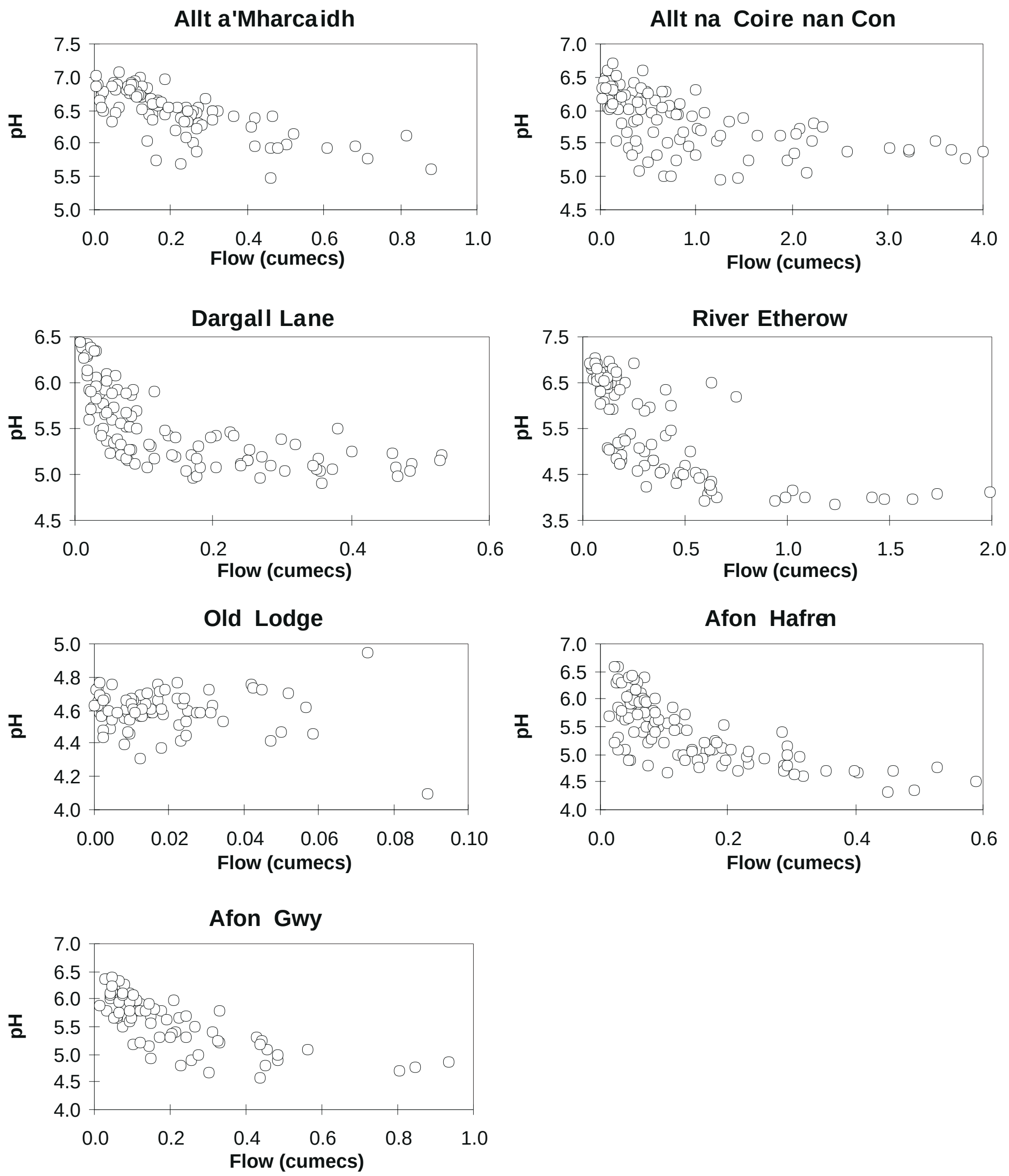


Figure 7.9

The relationship between spot sampled pH and flow for all UKAWMN stream sites for which there are monthly flow measurements

implications for trend detection, in that high inter-annual variability will mask potential recovery signals. It therefore seems likely that identification or statistical validation of epilithic diatom recovery will take considerably longer for streams than lakes. The period required for trend detection could be reduced by increasing the frequency of diatom sampling, perhaps to monthly, over the growing season. Chemical recovery may not involve obvious improvement at low flows, since these are the periods when chemistry is most buffered. With the current sampling regime, it is therefore likely that biological recovery will first become evident in a change through time in the diatom assemblages of high summer rainfall years.

7.4.2 Temporal variation in macroinvertebrate species richness

Spatially there is a general relationship between mean macroinvertebrate species richness and pH for UKAWMN sites (Figure 7.1), and similar links have been identified both spatially and temporally in the scientific literature. The identification of temporal trends in minimum

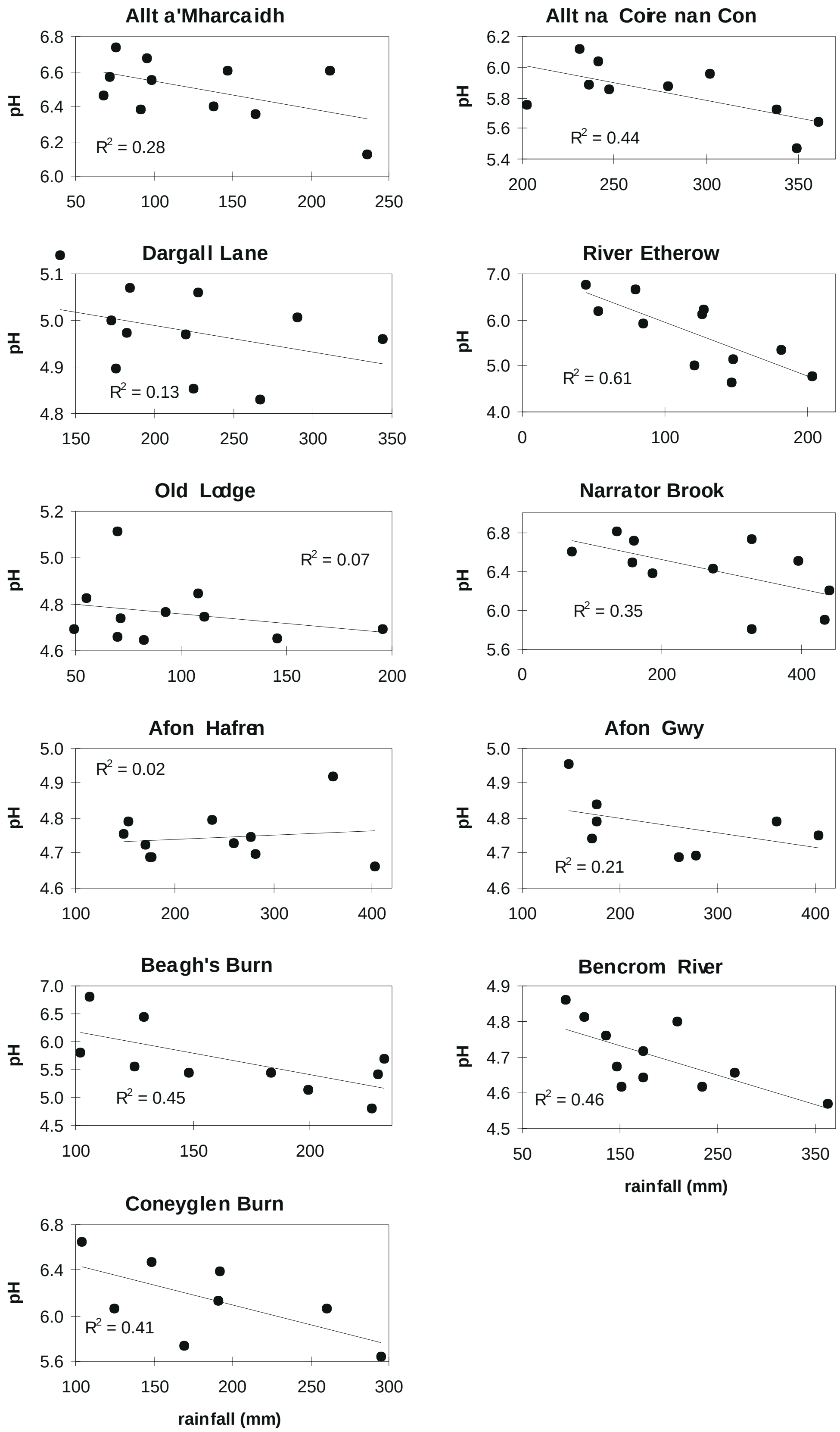


Figure 7.10

The relationship between mean annual epilithic diatom inferred pH (based on weighted averaging) and total June-July rainfall (mm) (recorded at nearby Meteorological Stations) for UKAWMN stream sites (1988-1998)

species richness (MSR) might therefore provide an indication of the extent of biological recovery. Time series for macroinvertebrate MSR for both lakes and streams are presented in Figures 7.11a and 7.11b, respectively.

Upward trends are apparent in MSR for most UKAWMN streams but no UKAWMN lakes. Loch Chon and Llyn Llagi, both of which show linear trends in the macroinvertebrate species composition which are indicative of biological improvement, provide no indication of a change in MSR with time, and the same is true for most other lakes which show linear trends. Conversely, few trends in species composition have been observed for streams. It therefore appears that temporal variation in species composition and species richness have been largely independent for most sites over the interpretative period.

Temporal patterns in MSR for several stream sites are well correlated (Table 7.5) and correlations appear to be stronger for sites which are geographically close. For example, high correlation coefficients were obtained between Scottish sites, and between these and sites in Northern Ireland. MSR for Old Lodge, which is geographically most remote, is only weakly correlated with that for other sites. The absence of correlations between stream sites and most lake sites (not shown) appears to rule out the possibility that the data represent a change in sampling efficiency over the years.

The most likely explanation for these geographically related, common patterns which are only observed in stream sites, and which do not appear to be directly linked to chemical change, is a change in the winter-spring flow regime. As has been discussed in several other sections of this report, throughout most of the interpretative period there has been a general decline in winter-spring westerly weather activity, and there is evidence from many of the Meteorological Stations close to UKAWMN sites that this was accompanied by a general decline in winter-spring rainfall.

Analysis of local rainfall data provides some indication of negative relationships between rainfall at this time of year and MSR but no common period has been identified for all sites. Negative relationships are apparent between MSR and total January - April rainfall at four sites (Allt na Coire nan Con, Dargall Lane, Old Lodge and Coneyglen Burn) (Figure 7.12), although a linear relationship is only statistically significant at the p=0.01 level for Old Lodge. Interestingly, Old Lodge is one of the few UKAWMN stream sites which shows no evidence for a relationship between flow and acidity (Figure 7.9), and the effect on MSR at this site is therefore more likely to be due to physical, rather than chemical, factors.

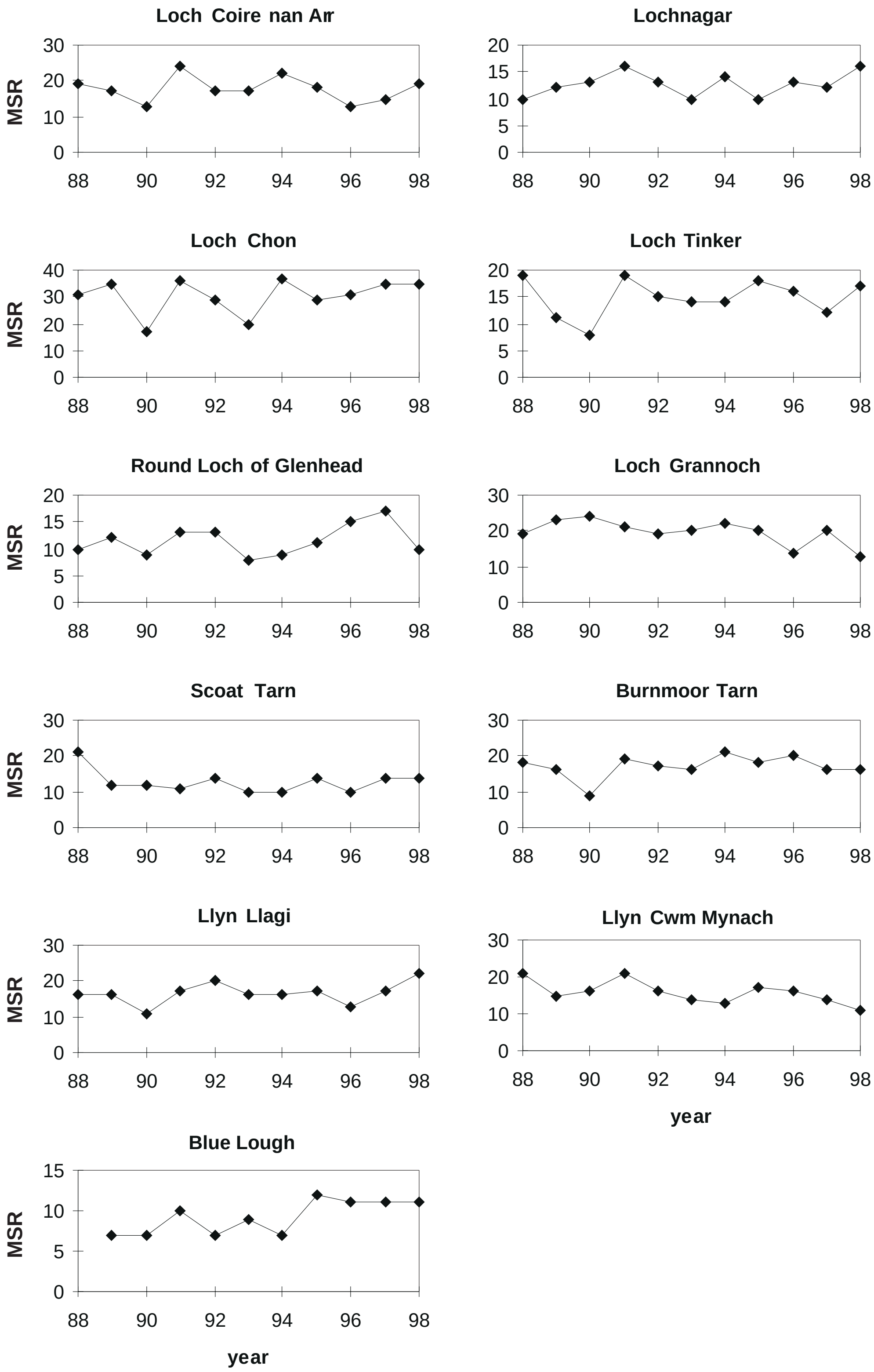
Table 7.5

Between-site relationship (correlation coefficient r) in the temporal variation in macroinvertebrate minimum species richness (10 year stream records only)

	site no.							
	3	9	12	13	14	17	19	20
Allt a'Mharcaidh (2)	0.72	0.59	0.59	0.32	0.58	0.46	0.68	0.63
Allt na Coire nan Con (3)		0.73	0.74	0.37	0.65	0.53	0.81	0.67
Dargall Lane (9)			0.82	0.39	0.82	0.64	0.86	0.92
River Etherow (12)				0.42	0.92	0.85	0.85	0.84
Old Lodge (13)					0.48	0.43	0.18	0.35
Narrator Brook (14)						0.87	0.72	0.79
Afon Hafren (17)							0.68	0.68
Beagh's Burn (19)								0.88
Bencrom River (20)								

Figure 7.11a

Time series for macroinvertebrate minimum species richness (MSR) for UKAWMN lakes (1988 - 1998)



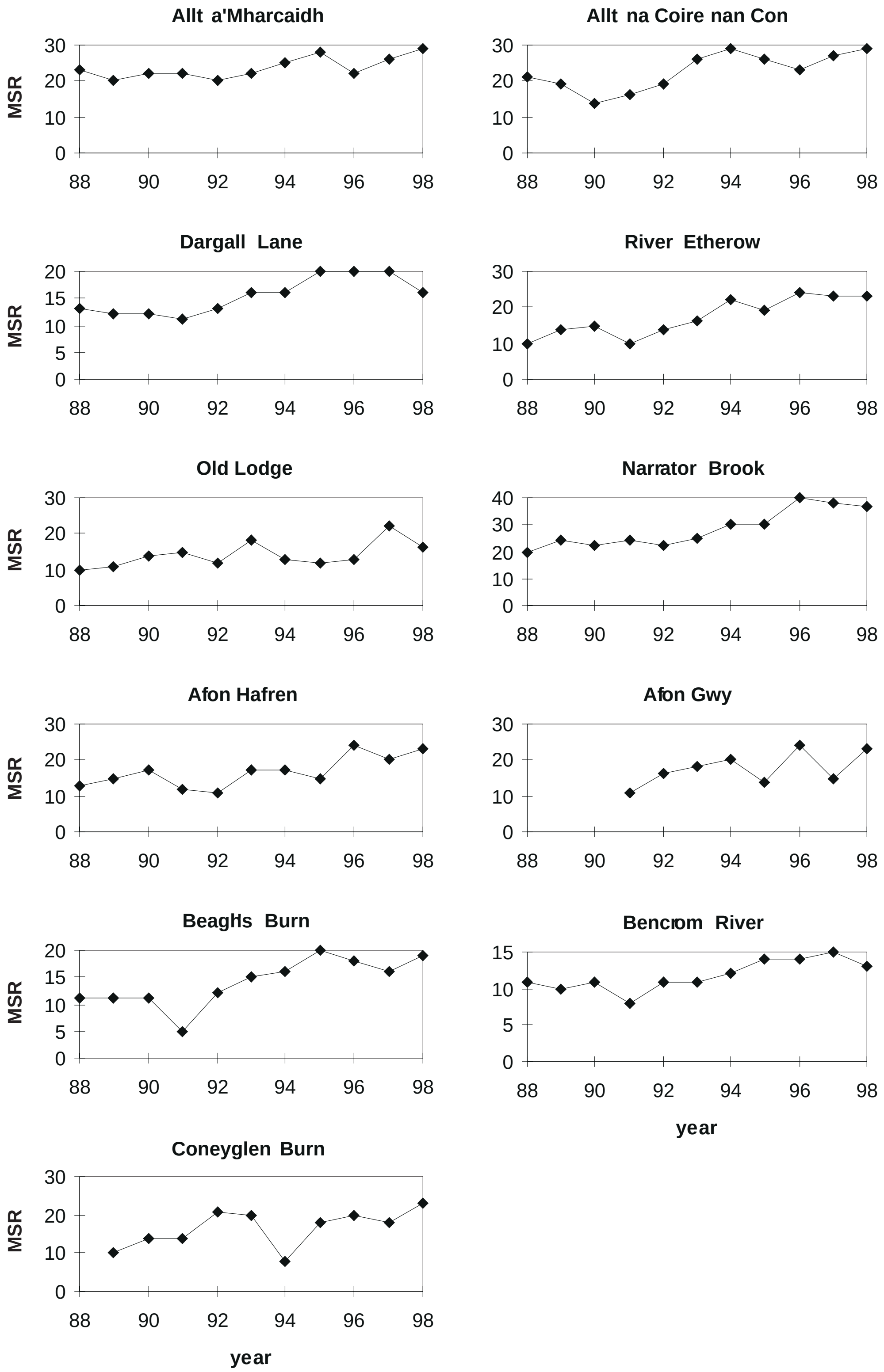


Figure 7.11b

Time series for macroinvertebrate minimum species richness (MSR) for UKAWMN streams (1988 - 1998)

Given the between-site correlations demonstrated in Table 7.5 it seems likely that changes in MSR observed in the majority of streams will reflect the influence of some feature of winter-spring flow, and it is therefore likely that the apparent increases in MSR will not be sustained in the longer term. These findings suggest that, in a monitoring context, macroinvertebrate minimum species richness may be of limited value as an indicator of ecosystem health, at least over the relatively short duration encompassed by this report.

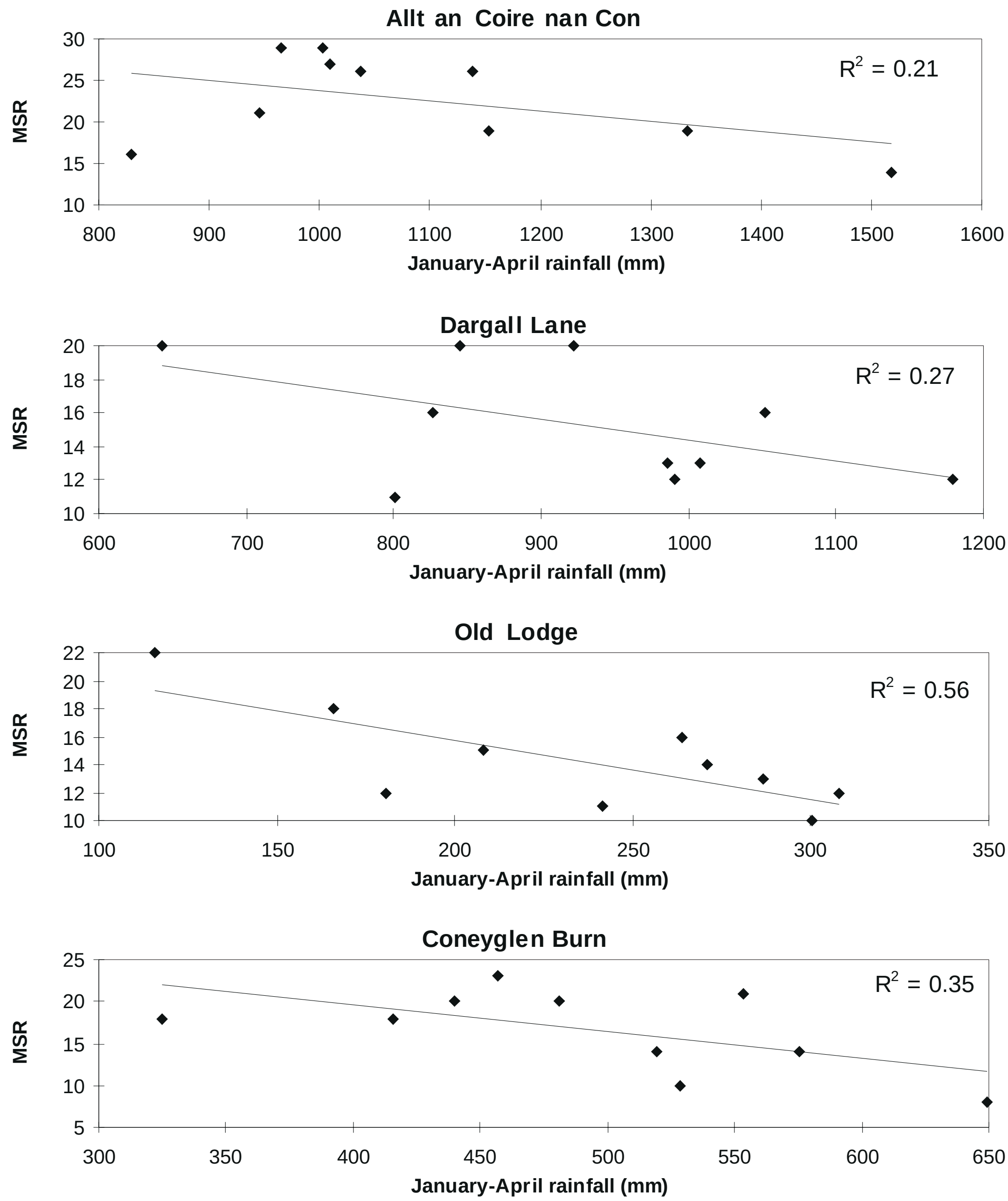


Figure 7.12

Relationship between the annual minimum species richness (MSR) of macroinvertebrate communities in samples from Allt na Coire nan Con, Dargall Lane, Old Lodge and Coneyglen Burn and total January-April rainfall (recorded at nearby Meteorological Stations)

7.5 Summary

- Biological characteristics of UKAWMN lakes and streams reflect site acidity. Generally, the most acid sites have the fewest species and support the lowest trout densities. The least acid sites tend to exhibit relatively high species diversity. However other chemical and physical factors are also likely to be important in determining biological properties. The outflows of the least acid lakes do not have high trout densities.

- For the majority of sites, trout density is lower than that predicted for non-polluted equivalent sites by HABSCORE HQS. Spatially, mean trout density can be linked to mean water chemistry. A roughly exponential decline in density with increasing labile Al concentration is observed, while healthy populations are not found in most sites which have a ten-year mean ANC of less than 0 $\mu eq\ l^{-1}$.

- Temporal trends have been identified in the assemblages of epilithic diatoms and macroinvertebrates at several sites. However, Llyn Llagi and Loch Chon are the only sites exhibiting trends indicative of recovery in both biological groups, which also show significant reductions in acidity.

- Temporal diatom species change in Llyn Llagi is also apparent in sediment trap samples and the trend in the latter is roughly the reverse of that observed in samples toward the top of a sediment core (indicative of acidification) taken from the lake in 1991. The recent changes therefore provide convincing evidence of the early stages of biological recovery, at least at the lowest trophic level, at this site. Similar evidence for ‘reversal’ of the diatom assemblage is apparent at Loch Chon. However here, changes in the epilithic flora can be linked to a reduction in March Cl concentration, and this suggests that the diatom response may be influenced, or even primarily determined, by a reduction in climatically induced acidity over the last decade.

- Of the nine sites with trends identified for epilithic diatoms, trends at five are indicative of an increase in pH, and one is indicative of deterioration. Four of the six sites with trends indicative of a change in acidity show consistent trends in measured pH. Generally for lakes, inter-annual variation in epilithic diatom assemblages can be linked to inter-annual variations in pH.

- Inter-annual variation in epilithic diatom assemblages can be linked to variations in summer rainfall at those stream sites for which there is a strong relationship between flow and pH. This suggests that these assemblages will be particularly dependent on relatively recent antecedent acidity, i.e. for the previous two months.

- Eleven sites exhibit linear trends in the macroinvertebrate assemblage, but trends at only two of these are interpreted as being indicative of recovery, while one is indicative of deterioration. The three sites for which faunal trends are indicative of change in acidity also demonstrate consistent significant trends in pH. Most of the sites where macroinvertebrate trends have been recognised have west coast locations, and the pattern of inter-annual variation in species is very similar between all of these. It is therefore possible that the observed trends reflect a response of the aquatic fauna to a decline in the frequency, duration and intensity of acidic conditions resulting from a reduction in ‘winter westerly’ weather activity. The January North Atlantic Oscillation Index can explain a significant proportion of variation in species assemblages of most sites for which linear trends have been identified.

- Upward trends have been observed in minimum species richness (MSR) of macroinvertebrate samples in most stream sites, and the correlation of temporal variation between sites is strongest for sites which are geographically close. Four sites show a negative relationship between MSR and total January to April rainfall measured at nearby Meteorological Stations. This relationship is strongest at Old Lodge, where there is little evidence of any link between flow and pH, suggesting that physical effects of flow may be more important than chemical effects in this respect.

- Trends in aquatic macrophyte assemblages have been identified at five sites, but all of these most likely result from physical disturbance rather than chemical change.

- Few linear trends were observed in trout population statistics. The relatively high mobility of fish, in comparison to other biological groups, adds to overall sample variability, and for most sites it is likely that even where conditions may be becoming gradually more favourable for fish, several more years of monitoring may be necessary to allow the possible detection of trends. However, in the survey stretch of Old Lodge there has been a striking increase in the density of newly recruited trout during a period of sharply declining labile Al concentration.