Chapter (non-refereed)

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Appendix 2

The chemical status of some lochs vulnerable to acid deposition in Scotland

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Summary
Water samples for chemical analysis were taken from the inflow and outflow streams of 83 Scottish lochs. Fifty-seven of these lochs had granite basins and catchments, whereas the catchments of the other 26 'control' lochs were of other types of bedrock. Samples were taken on 2 different occasions at each site. They were analysed for colour, pH, conductivity, calcium, magnesium, phosphorus, nitrogen, chloride and sulphur. The levels of these determinands found at each site are presented and discussed. Samples taken at different times from the same stream were always very similar and usually those from the inflow and outflow of each loch were too, although there were one or 2 notable exceptions. There was a general similarity among samples from the same geographic area but wide differences between some geographic areas. pH and calcium data, in relation to the curve proposed by Henriksen (1979), indicated that a number of sites could be regarded as acidified. The majority of these sites are in Galloway.

1 Introduction
Although considerable attention has been given to the chemistry of fresh waters in various parts of the world in relation to acidification (Vangenechten 1980; Wright *et al.* 1980; Brown & Sadler 1981; Bobee & Lachance 1984), relatively little information is yet available for Scotland, where the levels of acid deposition are known to be just as high as those in Scandinavia and North America (Cape *et al.* 1984). Though the main emphasis of the study of which this is part has been on the biology of the fish, a considerable number of chemical samples was taken during the survey and the results from their analyses are presented and discussed here.

Most attention within the project has been given to lochs whose basins and catchments lie on granite bedrock—much of the present evidence suggests that these sites are likely to be among the most vulnerable to acid deposition (Almer 1974), and that some of them at least have been acidifying since the Industrial Revolution (Flower & Battarbee 1983; Battarbee 1984). However, a number of 'control' lochs (whose basins and catchments lie on non-granitic rocks) were included in the study series also, for comparison.

2 Methods
Eighty-three lochs in the study series selected from maps were visited during 1984 and 1985. At each loch, water samples were taken from the major inflowing stream and the outflow, at the beginning and again at the end of each trip (Plate 1). The time interval involved here was usually one day, but occasionally 2 or 3 days. Water from the outflow was assumed to be representative of the loch itself.

Samples were always taken in the same way, using 250 ml bottles. Each bottle was rinsed twice using site water and then filled from just below the surface, making sure that no contaminant materials from the surface or elsewhere entered the bottle. Each sample was then kept dark and as cool as possible (but not frozen) until analysis.

Analysis of the determinands shown in Table 1 was carried out on each sample. For various reasons it was not possible to sample streams at all 83 loch sites. Several lochs had no evident inflows, a few had no running outflow at the time of the visit, or both were completely silted or dried up. Groundwater was assumed to be especially important to such systems (Anderson & Bowser 1986). Where inflow or outflow could not be sampled for any reason, 'substitute' samples were taken in the loch close to the most likely inflow and outflow during wet weather.

3 Chemistry
The general nature of the results of the chemical analyses are indicated in Figure 1 for all the determinands, with the exception of phosphorus and nitrogen. The values for both of these were extremely low at the great majority of sites and they are not discussed further here. A general point to note is that for several determinands there appears to be little difference between the distribution of the data from the granite lochs and those from the 'control' lochs. In general,

Table 1. Chemical determinands measured in this study

1.	Hazen colour
2.	pH
3.	Conductivity
4.	Calcium
5.	Magnesium
6.	Aluminium
7.	PO_4 phosphorus
8.	NO_3 nitrogen
9.	NH_4 nitrogen
10.	Chloride
11.	SO_4 sulphur

Plate 1. Taking a sample of the water in one of the burns visited during the study for subsequent chemical analyses (Photograph R N B Campbell)

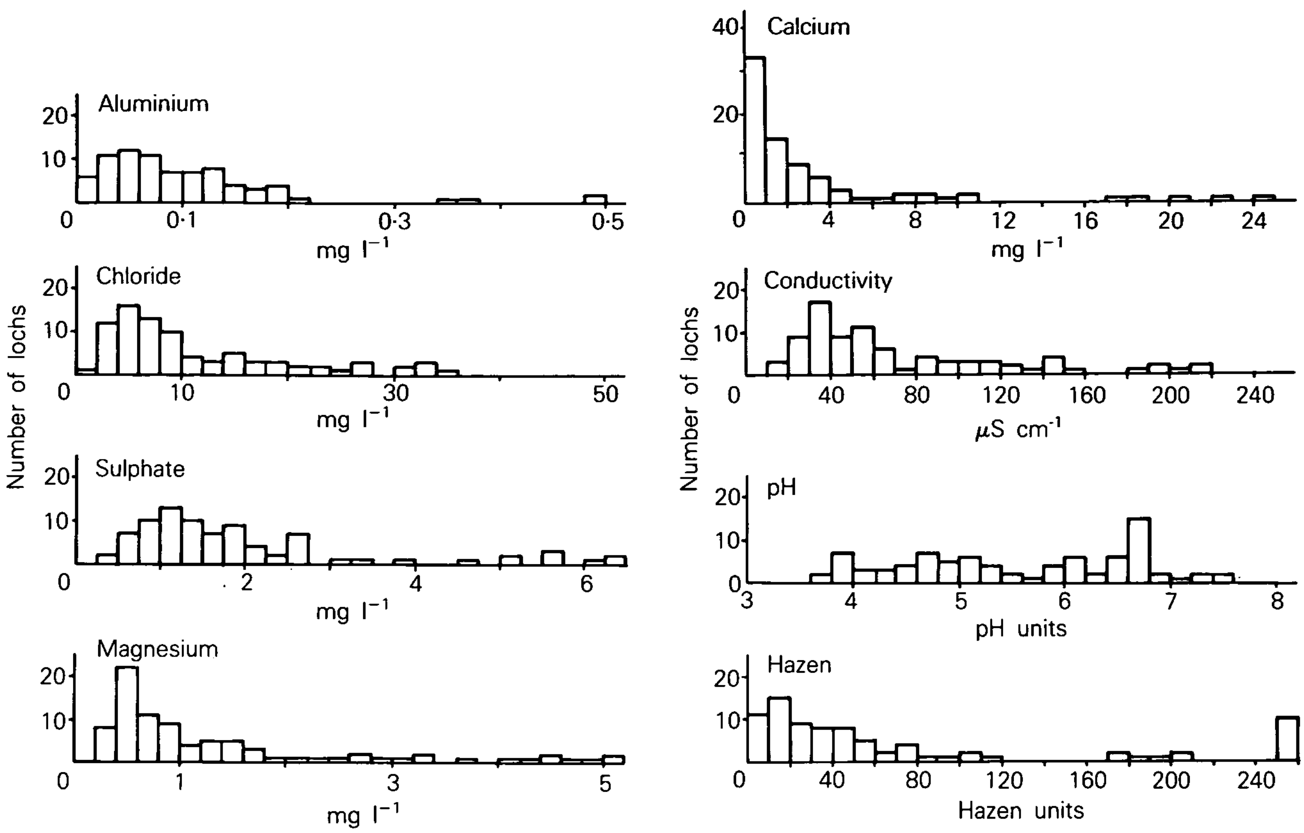

Figure 1. The frequency distribution of chemical determinands at all sites studied. The values are means for the outflow from each loch

too, there are few major differences between values from the inflow and outflow samples taken at any one loch (Figures 2 & 3).

The pH of most of the waters lay between 4.0 and 7.0, though a number of samples were below 4.0 (mainly the organically stained lochs on Islay) and a few above 7.0. Calcium levels were mostly low (the great majority less than 5.0 mg l^{-1}) with only 5 sites greater than 15 mg l^{-1}, and values for magnesium were all less than 5 mg l^{-1} with the exception of 2 sites.

As might be expected, the distribution of the values of chloride was similar to that of total conductivity, the majority of sites falling between 2.0–10.0 mg l^{-1} and 10-70 µS cm^{-1} respectively. Sites with the highest values were fairly obviously those nearest the sea and likely to be affected by windblown salts.

Values for Hazen were mostly less than 100 units, indicating rather clear water for the most part, but a few sites were exceptional in being over 250 units. These stained lochs were on Arran, Islay and Nairn.

Levels of total aluminium were almost all less than 0.2 mg l^{-1} but 5 lochs were, exceptionally, above this figure. Similarly, levels of sulphate were mostly low (the majority less than 5 mg l^{-1}) but there were a few sites with moderately high values. Sulphate is reduced in organically stained acid waters so the values from such waters (eg those on Islay) are not realistic.

One of the most interesting aspects of the chemistry in connection with the acidification problem lies in the values of pH and calcium in relation to the 'acidification curve' proposed by Henriksen (1979). Data from the present study are shown in Figure 4, and it is clear that there are a number of sites (mostly with pH values of less than 5.0) which would be classified as being acidified according to this criterion, although on a purely chemical basis it is important to look at other determinands as well (Brown 1982).

In looking more closely at the distribution of the sites in Figure 5, it can be seen that, in many cases, there is a close similarity between the chemistry of sites from the same geographic area, and that there are widely differing values from different areas. Thus, the lochs on Islay and in Galloway have low pH and calcium levels (Plate 2), whereas those from Criffel, Nairn (Plate 3) and Aberdeen have very much higher values for these determinands and would not be classified as acidified. However, only the Galloway lochs would be considered by Henriksen (1979) to be acidified, for he points out that his hypothesis is relevant to clear waters only and not to organically stained systems such as those on Islay.

4 Discussion

In view of the potential importance of episodic events (Bjarnborg 1983), the low numbers of water samples which it was possible to take during this study (one pair at the inflow and at the outflow of each loch) mean

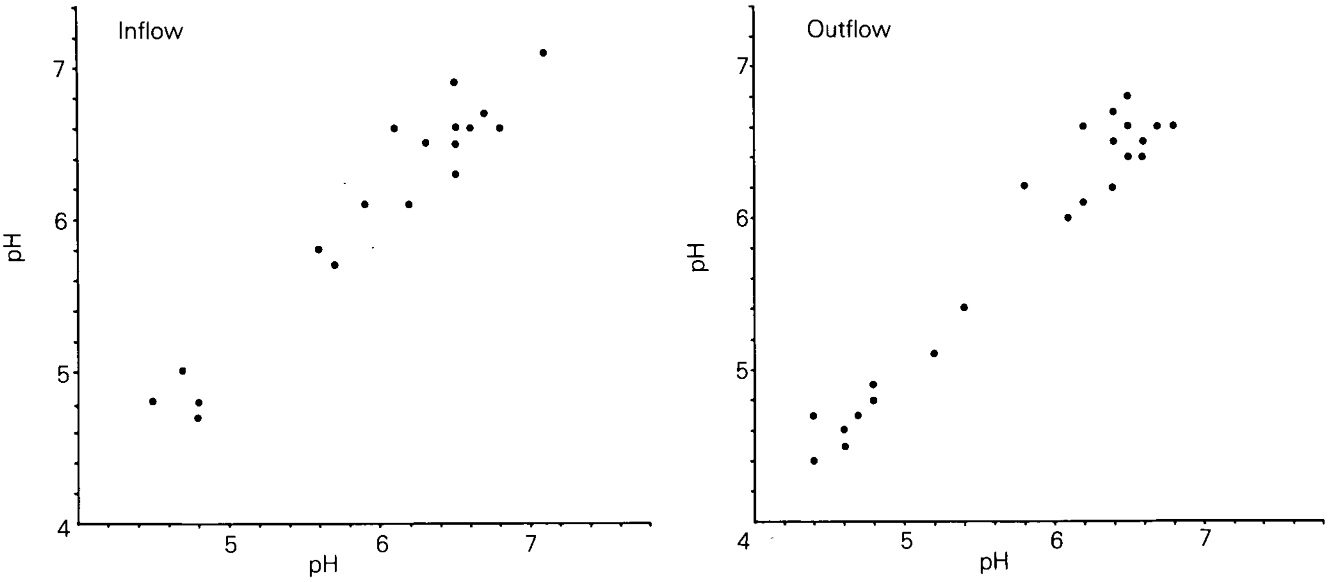

Figure 2. The distribution of cross-plots of pH values from pairs of samples taken from the inflows and the outflows of the lochs studied during 1984

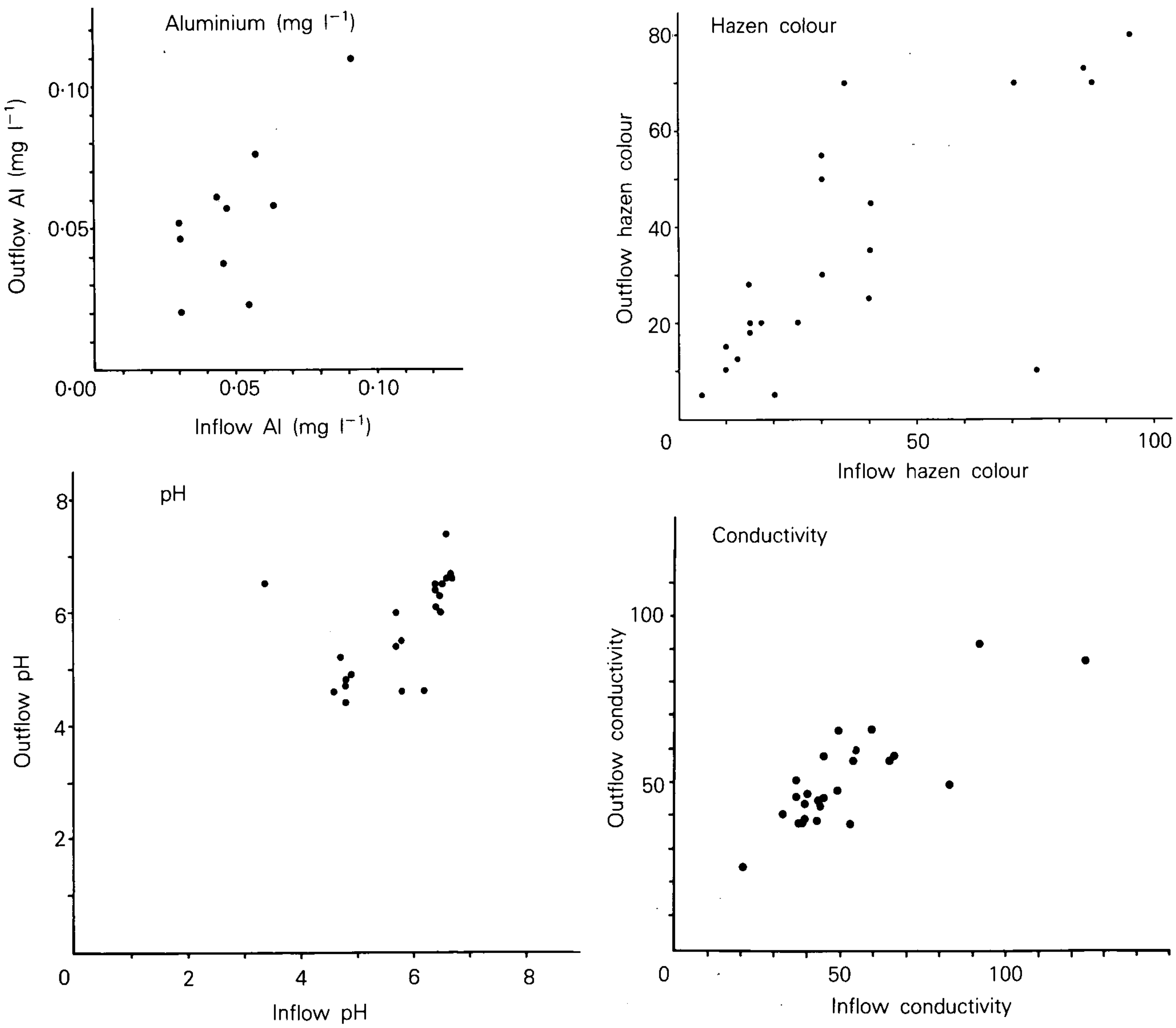

Figure 3. The distribution of cross-plots of pH and other determinands from inflow and outflow samples from the sites studied during 1984

Plate 2. The Long Loch of the Dungeon in Galloway, one of several lochs in this area which, though now partially acidified, still maintains a population of brown trout (Photograph R N B Campbell)

Plate 3. Loch Kirkaldy near Nairn, where there is no evidence yet of chemical acidification and the brown trout population is large and healthy (Photograph R N B Campbell)

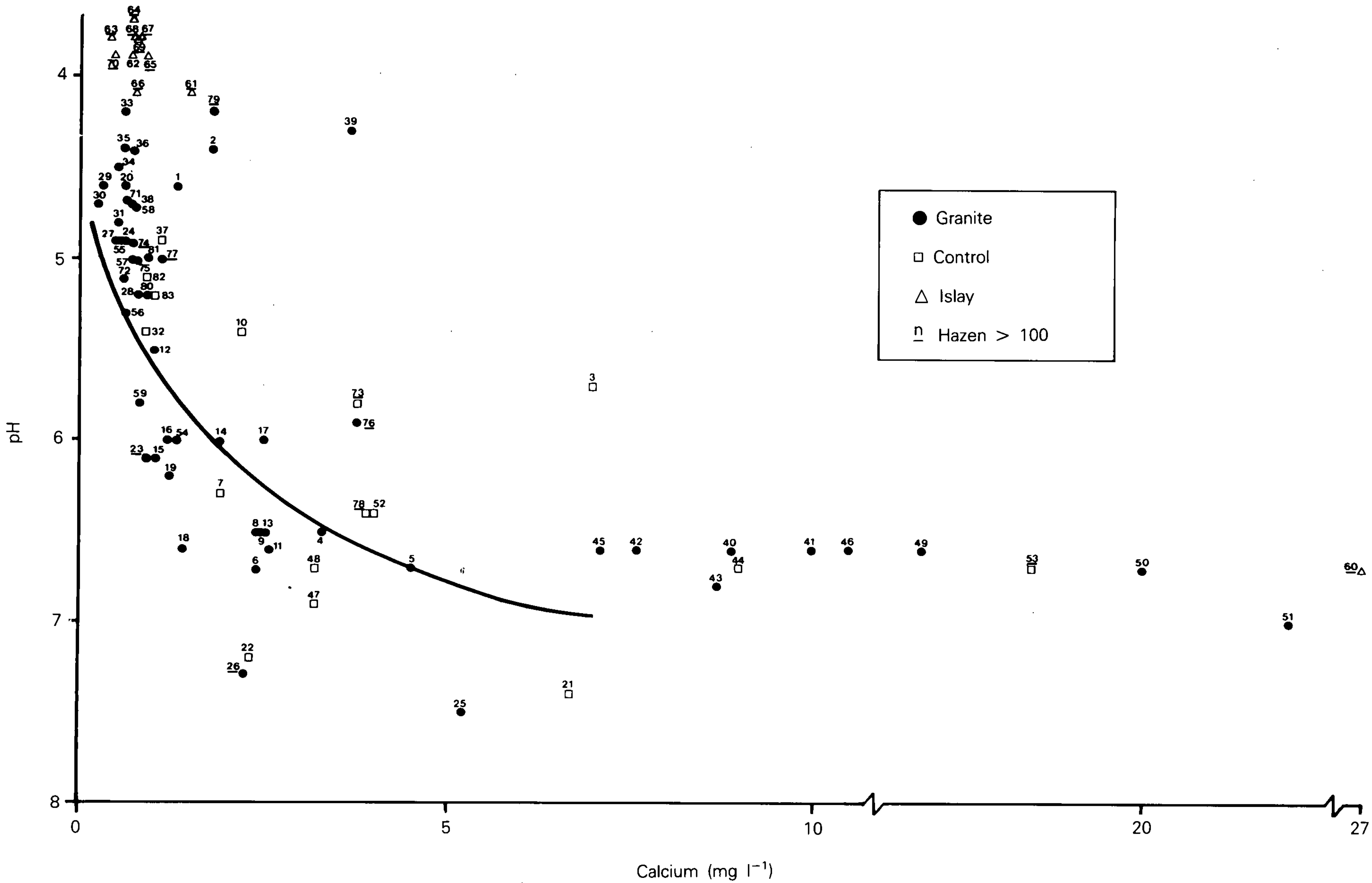

Figure 4. *The distribution of pH and calcium values from all the sites studied. The values are the means from outflow samples. The curve is that of Henriksen (1979) but not all the sites are applicable because of their alkalinity or organic content.*

that any general conclusions concerning the chemistry must be drawn with care. However, the close relationship which exists in the chemistry of most pairs (Figure 2), which were almost always collected at least 24 and sometimes as much as 72 hours apart, suggests that the data are meaningful for these waters, at least during the period of sampling. In addition, extensive data of this kind have been rare in the past (Watt Committee on Energy 1984; United Kingdom Acid Waters Review Group 1986) and should be explored when available.

The water sample taken from the outflow of each loch was assumed to be representative of the chemistry of that loch at that time. This was not necessarily true of the sample from the main inflow, whose chemistry bore a variable relationship with that of the outflow depending on local conditions. At most sites, the chemistry of the outflow and the main inflow was similar (Figure 3). However, there are a number of exceptions which are of considerable interest, where one or more of the chemical determinands differed substantially in the inflow and outflow waters. A good example of this difference was at Loch Grannoch in Galloway in May 1984, where the pH of the inflow was 6.2 whereas that of the outflow was 4.6. Smaller differences were noted at subsequent visits, but it is evident that inflows of this type may be very significant in allowing the survival of brown trout in a system which is elsewhere lethal to them. Arctic charr, which are now extinct in Loch Grannoch, would not have entered these streams and would have been confined entirely to the loch.

The area of Scotland most affected by acidification appears to be Galloway in the south-west. Only here was a considerable proportion of the lochs chemically acidified, and this coincided with a loss of fish populations in many of them. In the same area at present, there are attempts to restore 2 of these systems chemically—Loch Dee (Burns *et al.* 1984) and Loch Fleet (Central Electricity Generating Board 1985). Judging by experience in Scandinavia (Henriksen 1982), these projects are likely to be successful in the short term, but expensive. A small number of lochs in other parts of Scotland are also affected by acidification (Plate 4).

These results reflect the experience in several other parts of the northern hemisphere (Drablos & Tollan 1980; Overrein *et al.* 1980; Haines 1981; Harvey & Lee 1982; Johnson 1982; Howells 1983) and agree with data produced by other workers in Scotland (Wright & Henriksen 1980; Harriman & Morrison 1980, 1981, 1982). However, a feature of the fresh waters in Scotland which seems to distinguish them, to some

Plate 4. Loch a Mhill Bhig near Loch Sloy in Strathclyde. Four small lochs close together were sampled in this area; 2 were on the granite block and contained no fish, whilst 2 adjacent 'control' lochs off the granite (Loch a Mhill Bhig being one of them) had normal populations of brown trout (Photograph K H Morris)

extent, from many of those in other geographic areas is the large proportion which have high organic staining. This factor needs to be emphasized more (cf Harriman & Wells 1985) and should be the subject of future research

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