Chapter (non-refereed)

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Appendix 1

The bathymetry and hydrology of some lochs vulnerable to acid deposition in Scotland

A A LYLE

Summary
Bathymetric surveys were carried out on previously unsurveyed Scottish lochs as part of a programme studying acidification. These surveys provided background information on the physical character of the sites and made possible a basic examination of relationships between water retention times and acidification. The results indicate that lochs with retention times of a few months are most likely to suffer from long-term acidification, but that longer-term chemical information is required for more definite conclusions.

1 Introduction
Information on the bathymetry of a loch is an important part of any study of its ecology. In the context of acidification research (Maitland *et al.* 1986), bathymetric information, together with catchment and climatic data, enables the calculation of theoretical retention time—an important hydrological parameter. Thereafter, a differentiation between lochs can be made with regard to the impact and duration of influence of episodic acid inputs, in terms of hydrological parameters, which may be used to identify their vulnerability to acidification.

A loch with a short average retention time of a few days may be completely flushed out during periods of heavy rainfall, particularly if this occurs after a prolonged dry spell, when runoff is faster and loch levels (and therefore volumes) are low. Given the episodic nature of acid influxes, a rapid water replacement in such a loch could mean a dramatic change in the chemistry of the whole loch and the environment of its aquatic biota. Most likely, such an event would be short-lived, but, depending on its seasonal timing, considerable biological damage could be caused. Such a sequence of events would be unlikely in lochs which have retention times of, say, a few months, but an acidic input would obviously remain in such lochs for a

Plate 1. The boat and echo sounding equipment used during this study (Photograph P S Maitland)

longer time, perhaps leading to a slower but more stable period of acidification.

2 Methods

Echo sounding surveys were made from small boats (either fibreglass or inflatable) which were dragged or carried to the sites (plate 1). A compact, portable echo sounder and battery pack were fitted to a rucksack frame and also carried to the sites. The echo sounder used was a Lowrance X15A operating at 192 KHz with a 20° beam angle transducer, powered by a 12 volt dry cell battery. This equipment proved ideal for the bathymetry concerned because of its shallow depth capability and control flexibility, but on a few occasions, in very shallow waters of less than 0.5 m, measuring poles were needed.

At each site surveyed, echo sounding transects were run between identifiable points on the shore. Transect lines and end points were marked on to large-scale field maps. The number of transects taken varied according to loch size and morphometry, weather conditions and time constraints. At the smallest sites, only 4 or 5 transects were required, whereas the most taken at any one site (Loch Valley) was 35—a total transect length of 6 km. The most demanding requirement of the surveys was to keep the transect lines straight and to row them at constant speed. This was difficult in a small boat in windy conditions. An assessment of the quality of each survey was made by calculating Hakanson's Information Value (I') (Hakanson 1981), although this Value does not take account of individual transect quality.

The time taken to survey individual lochs varied with their size. The smallest took about 30 minutes, whereas larger sites took up to one day. This figure does not include the time taken to carry equipment to the site, which was often several hours. The highest number of sites surveyed in a single 4-day field trip was 8 lochs (twice), but this was only possible where the sites were close together (eg Rannoch Moor) or there was easy access by road (eg Criffel).

Overall, new bathymetric information was obtained for 49 lochs, and existing data were available for 15 additional sites, mostly from Murray and Pullar (1910), making a total of 64 sites.

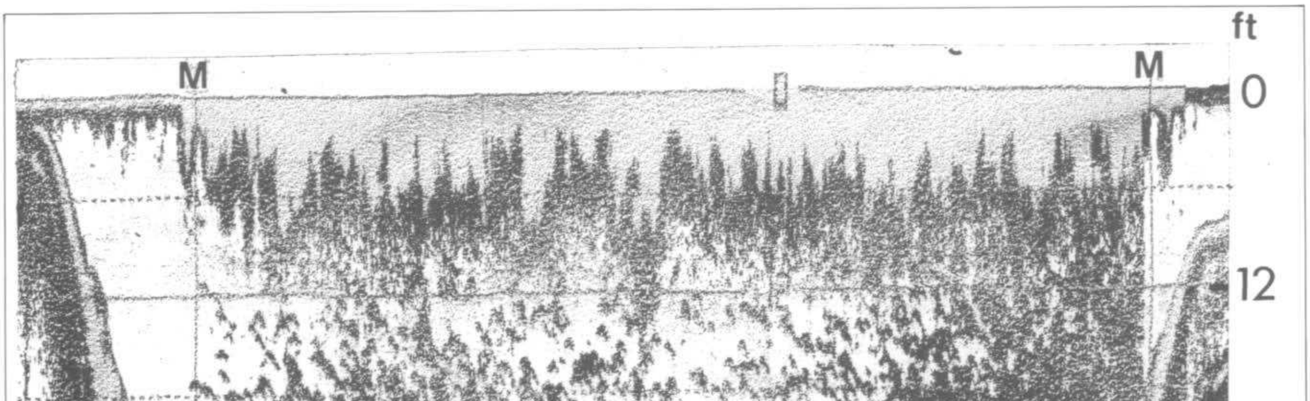

Plate 2. An echo trace from the fishless Loch Valley in Galloway, showing the unexpected dense echoes referred to in the text. M indicates changes in recording sensitivity

Base maps of all the lochs surveyed were produced by digitizing the loch shorelines and islands from 1:10000 scale OS maps. Once digitized, outline maps of the lochs could be made at suitable working scales. Echo sounding transects were marked on to these maps from the field reports. Depths were then plotted along the transects from the echo sounding charts (Plate 2), following the method described by Hakanson (1981), and illustrated in Figure 1. Finally, contour lines of equal depth were drawn on to the maps by eye (see Figure 1).

The areas within shorelines and depth contours were measured from maps by planimetry and, from them, loch volumes and mean depths were calculated. This calculation was done for the 49 lochs surveyed during the project, and equivalent information for the 15 remaining sites was obtained from the sources indicated in Table 1. Loch altitudes were estimated from the 1:10000 OS maps.

An approximation of the hydrological budget of the lochs was made by considering the loch volume, catchment area and net precipitation. This method is a simplification of any one situation, but by applying it to all the sites consistently it can identify broad similarities and differences in their hydrological regimes.

First, the topographical catchment area of each loch was defined from 1:25000 OS maps and measured by planimetry. In upland areas, the watershed is usually clear, but becomes progressively less so on flatter land forms, particularly peat bog areas such as Rannoch Moor.

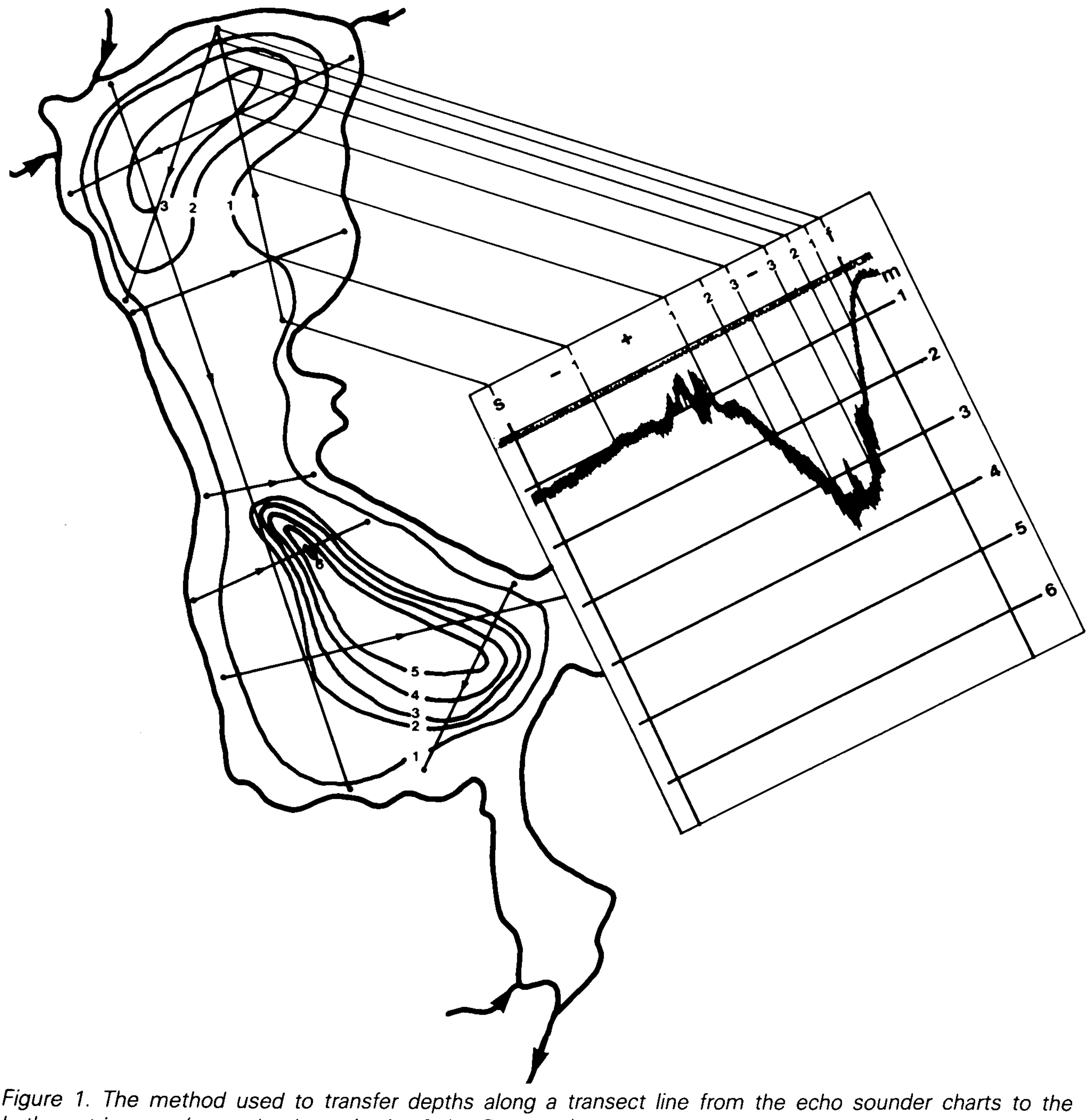

Figure 1. The method used to transfer depths along a transect line from the echo sounder charts to the bathymetric map (example: Long Loch of the Dungeon)

Table 1. Bathymetric data for the survey lochs

Number	Loch name	Data source	Altitude (m OD)	Loch area (ha)	Mean depth (m)	Survey I' value
1	Grannoch	M&P	211	117.30	6.35	—
2	Fleet	M&P	339	17.40	6.67	—
3	Lochenbreck	M&P	199	15.80	2.33	—
4	am Fhaing	BS	258	1.08	0.69	0.9960
5	nan Craobh	BS	238	3.61	0.72	0.9770
6	Tearnait	M&P	140	42.90	4.95	—
7	Dubha 'Morvern'	BS	204	6.03	0.85	0.9650
8	Caol	BS	249	2.46	0.96	0.9290
9	Uisge	BS	149	17.60	4.36	0.9277?
10	Mhic Pheadair Ruadh	est	303	1.13	0.40	—
11	Dubh 'Kingshouse W'	BS	302	3.32	0.32	—
12	Dubh 'Kingshouse N'	BS	311	3.20	0.90	—
13	Dubh 'Kingshouse E'	M&P	305	6.87	0.82	—
14	Mathair Eite	BS	296	15.80	0.72	0.9158
15	Gaineamhach	BS	294	27.20	1.42	0.9860?
16	Gaineamhach 'NE'	BS	296	11.20	0.60	0.9080
17	Gaineamhach 'SE'	est	292	1.70	0.15	—
18	Einich	JP	496	79.60	18.98	—
19	Beanaidh	BS	583	1.33	1.53	0.9510
20	Mhic Ghille-chaoil	BS	494	10.00	2.52	0.9940
21	Pityoulish	M&P	206	27.10	7.00	—
22	na Seilge	BS	119	56.00	1.79	0.9460
23	Talaheel	BS	187	6.80	0.71	0.9550?
24	nan Clach Geala	BS	193	7.70	1.14	0.9560
25	Dubh Cul Na Beinne	BS	189	6.38	0.67	0.9771
26	Tuim Ghlais	BS	165	40.30	1.21	0.9793
27	Long L of the Dungeon	BS	267	4.40	1.62	0.9400
28	Round L of the Dungeon	BS	275	4.50	3.68	0.9370
29	Enoch	ns	493	48.90	—	—
30	Arron	BS	445	2.70	1.03	0.9640
31	Neldricken	BS	348	32.90	4.29	0.8840
32	Dungeon	M&P	306	35.60	6.92	—
33	Narroch	BS	328	3.53	2.96	0.9484
34	Round L of Glenhead	B	295	12.50	4.29	—
35	Long L of Glenhead	BS	295	10.40	3.79	0.9652
36	Valley	BS	322	35.80	4.28	0.9249?
37	Harrow	M&P	247	15.40	3.49	—
38	Dow	ns	475	0.50	—	—
39	Dalbeattie Plantain	BS	27	3.07	2.72	0.9598
40	Fern	BS	83	5.89	1.43	0.9610
41	White	BS	33	12.00	4.10	0.9026
42	Barean	BS	44	9.42	3.65	0.9139
43	Clonyard	BS	42	4.71	3.11	0.9137
44	Fellcroft	BS	139	6.96	1.07	0.9627
45	Bengairn	BS	48	2.89	0.86	0.9672
46	Duff's	BS	41	1.23	1.47	0.9481
47	Kernsary	M&P	21	80.80	11.67	—
48	Ghiuragarstidh	M&P	36	23.40	2.78	—
49	Policies	BS	105	3.38	1.61	0.9596
50	Waterton	BS	101	1.93	1.06	0.9056
51	of Skene	M&P	84	119.00	1.43	—
52	Brandy	BBHS	637	27.30	22.44	—
53	Corby	BS	82	12.60	0.73	0.9546
54	Muick	M&P	400	222.20	35.31	—
55	Dubh 'Muick'	ns	638	19.30	—	—
56	Buidhe	BS	668	1.98	1.56	0.9600
57	Lochnagar	ns	785	10.36	—	—
58	nan Eun	BS	895	7.64	10.35	0.9246
59	Sandy	BS	792	4.71	1.04	0.9707
60	Bharradail	BS	99	3.97	1.45	0.9538
61	Beinn Uraraidh	BS	295	21.29	8.33	0.9478?
62	nam Breac	BS	362	5.16	4.16	0.9004
63	nam Manaichean	ns	—	—	—	—
64	Laoim	ns	—	—	—	—
65	Sholum	ns	—	—	—	—
66	Sholum 'W'	ns	—	—	—	—
67	Leorin 'W'	ns	—	—	—	—

68	Leorin 'E'	ns	—	—	—	—
69	na Beinne Brice	ns	—	—	—	—
70	'Moine na Surdaig'	ns	—	—	—	—
71	Coirre Fhionn	ns	—	—	—	—
72	Iorsa	ns	—	—	—	—
73	Garbad	ns	—	—	—	—
74	Cnoc an Loch	ns	—	—	—	—
75	a'Mhuillin	ns	—	—	—	—
76	Kirkaldy	BS	229	3.80	0.96	0.9685
77	a'Chaoruinn	BS	279	2.89	1.62	0.9323
78	an t'Sidhein	BS	355	8.10	1.79	0.9683
79	nan Stuirteag	BS	338	0.70	1.10	0.9722
80	a'Mhill Bhig	BS	475	3.46	0.75	0.9395
81	a'Mhill Bhig 'Lower'	BS	465	0.24	0.40	—
82	Maol Meadhonach 'Upper'	ns	490	0.40	—	—
83	Maol Meadhonach 'Lower'	ns	485	0.50	—	—

BS = bathymetric survey
M&P = Murray and Pullar (1910)
JP = J Pytches (pers. comm.)
BBHS = Bell Baxter High School (pers. comm.)
B = R Battarbee (pers. comm.)
est = estimate from site visit
? = doubtful survey
ns = no survey

Average annual rainfall over the catchments was taken from the Meteorological Office map for the period 1941–70. Water losses to the atmosphere were estimated from tables of potential transpiration (Ministry of Agriculture, Fisheries & Food 1967) which incorporate an altitude correction. A standard approximate mean catchment altitude was used for this correction and was taken to be one third of the catchment range above loch level. Evaporation from loch surfaces was taken as 1.2 times the tabulated potential transpiration (see Penman 1948). The approximate net runoff volume is therefore the product of net precipitation and catchment (including loch) area.

Theoretical retention time (RT) is the end product of this approach and is calculated by:

365/(RUNOFF VOLUME/LOCH VOLUME)

and expressed as a number of days.

3 Results

The primary information is presented in Table 1, which gives the morphometric data for each site resulting from the bathymetric surveys and from other sources, which are identified. This information is not available for all 83 sites as surveys were prevented or curtailed on some by bad weather, and others were sampled only for water chemistry.

There is a considerable range in the size and type of loch included in the survey (Plate 3), from peat pools to large valley lochs, from shallow silty depressions to very steep-sided basins, and from lowland recreational sites to isolated alpine lochans. Some are totally artificial or have some throughflow control, but the majority are entirely natural. The extreme ranges from Table 1 are:

Areas (ha)	0.24	222.20
Maximum depths (m)	0.60	78.00
Mean depths (m)	0.15	35.31
Volumes ($m^3 \times 10^3$)	1.00	78,466.4
Altitudes (m OD)	21	895

An assessment of the quality of the bathymetric surveys conducted during this study was made by calculating part of the Hakanson Information Value (I' in Table 1) (Hakanson 1981):

$$I' = \frac{1}{A}\left[A - (0.14 \times \frac{A}{L} \times F^2 \times \sqrt{\frac{1}{n+a}} \times \sum_{i=1}^{n} \sqrt{a_{i-n}}\,)\right]$$

where: A = loch area, L = transect length, F = shoreline development, n = number of contours, and a = contour area.

In general, the I' values obtained were high and indicate that the amount of work carried out on the sites should produce satisfactory representations of bathymetry. However, this calculation, as it must do, neglects the quality of echo sounding transects in terms of uniform velocity and straightness. As mentioned earlier, wind—which affects both these requirements—was the major difficulty encountered on the surveys, and so only a subjective assessment of the real quality of each survey can be made by the surveyor. No systematic attempt has been made at such an assessment, but lochs where there is some doubt have been identified in Table 1.

Water retention time (RT) and the parameters required for its calculation are given in Table 2. Again, all the necessary information is not available for all the survey lochs, but a calculation has been made for 64 lochs.

Plate 3. Among the most difficult sites to survey were shallow rocky waters, such as Loch Gaineamhach on the Moor of Rannoch (Photograph K H Morris)

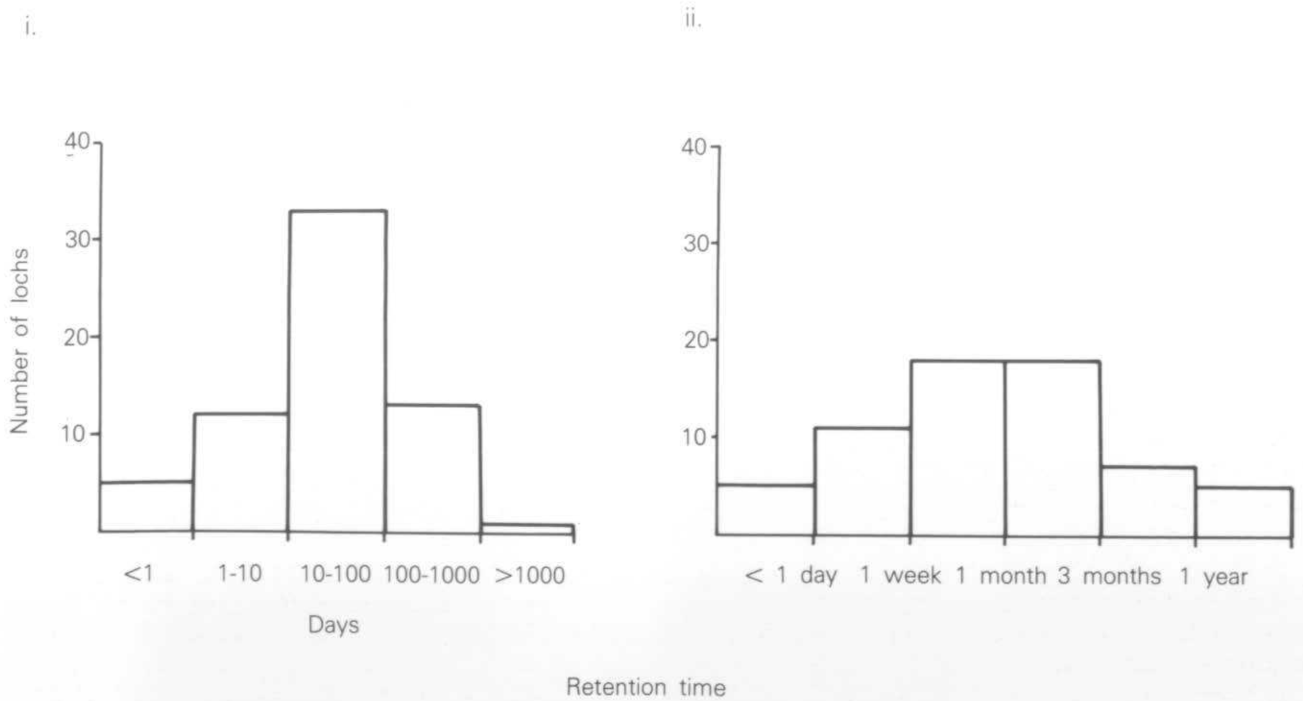

Figure 2. The frequency distribution of retention time for 64 of the survey lochs: (i) in logarithmic groups of days, and (ii) on a calendar scale to illustrate more ecologically relevant periods

There is a considerable range in mean RT for these lochs from 1.2 hours (Plate 4) to 4.25 years (Plate 5). Figure 2 shows the distribution of RT. Figure 2i is plotted against a logarithmic RT scale and shows the predominant category to be between 10 and 100 days, which accounts for 52% of the sites.

In Figure 2ii, RT is plotted against a calendar scale to illustrate more ecologically relevant water quality stability periods. For example, lochs in the longest category have an RT greater than one year, so slow long-term changes in their water quality associated with annual or longer variations in inflow quality would be expected. Those between 3 months and one year should have stability beyond seasonal trends, but most lochs fall into the next 2 lower categories and will follow monthly or weekly variations. The 2 lowest categories, less than one week, and less than one day, are those most susceptible to large and relatively rapid fluctuations in water quality and, indeed, to large proportional changes in their actual water retention times (see discussion below).

Chemical results from the inflow and outflow streams (2 sets taken, usually on consecutive days) were used to examine retention time effects on changes between inflow and outflow acidity. Figure 3 shows the relative differences for each sample set plotted against RT. Hypothetically, sampling over suitable periods would show such differences increasing with RT, but to some extent basing such calculations on spot samples introduces an element of chance. Also, the influence of other inflow streams is not taken into account. For example, at Loch Grannoch (RT = 98.2 days), pH was measured on 3 separate visits (May and December 1984, and May 1985). Outflow pH was fairly constant (4.6, 4.3 and 4.6 respectively), but inflow pH was not (6.2, 4.5 and 4.8) and hence the differences (1.6, 0.2 and 0.2) could vary markedly. So, although the distribution of points in Figure 3 partly supports the hypothesis, longer chemical records are required for a reliably informative relationship.

If consideration of RT is confined to those lochs assumed to be fully vulnerable to acidification (ie excluding peaty and alkaline lochs—see Table 2 and Appendix 3), then there is a highly statistically significant difference between the RT of lochs above and below the Henriksen (1979) curve (see Section 4) at the 1% level ($P=0.01$). The respective means for RT for those groups are 143.0 days ($n=22$) and 62.2 days ($n=19$), although the standard deviations are large, being 319.0 and 147.0 respectively. Median values are 74.8 and 9.7 days.

Another, though related, concept is to examine the ratios of catchment area/loch area of the above-mentioned group of lochs on the basis that this

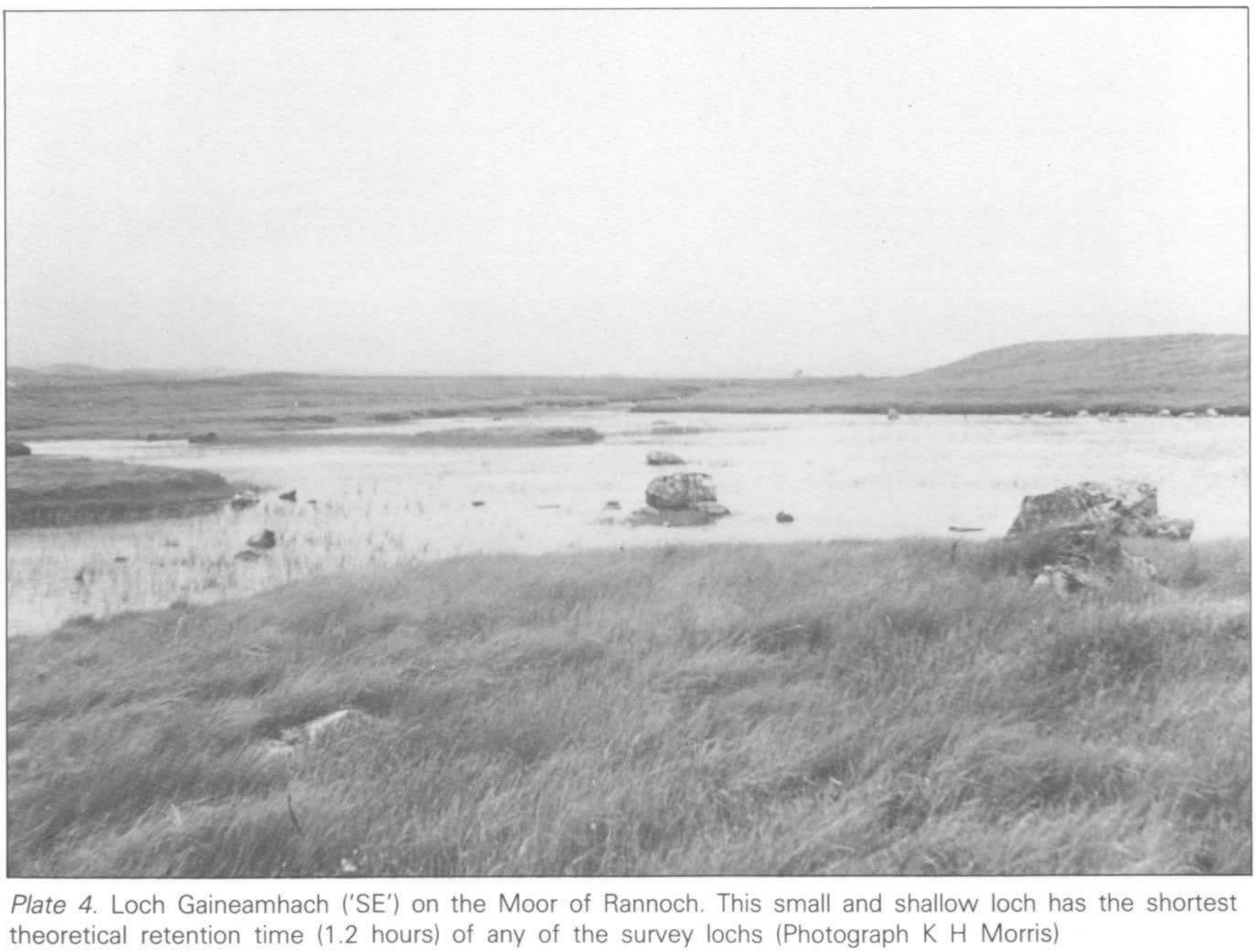

Plate 4. Loch Gaineamhach ('SE') on the Moor of Rannoch. This small and shallow loch has the shortest theoretical retention time (1.2 hours) of any of the survey lochs (Photograph K H Morris)

Plate 5. Loch Brandy in Angus, one of the 'control' sites in the study. This deep corrie loch has the longest theoretical retention time (4.25 years) of any of the survey lochs (Photograph K H Morris)

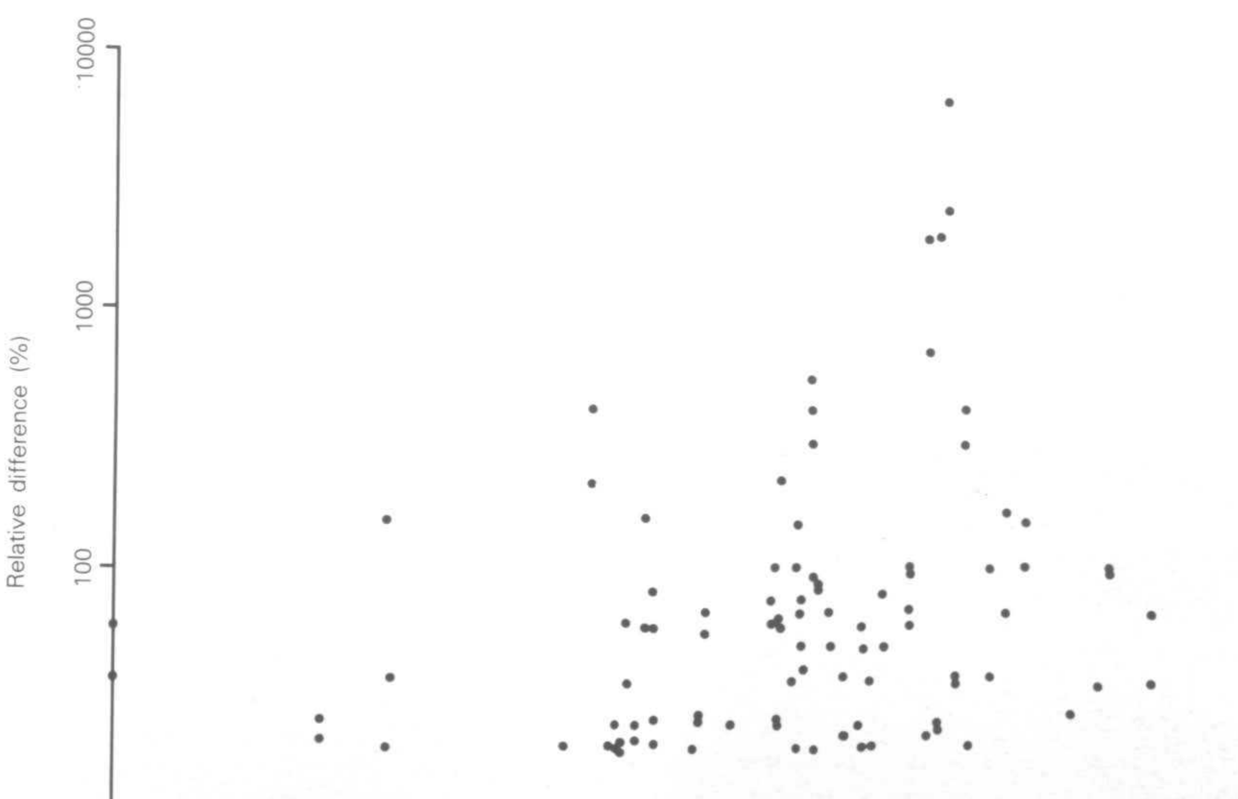

Figure 3. The relative difference in inflow and outflow acidity (ie the inflow, outflow difference in H^+ $\mu eq\ l^{-1}$ as a percentage of the inflow value) for each chemistry sample set plotted against retention time

Table 2. Hydrological data for the survey lochs

Number	Loch name	Loch volume ($m^3 10^{-3}$)	Catchment area (ha)	Annual rainfall (mm)	Potential evaporation (mm)	Total runoff ($m^3 10^{-3}$)	Retention time (days)	'Acidifiable' lochs
1	Grannoch	7447.6	1334.00	2300	386	27687	98.20	A
2	Fleet	1161.0	107.60	2100	386	2129	199.00	A
3	Lochenbreck	368.1	129.20	1600	434	1677	80.10	A
4	am Fhaing	7.5	25.82	2300	518	478	5.70	B
5	nan Craobh	25.9	102.69	2400	518	1997	4.70	B
6	Tearnait	2123.8	1016.50	2200	518	17775	43.60	B
7	Dubha 'Morvern'	51.1	118.97	2000	518	1846	10.10	B
8	Caol	23.7	45.04	2400	518	891	9.70	B
9	Uisge	766.9	874.90	2900	518	21241	13.20	B
10	Mhic Pheadair Ruadh	4.5	239.47	2500	338	5201	0.32	B
11	Dubh 'Kingshouse W'	10.7	293.58	2550	312	6643	0.59	B
12	Dubh 'Kingshouse N'	28.8	16.80	2200	389	360	29.20	A
13	Dubh 'Kingshouse E'	56.6	27.53	2200	389	618	33.40	B
14	Mathair Eite	114.0	411.70	2300	373	8226	5.10	B
15	Gaineamhach	386.7	304.10	2100	366	5725	24.70	B
16	Gaineamhach 'NE'	67.2	457.60	2100	357	8163	3.00	B
17	Gaineamhach 'SE'	2.6	1082.20	2200	369	19845	0.05	B
18	Einich	15107.0	1106.7	1800	229	18600	296.40	B
19	Beanaidh	20.4	41.17	1500	255	528	14.10	B
20	Mhic Ghille-chaoil	252.4	74.40	1500	293	1013	91.00	A
21	Pityoulish	1897.2	667.90	900	367	3684	187.90	—
22	na Seilge	1003.2	324.60	1000	405	2219	165.00	—
23	Talaheel	48.2	35.70	1000	390	254	69.30	B
24	nan Clach Geala	87.7	51.70	1000	387	358	89.40	A
25	Dubh Cul Na Beinne	42.8	78.62	1000	381	521	30.00	—
26	Tuim Ghlais	485.9	1084.70	1000	389	6842	25.90	—
27	Long L of the Dungeon	71.2	215.00	2150	400	3836	6.80	A
28	Round L of the Dungeon	165.4	64.90	2010	402	1112	54.30	A
29	Enoc	—	160.50	2350	348	4158	—	A
30	Arron	27.8	22.30	2350	374	492	20.60	A
31	Neldricken	1410.8	423.40	2200	385	8257	62.40	A
32	Dungeon	2463.6	621.00	2350	376	12935	69.50	A
33	Narroch	104.6	74.57	2200	404	1400	23.30	A
34	Round L of Glenhead	536.3	85.60	2200	407	1749	111.90	A
35	Long L of Glenhead	393.9	89.00	2200	414	1767	81.40	A
36	Valley	1533.8	668.00	2200	404	12611	44.40	A
37	Harrow	538.0	367.70	2250	388	7121	27.60	A
38	Dow	—	3.90	2200	367	80	—	A
39	Dalbeattie Plantain	83.4	182.53	1200	532	1237	24.60	A
40	Fern	84.1	186.61	1350	532	1568	19.60	—
41	White	492.5	180.50	1200	532	1273	141.20	—
42	Barean	343.7	40.58	1200	532	324	387.20	—
43	Clonyard	146.5	75.29	1200	532	529	101.00	—
44	Fellcroft	74.6	104.94	1400	532	964	28.20	—
45	Bengairn	24.8	154.01	1400	532	1359	6.70	—
46	Duff's	18.1	186.27	1200	532	1251	5.30	—
47	Kernsary	9429.6	2136.20	1700	485	26858	128.10	—
48	Ghiuragarstidh	651.3	203.20	1700	485	2730	87.10	B
49	Policies	54.3	86.02	900	418	428	46.30	—
50	Waterton	20.5	2428.77	900	394	12298	0.61	—
51	of Skene	1699.0	3259.10	900	414	16319	38.00	—
52	Brandy	6126.0	100.20	1400	258	1442	1550.60	A
53	Corby	91.9	305.50	900	499	1263	26.60	—
54	Muick	78466.4	3521.60	1500	263	46194	620.00	B
55	Dubh 'Muick'		841.30	1600	221	11859	—	A
56	Buidhe	30.9	176.12	1600	220	2457	4.60	B
57	Lochnagar	—	93.44	1600	186	1464	—	A
58	nan Eun	790.9	39.26	1600	175	666	433.70	A
59	Sandy	48.9	258.39	1600	215	3642	4.90	B
60	Bharradail	57.7	211.03	1450	542	1948	10.80	—
61	Beinn Uraraidh	1772.4	91.21	1400	542	942	686.60	—
62	nam Breac	214.7	58.84	1600	542	672	116.70	A
63	nam Manaichean	—	1.70	1600	542	25	—	—
64	Laoim	—	—	—	—	—	—	—
65	Sholum	—	—	—	—	—	—	—
66	Sholum 'W'	—	—	—	—	—	—	—
67	Leorin 'W'	—	—	—	—	—	—	—

68	Leorin 'E'	—	—	—	—	—	—	—
69	na Beinne Brice	—	—	—	—	—	—	—
70	'Moine na Surdaig'	—	—	—	—	—	—	—
71	Coirre Fhionn	—	—	—	—	—	—	A
72	Iorsa	—	—	—	—	—	—	A
73	Garbad	—	—	—	—	—	—	—
74	Cnoc an Loch	—	—	—	—	—	—	—
75	a'Mhuillin	—	—	—	—	—	—	A
76	Kirkaldy	36.3	126.80	880	415	604	21.90	—
77	a'Chaoruinn	46.7	853.41	870	355	4408	3.90	—
78	an t'Sidhein	144.6	190.00	900	351	1082	48.80	—
79	nan Stuirteag	7.7	24.90	900	362	137	20.50	—
80	a'Mhill Bhig	25.8	52.14	3000	325	1485	6.30	A
81	a'Mhill Bhig 'Lower'	1.0	63.46	3000	308	1715	0.21	A
82	Maol Meadhonach 'Upper'	—	2.10	2700	—	67	—	A
83	Maol Meadhonach 'Lower'	—	48.30	2700	—	1318	—	A

A = above Henriksen curve
B = below Henriksen curve
— = excluded

evaluates them according to the proportional amounts of rain passing through the catchments to that falling directly on to the loch. Again, the differences between the groups are highly significant at the 1% level ($P=0.01$), the mean ratios being 26:1 ($n=23$) for lochs above the curve and 73:1 ($n=19$) for those below the curve. The respective median values are 9:1 and 26:1. The relevance of these relationships is discussed below.

4 Discussion

The results of the bathymetric surveys have made possible a brief examination of the possible influence of basic hydrological factors on the acidification status of the sample lochs. While the water chemistry sampling programme was not ideal for such analyses, there is some evidence of a relationship within the vulnerable oligotrophic group of lochs, separated by the Henriksen (1979) criteria for acidified waters. Two comparisons were found to be highly significant.

The simpler concept is the comparison of the proportional amounts of catchment-affected and direct rainfall entering a loch. (Low groundwater input has

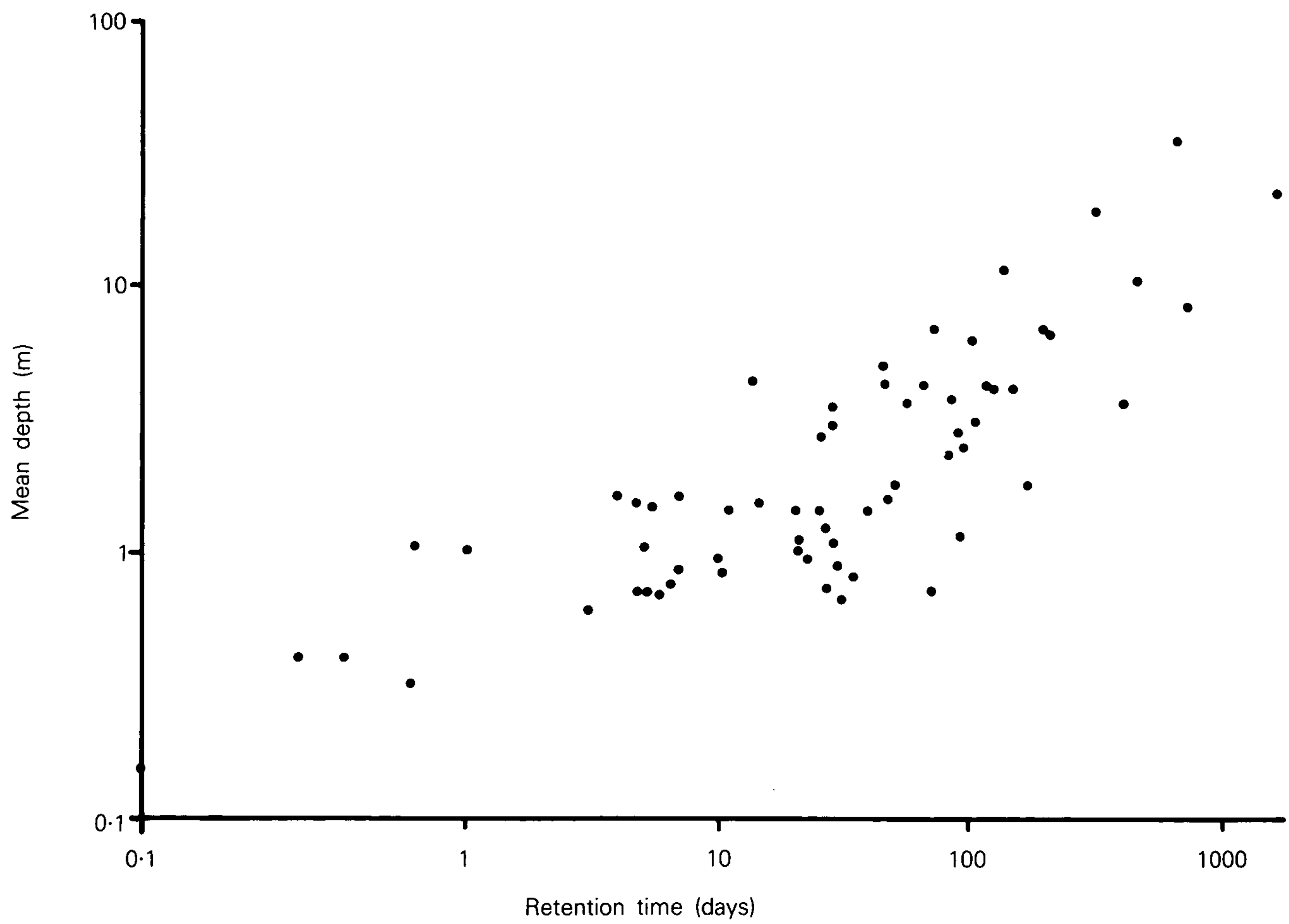

Figure 4. A plot of mean depth against retention time for the survey lochs

been shown to be a common feature of susceptible lakes in North America (Eilers 1983).) Although none of the sites approaches parity on this score, and they are all, to varying degrees, dominated by through-catchment water, the closest ratio of 3.28:1 belongs to Loch Enoch, an acidified fishless loch. In the short term, if the loch volume/area ratio (ie mean depth) is low, and catchment runoff response is slow, then there could be a direct rainfall-induced acidic 'pulse' in the loch, but such sites would normally be expected to have a short RT and catchment-affected water would soon dominate. Figure 4 illustrates the trend of decreasing RT with lower mean depths. However, it is also clear that shallow (say <1 m) lochs have RTs of up to 100 days, thus lengthening the period of direct rainfall influence.

Second, if the catchment runoff becomes acidified, however, then the stronger influence will be exercised by loch throughflow characteristics, considered here by retention time. As RT decreases, the greater is the similarity between a loch and its current inflow water quality and variability. With longer RT, loch water quality gains a stability beyond inflow fluctuations and becomes increasingly affected by changes which take place within the loch itself, related to normal seasonal and annual trends in its physical and biological characteristics.

Although the above deals with 2 different hydrological concepts, RT and loch catchment area/loch area ratio are themselves strongly interrelated (see Figure 5) and their relationships with the acidity of the survey lochs are perhaps inseparable without more detailed study.

The biological importance of RT can be expressed similarly to that for water quality. Lochs with a short RT and whose hydrodynamics are dominated by their inflows provide little escape or dilution for biota from acidic influxes, but these last for only a short time. A longer RT should make avoidance easier within the loch where fish may select 'favoured' areas away from the direct influence of inflows (see Muniz & Leivestad 1980). Also, there will probably be a considerable dilution of inputs. However, if the frequency of inflow acidifications is such that the effects within the loch overlap temporally, then acidity will accumulate in the loch, and this acidity may reach dangerous levels for long periods. A summary of this relationship is illustrated in Figure 6. It is assumed here that the lochs are subjected to acidic inputs, but the frequency and intensity of these inputs are not known. However, it seems reasonable to assume that, if RT is greater than (say) one year, then dilution of isolated acidic runoff will negate its toxicity. So, lochs most vulnerable to prolonged acidification and chemical and biological change are those with an RT of one to a few months.

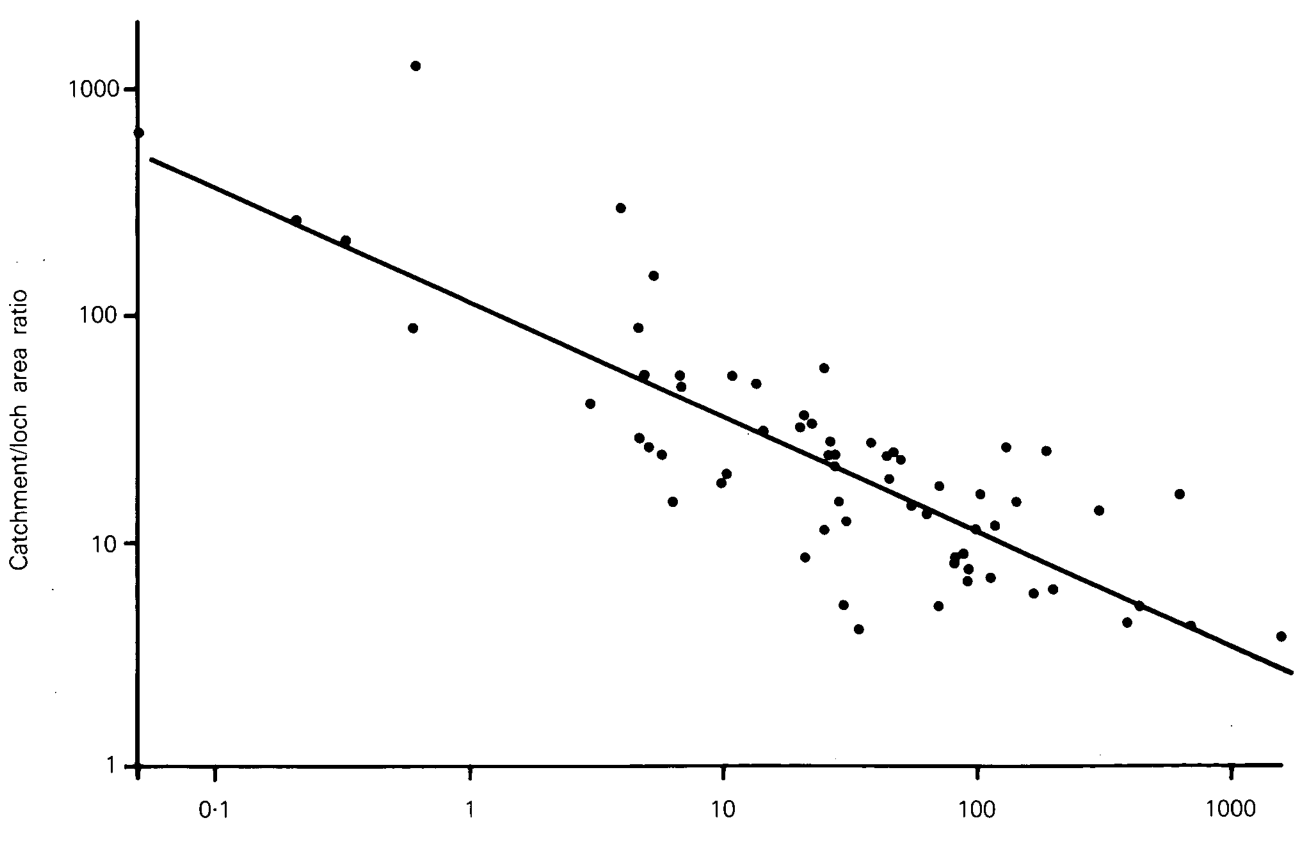

Figure 5. The relationship between catchment area/loch area ratio and retention time, where $C/L = 118.4 \times RT^{-0.51}$ and the correlation coefficient is −0.83

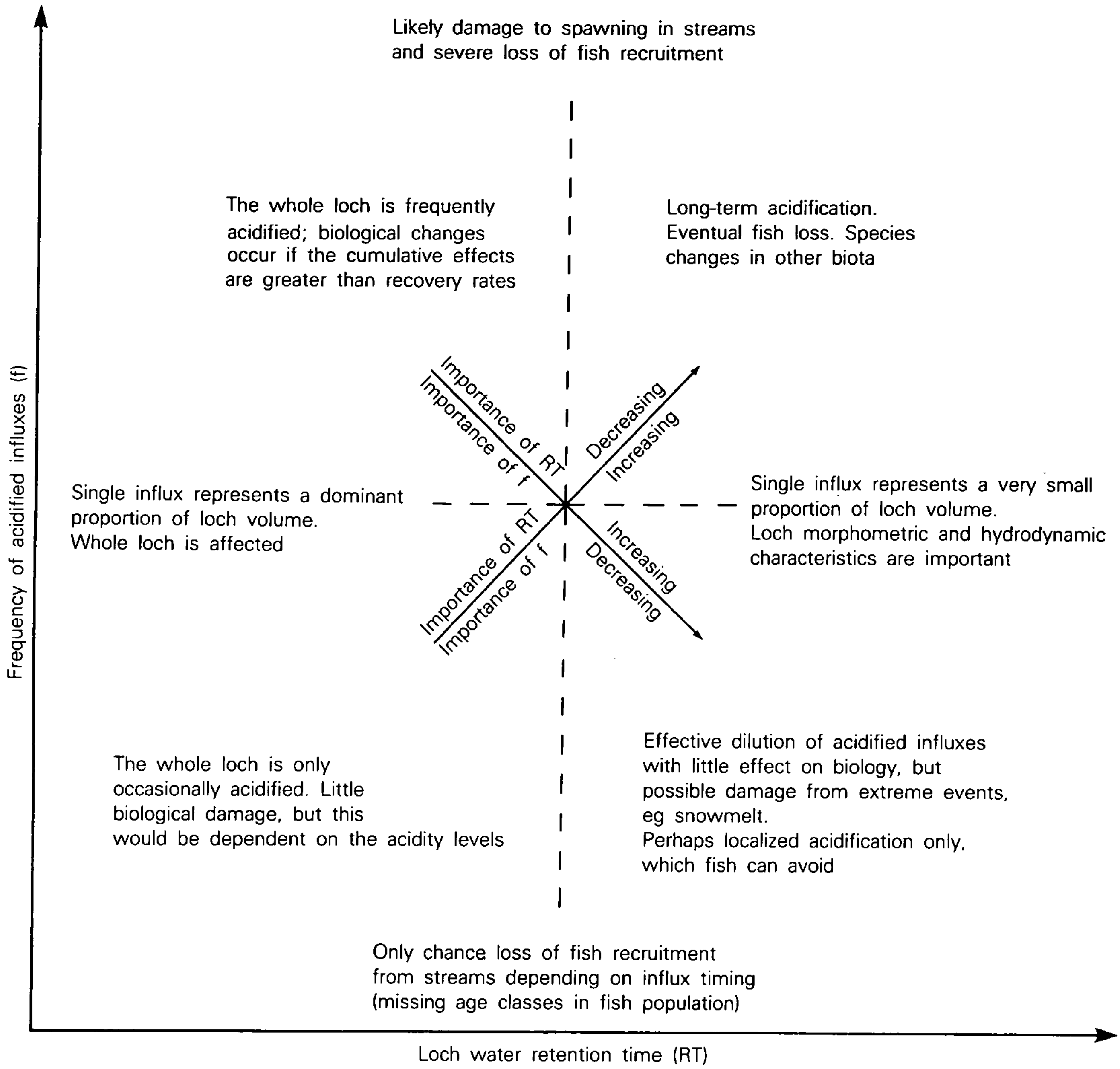

Figure 6. A diagrammatic summary of the relationship between loch retention time, the frequency of acidic inputs and the biological effects in lochs vulnerable to acidification

This range covers the majority of lochs involved in the survey and includes the Galloway lochs which, as a group, are considered to be those most severely acidified and, consequently, to have lost their fish.

This analysis has relied on generalities, and it is important to note that retention time should be regarded as a variable. The calculations used here are estimates of the mean, over a number of years. The longer the estimated RT, the more realistic is it likely to be at a given time. Lochs with a short RT may fluctuate greatly from their mean; indeed, a rough guide for natural drainage systems is that the average flow is only equalled or exceeded for *ca* 30% of the time. Many other factors will influence RT at any given time: catchment runoff characteristics; inflow/outflow locations; exposure to wind-driven mixing; summer thermal stratifications; ice cover and sudden flooding (eg snowmelt).

While it cannot be shown within the scope of this survey that morphometry or hydrology is a strongly limiting factor for acidification, consideration of this aspect has indicated that they must contribute to the already very complex set of circumstances which determine the extent to which the chemistry and biology of a loch are affected.

5 References

Drablos, D. & Tollan, A. 1980. *Ecological impact of acid precipitation.* (SNSF Project 72/80.) Oslo: SNSF.

Eilers, J. 1983. Hydrologic control of lakes' susceptibility to acidification. *Can. J. Fish. aquat. Sci.,* **40,** 1896-1904.

Hakanson, L. 1981. *A manual of lake morphometry.* New York: Springer.

Henriksen, A. 1979. A simple approach for identifying and measuring acidification of freshwater. *Nature, Lond.*, **278,** 542-545.

Maitland, P. S., Lyle, A. A. & Campbell, R. N. B. 1986. *The status of fish populations in waters likely to have been affected by acid deposition in Scotland.* Natural Environment Research Council contract report to the Department of Environment and the Commission of the European Communities. Edinburgh: Institute of Terrestrial Ecology. (Unpublished.)

Ministry of Agriculture, Fisheries & Food. 1967. *Potential transpiration.* (Technical bulletin no. 16.) Edinburgh: Department of Agriculture and Fisheries for Scotland.

Muniz, I. & Leivestad, H. 1980. Acidification—effects on freshwater fish. In: *Ecological impact of acid precipitation,* edited by D. Drablos & A. Tollan, 84-92. Oslo: SNSF.

Murray, J. & Pullar, L. 1910. *Bathymetrical survey of the Scottish freshwater lochs.* Edinburgh: Challenger Office.

Penman, H. 1948. Natural evaporation from open water, bare soil and grass. *Proc. R. Soc.,* **193,** 120-145.