The Chemical Composition of Some Natural Waters in the Cairn Gorm-Strath Spey District of Scotland¹

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ABSTRACT

Some chemical properties of natural waters in the Cairn Gorm-Strath Spey area have been investigated. Differences of ionic concentrations in twenty-four waters analyzed for pH, Na, K, Ca, Mg, HCO_3 , Cl, SO_4 , NO_3 , PO_4 and SiO_2 are interpreted in terms of variation in geology, topography, local climate and vegetation.

INTRODUCTION

In recent years the ecology of the Cairn Gorm mountains has been studied in some detail by Cambridge botanists (Watt and Jones (1948), and the establishment of a large nature reserve in the area will no doubt stimulate interest in its flora and fauna. The aim of the present paper is twofold: first, to contribute some background data on the chemistry of the waters, with especial reference to dissolved constituents in the waters of upland and lowland lakes, and second, to examine the influence of environmental factors upon chemical composition.

DESCRIPTION OF THE AREA

The general area of this survey, covered by sheet 43 of the Ordnance Survey inch-to-the-mile map of Scotland, is well described in the National Forest Park Guide *Glen More*, edited by Walton (1949). The main mountain mass making up the Cairn Gorm plateau, about 1100–1200 m high, is of granite intruded into the metamorphic Moine Series of schists and gneiss, which in the Spey valley is covered by a thick mantle of glacial deposits composed of varying mixtures of sand, gravel, and clay. Many of the lakes owe their existence to damming

by moraines, while Loch Morlich is a large kettle-hole left after the melting of a huge ice-block in the valley. The detailed geology of the district has been discussed by Hinxman and Anderson (1915) and their collaborators.

Rainfall in the valley is approximately 75 cm per annum, and mean annual temperature about 7.5°C, with the three summer months averaging about 13°C. In the uplands conditions are of course much more severe, but unfortunately no data are available. However, it may be noted that at the end of July, in the very warm summer of 1955 when the water samples were collected, occasional snow patches were still to be found in protected places near the summits of the hills. According to Watt and Jones (1948) the hills may be covered by snow for short periods in September, and snow lies generally from October to May or June on the upland plateau.

The vegetation of the valley glacial deposits, which has been described briefly by Tansley (1939), is largely open pine forest and heath, which may extend to above 450 m in many places, and occasionally above 600 m. Above these levels is found a more montane group of heath and moorland communities, whose cover gradually thins out above about 750 m. The upland areas have been described recently by Watt and Jones (1948), Metcalfe (1950) and Burges (1951).

THE SOILS

The soils of the region are commonly acid and base-deficient at the surface, as has been

¹ The water analyses for nitrate, phosphate, and silica were kindly made by Mr. J. Heron, and the total nitrogen analyses of the soils by my wife, who also assisted in their collection. Financial assistance from the Central Research Fund of London University during the soil investigations in 1949 is also gratefully acknowledged.

TABLE 1. *Some chemical properties of upland soils on Cairn Gorm and lowland soils near Loch Morlich*

A. Characteristics of some shallow upland soils.										
pH glass electrode	Water content per cent dry weight	Ignition loss per cent dry weight	Total nitrogen m.equiv./100 g dry weight	Exchangeable cations*			Base saturation per cent			
				Total bases m.equiv./100 g dry weight	Hydrogen ions	Exchange capacity				
4.5	10	4	0.16	12	3	15	80	Beneath patches of alpine vegeta- tion at about 1150 m		
4.3	25	5	0.17	9	5	14	64	ditto		
4.1	15	6	0.22	7	5	12	58	ditto		
4.0	20	6	0.24	5	5	10	50	ditto		
3.9	10	6	0.19	5	5	10	50	ditto		
3.8	165	48	1.38	17	34	51	33	<i>Nardus stricta</i> — <i>Trichophorum cae- spitosum</i> flush at about 750 m		
3.5	155	53	1.49	9	42	51	18	Beneath patches of alpine vegeta- tion at about 1150 m		
3.3	165	72	1.25	11	63	74	15	<i>Trichophorum caespitosum</i> — <i>Cal- luna vulgaris</i> moorland at about 600 m		
B. Acidity of humus layers in open pine-heath.										
Sample								pH		
1. <i>Mor</i> humus layer (30 cm thick) on sandy podzol with grey A ₂ horizon (8 cm thick)								3.2		
2. <i>Mor</i> humus layer (10 cm thick) on sandy podzol with grey A ₂ horizon (20 cm thick)								3.1		
3. <i>Mor</i> humus layers (5–10 cm thick) over shallow greyish A ₂ horizons, on top of								3.3		
4. fossil podzols buried by wind-blown sand								3.0		
5. fossil podzols buried by wind-blown sand								2.9		
C. Characteristics of a lowland podzol profile in pine-heath										
Horizon	Thickness of horizon cm	Depth of sample cm	pH glass electrode	Water content per cent dry weight	Ignition loss per cent dry weight	Total nitrogen m.equiv./100 g dry weight	Exchangeable cations*			Base saturation per cent
							Total bases m.equiv./100 g dry weight	Hydrogen ions	Exchange capacity	
A ₀ (F)	7	3	3.3	350	84	1.76	15	104	119	14
(II)	8	11	3.0	335	92	1.42	7	106	113	6
A ₂	8	19	3.9	15	1	0.05	1	2	3	33
B ₁	10	28	4.4	35	11	0.23	19	17	36	53
B ₂ iron pan	ca. 0.2	33	5.1	25	12	0.19	24	9	33	73
B ₂	>22	37	5.7	10	3	0.07	16	1	17	94
B ₂		50	6.0	5	1	0.09	9	1	10	90

* By the method of Brown (1943)

established by investigation of a series of upland soils on Cairn Gorm and a representative lowland podzol profile near Loch Morlich in 1949, followed by measurement of the acidity of five surface *mor* humus layers in open pine-heath near Loch Morlich in 1952. The results of the soil analyses are shown in Table 1.

The upland soils are all strongly acid (pH 3.3–4.5), and while the peaty organic samples exhibit the lowest pH values, it is

remarkable that even the least organic soil yields a pH of 4.5. In this connexion it should be pointed out that all samples were collected beneath patches of vegetation, and no bare soils were examined. In the lowlands the highly organic surface *mor* layers are even more strongly acid than the peaty upland samples, with a pH range of only 2.9–3.3. It seems probable that sulphuric acid, produced by oxidation of organic sulphur compounds, is responsible for these

very high acidities (cf. Gorham 1956b). From Table 1 it is also apparent that the base saturation of the soil adsorptive complex, determined chiefly by the amount of exchangeable hydrogen ions present, is related rather closely to pH and humus content.

The soil profile was chosen as fairly representative for the area, and had a plant cover of open pine-heath, with *Calluna vulgaris*, *Vaccinium myrtillus*, *V. vitis-idaea* and *Hylocomium splendens* abundant among the scattered Scots pines. It is developed in a stony sand near Loch Morlich, and probably overlies laminated fluvioglacial sands as in several road-cut exposures in the vicinity. The profile is typical of sandy podzol soils, with a thick and strongly acid humus layer above a heavily leached and base-deficient grey A₂ sand horizon. Beneath in the very stony and compacted sand of the B accumulation zone there is a marked increase of organic matter, exchangeable hydrogen ions, and exchangeable bases, while pH and base saturation rise considerably. An extremely impenetrable cemented hardpan of a few mm thickness, observed at 33 cm depth, marks the level of maximum iron precipitation.

THE WATERS

This district exhibits a great variety of lake types. In size the present series ranges from Loch Einich, about 3 km long and 0.8 km wide, down to very small lochans of less than 100 m across; and in altitude from just under 1000 m down to about 200 m above sea level. In the warm weather of July 1955 the surface waters of even the highest lochans ranged in afternoon temperature from about 20 to 25°C, with the exception of the snow-fed lochan in Coire an Lochain (15°C, temperature of inflow from snow patch 10°C), and the small pool in Coire an t-Sneachda (17°C), which was only about 1 m deep instead of its more usual depth of about 2 m (at bottom the latter pool had a temperature of only 12°C).

As regards geology, those waters above 500 m are on granite, while the lower ones lie on the Moine metamorphic series. In the latter case however, there is likely to be considerable variation in the makeup of the

overlying drift, with some lakes near the geological boundary probably lying on or draining predominantly granitic materials. Loch Morlich, and to a lesser extent Loch an Eilein, must derive a good deal of drainage from the granite uplands, although lying on top of Moine substrata. Another point to be remarked is that many of the waters come from very peaty surroundings. The three dried-out pools (9, 12, and 16) are the main examples, and of the lochans, Dubh a'Chadha (8), which lies in partly eroding *Trichophorum caespitosum*-*Calluna vulgaris* moorland.

Another major point of difference is in the type of drainage. Many of the lochans possess neither inflow nor outflow streams, and these are termed seepage lakes. Nos. 5, 8, 10, 13, 14, and 15 appear to belong to this class. Those lakes with inflow and outflow streams are called drainage lakes, though in the case of many of the smaller lochans these streams may be of negligible flow in dry summers.

The three almost dry peaty pools have already been mentioned, but it may be added that they are all in situations of normally stagnant drainage even in wetter seasons. The small artificial drainage lake by Drumintoul Lodge (22) was at the time of sampling also very low, and the water was full of *Nitella*; however, there was still a distinct trickle of water through the breached dam, and the inflow was still running. Moreover, the water was quite clear, in contrast to the strong brown peaty tint to the waters of the aforementioned pools.

Three springs were also sampled, two at high levels on the granite massif, and one on the Moine Series in the Spey valley close by Loch an Eilein. All were very cold, that above Loch Einich being at 4°C, the Marquis Well at 6°C, and the spring by Loch an Eilein at 7°C. The first of these springs marks the beginning of a long series of bryophyte cushions extending down the hillside along the line of flow.

METHODS

Surface waters were collected in pint polythene bottles from the edges of the lakes where there is least vegetation, between July 21 and July 25, 1955. On return to the

TABLE 2. *Dissolved constituents in waters from the Cairn Gorm and Strath Spey areas*

Name	Approximate altitude in m	pH		Total cations in m. aeration equiv./L	Na	K	Ca	Mg	HCO ₃	Cl	SO ₄	NO ₃ -N	SiO ₂	Remarks	Map reference (sheet 43)
		Before aeration	After aeration												
On Granite															
1. Spring, Marquis Well, Cairn Gorm	1200	5.3	5.7	0.11	1.6	0.1	0.4	0.2	nil	1.8	1.9	0.08	2.2	Spring flush	006042
2. Snow patch, Coire Cas.	1150	5.8	6.0	0.02	0.3	0.1	nil	0.4	<0.5	<0.5	<0.5	<0.02	0.8	Clean and coarsely crystalline snow from beneath surface	002041
3. Spring, above Loch Einich	925	5.4	6.0	0.12	1.6	0.2	0.6	0.1	0.5	1.9	2.1	0.06	2.9	Spring flush	925981
4. Lochan, Coire an Lochain, beneath Cairn Lochan	925	5.5	5.9	0.06	0.8	0.2	0.2	0.1	0.2	0.9	0.9	<0.02	1.9	Small drainage lake, still snow-fed, grassy area	981028
5. Lochan, Coire an t-Sneachda	925	6.0	6.5	0.12	1.5	0.2	0.8	0.1	1.0	1.5	2.2	0.05	2.1	Small seepage lake, very rocky	995032
6. Lochan, Coire an Lochain, beneath Cairn Lochan	900	6.1	6.7	0.14	2.2	0.3	0.3	0.2	1.9	2.2	1.5	0.02	6.7	Small drainage lake, peaty area	981080
7. Loch nan Cuapan	850	5.9	6.4	0.14	1.7	0.2	0.9	0.1	0.9	2.3	2.1	<0.02	1.0	Small drainage lake, <i>Nardus</i> grass-land	917960
8. Lochan Dubh a' Chadha	575	4.6	4.6	0.20	2.8	0.4	0.3	0.4	nil	4.7	2.8	<0.02	0.9	Small seepage lake, in peaty moor-land	969066
9. Former lochan about 1 km ESE of Lochan Dubh a' Chadha	550	4.4	4.4	0.92	13.7	2.6	0.8	2.2	nil	23.9	5.0	0.02	1.6	Brown water from quaking <i>Sphagnum</i> -sedge bog	977063
10. Lochan t-Sellich	500	5.7	6.2	0.21	2.8	0.3	1.3	0.2	1.1	4.2	3.3	0.04	1.0	Small seepage lake, between scree and eroded bog	915005
11. Loch Einich	500	6.4	6.7	0.17	2.0	0.2	1.3	0.2	1.0	2.7	3.1	0.07	2.2	Large drainage lake	915990
12. Raised bog, by Lochan t-Sellich	500	3.9	3.9	0.78	9.5	0.4	1.2	2.0	nil	14.5	14.6	<0.02	1.0	Brown water from bare peat pool on eroded bog	916005
On Moine Series															
13. Unnamed lochan W of Loch Morlich	350	5.8	6.2	0.20	2.7	0.5	0.7	0.3	1.2	4.4	1.5	0.08	1.0	Small seepage lake on hillside, <i>Sphagnum</i> and peat round margin	994095
14. An Lochan Uaine	350	6.7	7.5	0.60	5.2	0.8	5.9	0.9	16.9	7.6	4.9	0.02	1.2	Small rocky seepage lake	001105
15. Lochan nan Naitrach	350	5.4	5.7	0.25	4.2	0.3	0.6	0.3	nil	6.0	2.7	0.06	1.3	Small seepage lake	960085
16. Nearly filled in lochan SW of Loch Morlich	350	4.8	5.0	0.67	7.8	7.3	1.4	0.7	nil	14.6	5.1	0.02	4.5	Brown water from pool on peaty lake mud	995082
17. Lochan nan Geadas	325	6.7	7.2	0.44	5.9	0.4	2.6	0.5	9.1	7.1	3.0	0.03	3.5	Small drainage lake	955088
18. Loch Morlich	325	6.4	6.9	0.26	3.3	0.4	1.4	0.3	4.7	3.8	2.5	<0.02	3.5	Large drainage lake	965094
19. Lochan W of Loch an Eilein	300	6.6	7.3	0.49	6.2	0.6	3.0	0.7	8.2	8.7	3.8	<0.02	2.4	Small drainage lake	917078
20. Spring, near Loch an Eilein	275	6.7	8.1	1.52	12.3	1.8	13.3	3.9	56.7	13.9	7.3	0.03	27.0	Spring in hillside pinewood	902081
21. Loch an Eilein	250	6.5	7.2	0.43	5.4	0.6	2.7	0.5	7.6	7.1	4.0	<0.02	6.3	Large drainage lake	898075
22. Artificial loch at Drumintoul Lodge	250	8.8	8.6	0.97	7.8	1.5	9.5	1.4	32.6	9.0	5.7	0.04	4.5	Small drainage lake, dam breached and very low	922112
23. Lochan N of Loch an Eilein	225	6.8	7.7	0.89	8.7	1.4	6.9	1.6	25.1	10.6	6.1	0.03	1.1	Small drainage lake in grassy birch woods	899094
24. Loch Pitvoulsh	200	6.9	7.5	0.68	6.5	1.0	5.8	0.9	17.3	8.5	5.8	0.02	4.5	Large drainage lake in grassy birch woods	920135

laboratory within a few days the samples were filtered through washed Whatman 541 papers, the first portion being discarded. Analytical methods were as outlined by Gorham (1955), except that the bicarbonate endpoint was taken as pH 5.7 (the value for distilled water in equilibrium with atmospheric carbon dioxide). Silica was estimated by visual colorimetry using the ammonium molybdate procedure after reduction of the yellow color to molybdenum blue.

RESULTS

The analytical data are given in Table 2, in order of decreasing altitude, with the granite-Moine transition marked by samples 12 and 13. Results are given as parts per million (= milligrams per litre), except for pH and total cations, the latter being given as milli-equivalents per litre.

Total salts

Figure 1 shows a generally good balance between total cations and total anions,

FIG. 1. The balance of cations and anions in the waters.

except in the three almost dry pools (9, 12, and 16), where cations are distinctly in excess of anions. It seems reasonable to suppose that in these very brown and peaty waters there are appreciable amounts of organic acid anions balancing some of the cations. Even in the other waters there is a cation excess of a few per cent, but this is believed to be due to a slight (and for present purposes unimportant) under-estimation of the strong acid anions, as it occurs in the

waters from springs and rocky lakes as well as those from peaty sites.

The range of total salt concentration in these waters is rather great, although none of them could be said to be rich in salts. The melted snow, with about 0.02 m.equiv./L, is lowest; while the lowland spring yields the highest concentration of 1.52 m.equiv./L. The upland waters on granite are in general much poorer in salts than the lowland waters on the Moine metamorphic

FIG. 2. The relation between sodium and chloride.

rocks, owing partly to greater evaporation at the lower levels, and partly to the weathering of greater amounts of lime from the Moine rocks.

Chloride, sodium, and magnesium

The marked correlation of sodium and magnesium with chloride in these waters, illustrated in Figures 2 and 3, suggests that large proportions of these two cations derive from sea spray, which may be assumed to supply almost all the chloride (cf. Conway 1942, Eriksson 1955). However, the Na/Cl ratio in most of the present samples is considerably higher than in sea water, probably owing to some sodium release from weathering soils and rocks, far richer in this element than in chloride. Evidence of the high lake ratio is given in Figure 2, which shows that most of the points lie above the line representing the proportions of sodium and

chloride in sea water. It may also be seen from Figure 2 that the drainage lakes (dashed line in Fig. 2) exhibit a greater sodium excess than do the seepage lakes (including the almost dry peaty pools), which in general fall between the two lines in the figure. This might be expected, since the drainage lakes probably receive more moisture by ground-water percolation through mineral soil horizons, and the seepage lakes (and pools) more by runoff over the thick surface humus layers.

In the more dilute waters (chiefly on granite) the Mg/Cl ratio is on the average very similar to that in sea water, as appears from Figure 3. This suggests that rather little magnesium is leached from the granitic materials (which probably predominate also in the basins of the more dilute waters on Moine strata, since these are all rather near the geological boundary). Among the

FIG. 3. The relation between magnesium and chloride.

waters on granite the highest Mg/Cl ratio comes from the acid pool on an eroding raised bog (12), where it seems likely that magnesium adsorbed on the peat colloids has been displaced into solution by exchange for hydrogen ions, the latter being produced by oxidation of organic sulphur compounds in the peat to form sulphuric acid (cf. Gorham 1956b). In the lowland lakes the situation is different, with a trend toward higher ratios in the more concentrated waters, especially that of the spring. This may be taken to indicate release of magnesium by weathering of the Moine rocks and their derived soils.

A most noteworthy feature of the present results is that chloride, supplied almost entirely by atmospheric precipitation, increases greatly in concentration at the lower altitudes. From about 2 ppm at 900 m (only 0.9 ppm in the lake still fed by snow melt) this ion rises at an increasing rate to 9–10 ppm in the lakes between 200 and 300 m above sea level, and even greater concentrations are recorded from the three pools which had almost dried up. Results of this kind clearly point to evaporation as a factor of extreme importance in determining the salt concentrations of waters in this area, especially in periods of such abnormally hot dry weather. Moreover, at a given altitude the smaller lakes tend to show the higher chloride concentrations. For instance, on Moine strata the four small drainage lakes (17, 19, 22, 23) may be compared with the three large ones (18, 21, 24). In altitude the former average about 275 m, the latter 255 m, so that on the basis of altitude alone the smaller lakes might be expected to be if anything a trifle more dilute. In fact, the small lochans are almost 40 per cent richer in chloride, averaging 8.9 ppm as against 6.5 ppm in the large lochs. This difference reflects not only the greater *area/volume* ratio of small lakes, leading to a proportionally high degree of evaporation, but also the fact that the larger lakes receive a good deal of their water from levels far above them, where it has not been so subject to evaporation in the gathering ground. An additional factor to be considered here is the greater vegetation cover at lower levels, which through

transpiration may increase evaporation. Many of the smaller lowland lochans in particular lie in heavily vegetated drainage basins.

Calcium and bicarbonate

Calcium and bicarbonate ions are low in the waters on granite, the maximum concentrations being 1.3 and 1.9 ppm, respectively. The range of calcium concentrations, 0.2–1.3 ppm, is about the same as in pools on raised and blanket bogs dependent for their mineral supply solely upon atmospheric precipitation (Gorham 1956a, 1956b, and unpublished data; Gorham and Pear-sall 1956). It thus appears that the granite releases its calcium (in general about 0.5–2.0 per cent by weight) only very slowly. The waters on Moine rocks reach considerably higher levels of calcium concentration, ranging from 0.6 to 13.3 ppm, the latter value being recorded from the spring near Loch an Eilcin. While greater evaporation at the lower elevations of the lakes on the Moine Series is partly responsible for the higher calcium concentrations there, this is not the only factor involved, since the ratio of calcium to chloride is also distinctly above average in the richer Moine lakes. The correlation between bicarbonate and calcium, present in these waters in approximately equivalent amounts (see Fig. 4), indicates rock and soil weathering as the source of most of this calcium. Very little can be supplied from sea spray, as calcium is very low in sea water relative to chloride. Although the Moine rocks do not in general contain a great deal of calcium (as judged by analyses from northern Scotland compiled by Guppy 1931), they are perhaps somewhat richer than the granites. There are, in addition, occasional intrusions of rocks such as epidiorites and hornblende schists, which are often quite rich in calcium; and moreover the ordinary mica-schists of the Moine Series may well be more easily weathered than the granites, and so release their calcium more rapidly.

The two lakes on Moine strata which are lowest in calcium (13 and 15, with 0.7 and 0.6 ppm) are both seepage lakes in pine-heather moorland. Presumably they depend largely on surface runoff, or percolation

FIG. 4. The relation between calcium and bicarbonate.

through the leached horizons of the sandy podzols, while the drainage lakes receive some contribution from deeper subsoil waters. However, An Lochan Uaine (14), also a seepage lake, is much richer in calcium (5.9 ppm). In this connexion it may be pointed out that Watt and Jones (1948) suggest the presence of limestone in the vicinity; and it may also be significant that this lochan drains a bare rocky hillside, whose mineral debris is not much isolated from surface runoff by a layer of peaty *mor* humus as in the case of the other two lochans. Of the Moine drainage lakes Loch Morlich (18) is lowest in calcium, with 1.4

ppm, owing probably to its reception of much water from gathering grounds high up in the granite hills.

Acidity

Acidity varies considerably in these waters, with pH ranging from 3.9 in the sample from a raised-bog pool to 8.8 in the partly drained artificial lake by Drumintoul Lodge. In the three most acid samples (8, 9, and 12) there is a marked correlation between the concentrations of hydrogen ions and sulphate, from which it may be inferred that the high acidity is due to the presence of free sulphuric acid (cf. Gorham

1956b). The rather extreme alkaline pH of the Drumintoul water (22) before aeration is probably owing to exhaustion of most of the dissolved carbon dioxide present by the very dense growths of *Nitella*. That under natural conditions carbon dioxide contributes greatly to the hydrogen ion concentration of many of the less acid waters is shown by the marked increase in pH following aeration. After aeration, pH is found to be closely related to bicarbonate concentration, and hence to the amount of lime weathered from the rocks and soils. Above pH 7 (after aeration) bicarbonate concentrations rise sharply.

Only the small lochans reach high levels of acidity. The big lochs exhibit a pH range of 6.4–6.9 before and 6.7–7.5 after aeration.

Potassium

The ratio of potassium to chloride in these waters is considerably above that in sea water, suggesting that this element is derived more from weathering of rock and soil minerals than from sea spray. However, the low concentrations in the upland waters are very similar to those in rain (Gorham 1955; Emanuelsson, Eriksson, and Egnér 1954), so that much of the potassium probably comes from blown dust. The slightly higher K/Cl ratios in the richer lakes on Moine substrata point to a greater release of potassium from these rocks.

The two highest potassium concentrations, 7.3 and 2.6 ppm, come from the almost dried-up pools (16 and 9, respectively). The first figure represents a site still showing some areas of bare mud bottom, now being colonized by *Carex rostrata* and *Menyanthes trifoliata*, with occasional *Sphagnum* hummocks. This sample also shows an extremely high K/Cl ratio. The second figure in contrast represents a site where the former lake bottom has become completely covered by a quaking bog mat of *Eriophorum angustifolium*, *Carex rostrata*, and *Sphagnum papillosum* hummocks; and here the K/Cl ratio is not abnormal. Presumably the large quantity of potassium in sample 16 has been mainly released from decaying organic materials in the dried-out lake bottom, where at present there is not an

abundance of organisms to absorb it from the remaining water.

Sulphate

This ion may, like chloride, be assumed to come almost wholly from atmospheric precipitation, since rocks are generally very low in sulphur (cf. Conway 1942, Gorham 1955). Again like chloride, its concentration in these surface waters increases greatly with decreasing altitude. However, it is of much interest that the increase is not by any means proportional to the rise in chloride, so that the SO_4/Cl ratio is much less in the Spey valley than on the Cairn Gorm hills. For example, the lakes on the lowland Moine strata give a SO_4/Cl range of about 0.3–0.7, while for the lakes on the upland granites the range is about 0.6–1.5. Since it seems most improbable that the granites are supplying appreciably large amounts of sulphur to the upland lochans (sufficient to increase the SO_4/Cl ratio well above that in the lowlands), some other explanation of this phenomenon must be sought. In the absence of concrete evidence, the following conjecture may perhaps serve at least as a basis for further study.

A notable feature of the series of waters under investigation is that the lakes on Moine rocks lie below the tree line, while all the granite lakes are well above it. This fact may assume great importance when taken in conjunction with the studies of Eriksson (1955) and Tamm (1953), which strongly suggest that vegetation may capture giant sea salt particles from the atmosphere, these being subsequently washed into the streams and lakes during rainy weather. If such sea salt capture is an important source of chloride in natural waters, then lakes below the tree line might be expected to receive much more than those above it. However, in the present instance it is necessary to assume further that sulphate is not subject to the same degree of vegetation capture as chloride. This seems not unreasonable, as a good deal of the sulphur in the air is probably present in gaseous form, whereas the chloride must be largely derived from solid sea salt particles. An additional point of interest here is that, at comparable altitudes in both the upland

and lowland groups of waters, lakes draining the more rocky areas (*e.g.* 4, 5, 11, 14, 18, 21, 22, 24) tend to exhibit higher SO_4/Cl ratios than those in well-vegetated sites (*e.g.* 6, 8, 13, 16, 17, 19). The lochan in Coire an t-Sneachda (5), with clearly the most rocky surroundings of all, yields the maximum SO_4/Cl ratio of 1.5. As would be expected on this basis, the larger lakes tend to exhibit ratios on the high side, since they all drain fairly extensive areas of relatively open ground. Among the smaller lakes, no. 13 probably has the most heavily vegetated surroundings, and gives the minimum SO_4/Cl ratio for all the lakes, 0.3.

The two almost dry pools on granite (9 and 12) show a marked difference in SO_4/Cl ratio. The latter, a pool on the bare peat surface of an eroded raised bog, yields a rather high ratio of 1.0, probably due to release of sulphur from the decaying peat. The former, in contrast, gives the lowest ratio of all, about 0.2. In this site however, there is a complete cover of vigorously growing *Sphagnum* and *Carex*, and on pressing the sampling bottle into the spongy surface to obtain water, a distinct smell of hydrogen sulphide was noticed. In this instance then, reduction of sulphate may be inferred as bringing about the abnormally low SO_4/Cl ratio.

Nitrate and phosphate

Nitrate nitrogen is low in all these waters (at least in summer), never rising to 0.1 ppm in the present samples. Dissolved phosphate must be extremely scarce, since it was undetectable (<0.001 ppm) in all cases examined (2, 12, and 16 not tested).

Silica

The snow patch melt-water shows the lowest value for this constituent, as might be anticipated, with 0.8 ppm SiO_2 . The lowland spring gives the highest concentration, 27 ppm. The lakes range from 1 to 7 ppm, with most of them near the lower limit; and only a few drainage lakes with pH values above 6 possess waters with more than 2 ppm SiO_2 .

DISCUSSION

From the foregoing results it is evident that the amounts of dissolved materials in

the waters of the Cairn Gorm-Strath Spey area are influenced by several environmental factors. The climatic factor of evaporation is one of the most important, but is itself mainly dependent in this instance upon the nature of the relief, as determined originally by the way in which the Cairn Gorm plateau was dissected by the Spey River, and subsequently by the processes of glaciation. A more independent aspect of climate is however to be seen in the exceptionally warm dry summer conditions of 1955, which accentuated the significance of the evaporation factor.

The influence of topography is apparent in a variety of ways. As has been mentioned, both altitude and basin shape affect evaporation from a lake. In addition, the influence of relief upon persistence of snow may affect the water supply to many lochans (*e.g.*, the lochan in Coire an Lochain). Its effect upon drainage, which may be discerned not only in the very locations of the lakes in the glacial deposits but also in the contrast between drainage and seepage lakes, is necessarily of great importance, as is its effect upon peat accumulation. Lastly topography—partly through its effects upon local climate—has a good deal of influence upon the distribution of vegetation and the level of the tree-line, and hence in yet another way upon evaporation, and probably also upon the balance between atmospheric chloride and sulphate supply.

The underlying geology, besides being ultimately concerned in defining the patterns of relief, plays a large part in determining the amounts of bases reaching these natural waters. This may be seen for example by comparing the ratios of bicarbonate to chloride or sulphate in drainage lakes on granite with those in such lakes on Moine substrata.

The biological factor remains to be considered. In its dependent aspect (with plant distribution conditioned by climate, topography, and geology) it affects evaporation, and probably the supply of atmospheric salts. The sulphur balance may also be influenced by oxidation and reduction processes in peaty soils, and of course the concentrations of such biologically important substances as nitrate, phosphate,

and silica fluctuate markedly in relation to biological demand. Also to be remarked is the likelihood that man has had some influence (through deforestation, grazing, and atmospheric pollution) upon the composition of these waters.

A final feature of the present study deserving of emphasis concerns the importance of atmospheric precipitation in supplying dissolved ions to these waters. Comparison of the ionic concentrations in lake waters on granite with those of rain samples collected in the English Lake District (Gorham 1955) reveals considerable similarity in ionic concentrations, while consideration of analyses from both the granite and Moine lakes leads to the conclusion that the most evident effect of soil percolation upon rain is the addition of calcium bicarbonate released through weathering of the rock and soil minerals.

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