

Mass Balance of Dissolved Inorganic Substances in Three Representative Basins in Sweden

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During the International Hydrological Decade six representative basins were operated in Sweden. One of these represented an extensive raised bog area, Komosse, southwest of Lake Vättern. Another basin, Verka, north of Stockholm, represented a mixture of agricultural and forestry typical for this part of Sweden. A third covered an extensively glaciated area in the north of Sweden, well above the timber line.

The typical forested areas in Sweden were represented by three basins, Velen between Lake Vänern and Lake Vättern; Kassjöån in the middle of Sweden and Lapträsket in the far north.

The research programs for all these basins included hydrochemistry mainly for the purpose of establishing balances of dissolved inorganic matter. The present paper discusses the results from the three forested basins, Velen, Kassjöån and Lapträsket.

The Basins, a Short Description

The geology of the three basins is typical of forested areas in Sweden. The rocks are very old consisting of gneisses and granites of varying composition, the major drainage being through systems of fractures and fissures typical of old hard rock areas. The overburden is mostly morainic material, relatively thin. Along water courses glaciofluvial sorted material is found sporadically although seldom in eskerlike fashion. The morainic and the glaciofluvial material is relatively coarse -

the clay fraction is in general low – and can be described as sandy to fine sandy, seldom silty.

The soils in the basins are as a rule podzols developed since the last glaciation. In the lower flat reaches of the basins various types of peats and bogs have developed, with relatively shallow peat thickness. In general no forest trees are found on the bogs except on the margins where thwarted spruce, pine and birch is found. The forests and bogs mostly form a very complex pattern, a mosaic.

From a hydrologic point of view bogs and lakes mark the more permanent groundwater discharge areas whereas the forested parts on higher ground can be regarded as source areas for ground water.

The Velen Basin

A map of the basin is shown in Fig. 1 and some relevant data on these basins are listed in Table 1.

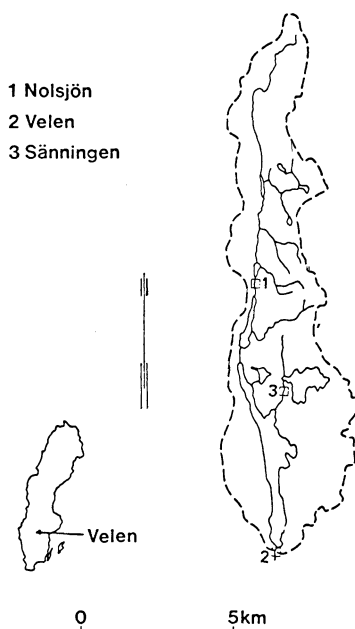


Fig. 1.

It is seen that nearly 10 per cent of the entire basin area is covered by lakes of which Lake Velen is the largest. The bog area is slightly larger than the lake area, bogs being more frequent in the northern part than in the southern.

The basin is relatively flat, the largest altitude difference being 60 m. Part of the area was invaded by the sea at the end of the last glaciation.

Mass Balance in Representative Basins

Table 1 - Some physiographic data on the Velen basins

Basin	Station No.	Area in km ²	Lake area %	Bog area %
Nolsjön	1	18.2	1.5	14.2
Velen	2	45.5	9.7	12
Sänningen	3	6.5	13.9	8.7

The Kassjöån Basin

A drainage map of the Kassjöån basin is shown in Fig. 2 and relevant data are listed in Table 2.

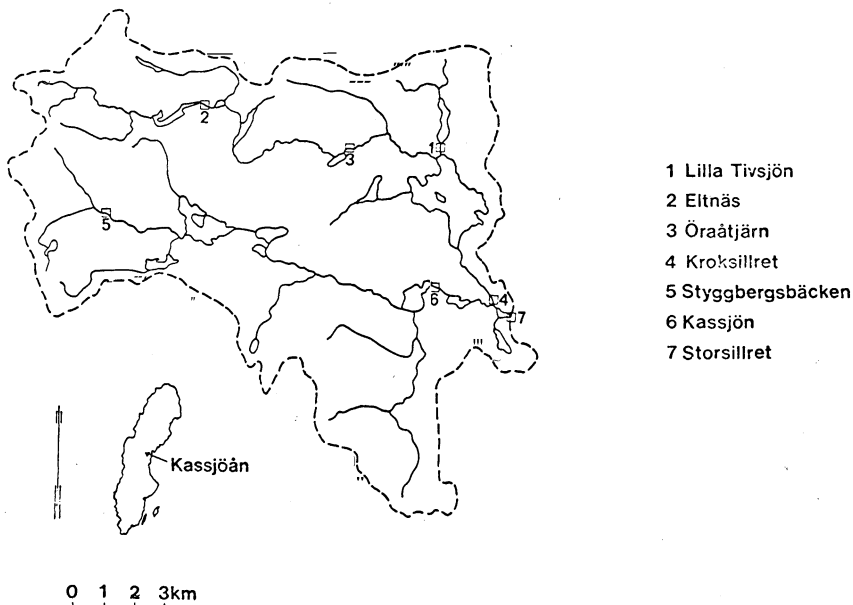


Fig. 2.

The entire basin is nearly 4 times larger than the Velen basin. The percentage lake area is, however, smaller but the percentage bog area is equal. The variation in lake- and bog area percentage between the sub-basins is quite large.

The topography of this basin is quite different from that of the Velen basin with rather steep slopes of considerable dimensions. There is a considerable increase in altitude towards the west. The altitude difference between the lowest and highest points is 305 m.

Table 2 - Some physiographic data on the Kassjöån basin

Basin	Discharge Station No	Area in km ²	Lake area %	Bog area %
Lilla Tivsjön	1	12.8	2.7	8
Elnäs	2	15.3	2.3	16
Öraåtjärn	3	36.7	2.6	9
Kroksillret	4	76.7	6.5	7
Styggbäcksbäcken	5	12.4	1.3	19
Kassjön	6	81.9	3.7	17
Storsillret	7	164.9	5.1	12

The Lapträsket Basin

The entire area of the Lapträsket basin is about 1,000 km². Fig. 3 shows a map of the basin and the discharge stations which together make up 11 sub-basins. Some data are assembled in Table 3.

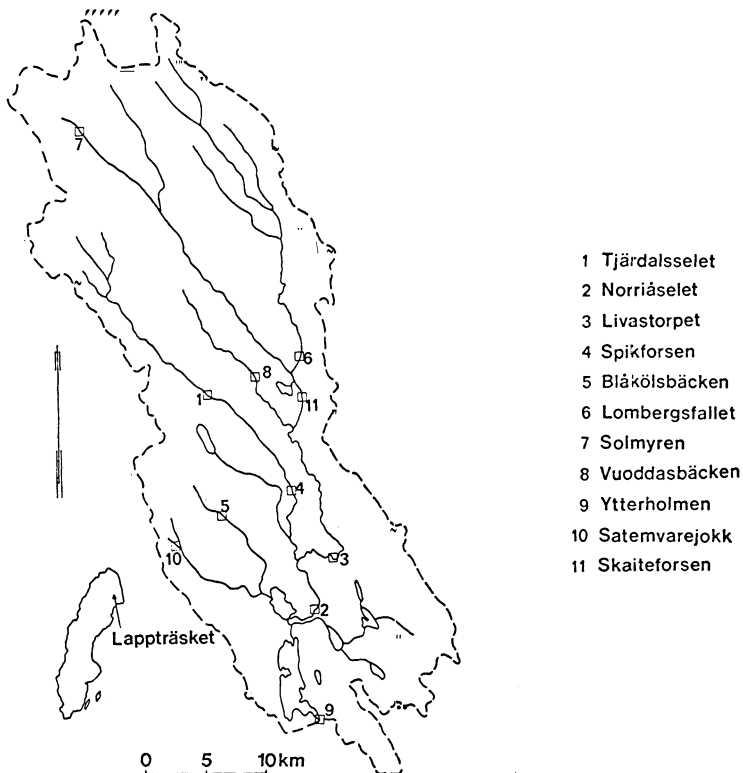


Fig. 3.

Mass Balance in Representative Basins

Table 3 – Some physiographic data on basins in the Lapträsk area

Basin	Discharge Station No	Area in km ²	Lake area %	Bog area %
Tjärdalsselet	1	104	0.2	34
Norriåselet	2	707	0.5	37
Livastorpet	3	366	0.2	41
Spikforsen	4	132		
Blåkölsbäcken	5	17.8	0.0	23
Lombergfallet	6	177	0.2	48
Solmyren	7	27	0.5	33
Vuoddasbäcken	8	42	0.7	27
Ytterholmen	9	1004	2.6	31
Satemvarejokk	10	1.7	0.0	14
Slakforsen	11	485		

It is seen that the basin has the smallest lake area percentage of the three but the largest percentage of bogs, about 1/3 of the entire basin. There is, of course, a considerable altitude difference between the outlet point and the highest point in the area, amounting to 435 m. Also some glaciofluvial deposits are found along some of the water courses, particularly at the downstream end. The depth of the morainic overburden seems to be considerable in places.

Comparing the physiography of the three regions the Velen basin seems to have a low general slope and a small scale relief pattern dominated by the small scale tectonic rock pattern so common in the southern part of Sweden. The Kassjöån basin has a rather strong slope and a pronounced large scale relief revealing old erosion pattern of a fjord type. Lapträsket shows a fairly gentle slope from north to south with also rather gentle large scale relief around a few protruding elements which have been described as a kind of Inselbergs.

The lake percentages decrease in the order Velen – Kassjöån – Lapträsket from 9.7 to 2.6. However, the Velen basin which is small is dominated by Lake Velen which makes the comparison somewhat unfair. As to the bog area percentages it is the same for Velen and Kassjöån, 12 per cent, whereas Lapträsket has a very much larger bog area percentage. Comparing Kassjöån and Lapträsket the difference in bog area percentages is no doubt due to differences in climate, evapotranspiration being smaller in the Lapträsket area than in the Kassjöån area, the precipitation being about the same.

As a final remark, the Velen basin is perhaps not entirely representative for the southern Sweden inland because its lake percentage is somewhat too large. The sub-basin, Nolsjön, is better in that respect.

Sampling and Analysis

Water samples were collected on the 15th every month at all the discharge stations shown in the maps. They were analysed at the Institute of Meteorology, University of Stockholm, under the guidance of Dr. Lennart Granath, Head of the Atmospheric Chemistry Section of this Institute. The analysis comprised chloride, sulphate, nitrate, bicarbonate (or strong acid) ammonia, sodium, potassium, calcium, magnesium, pH and electrical conductivity.

Precipitation was collected monthly at one station in each of the three basins and analysed for the same constituents, also at the Institute of Meteorology. The precipitation chemistry supplied data on the average composition of precipitation, used for estimating deposition of atmospheric salts.

As to the chemical analysis the analysis procedures were those recommended by a Nordic Working Group on Hydrochemistry for the laboratories taking part in the programme of the International Hydrological Decade within the Nordic countries (Denmark, Finland, Iceland, Norway and Sweden). Special intercalibrations to check analytical procedures were carried on a couple of occasions during the Decade.

Discharge of Dissolved Substances, Balances

Discharges of dissolved substances were computed for each month using the monthly discharge of water and the concentration figure obtained from the sample collected on the 15th of the month. Although such computed discharges of dissolved substances may be biased the bias will be small as long as concentrations are not too dependent on the water discharge rate. If discharge rate and concentrations are positively correlated within the month the estimates will be too small; if negatively correlated they will be too large. Eriksson (1974) compared this computation method with one which considers several samples per month (8 to 10) and found less than 5 per cent difference on yearly amounts and up to 10 per cent for monthly amounts. The greatest error will in general occur for the snow melt month.

The monthly discharges were added up according to "hydrologic years" i.e. from October one year to September the next. Deposition by precipitation were computed from the concentrations in the monthly samples collected and from the areal means of precipitation. Also here depositions for the hydrologic years were computed. No attempts were made to estimate "dry" depositions which, in the case of sulphur may be considerable.

The average depositions by precipitation and discharges for the various catchments are shown in Table 4. Before discussing the data listed we need to consider more in detail the deposition.

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We should first note that the chloride concentration in igneous rocks as well as in more common sedimentary rocks is extremely low. Consequently, practically all of the discharged chloride must be of different origin. There are two possibilities. One is obviously airborne sea salts the geochemical circulation of which was thoroughly investigated by Eriksson (1959, 1960). The other possibility is "fossil" sea water in the fracture system of the rocks in areas which were below sea level at the end of the last glaciation. The last mentioned source may be very likely in groundwater obtained by deep drilling but rather unlikely as a source of chloride in discharge considering the length of time passed since the last glaciation and the yearly amounts discharged.

The chemical composition of precipitation averaged over the entire period of investigation can be assumed to represent in a relative sense the average total deposition in basins where chloride deposition by precipitation roughly balances discharge. This means that the ratios between the various constituents obtained from long term averages are supposed to be the same also for the actual deposition. This would be a reasonable assumption for those elements which are present in the atmosphere as airborne particles. In the case of sulphur, however, this assumption may be misleading since sulphur can occur in the atmosphere as a gas, sulphur dioxide, and this can be absorbed directly by vegetation and hence contribute to the total deposition. Using precipitation chemistry data would

Table 4 - Depositions, discharges and balances in the various basins.
Units in kg km⁻² year⁻¹. Balance = Discharge - Deposition

Basin:, items	S	Cl	NO ₃ -N	H ₃ N-N	Na	K	Mg	Ca	Remarks
The Velen basin									1968-1974
Deposition by precipitation	999	536	300	290	373	164	120	536	
1. Nolsjön									Deposition comp.
Deposition	1026	1144	300	290	703	176	161	549	by assuming the
Discharge	830	1144	28	21	840	195	264	958	difference dischar-
Balance	-196	0	-272	-269	137	19	103	419	ged chloride minus
									deposited chloride
2. Velen									(by precipitation)
Deposition	1025	1093	300	290	681	175	157	548	to be sea salt
Discharge	870	1093	27	14	821	236	293	1014	particles of sea
Balance	-155	0	-273	-276	140	61	136	466	water composition.
3. Sänningen									
Deposition	1016	909	300	290	581	172	145	544	
Discharge	660	909	26	7	668	186	214	820	
Balance	-356	0	-274	-283	87	14	69	276	

Table 4. cont.

The Kassjöån basin									Prec. 69/70 to 73/74
Deposition by precipitation	902	267	229	210	221	124	67	435	Discharge June 69 to June 75
<i>1. Lilla Tivsjön</i>									
Deposition	723	214	184	168	177	99	54	349	Deposition comp. by adjusting deposition by precipitation to such a level that chloride balances
Discharge	402	214	22	9	364	113	340	1307	
Balance	-321	0	-162	-159	187	14	286	958	
<i>2. Elnäs</i>									
Deposition	486	144	124	113	119	67	36	235	Deposition comp. by adjusting deposition by precipitation to such a level that chloride balances
Discharge	301	144	14	12	258	74	217	922	
Balance	-185	0	-110	-101	139	7	181	687	
<i>3. Öraåttjärn</i>									
Deposition	787	233	200	183	193	108	58	380	Deposition comp. by adjusting deposition by precipitation to such a level that chloride balances
Discharge	440	233	16	11	385	148	364	1344	
Balance	-347	0	-184	-172	192	40	306	964	
<i>4. Kroksillret</i>									
Deposition	706	209	179	164	173	97	52	341	Deposition comp. by adjusting deposition by precipitation to such a level that chloride balances
Discharge	374	209	23	7	326	131	306	1181	
Balance	-332	0	-156	-157	153	34	254	840	
<i>5. Styggbergsbäcken</i>									
Deposition	750	222	190	175	184	103	56	362	Deposition comp. by adjusting deposition by precipitation to such a level that chloride balances
Discharge	353	222	13	10	414	119	285	2078	
Balance	-397	0	-177	-165	230	16	229	1716	
<i>6. Kassjön</i>									
Deposition	638	189	162	149	156	88	47	308	Deposition comp. by adjusting deposition by precipitation to such a level that chloride balances
Discharge	352	189	11	12	362	124	242	1233	
Balance	-286	0	-151	-137	206	36	195	915	
<i>7. Storsillret</i>									
Deposition	693	205	176	161	170	95	51	334	Deposition comp. by adjusting deposition by precipitation to such a level that chloride balances
Discharge	368	205	17	10	362	131	287	1274	
Balance	-325	0	-159	-151	192	36	236	940	

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The Lappträsket basin (4. cont.)

Deposition by precipitation	784	292	168	162	418	130	75	382	March 1969 - Aug. 1975
<i>Tjärdalsselet</i>									
Deposition	553	206	119	114	295	92	53	269	Deposition computed in the same way as for Kassjöån basin
Discharge	247	206	6	8	375	163	188	654	
Balance	-306	0	-113	-106	80	71	135	385	
2. Norriåselet									
Deposition	532	198	114	110	283	88	51	259	
Discharge	241	198	9	8	391	174	195	692	
Balance	-291	0	-105	-102	108	86	144	433	
3. Livastorpet									
Deposition	516	192	110	107	275	85	49	251	
Discharge	266	192	10	5	407	185	202	753	
Balance	-250	0	-100	-102	132	100	153	502	
4. Spikforsen									
Deposition	639	238	137	132	341	106	61	311	
Discharge	306	238	10	13	469	197	231	805	
Balance	-333	0	-127	-119	128	91	170	494	
5. Blåkölsbäcken									
Deposition	416	155	89	86	222	69	40	203	
Discharge	331	155	8	6	431	165	194	596	
Balance	-85	0	-81	-80	209	96	154	393	
6. Lombergfallet									
Deposition	346	129	74	72	185	57	33	169	
Discharge	214	129	10	5	327	173	170	583	
Balance	-132	0	-64	-67	142	116	137	414	
7. Solmyren									
Deposition	609	227	131	126	325	101	58	297	
Discharge	403	227	8	14	441	221	269	1017	
Balance	-206	0	-123	-112	116	120	211	720	
8. Vuoddasbäcken									
Deposition	526	196	113	109	281	87	50	256	
Discharge	235	196	12	7	447	149	201	715	
Balance	-291	0	-101	-102	166	62	151	459	
9. Ytterholmen									
Deposition	628	234	135	130	335	104	60	306	
Discharge	270	234	11	10	457	200	211	733	
Balance	-358	0	-124	-120	122	96	151	427	

therefore most likely underestimate sulphur deposition. The error would be greatest for the Velen basin since sulphur dioxide concentrations in air are much greater there than in Kassjöån and Lappträsket. However, being aware of this error we can nevertheless attempt a balance computation. As to ammonia the present situation is such that it would almost entirely occur as ammonium in particulate matter in the atmosphere over Sweden.

Considering chloride, we can assume that all the chloride discharged is airborne since there are no other chloride sources of importance in the basins.

We noted that deposition of chloride by precipitation nearly balanced discharge of chloride in the Kassjöån and Lappträsket basins; actually it looks as if more chloride is deposited than discharged. Now, the way the deposition by precipitation is computed is the following. Concentrations are determined monthly in the collected precipitation and multiplied by the precipitation amounts measured by precipitation gauges elsewhere in the basins. This may introduce some error because the chemistry precipitation gauges are not of the same design as for instance the totalizers or the precipitation gauges used. Evaporation losses are likely to be higher in the precipitation chemistry gauges which increase the concentrations somewhat. But the efficiency of the precipitation chemistry gauges is lower, particularly in winter, than the efficiency of the ordinary precipitation gauges. This means that the amounts deposited in the precipitation chemistry gauges are normally less than the actual. By using concentrations for computing depositions the computed values may come out higher than the actual because of the evaporation effects. Hence, one should not attach any great significance to smaller discrepancies between deposited chloride. The best one can do is to adjust the deposition data such that chloride balances. This procedure has also been adopted for the Kassjöån and Lappträsket basins, where apparently dry deposition of airborne particles by impingement on vegetation is insignificant.

In the Velen basin, however, the discharge of chloride greatly exceeds the deposition by precipitation. This indicates that dry deposition by impingement of sea salt particles is an important source. Considering the geographic location of the Velen basin this is not unlikely. Particularly during strong westerly winds a great amount of sea salt particles are added to the air over the North Sea and are carried into the southern part of Sweden.

However, the sea salt particles impinging on vegetation on these stormy occasions can hardly have the average composition shown by precipitation which is greatly influenced by terrestrial sources. We can assume that they show the chemical composition of sea water. Hence, the procedure to be adopted for the Velen basin in order to balance deposition and discharge of chloride is to take the difference between discharged chloride and chloride deposited by precipitation and assume that this difference represents chloride in sea salt particles which have the composition of sea water. In this way we can compute the contribution from dry deposition to the deposition of the other constituents. Hence we use the

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following ratios for sea water composition

$$\begin{array}{ll} \text{S/Cl} = 0.0465 & \text{Mg/Cl} = 0.067 \\ \text{Na/Cl} = 0.553 & \text{K/Cl} = 0.0204 \\ \text{Ca/Cl} = 0.021 & \end{array}$$

neglecting nitrate and ammonia which are present in sea water in very low concentrations. The procedure is, of course, probably not entirely correct but is the only one possible with the information at hand. A considerable amount of information exists on sea salt particles in the atmosphere in coastal areas. Cf Eriksson (1959, 1960).

In general we note that sulphur does not balance, much less is discharged than deposited. In the Velen basins the deficit amounts to between 150 and 350 kgs · km⁻² year⁻². Considering sulphur deposition by direct absorption of sulphur dioxide from the atmosphere the deficit easily could be larger. In the Kassjöån basins the deficit is between 40 to 50% of the total deposition or about the same in absolute terms as in the Velen basin and in the Lapträsket basin the deficit is also about the same in absolute terms. There is one exception, Blåkölsbäcken, where the deficit is rather small. Perhaps sulphides in the rocks may contribute sulphur to the discharge. For explaining the deficits there are two possibilities to consider. One is a steady accumulation of sulphur in soil organic matter. However, such storage changes cannot go on forever and the explanation is therefore doubtful. Of course, we can argue that the sulphur depositions have increased quite substantially during the last decades because of the remarkable increase in fossil fuel combustion. Because of this the soil organic matter is in a process of readjustment to new "equilibrium" levels accounting thus for the deficits. There is, of course, a considerable storage of sulphur in soil organic matter.

The other explanation is that part of the deposited sulphur is lost by release of volatile sulphur compounds, such as hydrogen sulphide and organic sulphur compounds like methyl sulphide or dimethyl sulphide. Very little seems to be known about these possibilities although the mechanism of formation of dimethyl sulphide from hydrogen sulphide is about the same as that forming dimethyl mercury. Considering the microbiological activity in soils none of the two possibilities are unlikely.

The results are not in agreement with the conclusions reached by Odén (1979) in his study of the sulphur budget of Sweden. He concluded that the discharge of sulphur is even somewhat higher than deposition from the atmosphere. However, the results are perhaps not entirely comparable. Odén (1.c.) bases his discharge rates of sulphur on analysis of major rivers in Sweden covering 78% of the area. It is possible the forested areas behave like the representative basin but that agricultural areas are losing more sulphur by run-off than gaining from atmospheric deposition.

The nitrogen compounds show deficits which are almost as large as the

depositions. However, organic bound nitrogen has not been determined but is certainly not greater than inorganic nitrogen in run-off. On the other hand precipitation also contains organic nitrogen which will at least partly escape the analytical procedures used and this certainly compensates the organic nitrogen in run-off. Hence, the deficits expressed as negative balances are certainly of the correct order of magnitude. Also in this case there are two possibilities open to account for the deficits. One is, of course, an increase in soil organic nitrogen for the very same reason as for sulphur – increased depositions in the last decades and consequently an adjustment of soil organic nitrogen to the new atmospheric environment. The other possible explanation is denitrification processes in the soils which convert inorganic water soluble compounds into the nitrogen and nitrous oxide, N_2O , which escape to the atmosphere. Escape of nitrous oxide from soils was discovered years ago (see e.g. Junge 1972) and recently global estimates have been attempted on denitrification processes in soils and water (Söderlund and Svensson 1976). Another possible escape seems to be through nitric acid HNO_3 , which can decompose and form volatile nitric oxide, NO .

Again, it is possible that both processes – increase in soil organic nitrogen and denitrification – account for the deficits in the nitrogen balance.

There is one important aspect of the deficits of sulphur and nitrogen compounds. The effect of acidity in precipitation, particularly in southern Sweden will be reduced in proportion to the deficits of sulphate sulphur and nitrate nitrogen. Both are anions of strong acids and, insofar they disappear from the soil solution they have to be replaced by bicarbonate ions which will neutralize equivalent amounts of hydrogen ions. Of course, the deficit of ammonia will work the other way. The carbon dioxide formed in this way is very small compared to the normal production of carbon dioxide in soils and will thus have no effect on weathering conditions. Hence, only the discharged sulphate and nitrate have to be accompanied by cations. It is therefore not correct to compute weathering and cation exchange effects from the acid deposited by precipitation.

The cations show in general a positive balance, i.e. more is discharged than deposited. The difference must then be accounted for by weathering of silicate minerals unless deposition of strong acids cause leaching of the soil by ion exchange. As to silicate minerals of interest in these hard rock areas they are mainly feldspars, biotite and hornblende. Of the feldspars the lime feldspar, $CaO \cdot Al_2O_3 \cdot 2 SiO_2$ seems to be most easily weathered followed by the plagioclases – sodalime feldspars – soda feldspar, biotite, hornblende, all of which are reasonably easily decomposed by carbonic acid. The potash feldspars and muscovite are considered rather resistant towards weathering. Thus feldspars would supply sodium and calcium, and biotite would yield magnesium and potassium.

In order to get a better view of the cation balances they are assembled in Table 5. We notice an overall consistency in the results.

The magnitudes are about the same as found by Johnson et al. (1968) for an

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Table 5 – Balances of cations in the various basins and sub-basins.
Expressed in kg km⁻² year⁻¹.

Basin, sub-basin	Na	K	Mg	Ca	Sum
<i>The Velen basin (Fig. 1)</i>					
1. Nolsjön	137	19	103	419	678
2. Velen	140	61	136	466	803
3. Sänningen	87	14	69	276	446
<i>The Kassjön basin (Fig. 2)</i>					
1. Lilla Tivsjön	187	14	286	958	1445
2. Eltnäs	199	7	181	687	1014
3. Öraåttjärn	192	40	306	964	1502
4. Kroksillret	153	34	254	840	1281
5. Styggbergsbäcken	230	16	229	1716	2191
6. Kassjön	206	36	195	915	1352
7. Storsillret	192	36	236	940	1404
<i>The Lapträsket basin (Fig. 3)</i>					
1. Tjärdalsslet	80	71	135	385	671
2. Norriåselet	108	86	144	433	771
3. Livastorpet	132	100	153	502	887
4. Spikforsen	128	91	170	494	883
5. Blåkölsbäcken	209	96	154	393	852
6. Lombergfallet	142	116	137	414	809
7. Solmyren	116	120	211	720	1167
8. Vuoddasbäcken	166	62	151	459	838
9. Ytterholmen	122	96	151	427	796

area in New Hampshire with similar rocks and similar climate. Their results were

Balance of Ca	800 kgs km ⁻² year ⁻¹
Balance of Na	460 kgs km ⁻² year ⁻¹
Balance of K	10 kgs km ⁻² year ⁻¹
Balance of Mg	180 kgs km ⁻² year ⁻¹

the major difference being higher balances for Na and lower for K which may be accounted for by differences in mineralogical composition of the rocks.

The next step is now to compute from which likely minerals these excesses are derived. In doing so we are ignoring possible leaching of exchangeable ions in the root zone by acid precipitation. This leaching is, in fact counteracted by plant uptake of cations, later deposited on the soil surface as litter. If this transport is greater than the downward transport of exchanged cations there the effect of acid

precipitation will be increased weathering below the root zone.

The minerals we will consider are the following:

Anorthite	$\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$
Albite	$\text{Na}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2$
Biotite	of a composition that contains equal weight proportions of potassium and magnesium
Hornblende	of a composition which contains equal weight proportions of magnesium and calcium

With these assumptions we can compute the masses of sodium, potassium, magnesium and calcium which are derived from anorthite, albite, biotite and hornblende. If x , y , z and u are the amounts of these ions being released from anorthite, albite and hornblende respectively, then we allot the following weights to the different ions

	Na	K	Mg	Ca
x from anorthite	0	0	0	1
y from albite	1	0	0	0
z from biotite	0	0.5	0.5	0
u from hornblende	0	0	0.5	0.5

This means that we can write the following systems of equations:

$$\begin{aligned}
 y &= (\text{Na}) & 0.5z + 0.5u &= (\text{Mg}) \\
 0.5z &= (\text{K}) & x + 0.5u &= (\text{Ca})
 \end{aligned}$$

where () stands for the amounts listed in Table 5. From this system of equations we obtain

$$\begin{aligned}
 x &= (\text{Ca}) - [(\text{Mg}) - (\text{K})] & z &= (\text{K}) \\
 y &= (\text{Na}) & u &= 2 [(\text{Mg}) - (\text{K})]
 \end{aligned}$$

from which x , y , z and u are readily computed. From the amounts in Table 5 we arrive at the amounts weathered from the four minerals considered. They are listed in Table 6. The results are, however, no proof of the assumptions made. There may be other minerals also contributing. For instance, calcite cannot be distinguished from anorthite. But we have other reasons to believe that the results could be realistic. The minerals chosen are common in hard rocks e.g. gneisses and granites.

Knowing the percentages of the cations concerned in the listed minerals we can, of course, also express the results in terms of amounts of weathered minerals.

As to anorthite and albite we cannot say whether the albite occur as plagioclase or not.

Comparing the main basins we note that the Velen and Lapträsket basins are

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Table 6 – Amounts of Na, K, Mg and Ca from anorthite, albite, biotite and hornblende in the different basins, all in $\text{kg km}^{-2} \text{ year}^{-1}$

Basin, sub-basin	Anorthite	Albite	Biotite	Hornblende
<i>The Velen basin</i>				
1. Nolsjön	335	137	38	168
2. Velen	391	140	121	150
3. Sänningen	221	87	28	110
<i>The Kassjöån basin</i>				
1. Lilla Tivsjön	874	187	28	168
2. Eltnäs	513	139	14	348
3. Öraåttjärn	698	192	80	532
4. Kroksillret	620	153	68	440
5. Styggbergsbäcken	1503	230	32	426
6. Kassjön	756	206	72	318
7. Storsillret	740	192	72	400
<i>The Lappträsket basin</i>				
1. Tjärdalsetet	321	80	141	128
2. Norriåsetet	375	108	172	116
3. Livastorpet	449	132	200	106
4. Spilsforsen	415	128	182	158
5. Blåkölsbäcken	335	209	192	116
6. Lombergfallet	393	142	232	42
7. Solmyren	629	116	240	182
8. Vuoddasbäcken	370	162	124	178
9. Ytterholmen	372	122	192	110

rather similar with respect to weathering amounting to a total of about 800 kgs. $\text{km}^{-2} \cdot \text{year}^{-2}$ for the cations considered. The Kassjöån basin in comparison releases about 1,400 kgs $\cdot \text{km}^{-2} \cdot \text{year}$, the major difference being anorthite weathering or calcite weathering. The rocks also appear to be rich in hornblende when compared to rocks in the other two basins.

The difference between the main basins in the total amounts weathered can at least partly be related to relief. The Velen and Lappträsket show rather gentle slopes between the main drainage channels whereas Kassjöån as mentioned before has rather steep slopes. There is a possibility that the depth of fractures in the rocks are correlated to the relief. The balances in cations no doubt originate to a large extent from the fracture systems in the underlying rocks even though the morainic overburden contributes. There are good indications of fairly deep fracture systems e.g. in the Styggbergsbäcken basin where ground-water levels

show a typical earth-tidal effect and even the electrical conductivity of water at the discharge station contains this effect (Andersson and Calles 1978). Of course there is certainly a difference in mineralogical composition between the basins as indicated in Table 6 but the amounts weathered may still depend on relief.

There also seems to be a considerable variation between sub-basins within the main basins. These variations are in no way related to the percentage lakes or bogs. One reason for the variation can be poor discharge records from some of the sub-basins, e.g. no winter records, only estimates. There are for instance at least one break in the Sänningen discharge measurements and also Solmyren lacks winter measurements.

References

- Andersson, U.M., and Calles, B. (1978): Variations in electrical conductivity of water in a small drainage basin. NHK 1978, Helsinki.
- Eriksson, E. (1959) The yearly circulation of chloride and sulphur in nature; meteorological, geochemical and pedological implications. Part I. *Tellus* II. 375-403.
- Eriksson, E. (1960) The yearly circulation of chloride and sulphur in nature; meteorological, geochemical and pedological implications. Part II. *Tellus* 12. 63-109.
- Eriksson, E. (1974) Transporthastighet (flöden) ur statistisk synpunkt. In Eriksson & Holtan. *Hydrokemi, kemiska processer i vattnets kretslopp*, p. 83-88. Nordic IHD Report Nr. 7, Oslo 1974.
- Johnson, Noye, M., Likens, Gene E., Bormann, F. H., and Pierce, Robert, S. (1968) Rate of Chemical Weathering of Silicate Minerals in New Hampshire. *Geoch. & Cosmochim. Acta*, 32, 531-545.
- Junge, C. (1972) The cycles of atmospheric gases - natural and man-made. *Q. Journ. Roy. Met. Soc.* 98, 711-729.
- Odén, S. (1979) The sulphur budget of Sweden. *Nordic Hydrology* 10, 2/3,
- Söderlund, R., and Svensson, B. H. (1976) The global nitrogen cycle. In SCOPE REPORT 7 *Ecol. Bull* (Stockholm) 22, 22-73.

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