Chemistry and Flow Patterns in some Groundwaters of Southeastern Norway

JENS-OLAF ENGLUND

Groundwaters in Quaternary deposits and in bedrock of southeastern Norway down to 120 m below surface range in chemical composition from very dilute waters to brackish waters. The total contents of dissolved solids ($Ca^{2+} + Mg^{2+} + Na^+ + K^+ + HCO_3^- + SO_4^{2-} + Cl^-$) are usually lower in recharge areas than in deep circulating groundwaters and in springs.

Chemical differences are explained by two main modes of groundwater flow patterns: (a) flow through shallow aquifers with active flushing, and ending up in springs; (b) long and deep flow, from Quaternary deposits through deep circulating groundwaters in bedrock, and ending up in springs and rivers. The highest pH and concentration values along any one flow path usually occur in the spring waters.

Acidification due to acid precipitation does not seem to have occurred because of the high buffer capacity of the deep groundwaters investigated, deeper than 15–25 m below surface.

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Introduction

The term groundwater is usually reserved to denote the water present beneath the surface of the ground in the zone of saturation. In Norway such water occurs in Quaternary deposits and in fractures in bedrock (e.g. Skjeseth 1953, 1956, Bryn 1961, Englund 1966). The purpose of this paper is to demonstrate that the groundwaters of southeastern Norway, down to 100–120 m below the surface, vary widely in chemical composition; from very dilute waters to brackish waters. This is illustrated by data (Ca^{2+}, Mg^{2+}, Na^+, K^+, HCO_3^-, SO_4^{2-}, Cl^- and pH) collected during the years 1975–1981 from the following areas (Fig. 1): Åstadalen, Lillehammer – Brøttum, Stensengbekken watershed at Mjøsa, Ås, Moss and Jeløy. The last three areas are situated below the Late Glacial sea-level, while the other areas are above this level. The mean annual precipitation is highest at Moss, Jeløy, Ås and in Åstadalen with 800–1000 mm, and lowest in the Stensengbekken watershed with 600–700 mm (Aune 1981).

Since seasonal variations are quite common in groundwater chemistry, especially in shallow aquifers, and as only large-scale chemical changes are discussed here, the data used are annual average results. 934 water samples from 113 wells and springs have been analysed (Table 1); these were sampled during winter, spring, summer and autumn. Additional information from 45
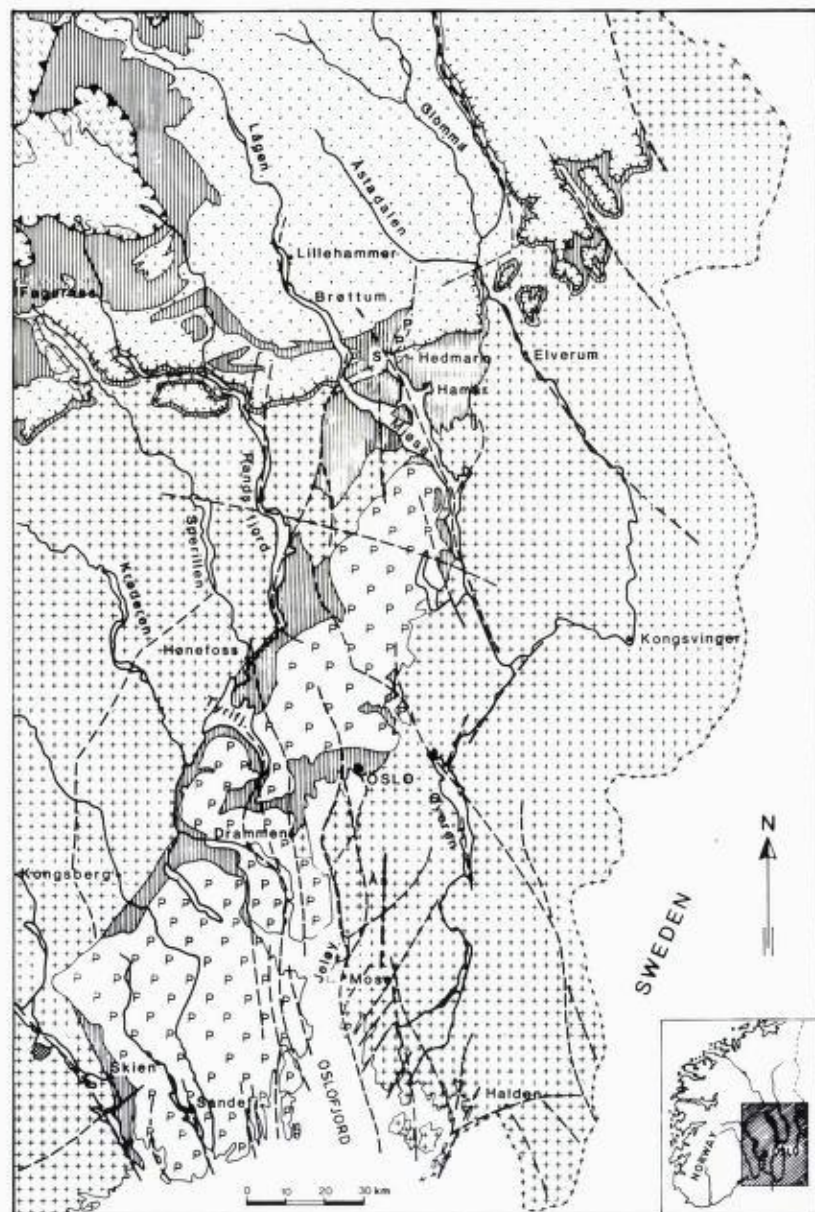
Precambrian crystalline
rocks ("Jotun nappe")

Lower Palaeozoic
sedimentary rocks

Late Precambrian
sedimentary rocks (sparagmites)

Precambrian, mainly
gneisses and granites

Fault or prominent joint

Thrust planes

Alkaline rocks of
the Fen area

Permian
igneous rocks

Fig. 1. Location map of areas in which the groundwater investigations were conducted: Jeløy, Moss, Ås, S = Stensengbekken, Brøttum–Lillehammer, Åstadalen. Geology mainly after Holtedahl & Dons (1960) and Ramberg & Larsen (1977).

water samples taken in 20 wells and springs has been used in working out the figures 6 and 7. Alle analyses were carried out by conventional methods on unfiltrated samples. Parts of the analytical data have earlier been published by Englund & Myhrstad (1980) and Englund & Meyer (1980).

General considerations

Nearly all the groundwaters of Scandinavia originate from rain or melting snow that infiltrates through soil or directly into rock fractures. The quality of groundwater at a given point in an aquifer thus depends on the integrated effects of a number of factors, such as: 1) the chemistry of the input water; 2) the pathway of water through the aquifer; 3) subsurface soil and rock types encountered along the pathway; 4) the residence time or flow velocity variations along the pathway; 5) hydrodynamic dispersion; 6) rates and threshold values of physical, chemical and biological processes. This paper is concerned mainly with the effects of the above factores 2, 3 and 4. The chemistry of the input water, however, varies between the investigated areas, due to variations in atmospheric deposition, agricultural activities, domestic sources, and leaching processes in the unsaturated zone.

Geochemical data from groundwaters in Scandinavia have been studied using theoretically calculated stability diagrams, of the types given by e.g. Helgeson et al. (1973); from crystalline Precambrian rocks in Sweden (Jacks 1973) and southeastern Norway (Englund & Myhrstad 1980). These studies indicate that alteration of feldspars, chlorites, micas and also calcite is a widespread process in groundwaters down to 120 m from ground surface. The cations released into the water are mainly Ca^{2+}, Mg^{2+}, Na^+ and to some extent K^+. Another consequence of these processes is a rise in the silica concentration as well as a rise in pH. These trends are also found in Late Precambrian and Cambro-Silurian sedimentary rocks (Englund et al. 1977) although saturation with respect to calcite often occurs in groundwaters from calcareous shales.

Groundwater chemistry in areas below the Late Glacial sea-level is also influenced by remnants of sea-water and salts(?), left over in marine sediments or in rock fractures from the time when areas were covered by the sea (Englund & Meyer 1980). Sodium and chloride are then the dominant ions in the groundwater. Such water is generally found in bedrock below clay deposits where the groundwater moves slowly or is almost stagnant.

Calcium and bicarbonate are, however, the dominant ions in most of the groundwaters studied here (Table 1, Fig. 2). They occur in approximately equal amounts; commonly, however, the amount of bicarbonate is more in harmony with the sum $Ca^{2+}+ Mg^{2+}$ (Fig. 3). Magnesium is relatively more important above than below the Late Glacial sea-level.

The HCO_3^- content in groundwaters is derived from soil-zone CO_2 and from dissolution of calcite and dolomite. CO_2 in the soil comes from the atmosphere, via plant respiration and decay of organic material.

Table 1. Average chemical composition of some groundwaters from southeastern Norway. Observation period 1975–1981

Area	Geology/ Land use	Occurrence of groundwater/ Depth below surface	pH	µeg/l							Number of wells/ springs	Number of analyses
				Ca	Mg	Na	K	HCO$_3$	SO$_4$	Cl		
15) Åstadalen	Glaciofluvial, till	Springs	5.9	178.5	48.5	57.5	8.5	222.5	25.5	30.0	3	35
14) "	Dominantly sandst., some congl.,shale	"	6.0	149.5	28.5	53.5	5.5	195.0	32.5	18.5	25	49
13) Lillehammer	Sandst.,congl.	In wells, 25–100 m b.s.	7.5	1605	238	191	18	1690	344	85	4	53
12) "	Sandst.,dark shale	In wells, 25–70 m b.s.	7.5	2190	590	491	36	1980	1085	176	9	96
11) Stensengbekken, at lake Mjøsa	Till/Forested land	Springs/wells 0–2 m b.s.	6.6	1005	213	157	14	933	313	82	4	25
10) "	Till/Arable land	"	6.6	1480	590	278	85	988	517	423	6	48
9) "	Sandst.,sandy limest., grey shale	In wells 25–60 m b.s.	7.2	3155	1287	757	120	4060	446	890	5	32
8) "	Limestone	In wells 25–55 m b.s.	7.6	3265	1131	1252	77	4550	794	321	2	11
7) "	Dark shale, limest.	In wells 25–45 m b.s.	7.1	7605	2795	1087	238	7590	2210	1256	2	12
6) Moss	Ice-edge deposits/ Forested land	In wells 0–5 m b.s.	6.4	300	172	543	115	380	417	372	2	4
5) Ås	Ice-edge deposits/ Arable land	"	7.4	2910	795	987	105	3360	821	727	4	9
4) Ås, Moss	Gneiss, amphibolite	In wells 30–100 m b.s.	7.5	1400	467	1695	120	1786	562	732	24	51
3) Jeløy	Volcanic rocks, sandst.	"	7.4	1850	492	1217	64	2459	438	563	13	32
2) Moss, Jeløy	Volcanic rocks, gneiss, amphibolite	Springs	7.1	2715	639	1383	61	2972	463	656	5	436
1) Ås, Moss	Gneiss, amphibolite	In wells 25–90 m b.s.	7.2	3645	934	9491	261	66	1421	14456	5	41
Ocean water (Rankama & Sahama 1950)			~ 8.0	20800	106147	467478	9974	2377	56271	544930		

Left margin labels: Above the Late Glacial sea-level (rows 15–7); Below the Late Glacial sea-level (rows 6–1)

Abbreviations: Sandst. = sandstone, congl. = conglomerate, limest. = limestone

Where the aquifers contain pyrite, oxygenated recharge water attacks the pyrite to produce SO_4^{2-}. Sulphate-bearing minerals such as gypsum and anhydrite occur in places. They dissolve readily when in contact with water.

Major-ion Evolution Sequences

As groundwater moves along its flow paths in the saturated zone, the contents of total dissolved solids and most of the major ions normally increase. Lower concentrations are usually found in groundwaters from recharge areas rather than in deep circulating groundwaters and in springs.

From the present investigation three main chemical evolution trends can be demonstrated, dependent upon the aquifer type in which the groundwaters occur.

ÅSTADALEN AND LILLEHAMMER–BRØTTUM AREA

The groundwaters are located in Late Precambrian sandstones, conglomerates and dark shales (Brøttum Formation), and in overlying Quaternary deposits such as tills and glaciofluvial sediments. The areas are little disturbed by man.
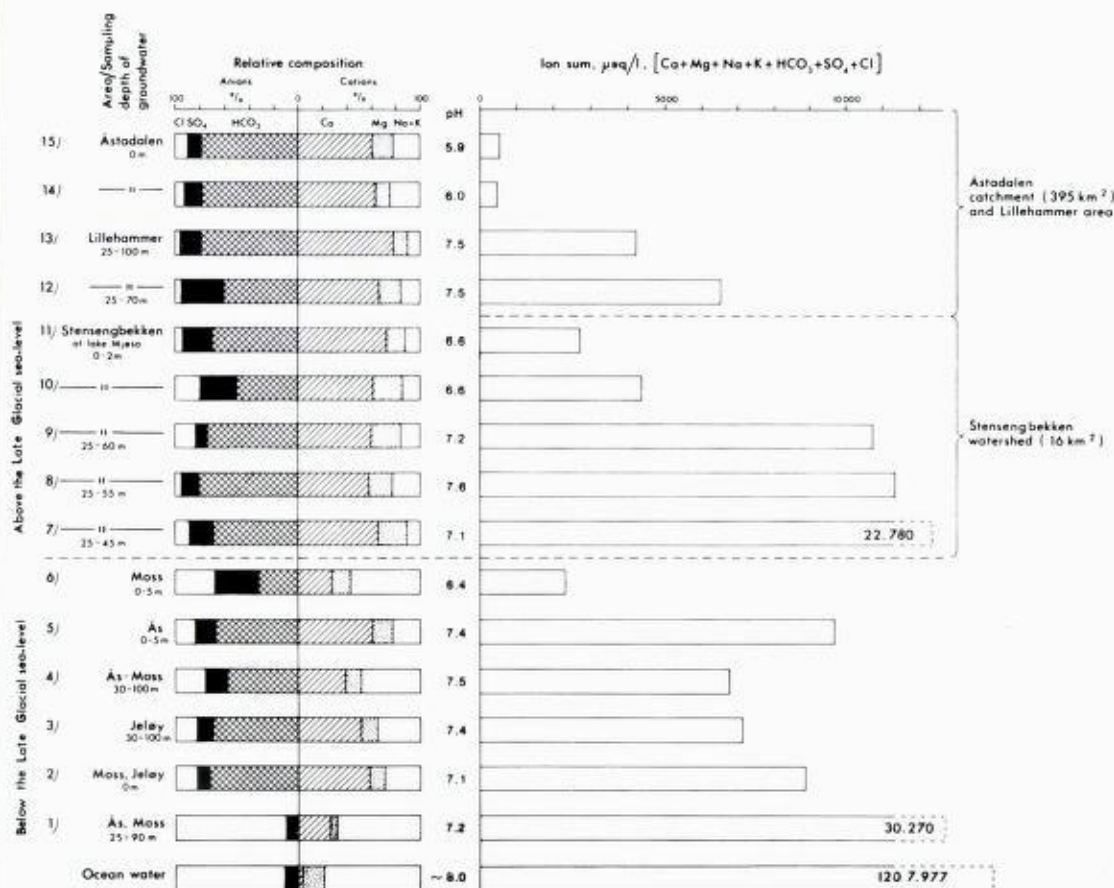
Fig. 2. Average groundwater compositions from southeastern Norway, as presented in Table 1, compared with ocean water after Rankama & Sahama (1950).
1) Precambrian gneiss, amphibolite (fresh-to-brackish water). 2) Springs from Precambrian and Permian rocks. 3) Permian volcanic rocks. Downtonian sandstone. 4) Precambrian gneiss, amphibolite. 5) Quaternary deposits, mainly ice-marginal deposits. Arable land. 6) Quaternary deposits, mainly ice-marginal deposits. Forested land. 7) Cambro-Ordovician dark shale, limestone. 8) Ordovician-Silurian limestone. 9)Ordovician sandstone, sandy limestone, grey shale. 10) Springs/wells from Quaternary deposits, mainly till. Arable land. 11) Springs/wells from Quaternary deposits, mainly till. Forested land. 12) Late Precambrian sandstone, dark shale (Brøttum Formation). 13) Late Precambrian sandstone, conglomerate (Brøttum Formation). 14) Springs from dominantly sandstones with some conglomerates and shales (Brøttum Formation). 15) Springs from Quaternary deposits, mainly glaciofluvial and till.

From a hydrogeological viewpoint the investigated springs of Åstadalen (Table 1, Fig. 2) are draining shallow zones with active flushing, 0–30 m below surface; while in the Lillehammer–Brøttum area the groundwater is older and with a more sluggish flow, down to 50–120 m below surface (Fig. 6).

The groundwaters studied belong to the bicarbonate facies (Fig. 4). There is, however, a clear chemical evolution from water in Quaternary deposits (loc.no. 15), through water in sandstones (loc.no. 14, 13), to the deep water in sandstones alternating with dark shale beds (loc.no. 12); an increase in the
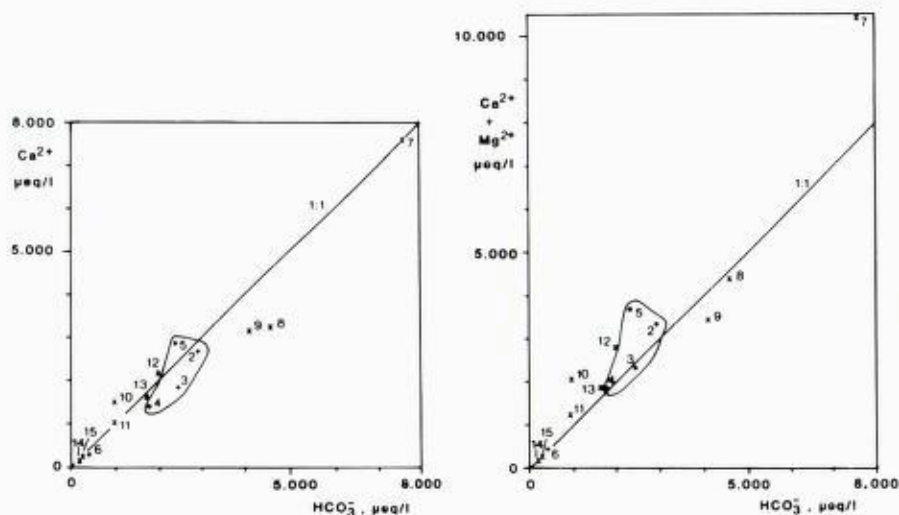
Fig. 3. Relationship between some important ions in groundwaters from southeastern Norway. • data from below, and × data from above the Late Glacial sea-level. Location numbers: see Table 1 and Fig. 2.

total ion content, relative increase of SO_4^{2-} compared to HCO_3^-, and an increase of pH from 5.9 to 7.5, and further to pH 7.7 in springs (Fig. 7). The total ion increase, coupled with the rise in pH, reflect an increased time of contact between water and rock towards depth, and chemical reactions whereby H^+ in the water is being consumed.

The occurrence of sulphate in the groundwater reflects mainly the existence of pyrite in the bedrock (Englund 1972, 1973). Sulphate-bearing weathering products on exposures of these rock units are known from many places, e.g. Fåvang–Ringebu in Gudbrandsdalen (Broch 1931, Caillere & Prost 1968).

STENSENGBEKKEN WATERSHED

The groundwaters occur in Cambro-Silurian shales, sandstones and limestones, and in overlying tills. The watershed represents an ecosystem which has been manipulated by man. Therefore, some of the groundwater, like the river Stensengbekken (Bjerve et al. 1981), is more or less polluted from agriculture, reflected in high concentrations of e.g. potassium and nitrate.

The groundwaters belong to the bicarbonate facies (Fig. 4), showing a chemical evolution with a relative increase in HCO_3^- concentration compared to SO_4^{2-} and Cl^- when going from Quaternary deposits (loc.no. 10–11) to the deep circulating waters in bedrock (loc.no. 7–9). At the same time the total ion content and pH are increasing (Table 1, figs. 2, 6 and 7). The increase of pH is largely coupled with a corresponding increase in the HCO_3^- concentration.
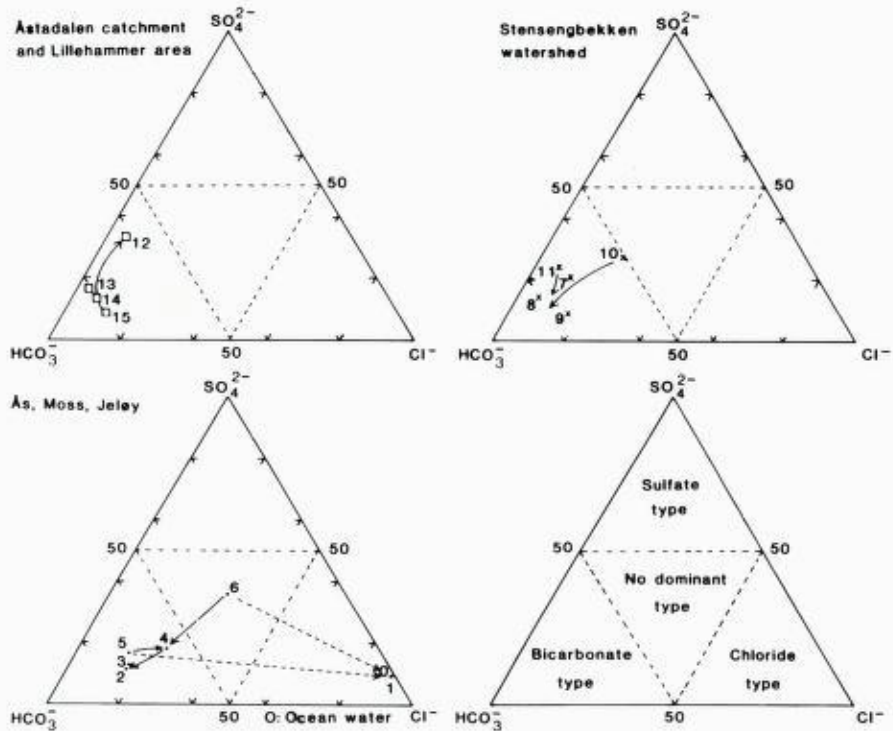
Fig. 4. Classification of the investigated groundwaters from southeastern Norway, based on the percentages of major anions. Water types are designated according to their position on the diagram segments (after Morgan & Winner 1962, and Back 1966). Arrows indicate evolution of water types along flow path. Location numbers: see Table 1 and Fig. 2.

The hydrochemistry of grundwaters in Cambro-Silurian sedimentary rocks is always strongly influenced by the rock types in which they occur (Englund & Myhrstad 1980). Especially important is the solution of calcite and dolomite, resulting in an increase of the HCO_3^- contents towards depth, as well as an increase in the contents of Ca^{2+} and Mg^{2+}.

Sulphate reflects largely the existence of pyrite in bedrock. The increased concentration in chloride towards depth, especially within dark shales alternating with carbonate beds (Table 1), indicates the existence of geological chloride sources (Englund & Myhrstad 1980, p. 43). However, chloride in the shallow groundwaters of the Quaternary deposits is mainly due to agricultural activities, e.g. fertilizers and animals.

ÅS–MOSS

The groundwaters are located in Precambrian gneisses which are commonly alternating with amphibolites, and in overlying Quaternary sediments, large-ly ice-marginal deposits. Generally, groundwaters in crystalline rocks from various parts of the world have low major-ion concentrations (Matthess 1973, p. 227, Freeze & Cherry 1979, p. 275). Within the present areas, however,

waters are found ranging from the bicarbonate facies to the chloride facies (Fig. 4); this is mainly due to the following factors:

1. Permian mineralization along fractures (e.g. carbonate minerals).
2 Remnants of Late Glacial/Holocene sea-water and sea salts(?) in rock fractures and/or in marine sediments.
3. Pollution from agriculture.

Two different chemical evolution trends have been found (Fig. 4): (a) a relative increase in HCO_3^- concentration compared to SO_4^{2-} and Cl^- during flow (loc.no. 6, 4 and 2); (b) transformation of HCO_3^--rich water into brackish water with a high content of chloride (loc.no. 1). It is believed that the first path occur within rocks carrying carbonate minerals, while the second path is mainly due to the supply of old sea-water/sea salts (factor 2 above). Both evolution trends are coupled with a corresponding increase in the content of total ions (Table 1, Figs. 2 and 6).

JELØY

Within the volcanic rocks of this island one chemical evolution trend has been found (Fig. 4): a relative increase in HCO_3^- concentration compared to SO_4^{2-} and Cl^- when going from deep groundwaters in wells and to springs (loc.no. 3 and 2). At the same time the total ion content is increasing (Table 1 and Fig. 2).

SOME CONCLUSIONS

The total contents of dissolved solids ($Ca^{2+} + Mg^{2+} + Na^+ + K^+ + HCO_3^- + SO_4^{2-} + Cl^-$) are usually lower in recharge areas than in deep circulating groundwaters and in springs (Table 1, Figs. 2 and 6). There is simultaneously a change in the relative anion composition, following three main trends (Fig. 4): (a) an increase of SO_4^{2-} compared with HCO_3^- and Cl^- (in pyrite carrying sandstones/shales); (b) an increase of HCO_3^- compared with SO_4^{2-} and Cl^- (in carbonate-bearing rocks); (c) an increase of Cl^- compared with HCO_3^- and SO_4^{2-} (mainly due to the supply of Late Glacial/Holocene sea-water and sea salts(?)).

Many groundwaters of the world show chemical evolution during flow, as described by Chebotarev (1955); from shallow zones of active flushing (HCO_3^--rich water) through intermediate zones ($HCO_3^- + SO_4^{2-}$-rich water) into zones where water flow is very sluggish and the water is old (Cl^--rich water). Most of the water investigated in this work belongs to the upper zone of Chebotarev. The different anion-evolution sequences are determined either by the sediment/rock types in which the groundwaters occur, or by the supply of old sea-water/sea salts (point c above).

Quality and Flow Patterns

A schematic picture of the groundwater systems investigated is presented in Fig. 5. The logical location of water samples along flow lines, representing
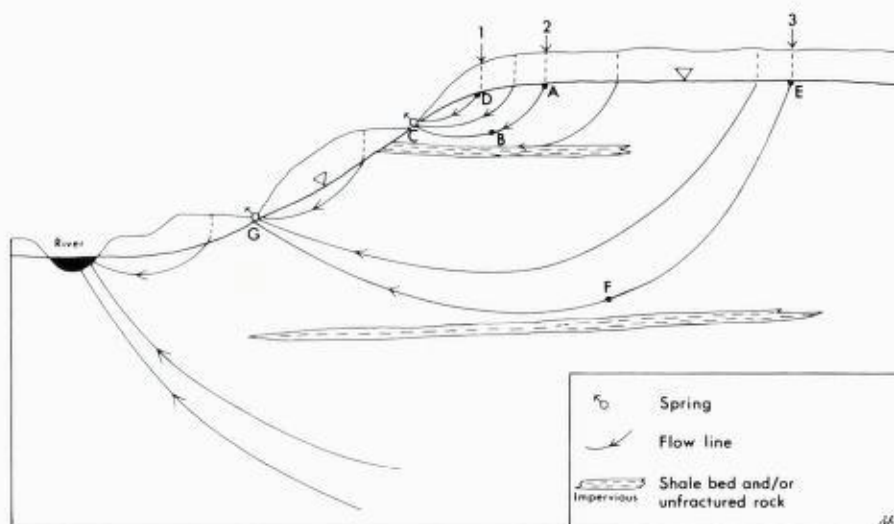
Fig. 5. Hypothetical flow lines in groundwater flow systems within fractured rocks. For further explanation, see text.

entrance (points A, D, E), average (points B, F) and final values (points C, G), are after Engelen (1981). From the present investigation the following statements can be made:

ÅSTADALEN

The flow through the aquifers is following shallow flow lines, mainly of the types 1 and 2 in Figs. 5–7. There are small chemical changes along the flow lines, from entrance values points A and D to the final or outlet values of the springs, point C. This is due to a rather short time of contact between water and rock, as well as to slow dissolution of the minerals.

During winter and dry seasons the flow to the springs is dominantly following flow lines of type 2, while heavy rain and snowmelt causes much flow along the very shallow flow line of type 1. Generally, the base flow of type 2 shows higher contents of geologically derived solids (e.g. Ca^{2+}) than the very shallow flowage along flow line 1.

LILLEHAMMER–BRØTTUM AREA

The groundwaters investigated appear to have followed long and deep flow lines, dominantly of type 3 in Figs. 5–7. At the considered depths (50–120 m below surface) the flow is slower than in Åstadalen (20–30 m below surface), resulting in higher ion concentrations in the groundwater than in Åstadalen (Table 1, Figs. 2 and 6).

STENSENGBEKKEN WATERSHED

Assuming the flow pattern to be dominantly of the types 2 and 3 in Figs. 5–7, Observed chemical changes then correspond to the changes from A to C or

from E to G; an increase in ion concentration within Quaternary deposits, as well as from Quaternary deposits to bedrock, and during flow within the bedrock aquifers (Table 1, Figs. 2 and 6).
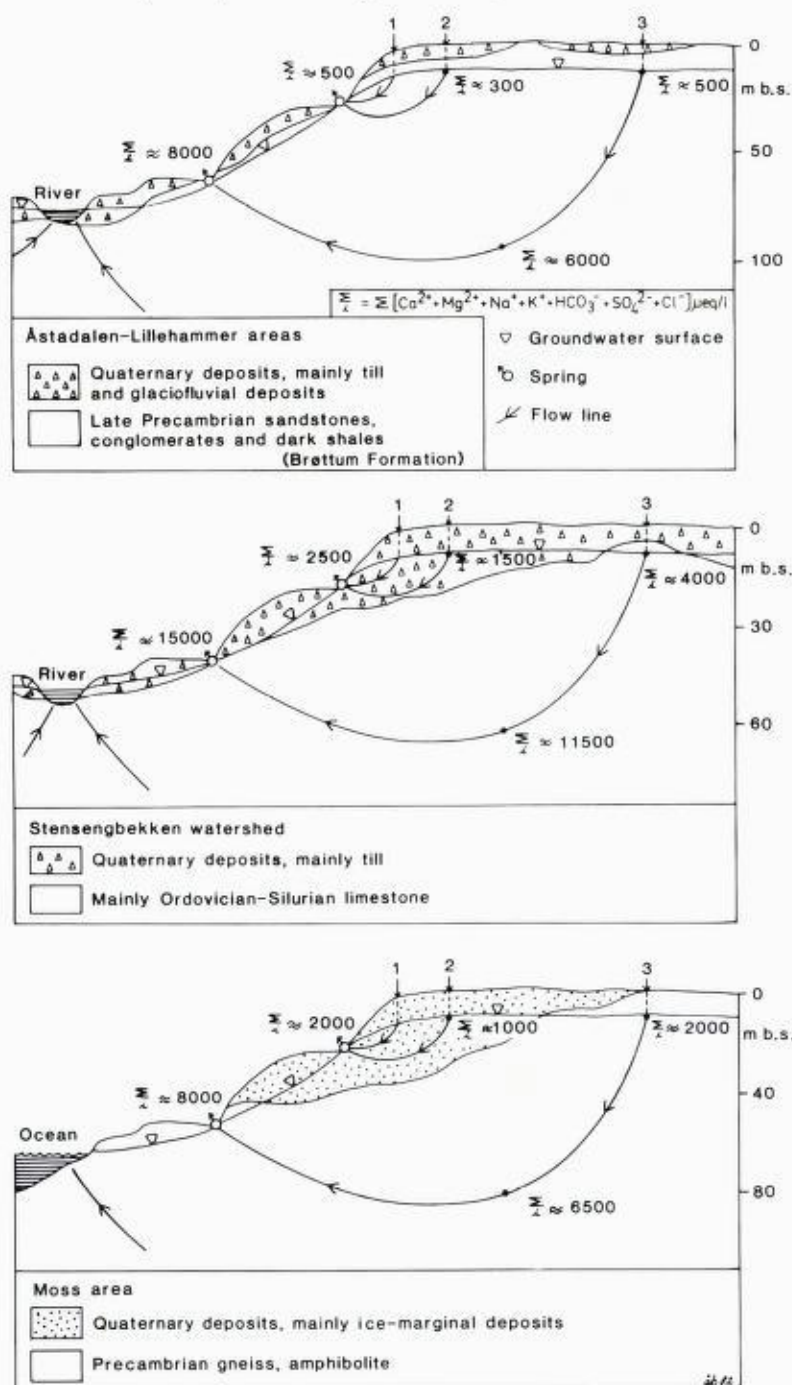

Fig. 6. Some generalized pictures of groundwater flow systems and the resulting changes in ion concentrations. Observation period 1975–1980.

ÅS – MOSS

Two main modes of flow are considered, following flow lines 2 and 3 in Figs. 5–7. Much of the water following flow line 3 has seeped through Quaternary deposits.

SUMMARY

Observed chemical differences are explained by two main modes of ground-water flow patterns: (a) flow through shallow aquifers with active flushing, and ending up in springs (Åstadalen, Stensengbekken watershed, Moss area); (b) long and deep flow from Quaternary deposits or exposed bedrock through deep circulating groundwaters in bedrock, and ending up in springs and rivers (Lillehammer–Brøttum area, Stensengbekken watershed, Ås–Moss areas. The highest concentration value along any one flow path is usually found in the spring waters.

The Acidity of Groundwater

The pH of investigated water types generally increases from about 4.40–4.45 in the precipitation to 5.5–6.5 near or just below, the groundwater surface. Deeper groundwater is usually buffered within the pH range of 7.0–8.5. The magnitude of these changes is dependent on (Fig. 7): (1) the flow pattern considered, and (2) the soil and rock types encountered along the flow path.

The decrease in H^+-concentration in percolating water and during ground-water flow is due to H^+ exchange with the cation exchange reservoir in the soil, and due to chemical weathering reactions with primary and secondary minerals. The extent of these reactions is highly dependent on soil and rock types.

Most investigated groundwaters have high buffer capacities against strong acids, as shown by the high concentrations of HCO_3^- (Table 1). Thus, acid precipitation seems not to have measurable effects on the acidity of the deep groundwaters investigated here; i.e. those deeper than 15–25 m below surface. The only effect observed which could be due to acid precipitation is in the springs of Åstadalen during the time of snow-melting; a decrease of pH from about 6.0 to 5.5 (Englund, unpublished).

Acid groundwaters are, however, known from Scandinavia. Groundwaters with pH<6.0, down to 4.0, have been reported in lime-poor sandy soils and in granites in southern Sweden, and have been interpreted as a result of acid precipitation (Eriksson 1981, Hultberg & Johansson 1981). Also in regions from southern Norway where lakes are acidified, shallow groundwater in superficial deposits appears to be acidified, but less so than in neighbouring lakes (Henriksen & Kirkhusmo 1982).
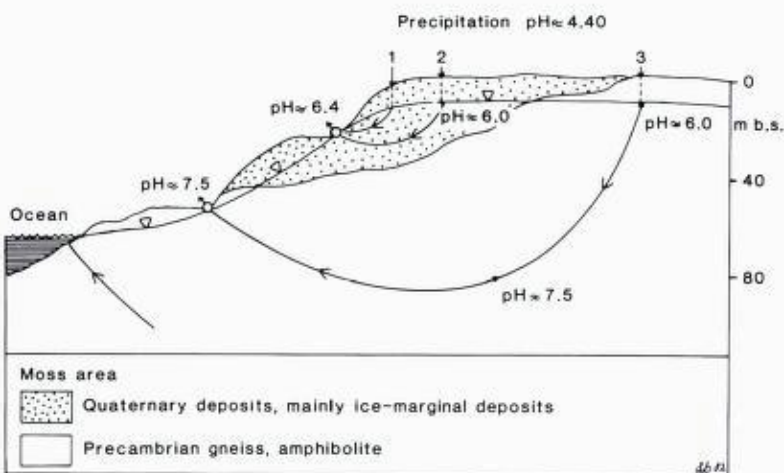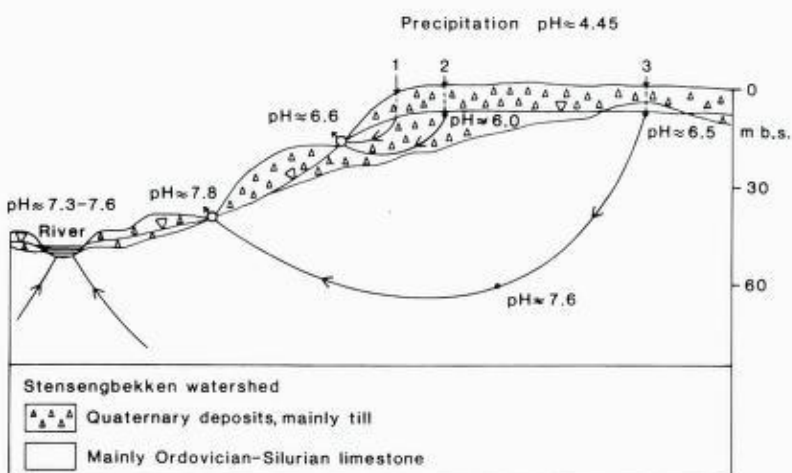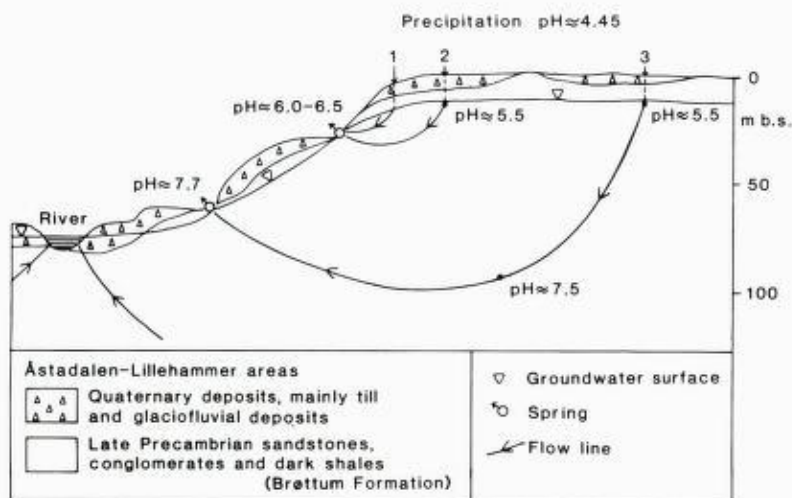
Fig. 7. Some generalized pictures of groundwater flow systems and the resulting changes in pH. Observation period 1975–1980.

Concluding remarks

1. Groundwaters in Quaternary deposits such as glaciofluvial, ice-marginal and till units, and in fractures in gneisses, amphibolites, volcanic rocks, sandstones, shales and limestones have been investigated during the years 1975–1981 from the following areas in southeastern Norway: Åstadalen, Lillehammer–Brøttum, Stensengbekken watershed, Ås, Moss and Jeløy.

2. Since seasonal variations are quite common in groundwater chemistry, especially in shallow aquifers, and since only large-scale chemical changes are discussed here, the data used are annual average results. 979 water samples from 133 wells and springs have been analysed, sampled during winter, spring, summer and autumn.

3. The chemical compositions down to 120 m below surface range from very dilute waters to brackish waters. Calcium and bicarbonate are generally the dominant ions. In areas below the Late Glacial sea-level (Ås, Moss and Jeløy), however, sodium and chloride ions are in places predominant.

4. The total content of dissolved solids (Ca^{2+} + Mg^{2+} + Na^+ + K^+ + HCO_3^- + SO_4^{2-} + Cl^-) are usually lower in recharge areas, than in deep circulating groundwaters and in springs. There is, simultanously, a change in the relative anion composition following three main trends: (a) an increase of SO_4^{2-} compared with HCO_3^- and Cl^- (in pyrite-bearing sandstones/shales); (b) an increase of HCO_3^- compared with SO_4^{2-} and Cl^- (in carbonate-bearing rocks); (c) an increase of Cl^- compared with HCO_3^- and SO_4^{2-} (mainly due to the supply of Late Glacial/Holocene sea-water and sea salts(?)). These different anion-evolution sequences are determined either by the sediment/rock types in which the groundwaters occur or by the supply of old sea-water/sea salts.

5. Observed chemical differences are explained by two main modes of groundwater flow patterns: (a) flow through shallow aquifers with active flushing, and ending up in springs (Åstadalen, Stensengbekken watershed, Moss area); (b) long and deep flow, from Quaternary deposits through deep circulating groundwaters in bedrock, and ending up in springs and rivers (Lillehammer–Brøttum area, Stensengbekken watershed, Ås–Moss areas). The highest concentration value along any one flow path is usually found in the spring waters.

6. Generally, the pH of water increases from about 4.40–4.45 in the precipitation to about 5.5–6.5 near, or just below, the groundwater surface. Deeper groundwater is usually buffered within the pH range of 7.0–8.5.

7. Acid precipitation does not seem to have measurable effects on the acidity of deep groundwaters; deeper than 15–25 m below surface. The only effect observed which could be due to acid precipitation is found in springs from shallow aquifers in Åstadalen. During melting of snow the pH in the spring waters is decreasing from about 6.0 to about 5.5.

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