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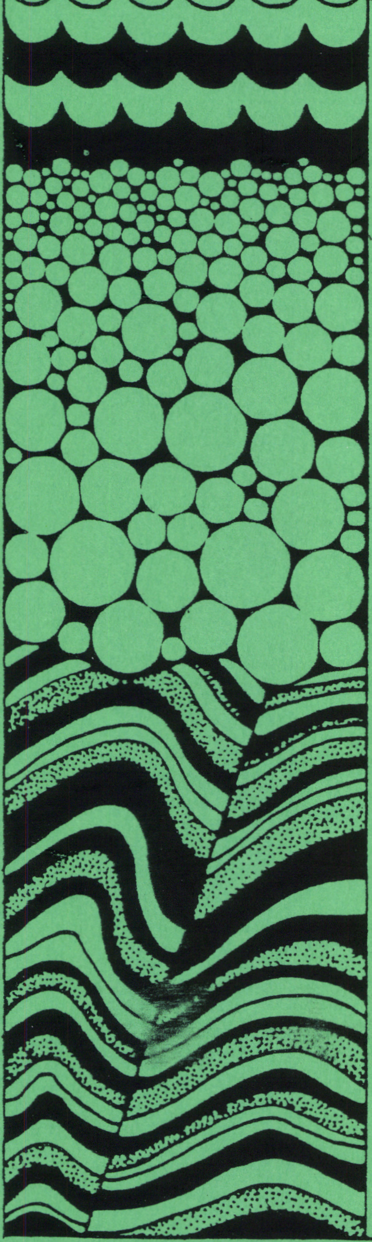

Rapport nr. 18
Ås 1983

Jens-Olaf Englund
and Sylvi Haldorsen

The Åstadalen catchment, southeastern Norway, geology and general hydrology

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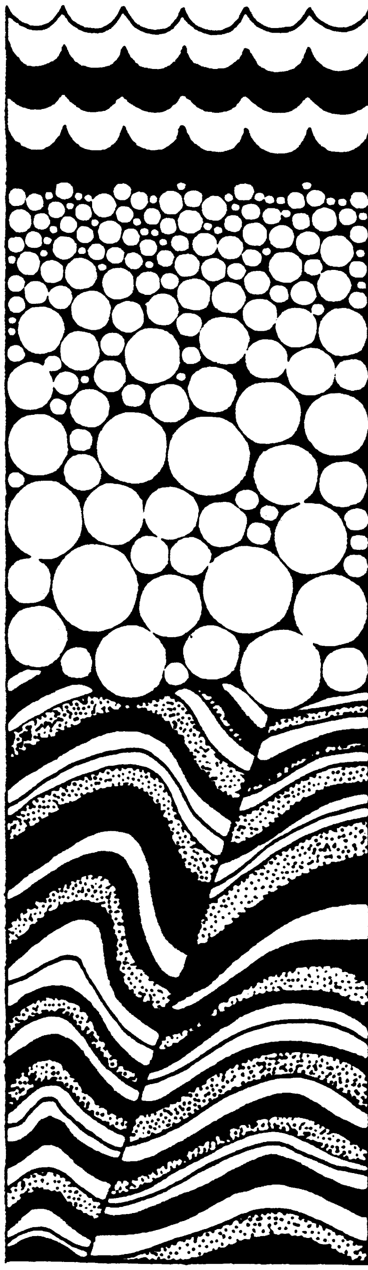

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Abstract

From a hydrological point of view the Åstadalen catchment in central southeastern Norway is typical for the higher central and southern parts of the Scandinavian Peninsula. It covers approximately 400 m^2, varies in altitude from 615 m to 1150 m and is underlain by fractured sedimentary rocks with a cover of unconsolidated Quaternary deposits. The climate is characterized by long cold winters and short cool summers, and mean annual precipitation 950-1000 mm.

This paper describes the general relationship between geology and hydrology, and forms the first part of a project aimed at developing a model of 1) the input-output flux of chemicals for the catchment and for parts of the catchment, 2) internal cycling of chemicals, 3) infiltration and percolation process of soil water, 4) hydrology of groundwater in some model areas.

The rocks in the area are themselves impermeable, but the presence of open fractures give them a significant porosity and permeability.

The surface drainage pattern is strongly influenced by the dominant fracture directions, NW-SE and NNE-SSW. Another drainage direction is E-W, parallel to the fold axes of the area.

Aquifers in Quaternary deposits are small compared to bedrock aquifers. A number of springs occur within the area and they are mainly fed from bedrock aquifers.

The main river of the catchment, river Åsta, shows sustained flow during long periods of drought, or when the precipitation is accumulated as snow. The catchment's high storage capacity is largely due to groundwater in bedrock aquifers.

CONTENTS

1. INTRODUCTION

The studied area, the Åstadalen catchment in central southeastern Norway (Fig.1), is about 400 m^2. It is underlain by fractured sedimentary rocks with a cover of unconsolidated Quaternary deposits. The mean annual precipitation is about 950-1000 mm.

The Åstadalen catchment has been chosen as a research area because the bedrock geology is rather uniform, and because the geology was well documented. The catchment represents largely a natural ecosystem, but parts of it have been manipulated by man.

The flux of both water and chemicals through the ecosystem is controlled by a great number of variables, including geological heterogenity, climate, biological structures and diversity, as well as anthropogenic pollution.

The importance of bedrock geology and its overburden for the quality of some freshwaters in Norway has been demonstrated by e.g. Strøm (1939) and Kjensmo (1966) for surface waters, and by Englund & Myhrstad (1980) for groundwater. Rosenqvist (1977) and Overrein et al. (1980) have shown that the effect of acid precipitation on the acidity of surface waters is highly dependent on geology.

This work forms an introductory part of a project, mainly supported by the Agricultural Research Council of Norway (NLVF) and the Norwegian Hydrological Committee (NHK). Co-operation with other institutions is of great importance. The aim of the project is to develop a model of the input-output flux of chemicals for the catchment and for parts of the catchment, to study internal cycling of chemicals, to describe in detail the infiltration and percolation process of soil water and the hydrology of groundwater in some model areas. This paper describes the general relationships between geology and hydrology.

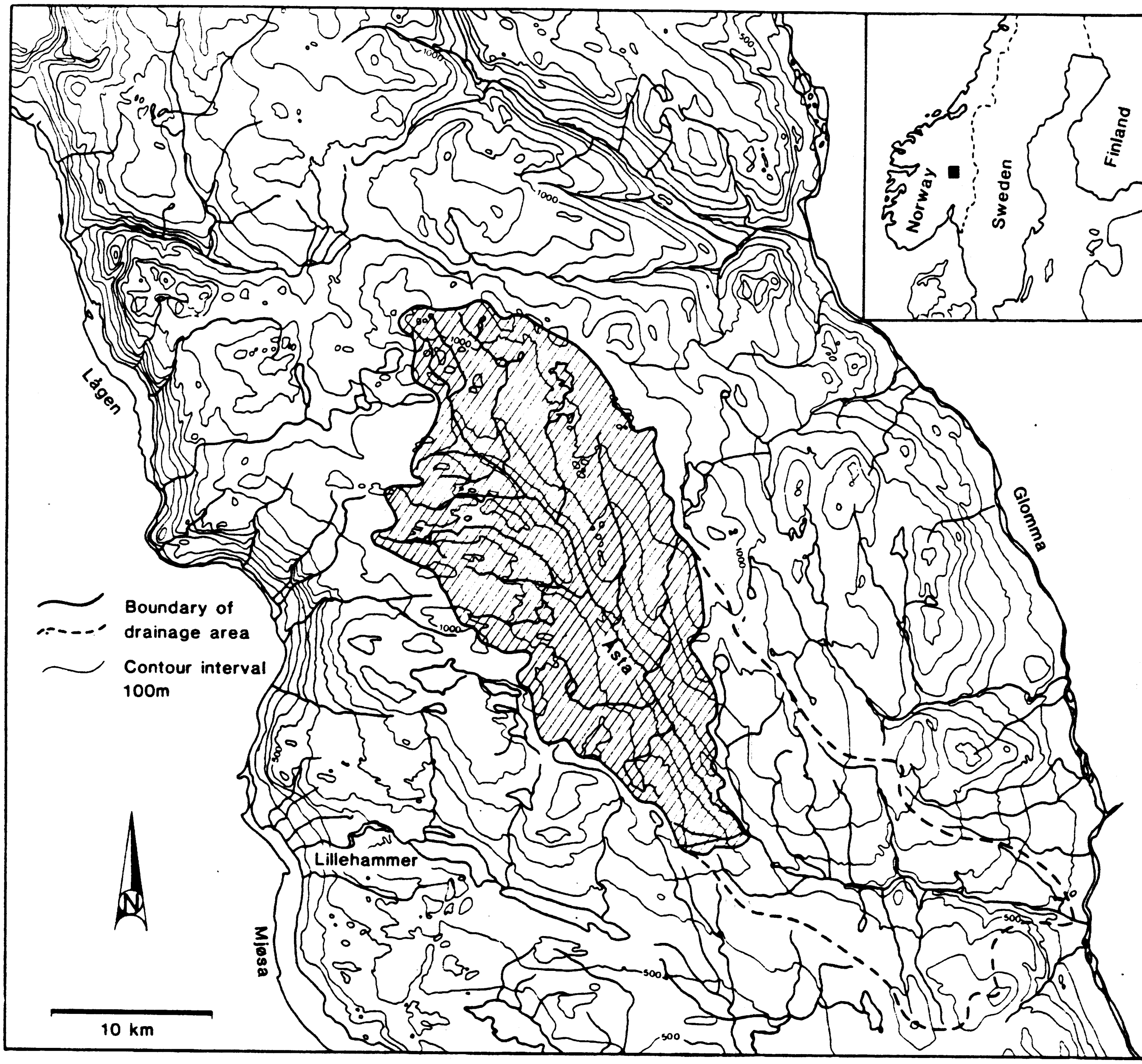


Fig. 1 Location of the Åstadalen valley. Shaded; the studied part of the Åstadalen catchment.

Fig.2 A. Åstadalen valley near Kvarstadsætra seen towards the east. B. Mountain areas at Skollfjellet, in the northeastern part of the catchment, showing the transition from exposed, fractured bedrock (boulder field) to a thin bouldery till. Locations: See Fig.6. The boulder fields form important shallow groundwater aquifers.

2. LOCATION AND TOPOGRAPHY

Åstadalen is a rather wide valley (Fig.2A) situated between Gudbrandsdalen and Østerdalen. The river Åsta joins the river Glomma near Rena (Fig.1). The studied area represents the Åsta's drainage area north of Bjørnåsbrua. Further in the text this is referred to as 'the Åstadalen catchment' or 'the catchment'.
The project area consists of mountains (Fig.2B) forests, peatlands, lakes, lakelets and rivers (Table 1). Some gravel roads are present as well as number of hill farms and cottages.

Within the project area the river Åsta varies in altitude from 615 m at the outlet (Bjørnåsbrua) to around 700 m in the central parts, rising to 900-1000 m in the north. The catchment has relatively distinct topographical divides. The heights of the bordering mountains are 1050-1100 m to the east, around 1150 m to the north and 930-1050 m to the west (Fig.1).

Table 1. Areal distribution of landscape types within the Åstadalen catchment.

	Åstadalen catchment	
	Area km^2	Area per cent
Mountain areas	80	20,3
Forest cover	128	32,4
Peatland	170	43,0
Lakes, lakelets, rivers	11,5	2,9
Hill farms, gravel roads	5,5	1,4
	395	100

3. BEDROCK GEOLOGY

The Åstadalen catchment is situated in the central part of the Sparagmite Region of south Norway. All the rocks belong to the

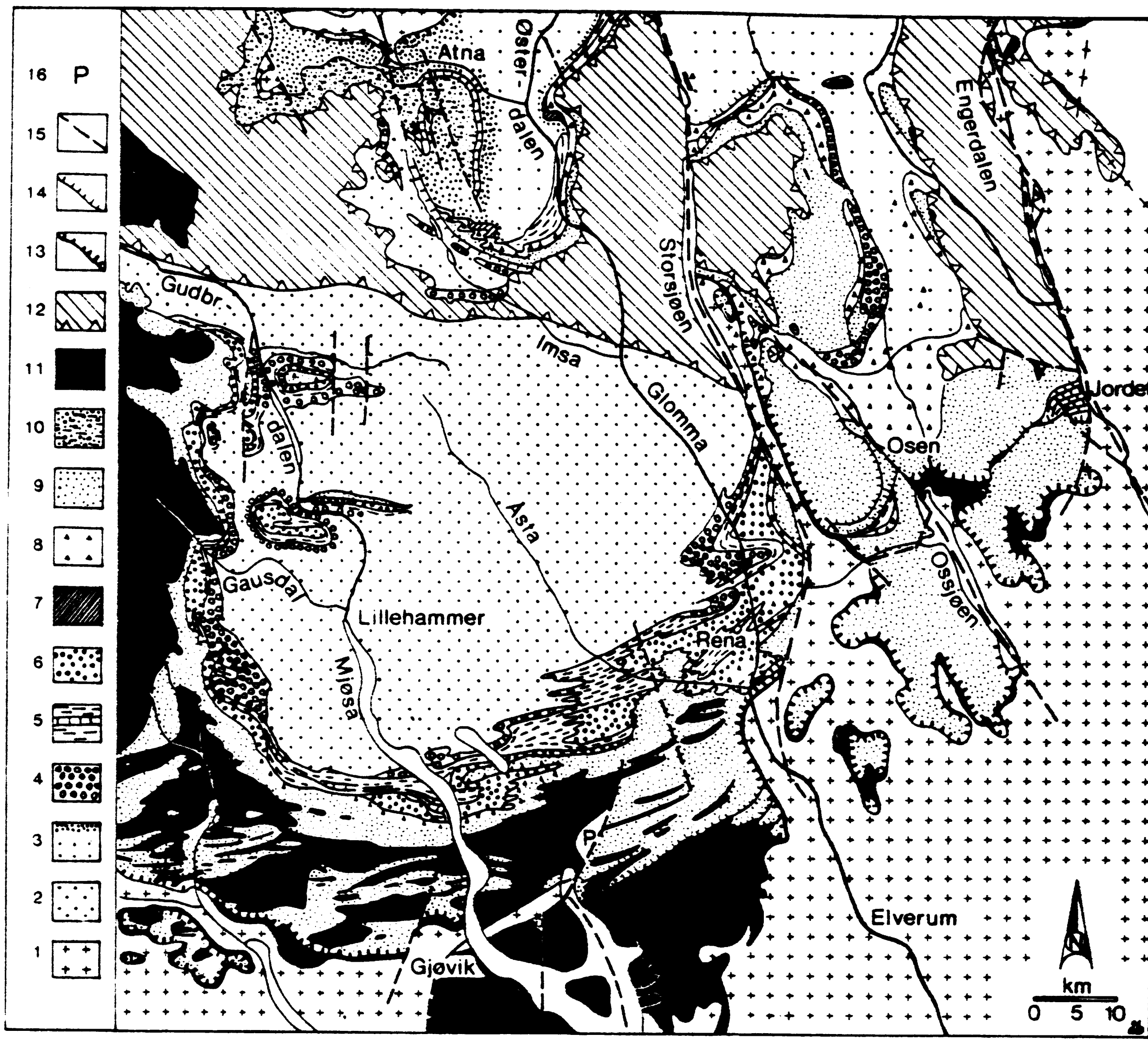


Fig. 3 Simplified geological map of a part of the Sparagmite Region, south Norway (Sæther & Nystuen 1981).
1) Precambrian crystalline basement, 2) Brøttum Formation,
3) Rendalen Formation with overlying Atna Quartzite (tight dots),
4) Biskopås, Osdalen & Imsdalen Conglomerate, 5) Biri Formation,
6) Ring Formation, 7) Svarttjørnkampen Basalt, 8) Moelv Tillite,
9) Vangsås Formation, 10) Sollia Formation, 11) Cambro-Silurian,
12) Kvitvola Nappe, 13) Thrust plane beneath the Osen-Røa Nappe complex, 14) Thrust plane in general, 15) Normal fault,
16) P=Permian.

Late Precambrian Brøttum Formation (700 million years old); feldspathic sandstones, conglomerates and silty shales (Figs.3 & 4). This lowermost unit of the Hedmark Group (Bjørlykke et al. 1967), about 2000-3000 m thick, covers large areas in southeast Norway (Fig.3, and e.g. Bjørlykke 1966, 1976; Englund 1966 a, 1972, 1973; Kirkhusmo 1968; Nystuen 1981; Skjeseth 1963).

The catchment lies within the Caledonian mountain chain, and the rocks were thrust and folded during the Caledonian orogeny in Silurian - Devonian time (about 400 million years ago). The area was also affected by post-Caledonian fracturing mainly during the Permian crustal rifting which gave rise to several major faults in the Sparagmite Region and the Oslo Rift farther south (around 225 million years ago).

The general topography of the area is determined by bedrock types and structural elements within the bedrock such as syn- and anticlines and fractures (Figs.4 & 5).

3.1 Rock types

The Brøttum Formation within the Åstadalen catchment can be divided into two associations of lithotypes, in accordance with the division made for areas further to the southwest (Englund 1972, 1978).

The lower lithotype occurs in the northern part, and is found in places to the west (Fig.4). It consists of an alternation of grey sandstone beds, up to 5-10 m thick, and dark grey to black silty shales usually thinner than 0.3 m. The sandstone beds constitute more than 90 % of this lithotype.

The upper lithotype occurs in the south and usually lacks shaly beds, it is a massive coarse-grained sandstone, often fine-conglomeratic.

A common feature for all the lithologies in the catchment is that they are practically impermeable. The porosity and permeability is governed by the presence of open fractures.

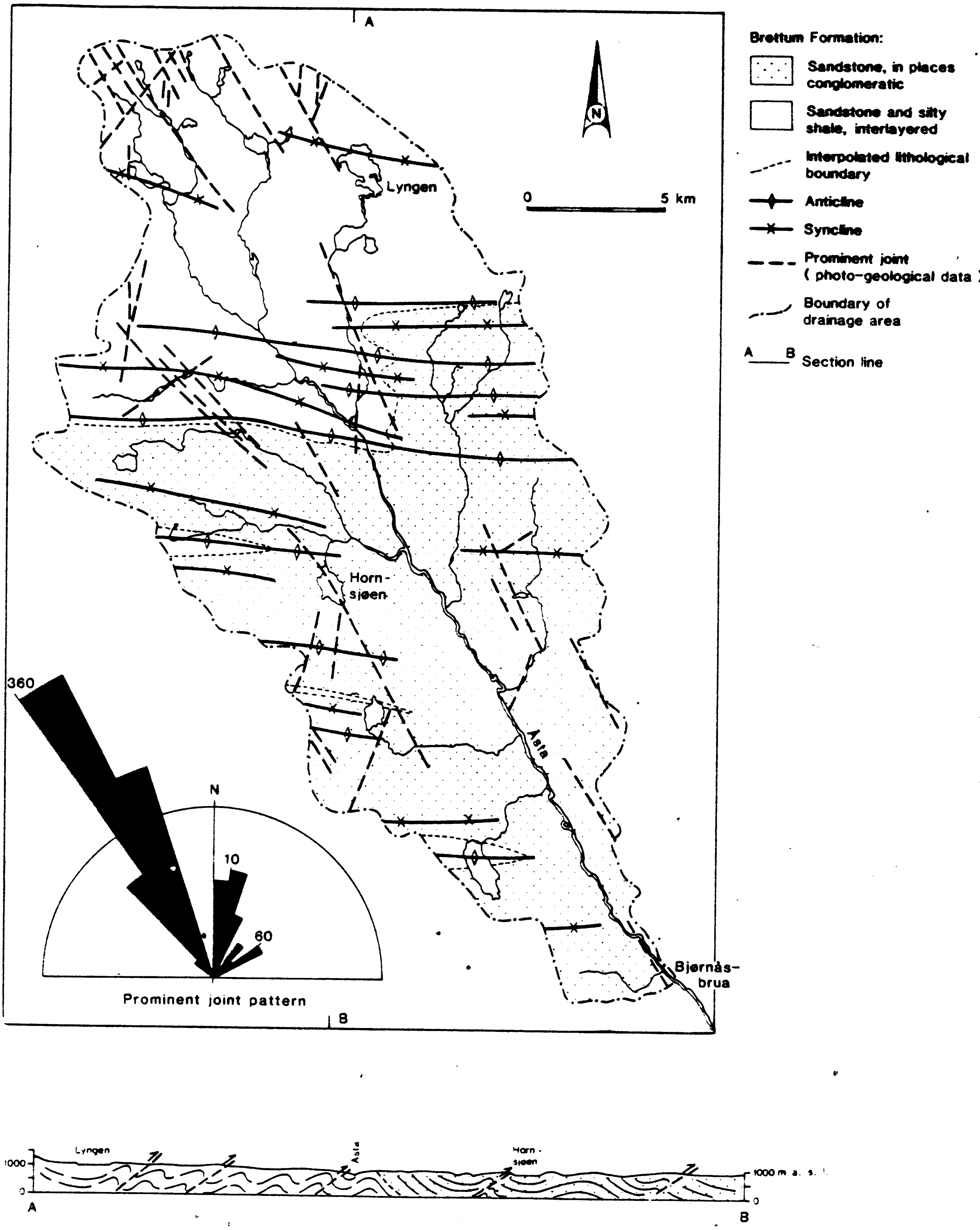


Fig.4 Map and north-south profile showing the bedrock geology of the Åstadalen catchment. In the joint pattern diagram the number of vector units of the length of prominent joints are plotted. Radius of sector= 20 units, each of length 1 km.

3.2 Fold structures

The Caledonian folds within the catchment have axes mainly aligned around E-W (Fig.4), and are up to 2-2,5 km broad. The fold axes are approximately horizontal or with plunges around 5^g - 10^g towards W. The folds can be followed up to 5-10 km.

The tectonic style is largely determined by the thick and competent rock units. The upper conglomeratic sandstone in particular has formed broad synclines and anticlines of a concentric type. Some folds are partly overturned towards the south, and in some cases broken up by thrust-faults. Generally however, the beds dip around $10\text{-}30^g$ either towards the N or S.

A secondary cleavage occurs in the shale beds, and in places also in the sandstones. Generally, they strike approximately E-W and dip N around $40\text{-}70^g$.

Sets of steeply dipping diagonal joints with trends around NW-SE and NE-SW are found in a number of places. Some of them seem to be genetically related to the folding. Both the secondary cleavage and these joints are closed and therefore subordinate as conduits for water.

Open fractures related to the folding strike about E-W, approximately parallel to the axial planes of the folds. They were probably produced by tension and act as good conduits for water (Fig.5). Sub-horizontal jointing, generally following the bedding, is probably also genetically related to the folding. This type of fracturing is very important for the water-bearing ability of the rocks (Fig.5).

3.3 Post-Caledonian fractures

The steeply dipping $70\text{-}100^g$ fracturing in the Åstadalen catchment is mainly post-Caledonian. Prominent joints are defined as longer than about 300 m, and were mapped from air--photos (Fig.4), while the word joint is here reserved for joints which have been observed in outcrops.

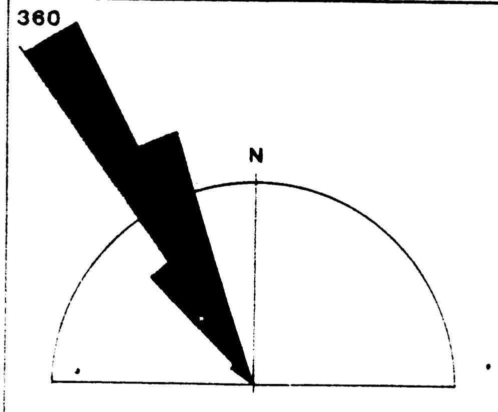
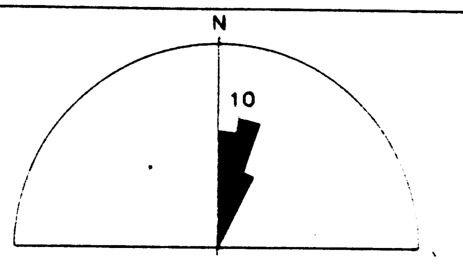
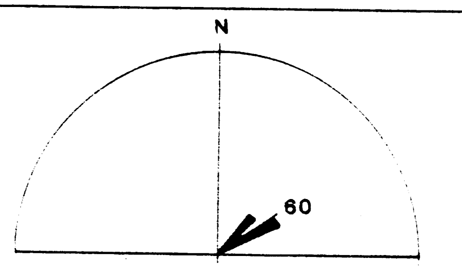
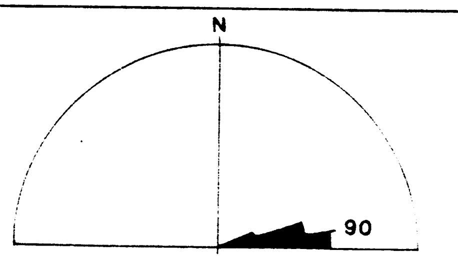
DEPTH	FRACTURE DIRECTIONS AND FREQUENCIES	SURFACE TOPOGRAPHY	HYDROGEOLOGICAL CHARACTERISTICS
Deep		Trend of main valley and stretches of tributary valleys	Important for groundwater transport Shallow and deep aquifers Interrelationship between these fractures determines the bedrock porosity and hydraulic conductivity
		Stretches of many tributary valleys	
			
		Trend of small scale topography, e.g. benches, ridges, depressions	
?	HORIZONTAL		
Shallow, 20-30m	BOULDER FIELDS	No preferred topographic directions Plateaus and knolls	Shallow aquifers High porosity and hydraulic conductivity

Fig.5 Relation between bedrock structures, surface topography and hydrogeological characteristics. Fracture frequency: see Fig.4.

3.3.1 Prominent joints. The Åstadalen valley follows the predominant direction, NW-SE, or around N 360^g E (Figs.4 & 5). No displacement have been observed. Other alignments are approximately NNE-SSW, or around N 10^g E, and roughly NE-SW, or between N 40 ^{g}E and N 70 ^{g}E (Figs.4 & 5). These directions are the same as those dominating within the Permian, lower Triassic Brumunddal Sandstone with underlying rhomb porphyry lavas at Mjøsa (Englund & Jørgensen 1975). The fracturing of the Mjøsa district continues into the southern part of the Sparagmite Region. The fracturing of the Åstadalen catchment is therefore probably largely of late Permian or early Triassic age, associated with the development of the Oslo Graben further to the south, studied by e.g. Skjeseth (1963), Ramberg et al. (1977) and Gabrielsen & Ramberg (1979).

3.3.2 Joints. In most outcrops sets of parallel or nearly parallel joints occur (Fig.21). The joint surfaces are plane and cut through irregularities within the strata. The most predominant directions are the same as those found for the prominent joints, but the pronounced E-W trending jointing of the catchment could partly be post-Caledonian.

The joint frequency varies, but is always very high in the neighbourhood of known prominent joints. The joint sets are either parallel, or approximately perpendicular to the prominent joints, or form a smaller angle. They all seem to be genetically related to the prominent joints.

3.3.3 Some conclusions. The post-Caledonian fractures have turned out to be very important for the water-bearing ability of the bedrock (Fig.5). Combined with water transport along the sub-horizontal joints they support a number of springs, as well as supplying a few wells with water. It seems that most of the post--Caledonian fractures remain open within the rock masses, at least to depths of 50-150 m. They are probably mainly formed in response to tension.

3.3.4 Joints connected with boulder fields occur at altitudes above 1000 m a.s.l (Fig.2B). In Scandinavia boulder fields are frequently found at such elevations (e.g. Holmsen 1960, Lundqvist 1969). Frost activity, which probably has taken place partly

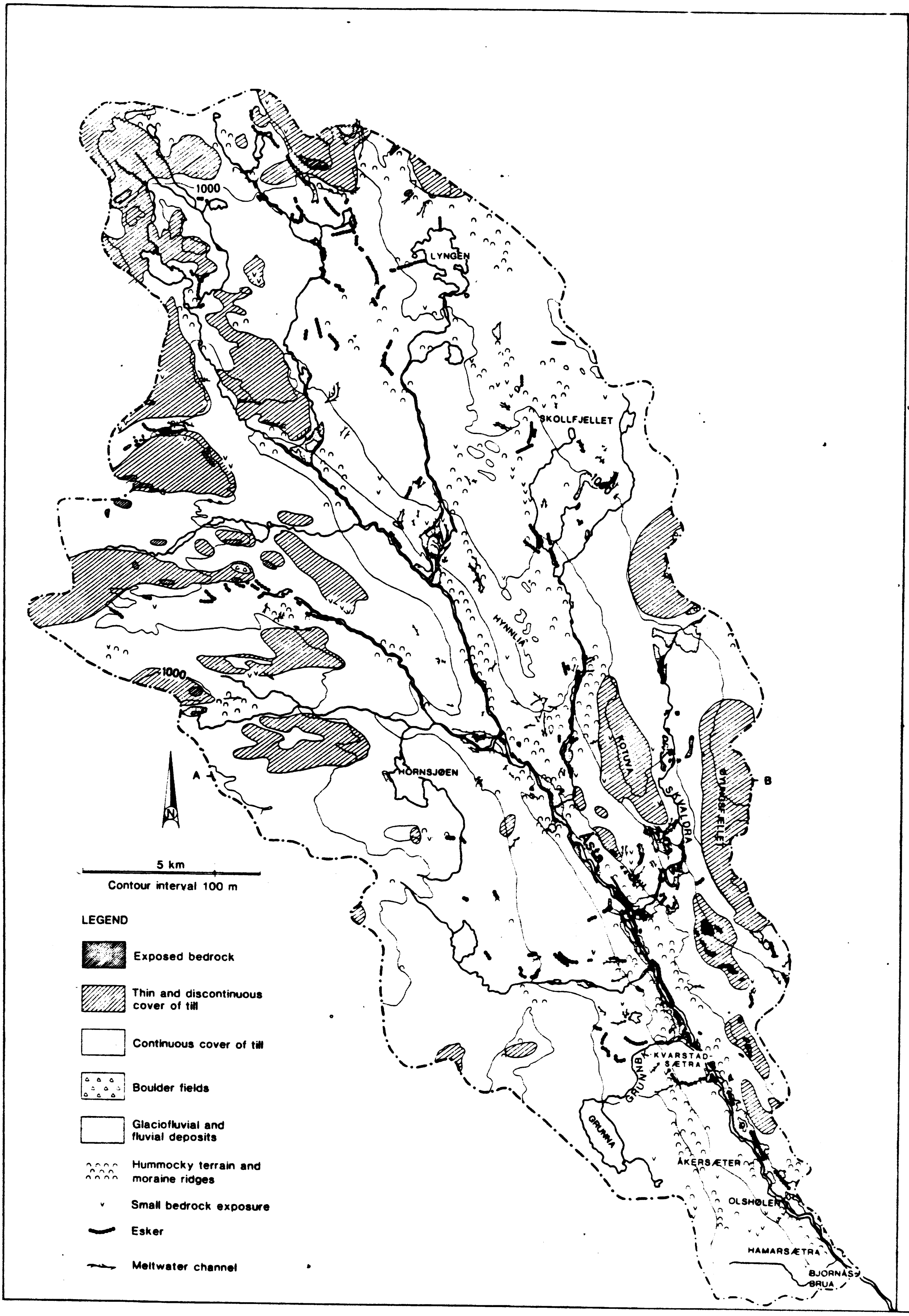


Fig.6 Map showing the Quaternary geology of the Åstadalen catchment, partly based on Østeraas 1978, 1982.

after the last glaciation, has enlarged pre-existing joints above 1000 m a.s.l and developed large boulder fields. The dominant fracture directions are therefore the same as those mentioned for tectonic fractures.

This type of fracturing, which reaches perhaps 15-20 m below the surface, provides very good conduits for water and supports a number of springs (Figs.5 & 19).

4. QUATERNARY GEOLOGY

Åstadalen was situated beneath the central part of the Scandinavian ice sheet during the maximum of the last glaciation, the Late Weichselian. The area was covered by ice until the end of the glaciation, and belonged to the central Scandinavian region of stagnation and decaying ice remnants during the deglaciation phase (Holmsen 1963). Such areas are characterized by rather continuous covers of glacigenic deposits (Holmsen 1971).

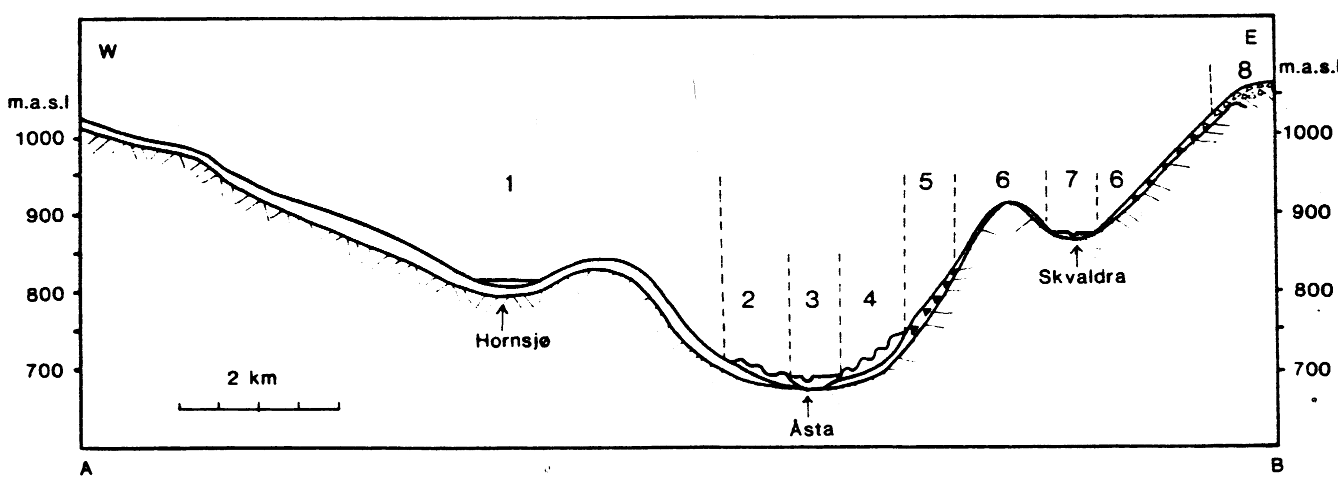


Fig.7 East-west vertical section A-B (Fig.6) showing the general distribution of Quaternary deposits in Åstadalen. Their thickness is somewhat exaggerated (see text for more representative values). Regional sediment zones:

1. *Continuous cover, (lodgement till and melt-out till)*
2. *Transverse moraine ridges (melt-out till);*
3. *Low fluvial and glaciofluvial terraces and eskers;*
4. *Hummocks of supraglacial sediments;*
5. *Bouldery melt-out till;*
6. *Thin and discontinuous cover of mainly melt-out till, locally with high frequency of boulders;*
7. *Glaciofluvial sediments along tributary rivers;*
8. *Exposed, fractured bedrock and boulder fields.*

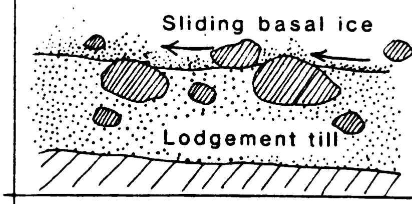
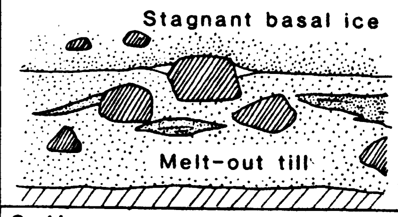
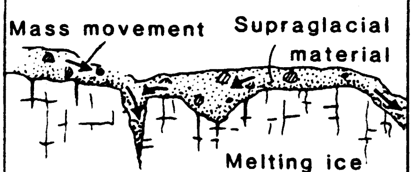
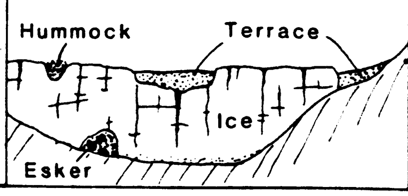
Sediment	Process of formation	Sediment characteristics	Hydrogeological characteristics
Subglacial till	A. Lodgement 	Uniform sheet High content of fines High compactness	Hydraulic conductivity moderate in upper 1m, low deeper down Shallow aquifers, partly perched Secondary and primary fissility important for water transport
	B. Melt-out 	Uniform sheet and moraine ridges Lower content of fines Lenses/bands of sorted sediments	Higher hydraulic conductivity Ridges situated above the groundwater level Sorted lenses and bands important for water transport
Supraglacial till	C. Mass movement of supraglacial material 	Hummocks Low content of fines Lenses/bands of coarse, sorted material	Usually high hydraulic conductivity Usually situated above the groundwater level Sorted lenses and bands important for water transport
Glaciofluvial sediments	D. Sedimentation in meltwater channels 	Hummocks, eskers and terraces Sand, gravel and cobbles Sorted	High hydraulic conductivity Productive aquifers, mainly along valley bottom

Fig.8 Probable formation of different glacigenic sediments in Åstadalen and their general hydrogeological characteristics.

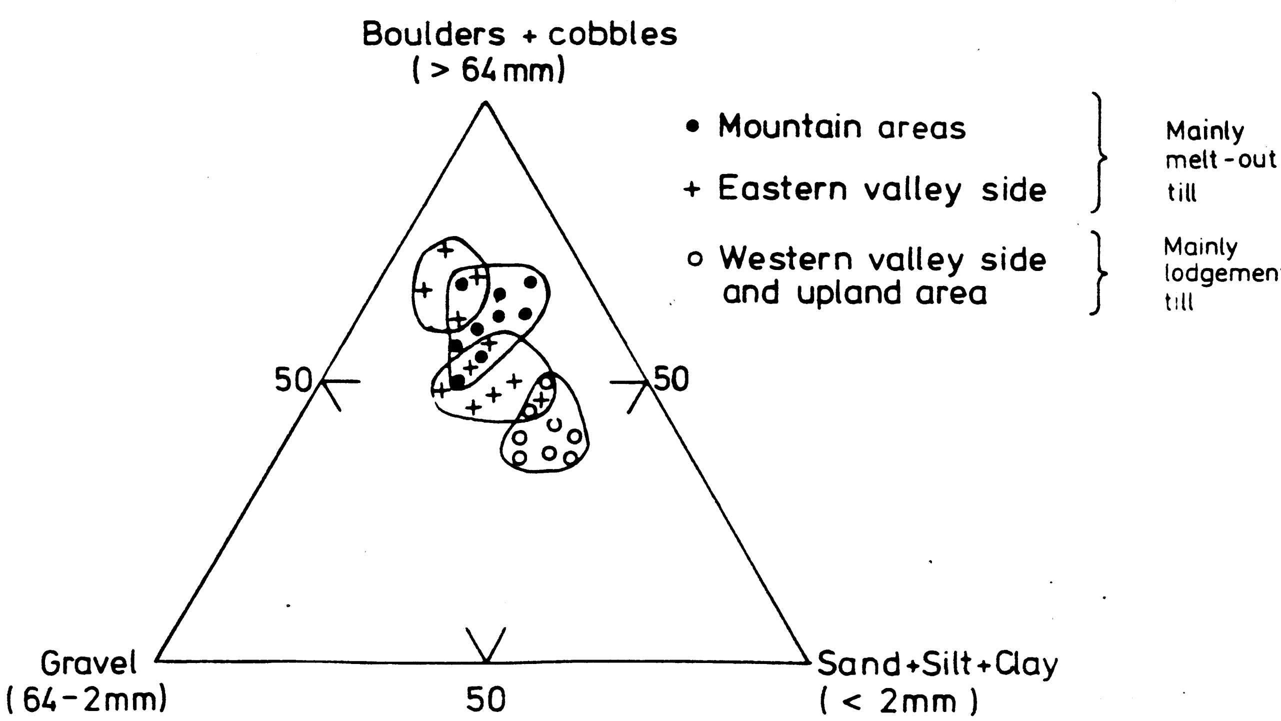
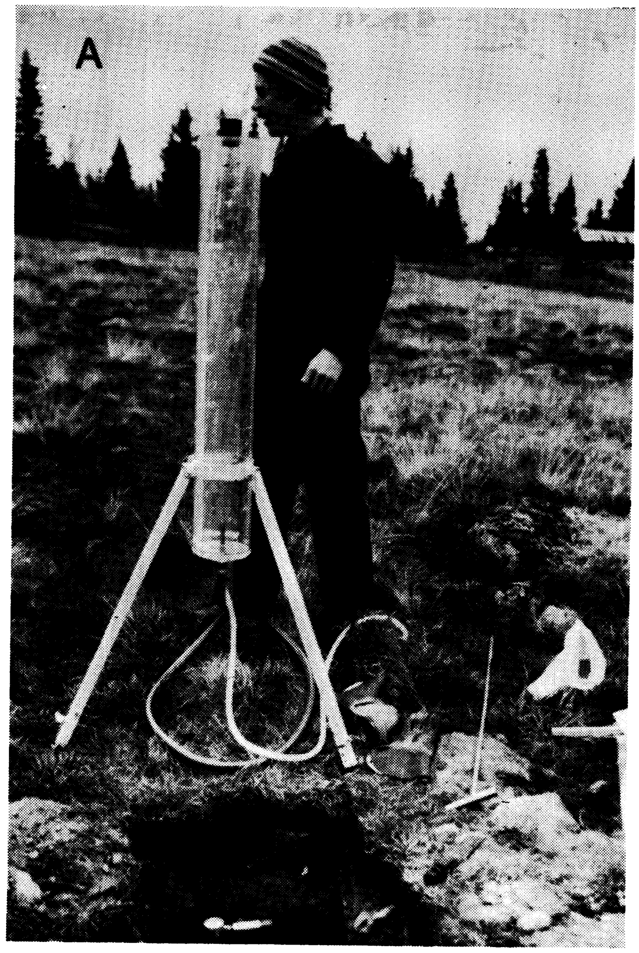


Fig.9 Total grain-size distribution of basal till types forming the regular till sheet in Åstadalen.



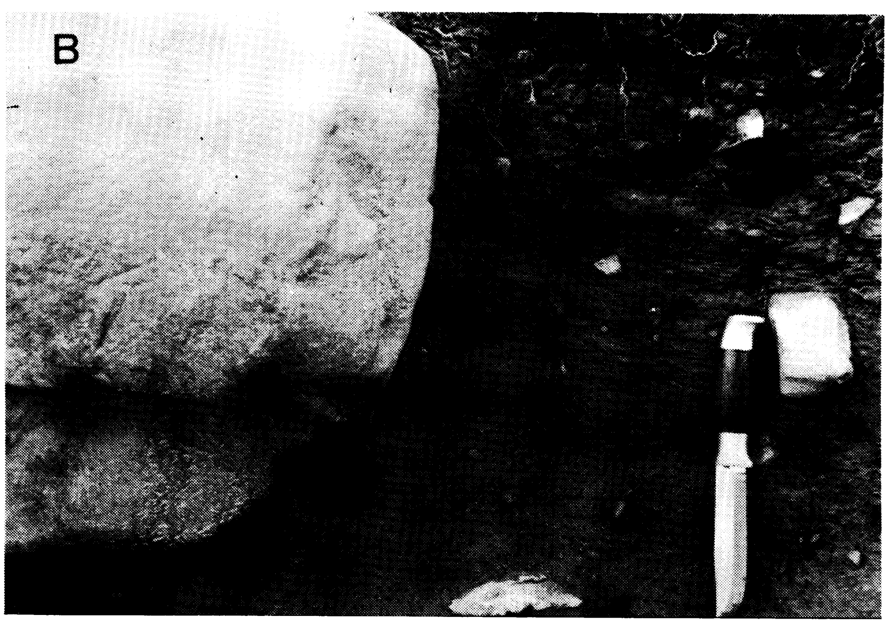


Fig.10 Lodgement till at Hammarsætra. A. Infiltration test.
B. Section in the fissile till with an abraded boulder.
The fissility is increased by weathering processes, and provides conduits for much of the percolating water.

A

B

Fig.11 Coarse, bouldery melt-out till southeast of Øyungsfjellet.
A. Till surface, B. Section in the till.

The Quaternary deposits of the area have been mapped by Østeraas (1978, 1982) and detailed descriptions of the sediments are given by Haldorsen (1981a, 1981b, 1982a, 1982b) and Haldorsen & Shaw (1982).

4.1 Tills

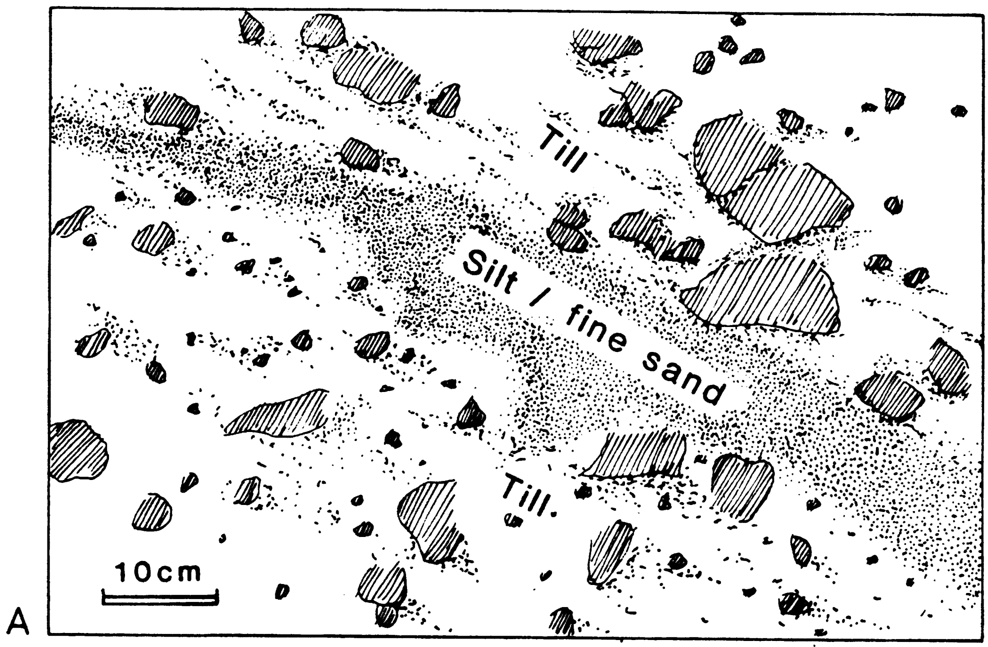
Tills are by far the most common Quaternary sediments in Åstadalen (Figs. 6 & 7, and Table 2), Three types of tills or till-like sediments have been recognized (Figs.7 & 8) (Haldorsen 1981a, 1982a, Haldorsen & Shaw 1982).

4.1.1 Lodgement till:Deposited from the sliding base of a dynamically active glacier. Such till is characterized by an overall dominance of abraded clasts, a relatively high content of fine-grained material (Fig.9) and by high degree of compactness. It is usually homogeneous except for a subhorizontal fissility (Fig.10).

4.1.2 Basal melt-out till: Deposited by a slow melting out of glacial debris from basal stagnant ice. The clast roundness may be variable from angular (Fig.11) to more abraded (Fig.12). The content of boulders, cobbles and gravel is commonly high (Fig.9) and the content of silt is low. Lenses and bands of sorted sand and silt are common (Fig.12). The degree of compaction is low.

4.1.3 Supraglacial till and till-like sediments: Deposited from material at the ice surface by mass movement and melting of underlying ice. Such sediments may have the same characteristics as basal melt-out till, but usually they are coarser (Fig.9) and have a higher concentration of coarse, sorted sediment zones (Fig.13).

Lodgement till dominates in some areas with continuous till west of Åsta (Figs. 6, 7 zone 1 & Fig.10). The thickness may



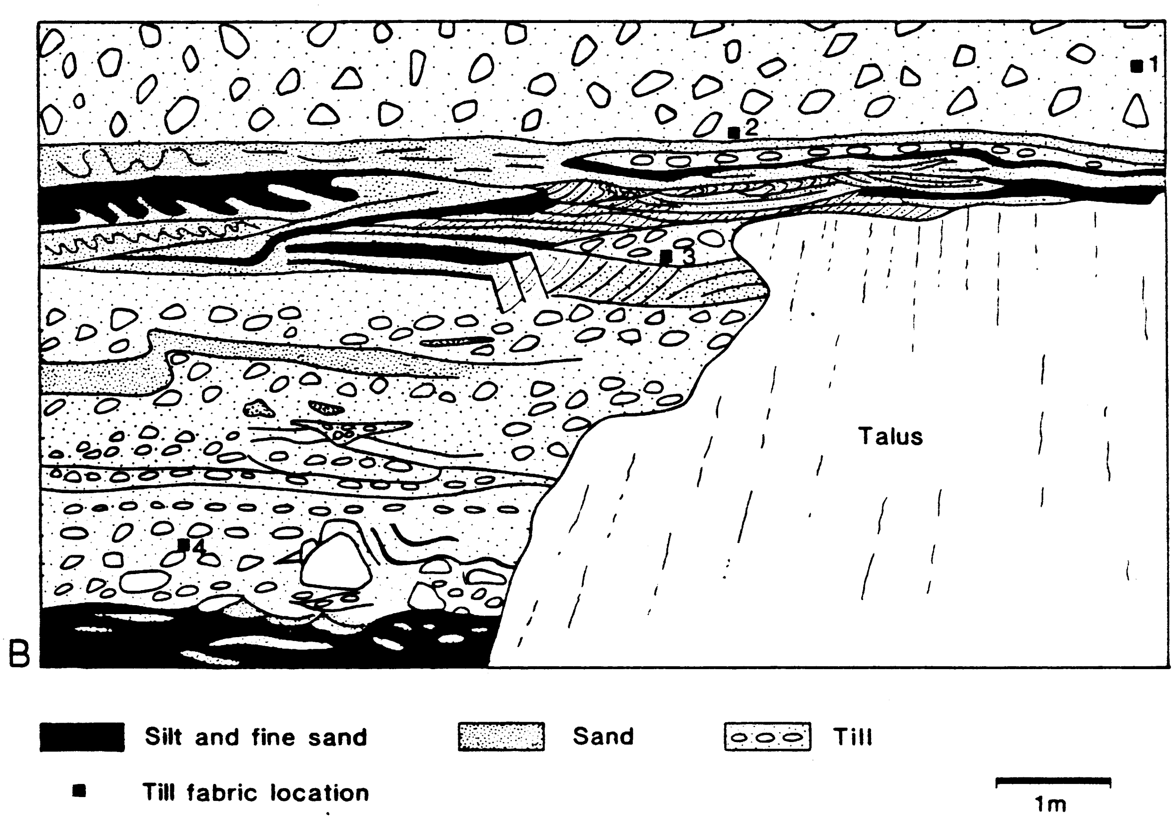


Fig.12 A. Internal part of a moraine ridge at Akersæter showing melt-out till with an extensive layer of silt and fine sand of low permeability.

B. Internal part of a moraine ridge at Kvarstadsætra showing melt-out till overlying permeable sand. Deeper down, zones of till-like sediments alternate with zones of sand and silt.

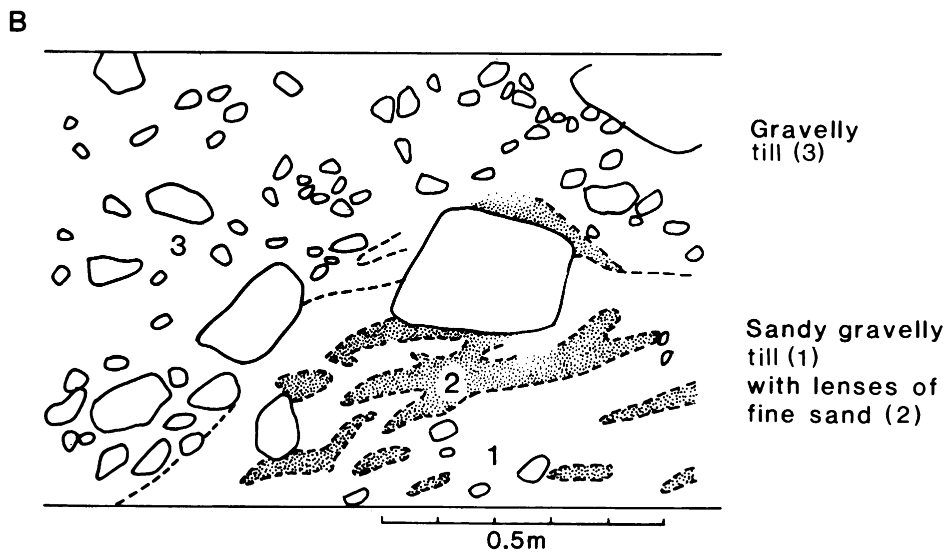


Fig. 13 A. Hummocky moraine near Skvaldra, consisting of coarse, permeable material.
B. Internal part of a hummock south of Skvaldra, 1 m below surface, central part. Numbers 1-3 indicate three different sediments with increasing permeability.

exceed 5 m in depressions, but on average it is usually not more then 3 m. In the highest areas the thickness is on average 1-2 m.

Basal melt-out tills form discontinuous sheets in the north and the east (Figs.2B, 6, 7 zones 5-6 & Fig.11). In the mountainous areas there is a gradual transition from this till cover (Fig.7, zone 6) to exposed fractured bedrock and boulder fields (Fig.7, zone 8). The melt-out till is characterized by a high content of coarse, angular material (Fig.9).

Basal melt-out till also forms moraine ridges along Åsta (Figs.6 & 7, zone 2) (Haldorsen & Shaw 1982). In such ridges, zones of sorted sediments are common (Fig.12).

Supraglacial tills and till-like sediments have accumulated in hummocks along the valley bottom (Figs.6, 7, zone 4 & Fig.13A). Their internal structures are variable (Fig.13B) and the sediments are usually coarse.

Biological activity, weathering and frost activity have affected the uppermost metre of the till and developed fractures and root channels.

4.2 Glaciofluvial sediments

The main part of the glaciofluvial sediments in Åstadalen are found along the bottom of the main valley and its tributaries (Figs. 6 & 7 zones 3 & 7). In addition, some glaciofluvial sediments are found along the valley sides where they were formed in connection with lateral meltwater drainage during the deglaciation phase. Glaciofluvial material also forms eskers down the valley sides and in the mountain areas.

Based on surface morphology and regional position the glaciofluvial sediments can be divided in four groups.

4.2.1 Hummocks of glaciofluvial origin are found along the valley bottom in the same areas where there are hummocks of till, and they form part of the supraglacial dead-ice sediment complexes. They are mainly deposited on top of the basal till sheet. The material is usually very coarse grained, indicating thorough removal of fines by meltwater during the deglaciation phase.

4.2.2 Local eskers extend from the valley sides towards the centre of the main valley and along the tributary rivers. The material is generally more sorted and finer grained than that comprising the kames. A section in a local esker along Grunnbekken (Fig.14) showed a marked bedding conformable with the surface. Like many other local eskers, this one is capped by till and starts up on the valley side immediately below a meltwater channel eroded in basal till.

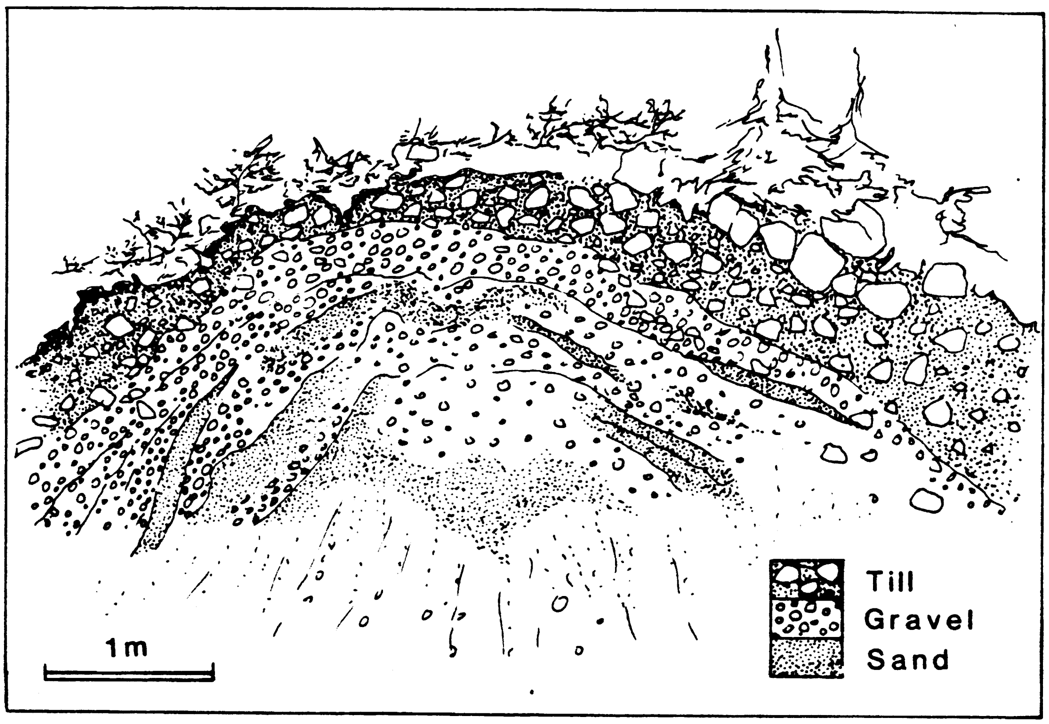


Fig.14 Internal part (cross section) of a local esker along Grunnbekken (see Fig.6); partly capped by compact till. Further up along the valley side the esker functions as a channel for groundwater.

4.2.3 The main esker is located along the centre of Åstadalen, partly situated in the middle of the present river (Fig.6). In other places it forms the eastern river bank of the Åsta (Fig. 15A). It can be followed continuously for many kilometres. It is composed of sand and well rounded gravel, and cobbly beds occur. The esker was formed in the main drainage tunnel along Åstadalen during the deglaciation phase when the valley was still filled with ice.

Fig.15 The main esker along Åsta, east of Olshølen, consisting of coarse, permeable material. At this site the esker forms a recharge zone. Low glaciofluvial terrace seen to the right.

Fig.16. Meltwater channel near Øyungen, shown by high concentration of coarse material. It acts as groundwater channels along the valley side.

4.2.4 Low glaciofluvial terraces composed mainly of gravel and sand, with cobbly top beds, are found along Åsta. These sediments were probably deposited in a subaerial ice-walled drainage channel during the last part of the deglaciation phase.

4.3 Meltwater channels

Erosion by meltwater has modified the basal till surface several places within the catchment. Continuous meltwater channels can be followed along the tributary valleys from the mountain area down to the bottom of the valley. Shorter channels in places penetrate the upper part of the till sheet. In such channels the fine-grained material was removed and the surface deposits consist of coarse cobble and boulder lags (Fig.16).

4.4 Fluvial sediments

After the complete deglaciation the river Åsta and its tributaries eroded into glaciofluvial deposits. The material was retransported and partly redeposited as fluvial sediments. The fluvial sediments are similar to the material in the low glaciofluvial terraces and the main esker.

4.5 Hydrogeological characteristics of the Quaternary deposits

The infiltration capacity and hydraulic conductivity depend on the content of soil water. In this paper only situations above field capacity are discussed.

Hydraulic conductivity has been calculated in the laboratory and in the field. In the laboratory, disturbed soil samples were packed by hand in permeameters. In the field the hydraulic conductivity was calculated by infiltration tests, following the theory of Kessler & Oosterbaan (1974).

The infiltration capacity and hydraulic conductivity vary according to variable sedimentology (Table 3). In areas with compact lodgement till (Fig.7, zone 1 & Fig.10) the infiltration and percolation down to 1-2 m depth mainly occurs along fractures formed by weathering (Fig.8) and along root channels.

Table 3. Hydraulic conductivity values of Quaternary deposits from Åstadalen. After Østeraas 1973, 1976, P.D. Jenssen pers.comm.1981, J.Chr. Køhler pers.comm.1982.

Sediment	Test type	K-value (m/s)	Number of tests
Till sheet,	Field [1]	$2\cdot10^{-4}-1\cdot10^{-5}$	6
compact till	Lab	$3\cdot10^{-8}-9\cdot10^{-7}$	5
Moraine ridges, hummocks	Lab	$1\cdot10^{-5}-1\cdot10^{-6}$	2
Glaciofluvial sediments	Lab	$2\cdot10^{-4}-1.3\cdot10^{-5}$	5

1) .8-1.2 m depth

Lodgement till samples packed in permeameters gave hydraulic conductivity values between $8.5\cdot10^{-7}$ and $3\cdot10^{-8}$ m/s (Table 3, Østeraas 1973). A field test at Hamarsætra (Fig.10), 0.7-1.0 m depth, indicated hydraulic conductivities between $2\cdot10^{-4}$ and $1\cdot10^{-5}$ m/s (Table 3). This test also showed that the hydraulic conductivity is greater in a horizontal than in a vertical direction, mainly due to the subhorizontal fissility which is typical for basal till. In the upper 1 m of the till this fissility is very pronounced due to secondary processes (Fig.10). The difference between field and laboratory data in Åstadalen indicates that more than 95 % of the percolating water follows root channels and fractures, horizontal as well as vertical. A conclusion is therefore that the percolation of water in the lodgement till mainly occurs through well established channels and that large part of the sediment is rather passive in the percolation process. This has also been shown by Knutsson (1966, 1971).

The hydraulic conductivity often decreases abruptly below 1 m depth (see also Dahl et al. 1981, Lundin 1982), where the influence from surface weathering and plant activity diminishes. Further down, the water movement mostly takes place along original planes of fissility and along the surfaces of cobbles and boulders.

The infiltration capacity and hydraulic conductivity is variable in melt-out tills and supraglacial sediments, due to their complex internal structures (Figs.12 & 13). Both zones of sorted permeable sand (Figs.12B & 13B) and extensive thin layers of compact silt (Fig.12A) occur in the till-like sediments. As a rule the melt-out tills and the supraglacial sediments are more permeable than the lodgement till, partly because of the lower content of fines (Fig.9). In connection with detailed studies of melt-out tills north of Kvarstadsætra, hydraulic conductivities between $1 \cdot 10^{-5}$ and $5 \cdot 10^{-5}$ m/s were measured for disturbed samples in permeameters (Table 3, Østeraas 1973). These are higher values than found for any lodgement till sample. However, according to Knutsson (1971) the water movement in tills is much more dependent of structural inhomogenities than of differences in the bulk grain-size distribution. The many horizons of sorted sand (Figs.12 & 13), through which the water obviously penetrates, make the difference between lodgement till and melt-out till even greater than indicated by the permeameter tests in the laboratory.

Sorted sediments occur through the whole vertical sequence of many melt-out tills, and as a result the hydraulic conductivity does not decrease with depth in the same way as for the lodgement till.

Glaciofluvial and fluvial sediments (Fig.7, zones 3 and 7) have significantly higher hydraulic conductivities than other sediments in Åstadalen (Table 3). The absence of damming horizons of fine-grained material generally allows a rapid percolation down to the groundwater level.

The infiltration capacity of the meltwater channels are comparable with those of the boulder fields. In addition, the meltwater channels are found in depressions, and surface water is therefore drained towards such channels. In areas with thin covers of till the meltwater channels are in places developed down to the bedrock surface and here the water percolates rapidly down to the bedrock aquifers.

5. HYDROLOGY

Precipitation entering the Åstadalen catchment must leave by two main routes: 1) evapotranspiration and 2) streamflow. The storage

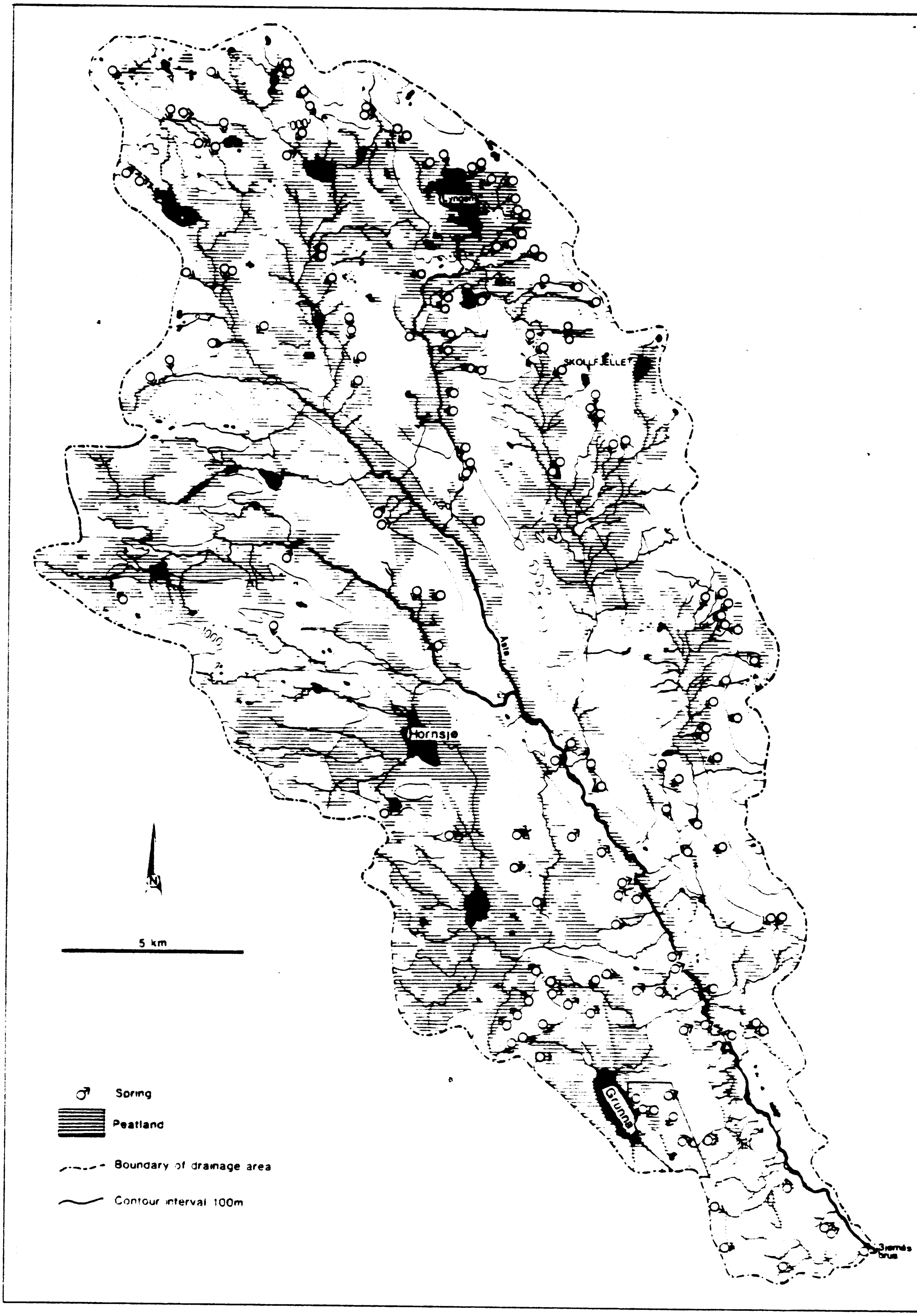


Fig. 17 The surface drainage pattern within the Åstadalen catchment. Location of springs partly based on Østeraas (1978, 1982) and Køhler (pers.comm. 1979). Framed area: Fig. 21. KS: Kvarstadsæter.

capacity of the catchment is high due to the following magazine types: a) unsaturated zone in Quaternary deposits and in rocks, b) aquifers in Quaternary deposits and in rocks, c) lakes, lakelets and rivers, d) peatlands and e) snow pack.

5.1 Climate

Generally, the Åstadalen catchment has a long cold winter from about the middle of October to the end of April. A continous snow pack develops each winter to the thickness of up to 1,5 m. The air temperature can remain at -15 to -25 °C for long periods.

The summers are usually short and cool, but temperatures up to 20-25 °C are attained for periods.

According to The Norwegian Meterological Institute the mean annual precipitation for the catchment is about 950-1000 mm, which is somewat higher than for surrounding areas in south-eastern Norway. It is estimated that more than 30 % of the annual precipitation falls as snow.

5.2 Infiltration and percolation. Groundwater recharge

There is snow cover and ice on the lakes and lakelets every winter preventing infiltration and groundwater recharge. Due to the insulating effect of the early snow cover in the autumn, the ground is generally unfrozen or only locally frozen during winter. From the spring thaw until the next winter period, the Quaternary deposits and the fractured bedrock have high enough infiltration capacities to allow immediate infiltration of the net precipitation.

The groundwater recharge varies according to differences in the geology. In the west (Fig.7, zone 7), a great deal of water is stored in the compact lodgement till (Table 2) but the amount percolating down to the bedrock aquifers is smaller than in the north and east. However, also in the west there are zones with thin and discontinuous till cover and where the recharge of the bedrock aquifers mainly occurs.

Along the valley bottom (Fig.7, zones 2, 3, 4 and 7) the sediments mainly have high hydraulic conductivities (Table 3) and the water penetrates easily down to the groundwater aquifers.

In areas where the Quaternary deposits are very thin or bedrock is exposed (Fig.7, zones 5, 6 and 8), there is direct percolation down to the rock aquifers. In mountainous areas above 1000 m a.s.l. the high frequency of open fractures (Fig.2B) promote an immediate infiltration and a rapid percolation through the unsaturated zone into bedrock. Such areas are abundant in the north and east.

However, in areas covered by peatlands there is considerable surface runoff and/or subsurface interflow.

5.3 Aquifers

The general picture within the Scandinavian Peninsula is that groundwater occurs in two main types of aquifers: 1) Quaternary deposits possessing a primary porosity (the voids between individual grains), and 2) bedrocks without primary porosity but with secondary passages such as joints and other fractures. The aquifers are generally small and local, with low productivity compared to the conditions further south in Europe (International Hydrogeological Maps of Europe, e.g. Sheets C3 Oslo and C4 Berlin).

From a hydrogeological aspect the present catchment is typical for the higher central and southern parts of the Scandinavian Peninsula.

5.3.1 Bedrock aquifers. A number of wells (diameter 4-6 inches) have been drilled in the Brøttum Formation both within (Fig.20) and outside the catchment (Englund 1966b, Englund & Myhrstad 1980). They usually supply around 300-1000 l/h at depths of 50-100 m. The large number of springs within the catchment (Fig.17) also demonstrates that water is stored in bedrock aquifers. Water occurs in and penetrates through open fractures (Figs.5 & 22) down to at least 100-150 m, and probably down to depths of 300-500 m.

The high effective porosity down to 15-20 m at altitudes above 1000 m (Fig.5) forms the basis of large shallow aquifers which supply a number of springs.

5.3.2 Aquifers in Quaternary deposits. Table 2 gives a rough estimate of the amount of groundwater stored in different types of Quaternary sediments in Åstadalen. Due to the large extent of the basal till sheet (Fig.6) more water is stored in this sediment

Fig.18 Permanent spring at Kvarstadsætra; end of winter, April 17th 1981. It is fed from a bedrock aquifer, but emerges at the surface through an esker. Discharge values, see Fig. 20B.

Fig.19 Permanent spring at Skollfjellet; autumn, September 9th 1981. It is fed from a bedrock aquifer, but emerges at the surface through a thin melt-out till.

type than in other types, though its porosity is low (Table 2). The permeability of the basal till sheet is however, to low to form productive aquifers.

Minor local magazines of perched groundwater are formed some places in the upper part of the till, due to the much higher porosity of the weathered zone than of the till deeper down (Østeraas 1973, 1976). This is further promoted by the occurrence of impermeable iron pans which are developed in different places and at different levels in the basal till (Holth-Nilsen 1971).

Transverse moraine ridges and hummocks are usually situated above the groundwater level and therefore do not provide any important aquifers. In many places the ridges and hummocks are surrounded by peatland and lakelets which define the groundwater level. They are underlain by compact basal till.

Local eskers and glaciofluvial hummocks are also usually situated above the groundwater level and do not then form productive aquifers. However, in some places the local eskers form important groundwater conduits down the valley sides, particularly in cases where they are partly capped by till.

The glaciofluvial and fluvial sediments along Åsta and its tributaries are the most productive of the aquifers in superficial sediments. Such aquifers are recharged directly from precipitation, from bedrock aquifers (e.g. at Kvarstadsætra and along Skvaldra), from surrounding peatland (e.g. the eskers west of Lyngen, Fig.6) or from rivers (e.g. parts of the main esker and the low terraces along Åsta (Figs.6 and 15).

5.3.3 Springs. A large number of springs occur within the catchment (Fig.17). Their topographic position is usually determined by a) the occurrence of impermeable peatland in contact with permeable sediment/bedrock, and b) topographic depressions. They are of the "Stauquellen" or "Uberlaufquellen" type in the terminology of Richter & Lillich (1975 p.144), or "overtopped unconfined springs" or "depression springs" in the sense of Brown et al. (1975).

Many springs have well-defined water outlets (Fig.18 and 19), and they are often found along horizons of approximately the same elevation.

From August 1th 1980, water yields were measured at least once every week in four selected springs. Their discharges vary with the

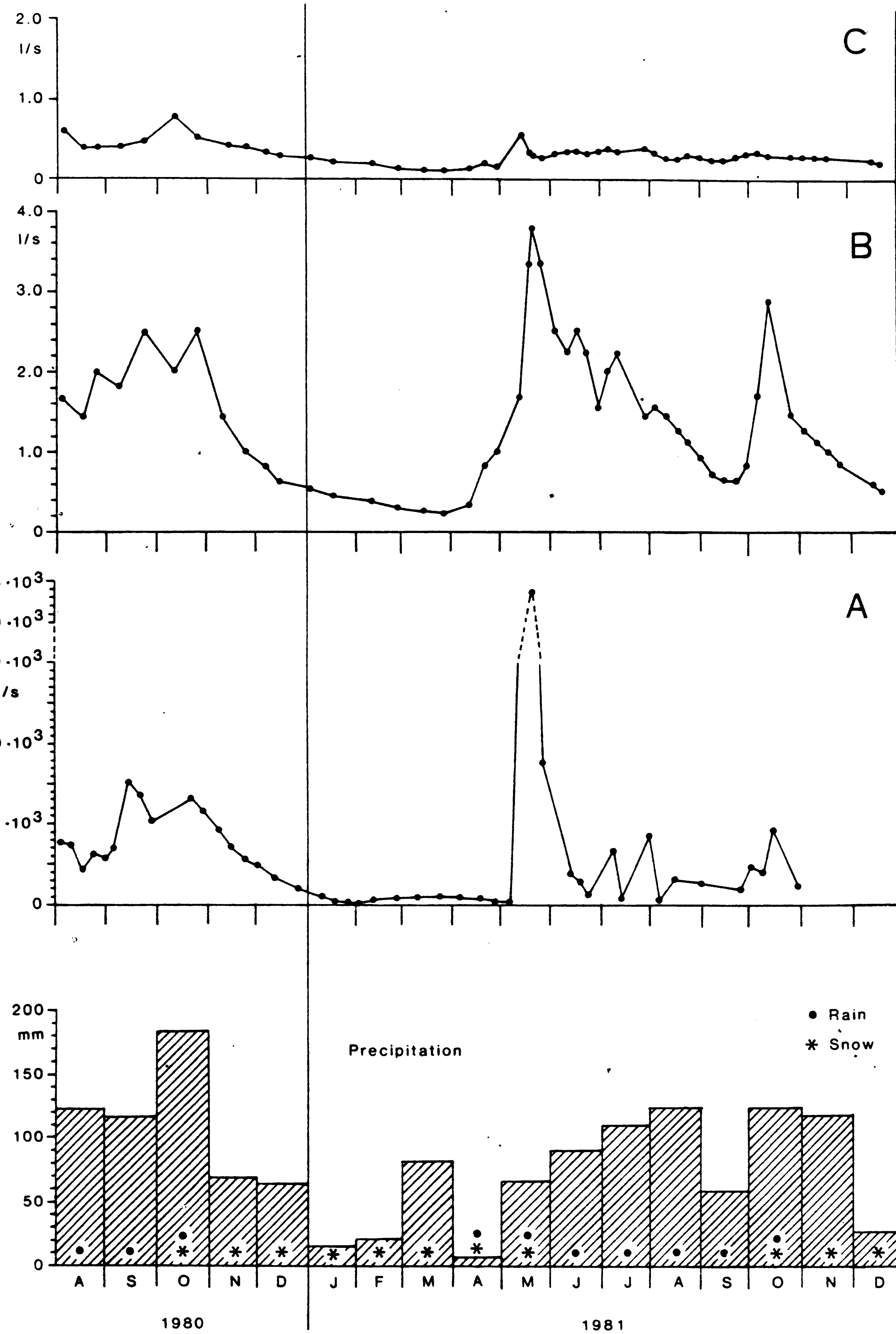


Fig.20 Observed precipitation at Kvarstadsætra and A. Discharge of the river Åsta at Kvarstadsæterdammen, just upstream of Kvarstadsætra, B. Discharge of a spring fed from a bedrock aquifer near Kvarstadsætra, west of Åsta (Fig.18) and C. Discharge of a spring fed from an aquifer in glacio-fluvial sediments, near Kvarstadsætra, east of Åsta.

rainfall, as illustrated for two of them in Fig.20. Other springs have been sporadically investigated during summer periods. Most of them show discharges in the range 500-4000 l/h.

The most permanent springs are found along river Åsta, in higher areas east of the river, and in the northern part of the catchment.

A great number of intermittent springs found in the mountains are largely fed by groundwater occurring in shallow aquifers.

In the southwest many of the springs show small yields, or are empty after long dry periods or in late winter time. This show the existence of small shallow groundwater bodies in the southwest, and rather large aquifers along, and east of, the river Åsta and in the northern part of the catchment.

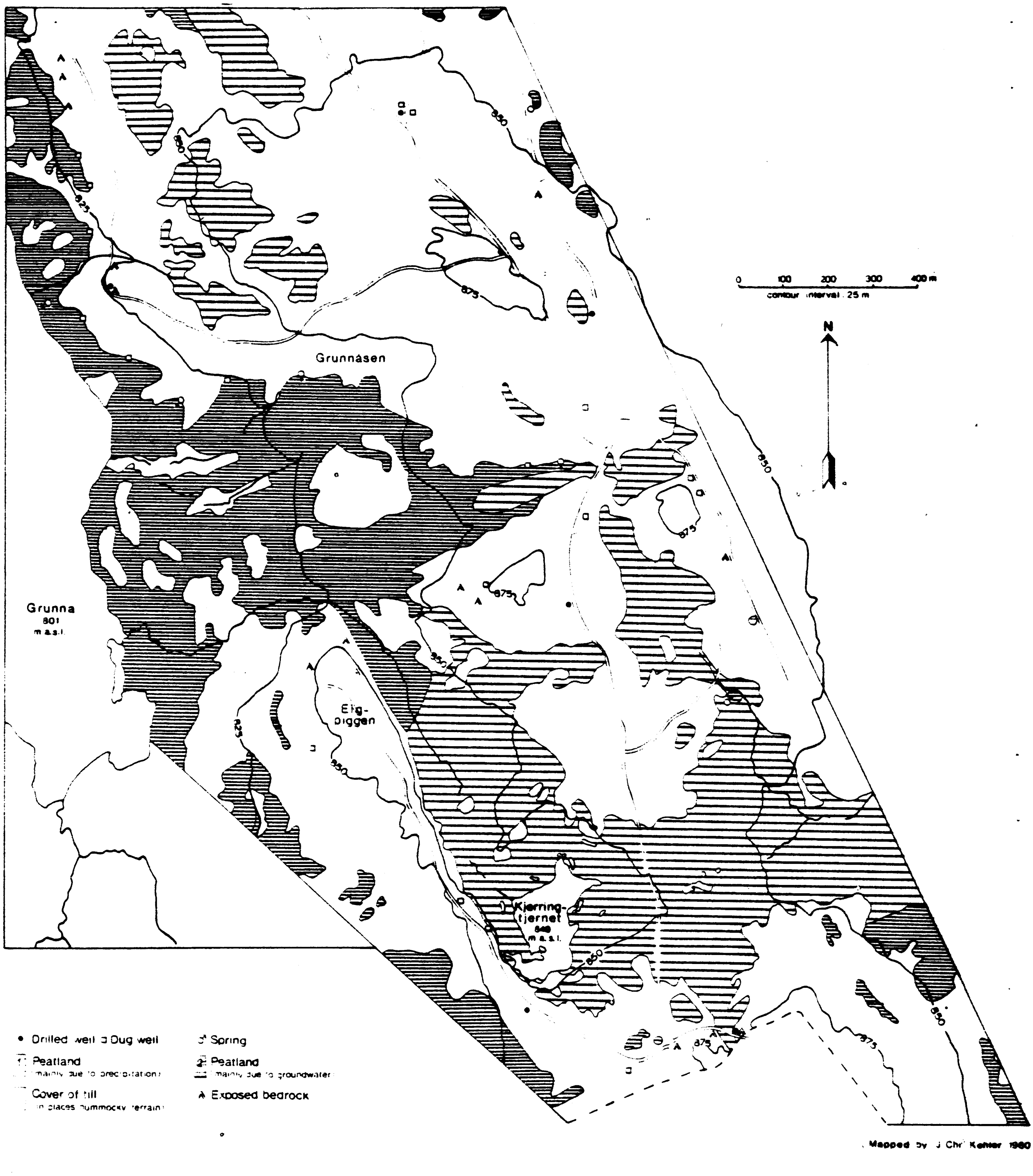
Most springs are mainly fed from bedrock aquifers, though their emergence at the surface is often through thin superficial sediments. Springs fed only from aquifers in Quaternary deposits are probably very subordinate, but some are connected to eskers and glaciofluvial terraces.

Examples of springs from the catchment are shown in Figs.18 and 19.

5.3.4 Conclusions. Generally, the Quaternary deposits have low permeabilities, except locally where they form productive aquifers, as along the valley bottoms. However, aquifers in Quaternary deposits are small compared with bedrock aquifers. The most productive bedrock aquifers are found on the eastern and northern side of the valley (Fig.17). As a result the base flow in the main river Åsta is largely maintained by these bedrock aquifers.

5.4. Peatlands

Peatlands cover 42 % of the catchment (Table 1); this is among the highest frequencies found in southeastern Norway (Næss 1969). Two main peatland types are found: 1) Peatland largely fed by groundwater, and 2) Peatland mainly dependent on the direct supply of precipitation. Generally, type 1 is most common along and east of river Åsta, and in the northern part of the catchment. Type 2 peatland



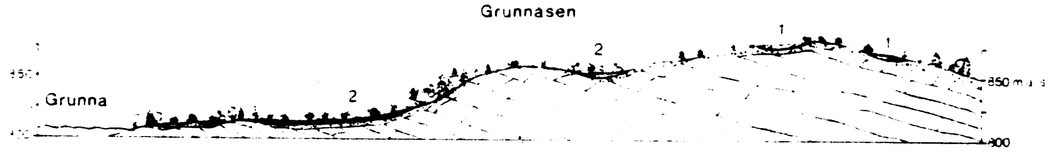


Fig.21 Peatland types in relation to topography and surface drainage pattern east of lake Grunna. Location: Fig.17.

dominates in the southwest. Interfingering of the two types occurs in places, as east of Grunna (Fig.21).

5.4.1 Peatlands due to groundwater have a more or less permeable substrate. The contact with the groundwater is good. Springs often occur along the peatland boundaries. It is believed that the supply of groundwater exceeds the supply of water directly from precipitation and surface runoff.

5.4.2 Peatlands mainly fed by precipitation occur either within basins surrounded by low relief, or near/on the tops of small rounded summits. The substrate mainly consists of watertight tills.

5.4.3 Conclusions. Most peatlands within the catchment function as groundwater discharge areas during much or all of the year. There is probably little water movement within them, in contrast to the movement in most aquifers and in streams. Since the peatlands cover large areas they represents an important part of the water storage capacity within the catchment.

5.5 Lakes and lakelets

Lakes, lakelets and streams cover 3 % of the catchment (Table 1). In places marshland is encroaching into the open water (e.g. Grunna, Hornsjøen, Lyngen).

The downhill movement of water towards lakes and streams is probably largely by subsurface interflow and groundwater flow. This is because the infiltration capacity of the soils and rocks is sufficiently high to allow immediate infiltration of most of the net precipitation. However, in areas covered by peatlands it is supposed that after heavy rain surface runoff is important.

In conclusion, many lakes and lakelets have a copious supply of groundwater. This is especially important along and east of the river Åsta, and in the northern part of the catchment.

5.6 Rivers

The surface drainage pattern within the catchment largely follows the main fracture directions (Figs.4, 5 and 17). The river Åsta as well as a number of its tributaries follow the predominant fracture direction, NW-SE, for long distances. Also the NNE-SSW fracture direction is followed by a lot of rivers, especially in the eastern and northern parts of the catchment. Another drainage direction is roughly west-east, i.e. parallel to the fold axes of the area.

Since July 13th 1979, the discharge of the river Åsta at the outlet of the catchment near Bjørnåsbrua, has been measured at least once a week. The flow ranges from $0{,}1 \cdot 10^3$ l/s during cold winters to more than $75 \cdot 10^3$ l/s during the spring thaw (Fig.22).

At Kvarstadsæterdammen, 5,5 km upstream from Bjørnåsbrua and with a catchment of 370 km^2, water discharges have also been measured in Åsta since August 1th 1980. Here the high discharge is related to rainfall and the spring thaw (Fig.20).

Generally, the river shows sustained flow during long periods of drought and when the precipitation is lying as snow. This prolonged base flow is due to the high storage capacity within the catchment, especially in bedrock aquifers.

5.7 Hydrology of the valley sides

Spring horizons at different altitudes characterize the sides of valleys in a number of places within the catchment especially to the east and north (Fig.17). The water from the springs have often created peatlands downslope and many spring horizons occur at the contact between exposed zones of fractured bedrock and peat cover. The water from the springs largely drains through the peatlands and then infiltrates into bedrock or in some cases into Quaternary deposits. Along the valley sides down to the river Åsta a characteristic groundwater flow pattern therefore seems to exist (Fig.23); flow from shallow aquifers through springs into surface/interflow drainage in peatlands and then partly back into the aquifers by infiltration. This cycle may be repreated up to 5 or 6 times before the water reaches the river.

5.8 Main groundwater flow pattern

The map Fig.17, shows that the Åstadalen catchment can be divided into recharge and discharge areas with respect to the groundwater.

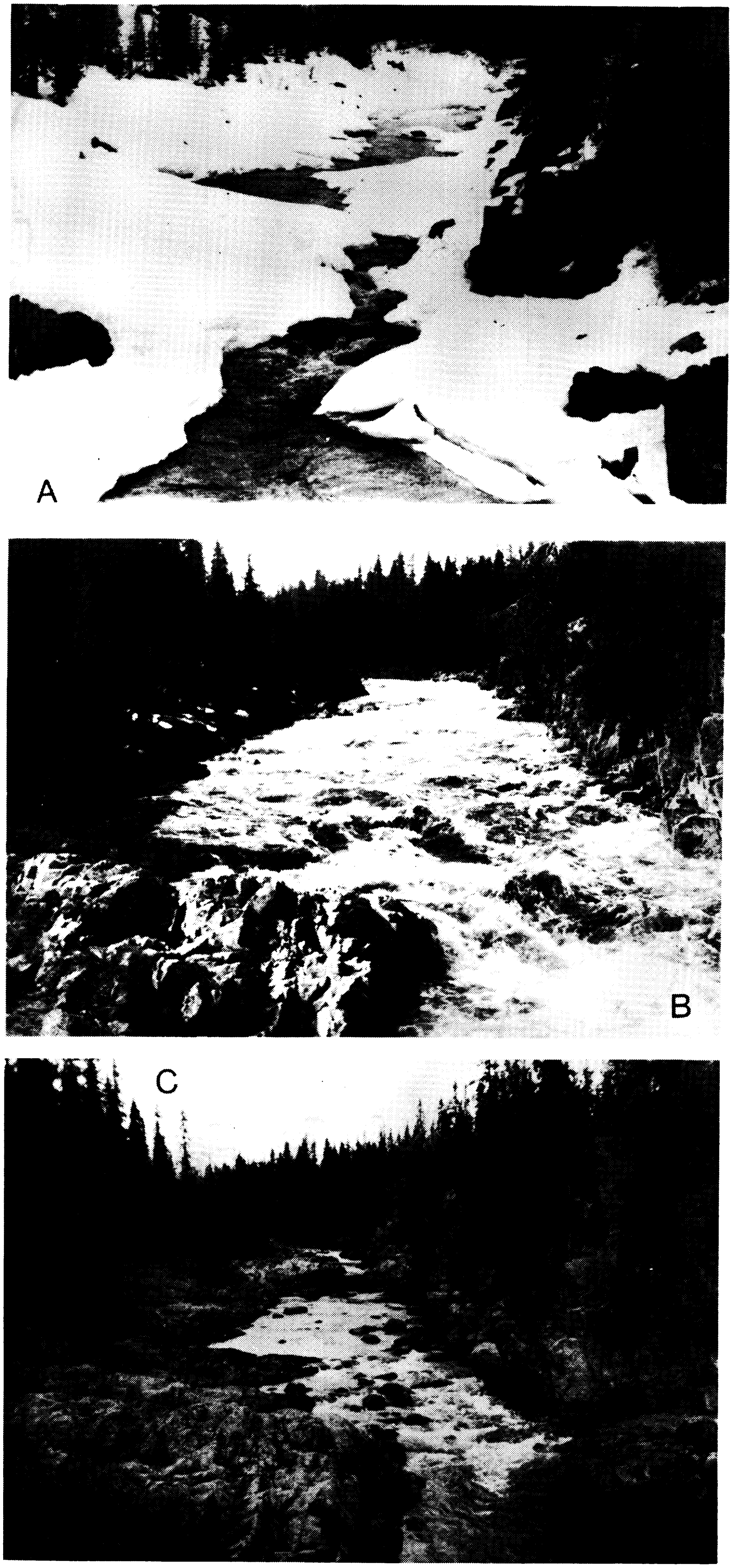


Fig.22 River Åsta at Bjørnåsbrua. A. End of winter, April 17th 1981.
B. Spring, May 20th 1981. C. Autumn, September 17th 1981.

Recharge generally occur in regions above the spring horizons and peatlands fed by groundwater. Lakes, lakelets and rivers as well as most peatlands constitute groundwater discharge areas during much or all of the year (Fig.23).

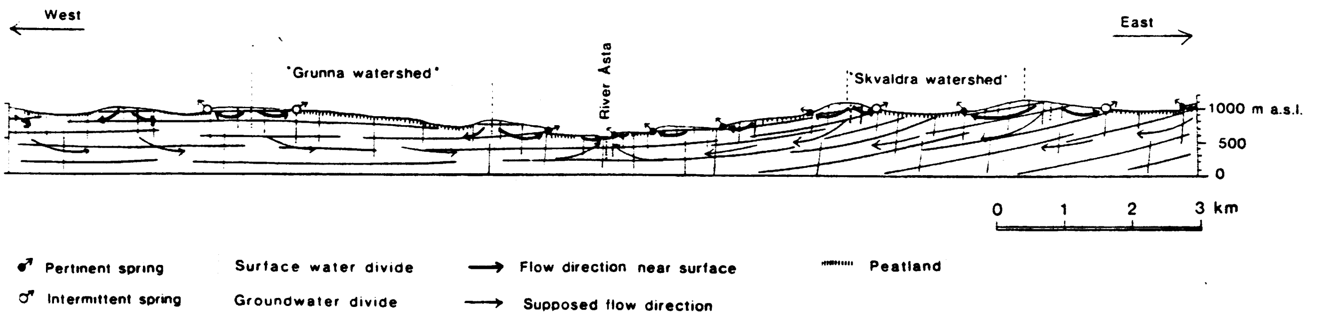


Fig.23 Diagrammatic flow pattern in the fractured Brøttum Formation of Åstadalen.

6. CONCLUDING REMARKS

The Åstadalen catchment represents largely a natural ecosystem. Vital for the maintenance of this system is the flux of water and nutrients across its boundaries, as well as internal cycling. In order to increase our understanding of such systems the catchment has been chosen as a research area. The increasing complexity of modern society has, however, placed stresses on the system: as pollution, deforestation, the building of the roads and cottages.

This paper is concerned with some basic data on the geology and general hydrology:

1) The Åstadalen catchment in S.E.Norway is about 400 km^2 and varies in altitude from 615 m to 1150 m. The climate is characterized by long cold winters and short cool summers, and mean annual precipitation about 950-1000 mm. The area is made up of mountain areas (20 %), forests (32 %), peatlands (43 %) and lakes, lakelets, rivers (3 %) and some hill farms and gravel roads (2 %).

2. The catchment is underlain by fractured sandstones, conglomerates and silty shales of Upper Precambrian age (Sparagmites), with

a thin cover of unconsolidated Quaternary deposits.

3) The rocks are themselves impermeable, but the presence of open fractures gives the rock masses a significant porosity and permeability. The fracturing is mainly Permian to Triassic in age, but some sets of joints are related to the Caledonian folding.

At altitudes above 1000 m these tectonic fractures have been enlarged by frost activity, probably partly after the last Quaternary glaciation.

4) Data derived from drilled wells show that groundwater occur in the fractures of the rocks, and the large number of springs within the catchment demonstrates that much water is stored in bedrock aquifers.

5) The Quaternary deposits are dominated by tills with low permeability. Perched groundwater is found in its upper, weathered part. The tills are in parts of the area thin and discontinuous and allow direct infiltration into the rock fractures. Areas in the west are partly covered by compact basal till which prevents groundwater recharge.

6) Aquifers of importance in Quaternary deposits are found in glaciofluvial and fluvial sediments, mainly in a narrow zone along the main valley and its tributaries.

7) The infiltration capacity of the soils and rocks is mostly high enough to allow immediate infiltration of the net precipitation. The downhill movement of water toward lakes, peatlands and streams is therefore largely by subsurface interflow and groundwater flow. However, much surface runoff do occur after heavy rain within areas covered by peatlands.

8) Most of the springs within the catchment are fed from bedrock aquifers, though their emergence at the surface are often within loose deposits.

9) The topography within the area is largely influenced by bedrock types, fold structures, fracturing and erosion by glaciers in Quaternary time.

10) The drainage pattern is strongly influenced by the dominant fracture directions, NW-SE and NNE-SSW. Another drainage direction is E-W parallel to the fold axes.

11) With respect to the groundwater, recharge occurs generally in regions higher than the many springs and peatlands. Most peatlands, as well as lakes, lakelets and rivers, constitute groundwater discharge areas during much or all of the year.

12) The river Åsta shows sustained flow during long periods of drought and when the precipitation is lying as snow. The high storage capacity within the catchment is largely due to bedrock aquifers.
Much of the discharge occurs, however, during the spring when the snow melts.

13) Along the eastern valley side, down to the river Åsta, the groundwater flows from shallow bedrock aquifers through springs into surface/interflow drainage in peatlands and then partly back into bedrock aquifers by infiltration. This cycle may be repeated up to 5 or 6 times before the water reaches the river Åsta.

SAMMENDRAG

ÅSTADALEN NEDBØRFELT, S.Ø.NORGE; GEOLOGI OG GENERELL HYDROLOGI

Åstadalen nedbørfelt representerer i det vesentlige et naturlig økosystem. Dette systemet opprettholdes av en fluks av både vann og næringsstoffer over økosystemets grenser, samt en indre syklisitet. For å øke vår forståelse om slike nedbørfelt er Åstadalen valgt som forskningsområde. Vårt moderne samfunn har imidlertid forårsaket et visst stress på dette systemet, ved forurensning, hogging av skog og bygging av veger og hytter.

Denne artikkelen gir endel grunnleggende informasjoner om geologi og generell hydrologi:

1) Åstadalen nedbørfelt i sørøst Norge er omtrent 400 km^2, varierer i høyde fra 615 m til 1150 m. Klimaet er karakterisert ved lange kalde vintre og korte kjølige sommere, og med en årlig nedbør omkring 950-1000 mm. Området består av fjell (20,3 %), skog (32,4 %), myr (43 %) og innsjøer, tjern og elver (2,9 %), samt endel setre, hytter og grusveger (1,4 %).

2) Berggrunnen i nedbørfeltet består av oppsprukne sandsteiner, konglomerater og siltige skifre av senprekambrisk alder (sparagmitter), med overliggende ukonsoliderte kvartære avsetninger.

3) Bergartene selv er impermeable, men tilstedeværelsen av åpne sprekker gjør at større enheter av bergartene får en betydelig porøsitet og permeabilitet. Oppsprekkingen er vesentlig av permisk-triassisk alder, men endel sprekker skyldes den kaledonske foldningen.

   I høyde over 1000 m er disse tektoniske sprekkene blitt utvidet ved frostsprengning, antakelig delvis etter den siste kvartære nedisning.

4) Data fra borede brønner viser at grunnvann opptrer i bergartenes sprekkesystemer. Også et stort antall kilder innen nedbørfeltet demonstrerer at mye vann er lagret i fjellakviferer.

5) Morenene innen deler av nedbørfeltet er tynne og usammenhengende, og tillater dermed infiltrasjon direkte ned i fjellsprekkene. Området i vest er for en stor del dekket av kompakt

bunnmorene som hindrer nydannelse av grunnvann.

6) Viktige og produktive akviferer i kvartære avsetninger opptrer i glacifluviale og fluviale sedimenter, vesentlig i smale soner langs hoveddalen og i sidedalene.

7) Infiltrasjonskapasiteten for jordartene og bergartene er generelt høy nok til at netto-nedbøren blir infiltrert. Vannbevegelsen ned mot innsjøer, myrer og elver foregår derfor vesentlig ved grunnvannstrømning og såkalt "interflow" i den umettede sonen. Imidlertid opptrer betydelig overflateavrenning innen myrområder etter mye regn.

8) De fleste kilder innen nedbørfeltet mates fra fjell-akviferer, selv om vannet ofte trenger fram til overflaten gjennom løsmasser.

9) Områdets topografi er i det vesentlige bestemt av bergartstyper, foldestrukturer, sprekkemønster og iserosjon i kvartær tid.

10) Områdets dreneringsmønster er for en stor del influert av hovedsprekkeretningene, NV-SØ og NNØ-SSV. En annen dreneringsretning går ca Ø-V, dvs. parallelt med foldeaksene.

11) Generelt foregår nydannelse av grunnvann ovenfor de mange kilder og myrer innen området. Disse mottar grunnvann mesteparten av året, i likhet med innsjøer, tjern og elver.

12) Elva Åsta har en høy og langsomt avtagende vannføring i tørre perioder om sommeren og om vinteren. Dette skyldes vesentlig stor vannlagringskapasitet innen nedbørfeltet, i første rekke i fjell-akviferer. Mye av års-avrenningen fra feltet foregår imidlertid om våren når snøen smelter.

13) I dalsidene, spesielt i øst og nord, opptrer kilder i flere nivåer, gjerne med myrdannelse nedenfor. Grunnvannet som stammer fra grunne deler av fjell-akviferer renner videre på overflaten eller i myra, for deretter å infiltrere nedenforliggende fjell-akviferer. En slik syklus kan gjentas opptil 5-6 ganger før vannet når Åsta.

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