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Subpermafrost Groundwater, Western Svalbard

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Subpermafrost groundwater aquifers are found in Ny-Ålesund, western Svalbard. Recharge of groundwater takes place along the base of the nearby glaciers, and groundwater flows in open bedrock fracture systems and porous sedimentary rocks. A subpermafrost sandstone with a primary porosity of more than 10% makes up a pore aquifer with a considerable storability. The water discharges into one of the old coal mines, with a flow rate of 11.5 l/s measured in the summer and fall of 1993 and 1994. There was a considerable discharge during the winters 1993 and 1994, a discharge making up nearly the whole annual water budget from the upper part of the Vestre Lovénbreen. Similar situations are found in other places on Svalbard and may have an important influence upon the glaciers' hydrological regime. The groundwater system in Ny-Ålesund is manipulated by human activity. Outflow channels in the old coal mines probably have increased discharge relative to an undisturbed system and may locally have melted the permafrost. The groundwater flow is an efficient mechanism for transferring geothermal heat, and may have an important influence locally upon the permafrost distribution on part of Svalbard.

Groundwater Systems in Svalbard

The permafrost thickness in Svalbard is between 100 and 400 m and is almost continuous (Liestøl 1977, 1980). The permafrost prevents groundwater recharge in most places.

The glaciers in Svalbard are mainly of a subpolar type with a frozen base near the

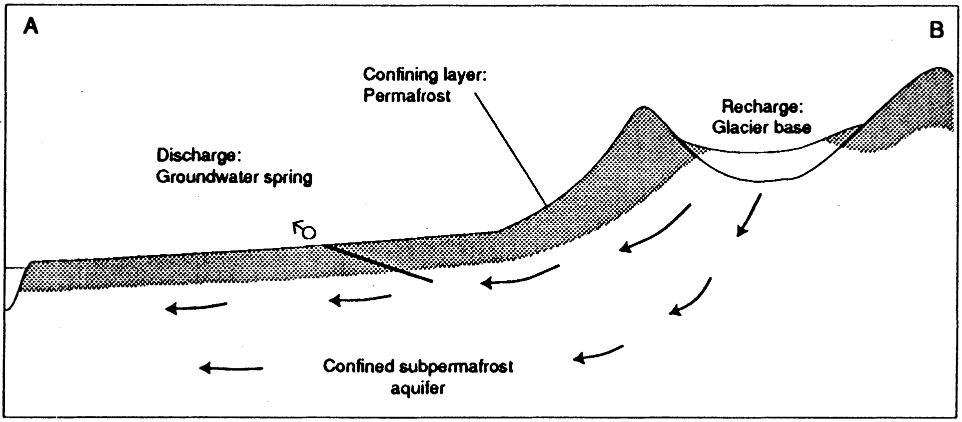

Fig. 1. Confined groundwater flow systems in Svalbard after Liestøl (1977), section A-B in Fig. 2 is used as an example. The permafrost is shaded.

front, and with basal temperatures close to the pressure melting point (slightly below 0 °C) above the firn line. Most of the water runs subglacially to the front of the glacier (Hagen *et al.* 1991; Hagen and Lefauconnier 1993), but a certain portion may penetrate along fractures into the underlying bedrock in areas where the base of the glacier is at the pressure melting point (Fig. 1). The general impression has been that this is the main recharge area for subpermafrost groundwater in Svalbard (Orvin 1934, 1944; Liestøl 1977), an idea which has been incorporated into recent studies (Haldorsen and Lauritzen 1993a, 1993b, 1993c; Lauritzen 1991, 1993).

Subglacial groundwater aquifers in Svalbard are confined with the permafrost as the capping aquitard (Fig. 1). A high pressure potential may occur beneath the permafrost in valleys. Terrestrial discharges form open-system pingos and high-discharge artesian springs (Liestøl 1977). Karst springs (Krawczyk 1989; Lauritzen 1991, 1993; Liestøl 1977; Pulina 1977; Salvigsen and Elgersma 1985; Salvigsen *et al.* 1983) are common, indicating that karst systems are the most important aquifers in Svalbard. However, groundwater aquifers in the fracture systems of silicate rocks are also found (Orvin 1934, 1944; Store Norske Spitsbergen Kulkompani, pers. comm. 1992). Groundwater temperatures, which may be several plus degrees centigrade, indicate deep circulation systems where groundwater receives the geothermal heat needed to keep the temperature well above freezing point on its way upwards through the permafrost.

The groundwater systems are thus controlled by the following time-variable and climate dependent factors (Fig. 1, Haldorsen and Lauritzen 1993):

1) Confining layer: The thickness of the permafrost zone
2) Recharge area: The size and properties of the glaciers
3) Recharge rate: The amount of water which flows through the glacier.

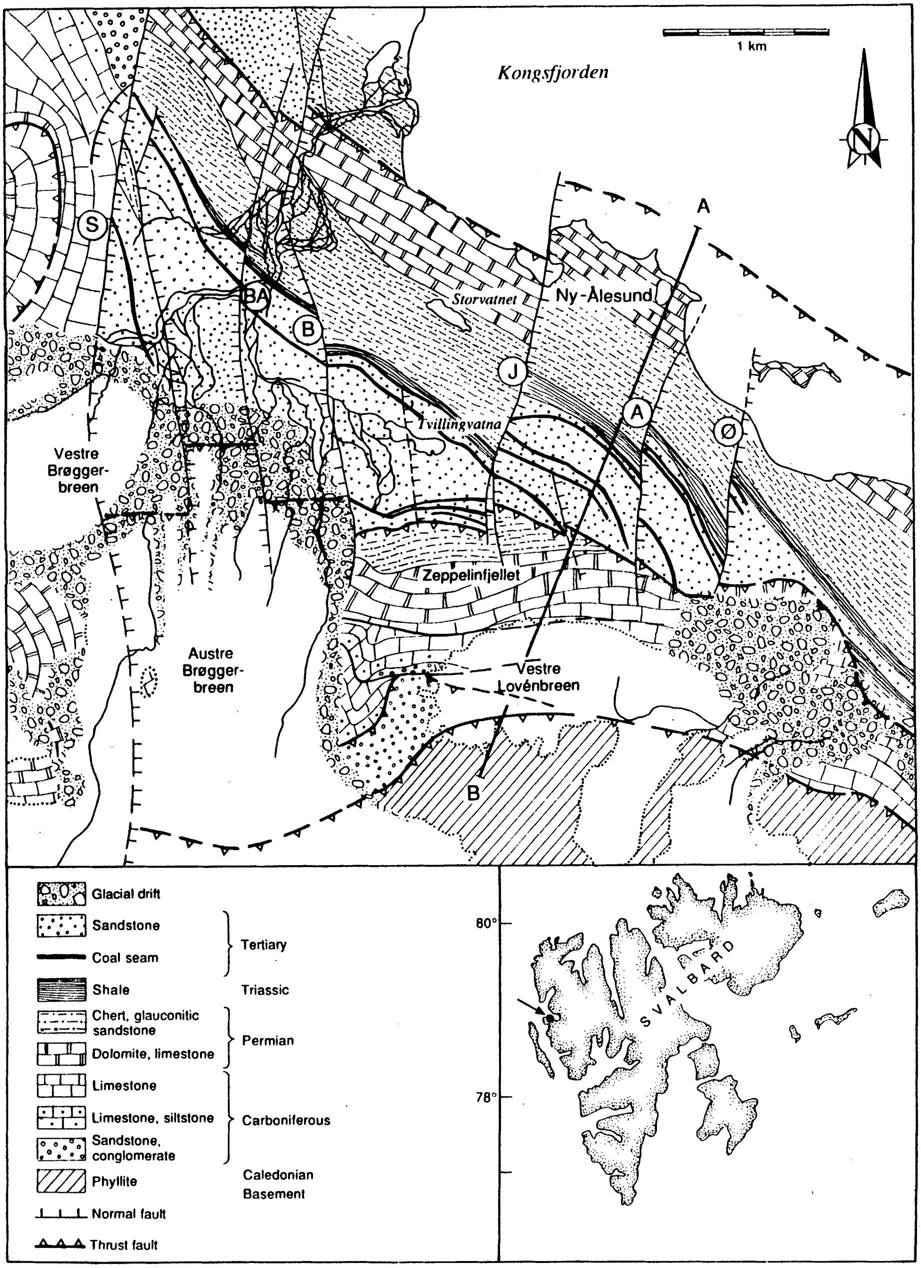

Fig. 2. Geological map of the Ny-Ålesund area (after Midbøe 1985; Orvin 1934 and Thiedig and Piepjohn (unpubl.)). Section A-B is shown in Figs. 1 and 3. Ø=Østre fault, A=-Agnes fault, J= Josefine fault, B=Brøggerdal fault, Ba=Bay River fault, S=Schetelig fault.

The Ny-Ålesund Area

Permafrost and Glaciers

The settlement of Ny-Ålesund, western Svalbard (Fig. 2) was primarily based on coal mining. During the first mining period (1917-1929), permafrost was reported to extend 130-140 m below surface in the mines close to the foot of the Zeppelinfjellet and 150 m further out on the plain (Orvin 1944). During the second mining period (1945-1963), the lower permafrost limit in the coal mines commonly occurred at shallower depths: approximately at 0-50 m b.s.l., *i.e.* permafrost thickness of 100 m or less, even on the plain (E. Grimsmo, pers. comm. 1992). However, Liestøl (1977) measured a permafrost depth of 140 m in a borehole in the front of the Brøggerbreen glacier (Fig. 2), west of the coal mining field.

The nearest glaciers to Ny-Ålesund, the Brøggerbreen to the southwest (size 8 km^2), and the Vestre Lovénbreen to the southeast (total size 4 km^2) (Fig. 2), are the most actual groundwater recharge areas in Ny-Ålesund. The basal ice of the Brøggerbreen is at the pressure melting point in its central part where the ice thickness exeeds 70-80 m (Hagen and Sætrang 1991; Hagen *et al.* 1991). There are, however, no direct measurements of the thicknesses and basal temperatures of the Vestre Lovénbreen.

Bedrock Geology

In the Ny-Ålesund area metamorphic rocks of Caledonian age are overlain by Carboniferous, Permian, Triassic and Tertiary sedimentary rocks (Figs. 2 and 3) (Challinor 1967; Midbøe 1985; Orvin 1934). Tectonic events during the Tertiary resulted in folding and thrusting of the rock pile. The Tertiary sediments, forming the core in a northeast vergent syncline, are partially overlain by a thrusted Palaeozoic sequence. Simultaneous or subsequent extension resulted in the formation of blocks bound by N-S trending normal faults.

The Upper Palaeozoic rocks are mainly highly fractured dolomite, limestone, and chert with conglomerates and sandstones in the lowest part and a glauconitic sandstone at the top. This sandstone has a thickness of about 100 m and a primary volumetric porosity of more than 10%. The Tertiary bedrock consists of sandstones with a thickness of about 200 m containing coal seams and shale horizons. These sandstones have a rather low primary porosity (E. Grimsmo, pers. comm. 1992).

The main faults were named from the east to the west (Fig. 2) (Kings Bay 1961; Midbøe 1985; Orvin 1934): Østre (Ø), Agnes (A, displacement 50-60 m), Josefine (J, displacement about 200 m), Brøggerdal valley (B, displacement 40-100 m), Bay River (BA, displacement > 70 m) and Schetelig (S, displacement > 200 m). In general the thickness of the zone of fracturing is found to be 2-3 cm for each metre of displacement (E. Grimsmo pers. comm. 1992). For the Josefine and the Schetelig faults the zone of fracturing has a mean thickness of about 4-6 m. Many minor faults with displacements of 1-10 m are found in between the major faults.

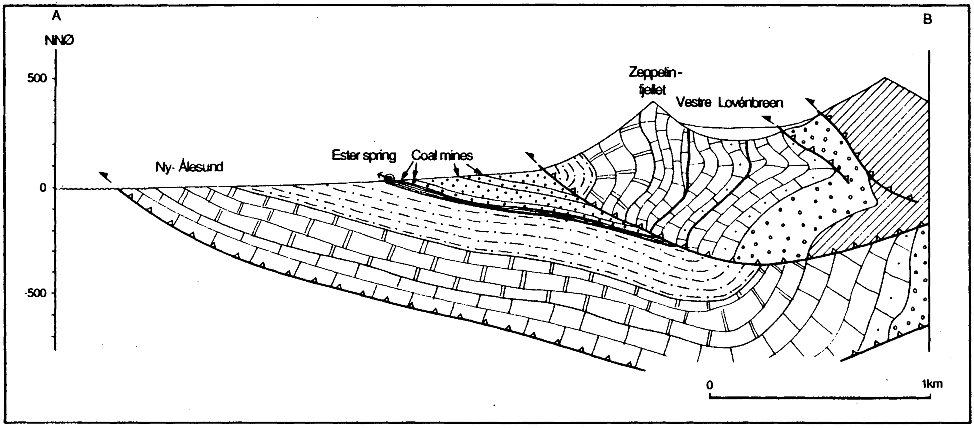

Fig. 3. Profile showing the bedrock geology along section A-B in Fig. 2. Legend: See Fig. 2.

Groundwater Aquifers and Groundwater Discharge in Ny-Ålesund

Groundwater Flow in the Mines

Most of the rocks in the area having lithologies with a rather low primary permeability, rock fractures are likely to be the most important groundwater flow channels (Fig. 4). The density of fractures is highest within and close to the faults. During both coal mining periods in Ny-Ålesund groundwater leakage was a large problem in some of the mines (Hoel 1967). The water inflow was considerable whenever one of the main extensional faults was crossed, and inflow rates of 15-40 l/s were reported in mines along the Agnes and Josefine faults. The inflow in the mines occurred mainly below the permafrost, where the fault zones make up subpermafrost aquifers, but in some instances water also flowed into the mines above the lower limit of the permafrost (Orvin 1944).

When the mines were closed after the first period in 1929, they were gradually filled by inflowing groundwater. Seventeen years later, in 1946, when mining started up again, there was still an outflow of 3 l/s of groundwater from the entrance of the main Ester mine (E. Grimsmo, pers.comm. 1992).

In addition to open faults and fractures, the porous glauconitic sandstone (Figs. 2, 3 and 4) forms subpermafrost aquifers. During the second mining period water generally flowed into the mines where this sandstone was penetrated (E. Grimsmo, pers.comm. 1992). The overlying Triassic shale forms a subpermafrost aquiclude.

Today only one point of significant terrestrial groundwater discharge is observed in the former coal mining area. Similarily as in 1946, the discharge point is at one of the entrances of the former Ester mines (Figs. 1, 3 and 4). Measurements taken August 10th and October 29th, 1993, by the salt dilution procedure recommended by

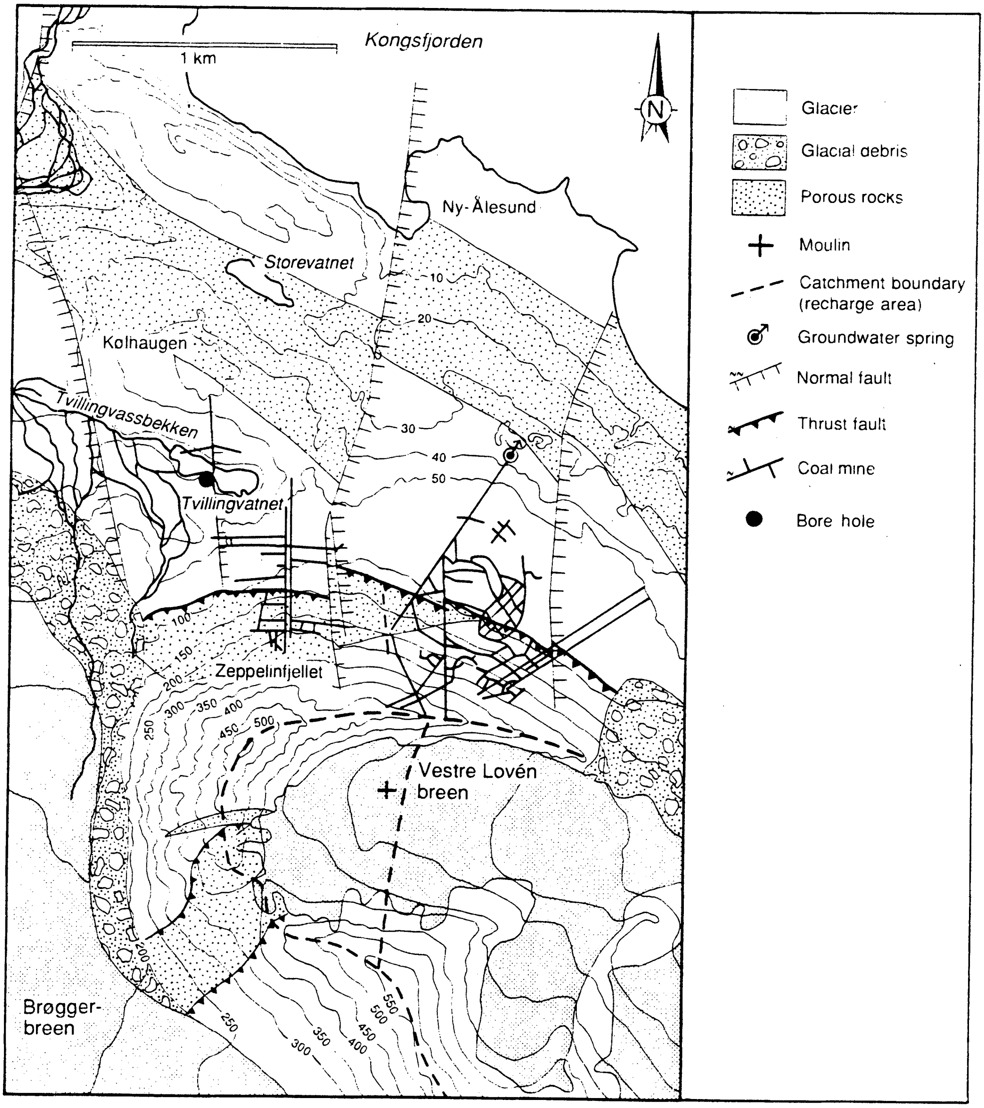

Fig. 4. Map showing supposed groundwater catchment, mines, permeable faults, porous sedimentary rocks, groundwater spring and borehole.

Hongve (1987), gave similar discharges of approximately 11.5 l/s. The discharges were considerable the entire winters of 1993 and 1994, indicating a leakage from a large permanent aquifer.

The Lake Tvillingvatnet

The lake Tvillingvatnet has been the water supply for Ny-Ålesund since the first mining period. The lake is about 400 m × 100 m, with a catchment of about 1 km^2 (Figs. 2 and 4). Groundwater was identified during a coal drilling in 1927, two metres from Tvillingvatnet (Fig. 4). Large amounts of artesian water gushed up from a depth of 18 m within the permafrost zone in the Tertiary sandstones. Below this level there were again permafrost conditions. Mapping in connection with the second mining period showed a minor fault crossing the Tvillingvatnet just where the drilling was carried out (Kings Bay 1963) (Figs. 2 and 4). A discharge from the Tvillingvatnet during the late fall was also observed long time after the surface drainage had finished. Orvin (1944) concluded that the lake receives groundwater from an underlying aquifer. However, when a mine was constructed 30 m below the Tvillingvatnet in 1963, permafrost was continuous along the whole mine (E. Grimsmo, pers. comm. 1992). It is therefore unlikely that any prominent open talik exists beneath the lake. The water-bearing zone more likely represents a transient talik which is fed by water through the fault. During the last winters (1992-1994) no significant ice formed along the stream from the Tvillingvatnet, and an eventual groundwater component is rather restricted and does not approach the size of the discharge from the Ester mine.

Groundwater Chemistry

The chemical composition of water samples from the Ester mine spring and the lake Tvillingvatnet was determined during 1992-1994 (Fig. 5). The Ester spring has significantly higher contents of sodium and silica than the Tvillingvatnet, and lower contents of calcium than the winter water from the Tvillingvatnet. Both water types are far from equilibrium with calcite and dolomite, indicating that long storage times in carbonate rocks are unlikely. The high sodium and silica contents in the groundwater from the Ester mines are due to weathering of silicate minerals. The groundwater chemistry thus indicates that the main groundwater aquifers are silicate rocks (chert, sandstones and conglomerates).

The Tvillingvatnet is totally dominated by a surface water component in the summertime. However, even in the middle of the winter the chemical composition is very different from the composition of the groundwater from the Ester mines. The water chemistry thus indicates that an eventual groundwater component is relatively modest compared with the surface water, even in the winter magazine. The compositon of groundwater from the Ester mine spring, on the other hand, is relatively constant through the year with no marked seasonal variations, indicating leakage from a large groundwater aquifer with transit times longer than one year.

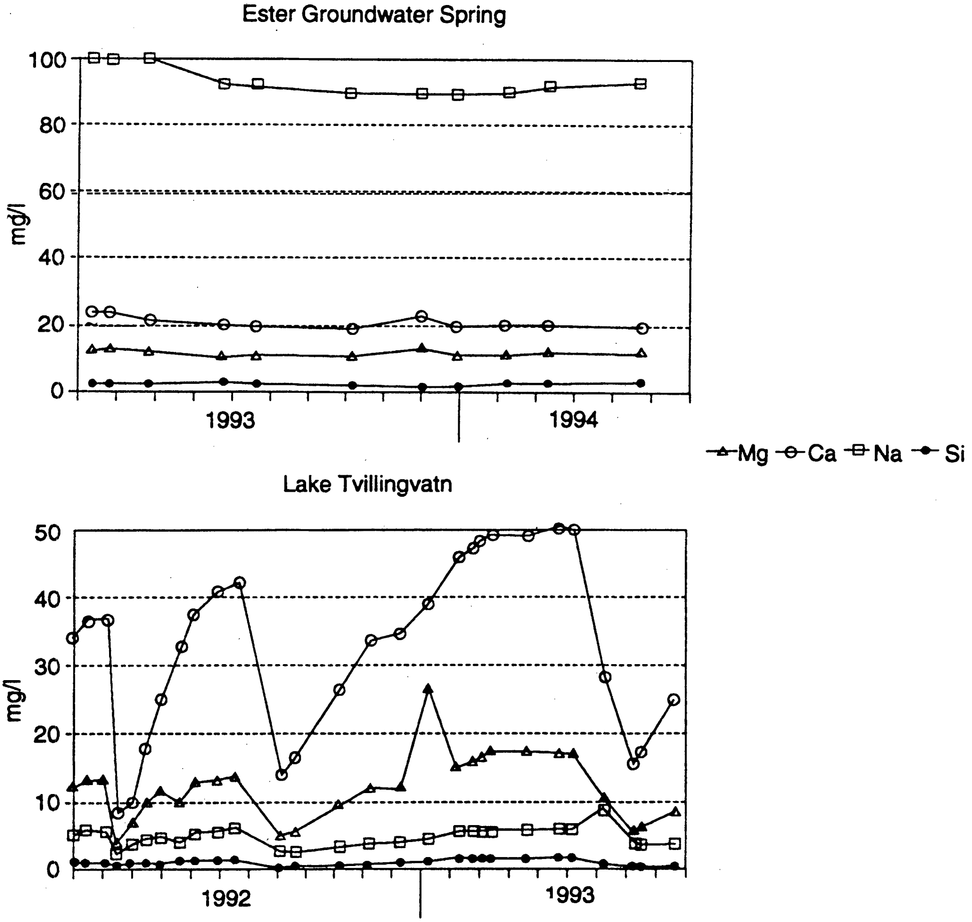

Fig. 5. Chemistry of water samples from Ester groundwater spring and the lake Tvillingvatnet.

Groundwater Recharge as Part of the Hydrological Budget

A direct connection between supraglacial water at the Vestre Lovénbreen glacier and influx of water in the mines was postulated in 1927, when a miner reported the drainage of a small lake on top of the glacier at the same time as a main water influx was reported in the deeper part of the Ester mines (Hoel 1967). The recharge area for the water in the Ester mine spring was, therefore, believed to be the upper part of the Vestre Lovénbreen.

The northwestern branch of the Vestre Lovénbreen glacier (Fig. 4) is the one of most interest in connection with groundwater in the coal mines. It can be divided into an upper and a lower part, probably separated by a ridge of bedrock or drift. All the supraglacial meltwater in the upper part disappears in a main moulin. The moulin is therefore supposed to be a main flow channel for water which later infiltrates the underlying bedrock. The central part of the glacier is underlain by steeply dipping, partly folded, limestone, sandstone and conglomerate (Fig. 3) which may form porous aquifers. The rocks contain at least two (thrust ?) faults, potential zones of increased permeability. The water may flow directly through these rocks or faults and be stored in deep porous aquifers before it flows upwards through the permafrost and discharges at the entrance of the Ester mine (Fig. 3).

If the discharge of 11.6 l/s measured from the Ester mines during the summer and fall of 1993 is representative, this could result in an annual discharge of 365.000 m^3/year. The annual precipitation in the Ny-Ålesund area is around 400 mm. The groundwater discharge thus at least accounts for a recharge area of 1 km^2. The upper part of the Vestre Lovénbreen is about 1 km^2, and the annual groundwater recharge may thus be very close to the total precipitation rate. This conclusion is also supported by the fact that the discharge in the front of the Vestre Lovénbreen is very small compared with neighbouring glaciers. However, it cannot be excluded that some of the recharge takes place also under the Brøggerbreen glacier. Similar sedimentary rocks and fault zones as found under the Vestre Lovénbreen are present also under the Brøggerbreen glacier. The conclusion is nevertheless the same: the groundwater component makes up an important part of the hydrological budget in Ny-Ålesund.

A high groundwater recharge was also the conclusion by Lauritzen (1993) for subglacial water flowing in karst systems from the Vitkovskibreen under the Hilmarfjellet area in Sørkapp, southern Svalbard. In addition, several other high-discharge springs at other glacier catchments in Svalbard (Liestøl 1977) indicate that groundwater may be a very prominent component of the hydrological budget. The subglacial groundwater drainage will then restrict the water flow via englacial and subglacial caves to the front of the glacier and in some cases it may prevent the build-up of high pore pressures along its base. This may have an important influence upon the subglacial and englacial drainage systems.

Interaction Between Different Aquifers

The mining in Ny-Ålesund has resulted in the opening of new, artificial groundwater channels. The present groundwater flow system must be very different from the natural one. The discharge point today is anthropogenically influenced, and the highly manipulated system probably gives a much higher groundwater discharge than would the natural one.

The discharge of groundwater at the bottom of the lake Tvillingvatnet during the first mining period is indisputable. A possible groundwater discharge at the bottom of the lake today is more doubtful, in any case, it is quite limited compared with the discharge through the Ester mines. The discharge might have decreased during and after the last mining period due to a decrease in the pressure potential resulting from the opening of new discharge points in connection with mining. The structural geology makes this quite reasonable. The fault which is found under the Tvillingvatn may continue back to the Vestre Lovénbreen or, more likely, down to the underlying subpermafrost aquifers. The local aquifer under the Tvillingvatnet thus probably belongs to the same groundwater system as the groundwater discharging from the Ester mine.

In a study in northeast China Wang (1990) showed that if the flux of water through the permafrost decreased under a critical value, the flow channel would freeze quickly, while above a certain value the flow would continue for an unlimited time. It is likely that the same model is valid in Svalbard. A manipulation of the groundwater system may result in the freezing of flow channels in the permafrost and end the discharge in moderate-flow springs.

Groundwater Influence on the Permafrost Conditions

The measurement of permafrost depth (140 m) made by Liestøl (1977) in the front of the Brøggerbreen must represent a normal permafrost condition in the area. The depth is in accordance with the conditions in the mines during the first mining period (Orvin 1944). The more discontinuous and shallower permafrost depth (less than 100 m) reported in several mines at the start of the second mining period (E. Grimsmo, pers. comm. 1992), implicates a partial melting of the permafrost between the first and second mining periods. The construction of the mines during the first mining period has made it possible for deep groundwater with a temperature of several plus degrees centigrade to flow upwards through the permafrost and heat the bedrock after the mining stopped. The continuous flow of groundwater through the Ester mines between 1929 and 1946 is therefore probably the direct cause of local melting of the permafrost during this period. Such deep groundwater gives a much more efficient heat transfer than the normal geothermal heat flow through the bedrock.

The relationship between permafrost thickness and groundwater discharge has been studied also other places in the world. Wang (1990) showed how high groundwater discharges in northeastern China resulted in a thinning of the permafrost. Deming *et al.* (1992) showed that the thermal pattern in boreholes along parts of the North Slope of Alaska is consistent with forced convection by a topographically driven groundwater flow system. The importance of groundwater flow systems in areas of permafrost is therefore clearly documented. In Svalbard the groundwater flow may locally have an important influence upon the permafrost thickness, particularly in areas where there are karst springs, but also in other areas where the groundwater fluxes are significant.

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References

Challinor, A. (1967) The structure of Brøggerhalvøya, Spitsbergen, *Geol. Mag. Vol. 104*, pp. 322-336.

Deming, D., Sass, J. R., Lachenbruch, A. H., and de Rito, R. F. (1992) Heat flow and subsurface temperature as evidence for basin-scale ground-water flow, North Slope of Alaska, *Geol. Soc. of Am. Bull., Vol. 104*, pp. 528-542.

Hagen, J. O., and Sætrang, A. (1991) Radio-echo soundings of sub-polar glaciers with low-frequency radar, *Polar Res., Vol. 9*, pp. 99-107.

Hagen, J. O., and Lefauconnier, B. (1993) Reconstructed runoff from the high arctic basin Bayelva in Svalbard based on mass-balance measurements. *In*: Prowse, T. D., Ommanney, C. S. L., and Ulmer, K. E. (eds.) Proc. of the 9th international Northern Research Basin Symposium/Workshop, Canada 1992, NHRI-symposium 10, pp. 155-168.

Hagen, J. O., Korsen, O. M., and Vatne, G. (1991) Drainage pattern in a subpolar glacier: Brøggerbreen, Svalbard. *In*: Gjessing, Y., Hagen, J. O., Hassel, K. A., Sand, K. and Wold, B. (eds.): Arctic hydrology, present and future tasks, NHP-Report 23, pp. 121-131.

Hanssen-Bauer, I., Kristensen, S. M., and Steffensen, E. L. (1990) The climate of Spitsbergen DNMI rapp. 39/90, 40 pp.

Haldorsen, S., and Lauritzen, S.-E. (1993a) Subpermafrost groundwater in Spitsbergen. *In*: Banks, S. and Banks , D. (eds.): Hydrogeology of hard rocks, *I. A. H. Mem., Vol. XXIV*, pp. 940-949.

Haldorsen, S., and Lauritzen, S.-E. (1993b) Grunnvann i Ny-Ålesund (in Norwegian), Nor. Comm. of Hydr. Rep. 24., 26 pp.

Haldorsen, S., and Lauritzen, S.-E. (1993c) Grunnvann på Svalbard: Ny-Ålesund. *In*: Forskermøte: Polar hydrologi, SINTEF-NHL Report STF60 A93081 (in Norwegian), pp. 79-85.

Hoel, A. (1967) *Svalbard III* (in Norwegian), Sverre Kildahls Boktrykkeri. 492 pp.

Hongve, D. (1987) A revised procedure for discharge measurements by means of the salt dilution method, *Hydrological processes, Vol. 1*, pp. 367-370.

Kings Bay (1961) *Østre Centerfelt. Map 1:1000*, Kings Bay Coal Company.

Kings Bay (1963) *Vestre Centerfelt. Map 1:1000*, Kings Bay Coal Company.

Krawczyk, W. E. (1989) Thermal springs below Raudfjellet, South-West Spitsbergen, *Acta Univ. Wratisl, Vol. 1069*, pp. 67-74.

Lauritzen, S.-E. (1991) Groundwater in cold climates: interaction between glacier and karst aquifers. *In*: Gjessing, Y., Hagen, J. O., Hassel, K. A., Sand, K., and Wold, B. (eds.): Arctic hydrology, present and future tasks, NHK-Rep. 23, pp. 139-146.

Lauritzen, S.-E. (1993) Grunnvann på Svalbard: Hilmarfjellet, Sørkappland. *In*: Forskermøte: Polar hydrologi, SINTEF-NHL Report STF60 A93081 (in Norwegian), pp. 69-77.

Liestøl, O. (1977) Pingos, springs and permafrost in Spitsbergen, *Nor. Polarinst., Årbok 1975*, pp. 7-29.

Liestøl (1980) Permafrost conditions in Spitsbergen, *Frost action in soils*, Oslo, Publ. No. 21.

Midbøe, P. S. (1985) Kongsfjordfeltet (Paleocen) Spitsbergen, Thesis, Univ. of Bergen, 226 pp.

Orvin, A. (1934) Geology of the Kings Bay region, Spitsbergen, *Skr. om Svalbard og Ishavet*, 57, 336 pp.

Orvin, A. (1944) Litt om kilder på Svalbard (in Norwegian), *Nor. geogr. tidsskr. Vol. 10*, pp. 16-38.

Pulina, M. (1977) On karst phenomena occurring in the southern part of Spitsbergen, *Kras i Speleologia, Vol. 1 (X)*, pp. 67-74.

Salvigsen, O., and Elgersmaa, A. (1985) Large-scale karst features and open taliks at Vardeborgsletta, outer Isfjorden, Svalbard, *Polar Res., Vol. 3*, pp. 145-153.

Salvigsen, O., Lauritzen, Ø., and Mangerud, J. (1983) Karst and karstification in gypsiferous beds in Mathiesondalen, Central Spitsbergen, Svalbard, *Polar Res. Vol. 1*, pp. 83-88.

Wang, B. (1990) Permafrost and groundwater conditions, Huola Basin, northeast China, *Permafrost and Perigl. Processes, Vol. 1* (1), pp. 45-52.

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