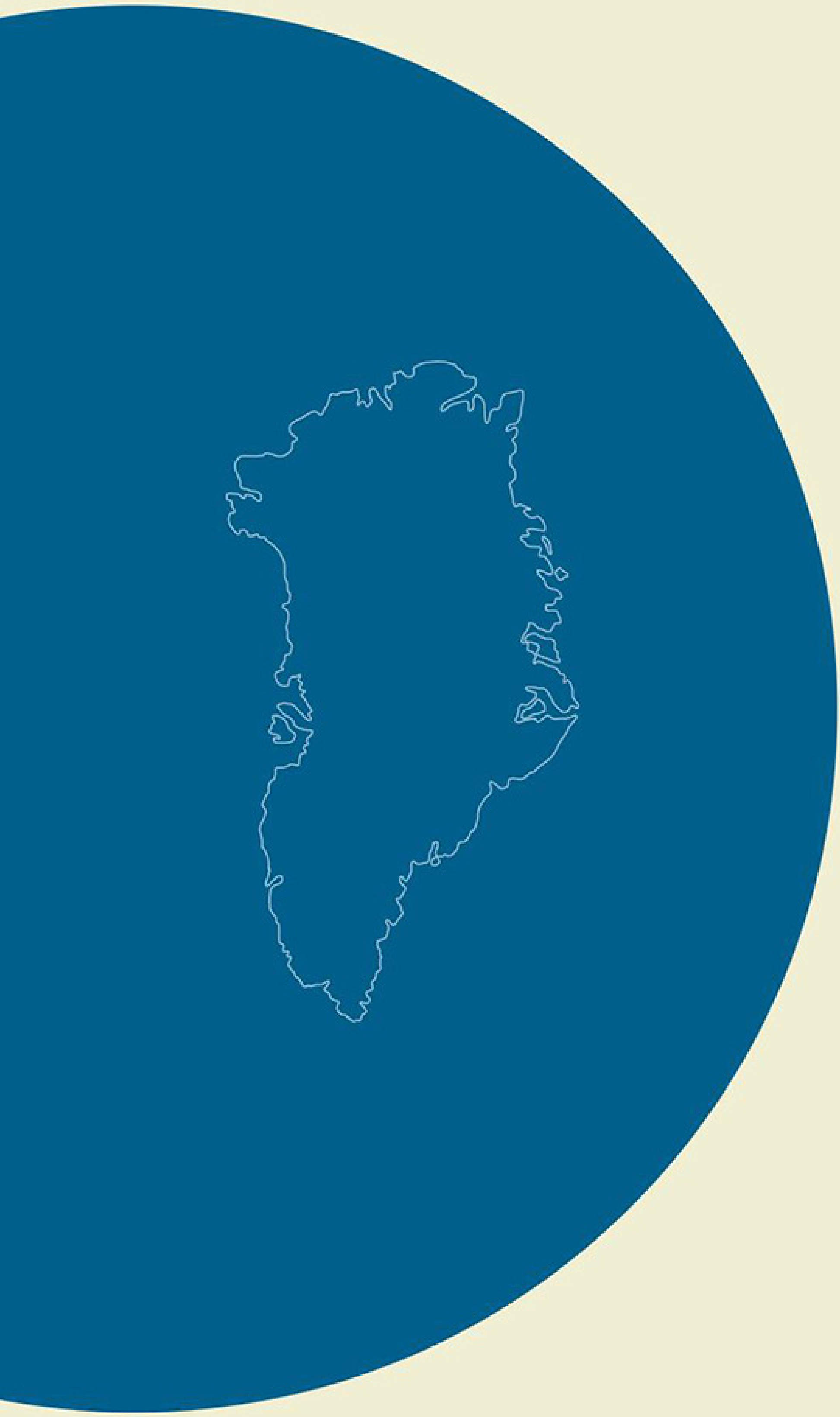
DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2010/97

Previous glaciological activities relating to hydropower in Johan Dahl Land, South Greenland

Andreas Peter Ahlstrøm



GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF CLIMATE AND ENERGY

GEUS

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Contents

1. Introduction

This report provides an overview of the glaciological data and results obtained by the Geological Survey of Denmark and Greenland (GEUS, formerly GGU) in Johan Dahl Land, South Greenland during the observational period from 1977-1983 and from modelling work following this. The report contains no additional work; it is solely intended as an overview of previous glaciological activities by GEUS in the area. The present report relies primarily on the concluding report published (in Danish) by GGU at the termination of the survey in 1983, namely Clement (1983). However, all available reports and publications have been evaluated with regard to the information they contained on the subject of the present report.

The purpose of the survey in 1977-1983 was primarily to acquire data material that could substantiate an evaluation of the importance of the glacial conditions for a possible hydropower production from the Nordbosø basin. The survey was not concluded due to sufficient data and adequate knowledge of the area, but due to lack of appropriation and a change of interest in regional basins to smaller, so-called local basins for the production of hydropower. It was concluded that unresolved problems in Johan Dahl Land still remained at the end of the survey and that sufficiently long time series for a realistic evaluation of the area's potential for hydropower had not been attained.

1.1 The Johan Dahl Land project

The hydropower plans for Johan Dahl Land were started in 1975, when the area was selected as a promising possibility of energy supply for Narssaq, Qaqortoq/Julianehåb and Narssarssuaq and for possible energy demanding industries and mining in the area. (ACG/VBB 1975). With an annual average discharge from Nordbosø (1976–1983) of 170 million m^3 and a drop from the reservoir to the power station at Tunugdliarfik of 640 m, the annual energy production could amount to *c*. 250 GWh/yr. This production can be increased – if necessary – by including neighbouring basins (Thor Sø, Oden Sø, Hullet) to a varying degree (ACG/VBB 1980, GTO 1980).

The survey of Johan Dahl Land was started in 1975 by Grønlands Tekniske Organisation (GTO, now ASIAQ Greenland Survey), which mainly investigated the aspects of discharge and plant construction. In 1977, Geological Survey of Greenland (GGU, the later GEUS) started its glaciological surveys. In 1979, the survey programme was intensified for GGU as well as GTO due to energy research appropriation from the Ministry of Energy. In 1982, Grønlands Fiskeriundersøgelser (GF, now the Greenland Institute of Natural Resources) was included in the project to make environmental investigations.

1.2 The contents of the report

The report provides an overview of the glacio-hydrological conditions of the Nordbosø basin with an emphasis on factors influencing the estimation of the basin's hydropower potential, as this was the focus of the survey conducted in 1977-1983. The references provide an overview of the reports and literature published on the subject. The following sections listed presents the information gathered during the GGU survey in 1977-1983, information that is rather comprehensive although important gaps in our understanding of the basin remained at the end of the survey.

In section 2, a brief account is presented of the meteorological observations made at Base Camp by Nordbogletscher in the summer period of 1978–1983. A comparison is made to corresponding observations in Narssarssuaq, and temperature and precipitation correlations are made. The acquired data are later used for the calculation of the ablation conditions of the Nordbogletscher.

In section 3, an overview of the glacial conditions of the area is given. The Inland Ice sector in the Johan Dahl land area has probably been expanding since the beginning of the 1800 century.

In section 4, the conditions of the Nordbogletscher area are described. It is stated that on Nordbogletscher, a distinction between a topographical and hydrological accumulation area has to be made for Nordbosø. Based on temperature measurements in the accumulation area the refreezing problem is described. The hydrological accumulation area is defined and used for a calculation of the ablation volumes.

The ablation conditions on Nordbogletscher are primarily dependent on temperature variations, and in section 5, a correlation between the total ablation and the temperature conditions in Narssarssuaq is given.

Since Nordbogletscher is not situated in a well-defined basin, its mass balance cannot be calculated directly. To get an idea of the mass balance conditions in the area, the neighbouring, local and more well-defined glacier on the Valhaltinde massif was chosen. The mass balance was subsequently measured 1978-1983. The results are described in section 6. Furthermore, a model calculation of the mass balance of the Valhaltindegletscher for the period 1962–1983 is presented.

In section 7, the influence of Nordbogletscher on the discharge from Nordbosø is described. Nordbogletscher is the most important water resource of the area and also has a stabilising effect on the variations of the annual discharge. Complete agreement between GTO's measured discharge from Nordbosø and the calculated discharge from the measured ablation and precipitation data from GGU is shown.

In section 8, the most important ice-dammed lakes' drainage conditions in the area are described. Base Camp Sø is located in the accumulation area of Nordbosø and therefore has a direct impact on the discharge volume from Nordbosø, while an exploitation of the water resource from Hullet may be possible at a later stage if the hydropower potential is to be increased.

2. The climatic conditions in Johan Dahl Land

2.1 General climatic conditions

The general climatic conditions in South Greenland can be characterised by a mixture of a temperate and sub-arctic climate dominated by maritime conditions.

The most important air masses influencing the area are the continental polar air mass which is cold and dry and the north Atlantic more humid maritime air mass. The clash between the two air masses gives rise to cyclone activity responsible for the major part of the precipitation. The cyclone passage is generally from west to east, but due to the Inland Ice the cyclones can be pushed along the west coast of Greenland, making South Greenland the dividing point of the track of the cyclones. From the coastal areas to the inner parts at the bottom of the fjords and close to the edge of the Inland Ice the climate changes from maritime conditions to more continental conditions.

South Greenland is characterised by its many Foehn winds. The Foehn, which is a relatively hot and dry wind, blows from the Inland Ice towards the coastal areas with sometimes hurricane force. The frequency is highest during the autumn and winter months in connection with the filling of passing depressions at the coasts.

The nearest meteorological station to Johan Dahl Land is Narssarssuaq (26 m a.s.l.) operated by the Danish Meteorological Institute (DMI) since 1961. The annual mean temperature in Narssarssuaq for the period 1961–1980 was 1.3°C, July being the warmest month (10.2°C) and December being the coldest month (–6.1°C) (Fig. 2.1). The annual precipitation (1961–1980) was on average 632 mm with a variation from 379 mm in 1968 to 1067 mm in 1975. In general, the amount of precipitation is highest during the late summer and autumn months (Fig. 2.1). As the warmest month is above 10°C on average, Narssarssuaq belongs by definition to the temperate climate zone, but the term sub-arctic must be said to be more appropriate in this case.

2.2 Meteorological measurements at Nordbogletscher

At GGU's camp by Nordbogletscher (Base Camp station, 850 m a.s.l.) meteorological observations were carried out in the summer period 1978–1983. The station was read and checked twice a day (08.00 and 20.00); the most important results, on a monthly basis, are summed up in table 2.1.

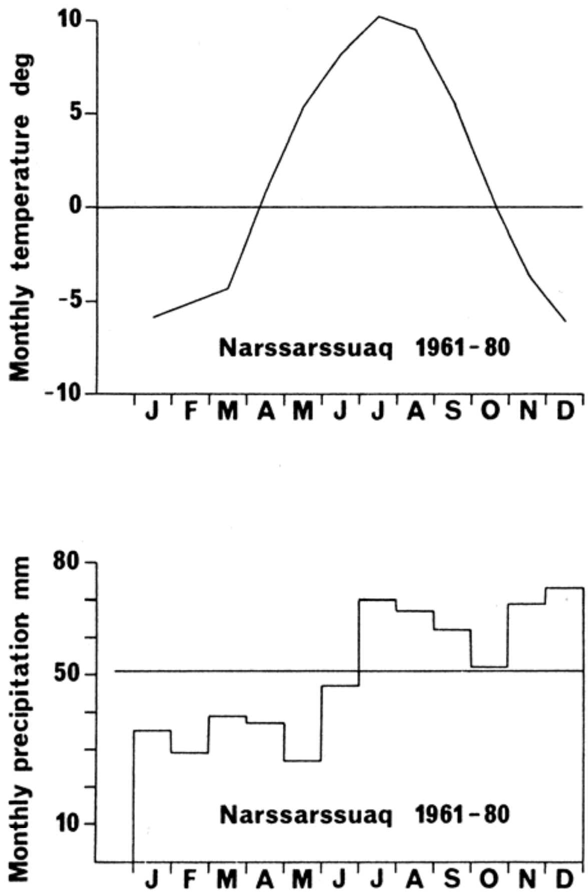


Figure 2.1 *Monthly temperature and precipitation conditions in Narssarssuaq 1961–1980. Data from DMI.*

2.2.1 Temperature conditions

The temperature was registered on a 7-day thermo-hygrograph installed in a Stevenson hut 2 m above terrain. The temperature curve was calibrated with a set of extreme thermometers and a standard thermometer.

During the period 1978–1983 the average temperature in June was 2.7°C, in July 5.3°C and in August 3.8°C. The warmest month registered was July in 1978 with 6.8°C. The highest temperature registered on the maximum thermometer was 16.4°C (30 July 1981). While the variation in the summer average temperature was relatively small from year to year (3.9°C ± 0.6°C) the individual months have shown larger variations.

2.2.2 Precipitation conditions

Precipitation was measured 1.5 m above terrain in a standard precipitation meter of the Hellman type. The average precipitation during the summer period 1978–1983 was 279 mm with a variation from 169 mm to 424 mm. By far the largest amount of precipitation falls in the form of rain, however, snow may occur at the beginning of June or at the end of August.

Precipitation shows large monthly variations as well as variations over the summer. The highest registered monthly precipitation was in August 1978 (181), on the other hand, August 1980 was the driest month with only 8 mm. The highest daily precipitation was registered on 5 August 1978 (50.2 mm).

2.2.3 Hours of sunshine

The number of hours of sunshine was registered on a Campbell-Stoke sunshine recorder. July peaks with an average of 211 hours, while June and August both had c. 189 hours of sunshine. Great variations have, however, been registered in July, from an average of 10.4 hours/day in 1979 to 3.8 hours/day in 1983.

2.2.4 Potential evaporation

The potential evaporation was registered using an evaporimeter with a weight device of the Piche type from Lambrecht. The total, potential evaporation in the summer period was on average 180 ± 23 mm.

From 1981 the potential evaporation was also measured with a Class A pan from Belfort (10” deep and 47.5” inner diameter) installed directly on the ground. The results were corrected with a pan coefficient of 0.75. The two meters were in fine agreement.

2.2.5 Humidity

The relative humidity was registered on the thermograph and converted to absolute values on the basis of the temperature measurements. On average the absolute humidity was 6.3 mb.

2.2.6 Wind conditions

The wind velocity was registered 4 m above terrain by means of a cup anemometer plugged into a counter. The distance covered by the wind in kilometres was by and large the same for the individual summers. The average wind velocity was 3.2 m/s; however, this measurement is not really representative for the areas, since the tendency is that there is no wind at all or the wind is strong. The wind direction is in general light from N–NV, but if a change of wind direction to Ø–NØ or SØ occurs the wind picks up (often Foehn or passages of low pressure).

Base Camp Station	June	July	August	Summer
Monthly mean temperature (°C)				
1978	1.0	6.8	5.0	4.3
79	2.2	4.3	4.6	3.7
80	3.3	4.9	4.3	4.2
81	4.3	6.2	3.7	4.7
82	2.8	4.8	3.3	3.6
83	2.3	4.5	2.1	3.0
Mean	2.7	5.3	3.8	3.9
Monthly precipitation (mm)				
1978	84	101	181	366
79	117	52	35	204
80	118	43	8	169
81	81	88	41	210
82	29	161	108	298
83	139	138	147	424
Mean	95	97	87	279
Sunshine duration (hrs)				
1978	188	226	106	520
79	203	321	263	787
80	182	262	286	730
81	205	172	168	545
82	220	170	180	570
83	134	117	125	376
Mean	189	211	188	588
Potential evaporation (mm)				
1978			61	
79	39	64	107	210
80	54	63	69	186
81	57	79	50	186
82	53	56	64	173
83	49	43	54	146
Mean	50	61	69	180
Absolute humidity (mb)				
1978	4.9	6.8	6.3	6.0
79	5.4	5.8	5.8	5.7
80	6.0	6.3	5.8	6.0
81	6.1	6.7	6.2	6.3
82	6.7	7.5	6.6	6.9
83	6.3	7.7	6.4	6.8
Mean	5.9	6.8	6.2	6.3
Global radiation ($cal/cm^2\ d^{-1}$)				
1981	430	313	279	340
82	427	335	290	350
83	356	278	243	292
Mean	404	309	271	327
Mean wind speed ($m/s\ d^{-1}$)				
1978	3.4	3.7	3.3	3.5
79	2.5	3.0	3.8	3.1
80	3.0	3.0	3.2	3.1
81	3.0	3.9	2.8	3.2
82	2.7	3.4	3.9	3.3
83	3.9	2.8	3.0	3.2
Mean	3.1	3.3	3.3	3.2

Table 2.1 *Summary of meteorological observations at Base Camp, 850 m a.s.l., Johan Dahl Land, 1978–1983.*

2.2.7 Radiation conditions

Measurements of the global radiation (shortwave radiation) were made with a pyranograph from Belfort. The registered radiation curve was measured with a planimeter, and the daily radiation calculated. The average, daily radiation in June was 404 cal/cm^2, in July 309 cal/cm^2 and in August 271 cal/ cm^2.

2.3 Other meteorological measurements in the area

Besides at the Base Camp, measurements of temperature and precipitation were made at 'Glacier Station', located in middle of the Nordbogletscher 850 m a.s.l. and 2 m above the glacier surface. The temperature at Glacier Station is in general lower than at Base Camp due to the cooling of the air masses when passing over the ice. The temperature correlation between the two stations is given by

$$T_{G1} = 0.78\ T_{BC} - 0.90 \qquad (r^2 = 0.89)$$

where T_{G1} = monthly mean temperature at Glacier Station °C

and T_{BC} = monthly mean temperature at Base Camp °C

The precipitation at Glacier Station was a bit higher than at Base Camp, but the difference is not significant.

The precipitation was also measured by 14 meters placed in the ice-free accumulation area of Nordbosø at various elevation intervals on the Valhaltinde massif. The tendency is that the precipitation increases from Nordbosø to the *c*. 1000 m level, and then it remains more or less constant. Calculations show that the average precipitation for the entire Valhaltinde area (considering the height–area distribution) is by and large identical to the measured precipitation at Base Camp (Clement 1981). The precipitation measurements at Base Camp must thus be representative for the entire Nordbosø basin.

2.4 Regional climatic conditions

It is possible to make a comparison between the results from Base Camp Station and the meteorological station in Narssarssuaq for the summer period.

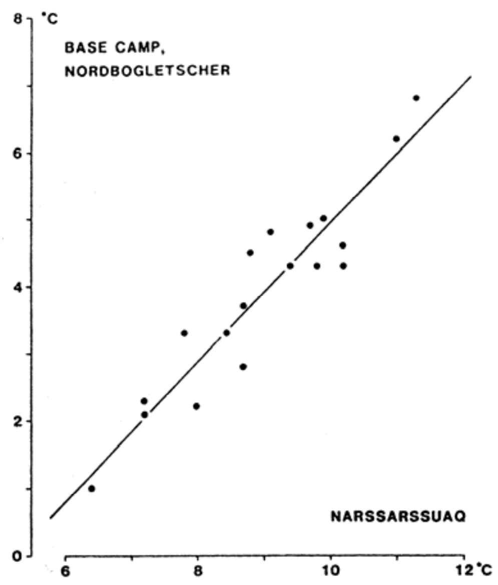


Figure 2.2 *Relation between monthly mean temperature at Narssarssuaq and Base Camp during the summer months 1978–1983.*

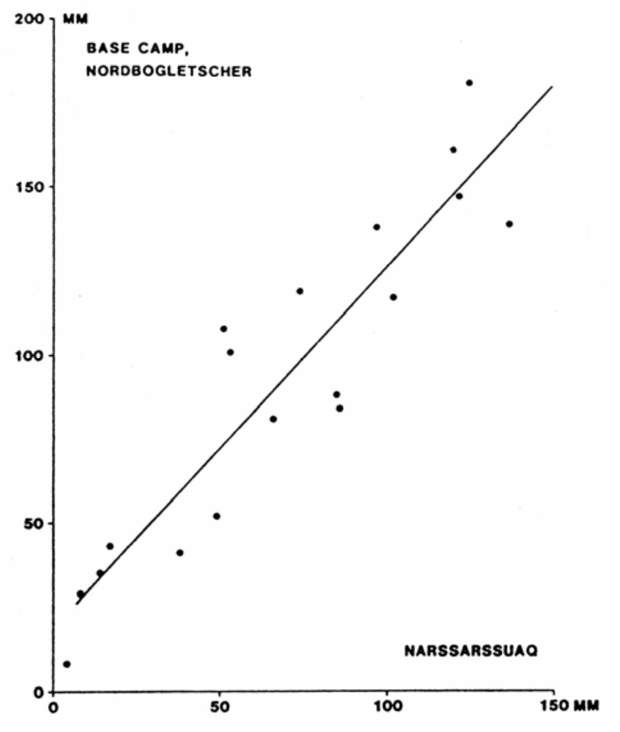


Figure 2.3 *Relation between monthly precipitation at Narssarssuaq and Base Camp during the summer months 1978–1983.*

Between the two stations there is a temperature lapse rate of 0.62 ± 0.06°C/100 m. Fig. 2.2 shows the correlation between monthly mean temperatures at the two stations. The correlation is given by

$$T_{BC} = 10.03\ T_{NSSQ} - 5.38 \qquad (r^2 = 0.88)$$

where T_{BC} = monthly mean temperature at Base Camp (°C)

and T_{NSSQ} = monthly mean temperature in Narssarssuaq (°C)

The precipitation at Base Camp is higher than the precipitation in Narssarssuaq (Fig 2.3). The precipitation correlation is given by

$$P_{BC} = 1.08\ P_{NSSQ} + 18.21\ (r^2 = 0.85)$$

Where P is the monthly precipitation (mm) in Narssarssuaq and at Base Camp.

3. Glacial conditions in Johan Dahl Land

3.1 Overview

From the inner parts of the Inland Ice, the ice moves towards the coast and close to the margin of the Inland Ice the ice is directed into separate outlet glaciers. Two types of sectors can in principle be distinguished along the margin of the Inland Ice:

Active sectors: In these sectors the ice moves all the way to or close to sea level. It is often large calf-ice producing glaciers situated at the bottom of large fjord complexes. The glacier movement is normally high (1–10 km/yr), the glaciers are often strongly crevassed, but with marked flowlines.

Quiet sectors: These sectors are situated between the active sectors, causing the margin of the Inland Ice to be relatively high above sea level.

The active sectors have a very large accumulation area. On satellite pictures, the drainage areas can be traced far into the Inland Ice, where they fan out and almost 'suck the ice up' from the more quiet neighbouring sectors (Thomsen 1983). Seen in a glacial-hydrological perspective the delineation between the active and quiet sectors constitutes a major problem.

The active sectors cannot be used for hydropower production due to the low elevation above sea level of the glacier front and lack of suitable reservoirs. Therefore the identification of suitable basins for hydropower is always connected to the quiet sectors; this identification, however, may have a reducing effect on the size of the drainage areas on the ice, and thus on the volume of meltwater at disposal.

The Johan Dahl Land area is surrounded by two active sectors, Eqalorutsit kangigdlît sermiat (the name most often appearing on maps, although a more correct name for the glacier is Qajuttap Sermia) and Qôrup sermia (Fig. 3.1), which both drain to sea level. Between these two main glaciers, the northerly and more quiet sector of the Inland Ice consisting of Nordbogletscher, Nordgletscher and Østgletscher is found. Their terminus positions are all within the elevation interval of 600–700 above sea level. Both Nordbogletscher and Nordgletscher may, however, be regarded as side glaciers in the main drainage system, which runs through Eqalorutsit kangigdlît sermiat.

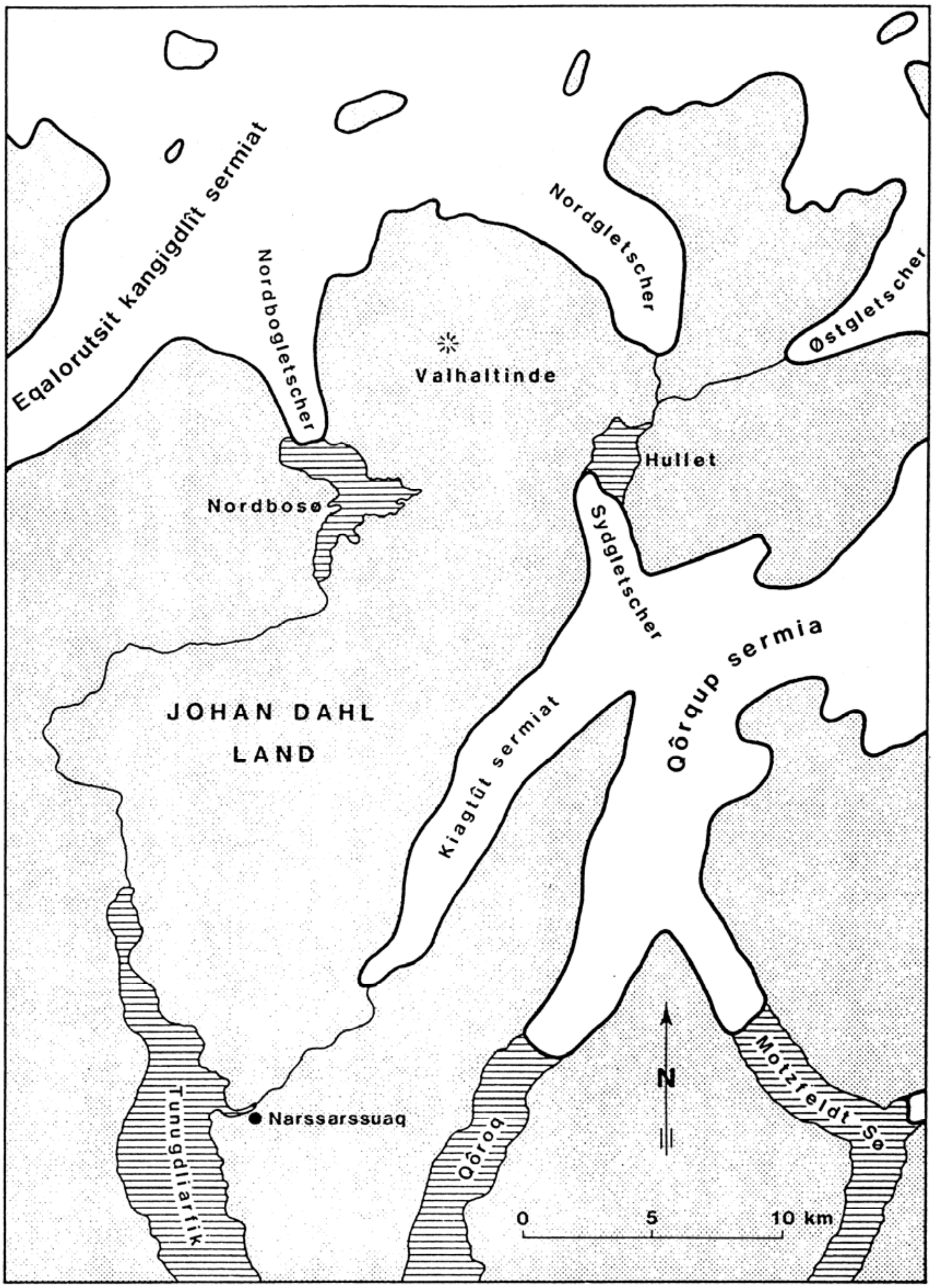


Figure 3.1 *Map showing the Johan Dahl Land area, South Greenland.*

3.2 Glacier front conditions

The Inland Ice outlet glaciers in South Greenland have in general been receding and thinning since the 18th century (Fig. 3.2) This recession, which applies both to the active and the quiet sectors, has most likely primarily been caused by a warmer climate after the culmination of ‘the little ice age’ in the 17th century. The recession has locally been very marked (10–20 km), and has left wide-spread boulder fields, moraine systems and trimline zones in front of the present glacier fronts. From 1900 to 1920 a small advance occurred, but after that the general recession tendency was resumed.

The Johan Dahl Land area, however, is a special case (Fig. 3.2.), because the general recession trend has not been followed here. Eqalorutsit kangigdlît sermiat, Nordbogletscher as well as Nordgletscher are characterised by the lack of a trim line zone, and their present frontal positions are presumed to be the most advanced in historical time. The entire area has probably been expanding during the past centuries; it is difficult to date the start of this advance, but historical accounts exist that Eqalorutsit kangigdlît sermiat in the beginning of the 19th century advanced and buried Norse settlers’ ruins (Weidick 1982). More detailed investigations during the past years have substantiated that the advance trend continues (Clement 1982). Both Nordbogletscher and Nordgletscher have advanced considerably and both fronts have seen the 1940s advanced with an average velocity of 17 m/year.

As it appears from Fig. 3.2 it is a connected part of the Inland Ice that is expanding. As the main drainage is through Eqalorutsit kangigdlît sermiat, it is reasonable to suppose that the trends of Nordbogletscher and Nordgletscher have been determined by the larger glacier. The question is why this part of the Inland Ice has advanced, while the surrounding sectors all have receded. This question remains unsolved.

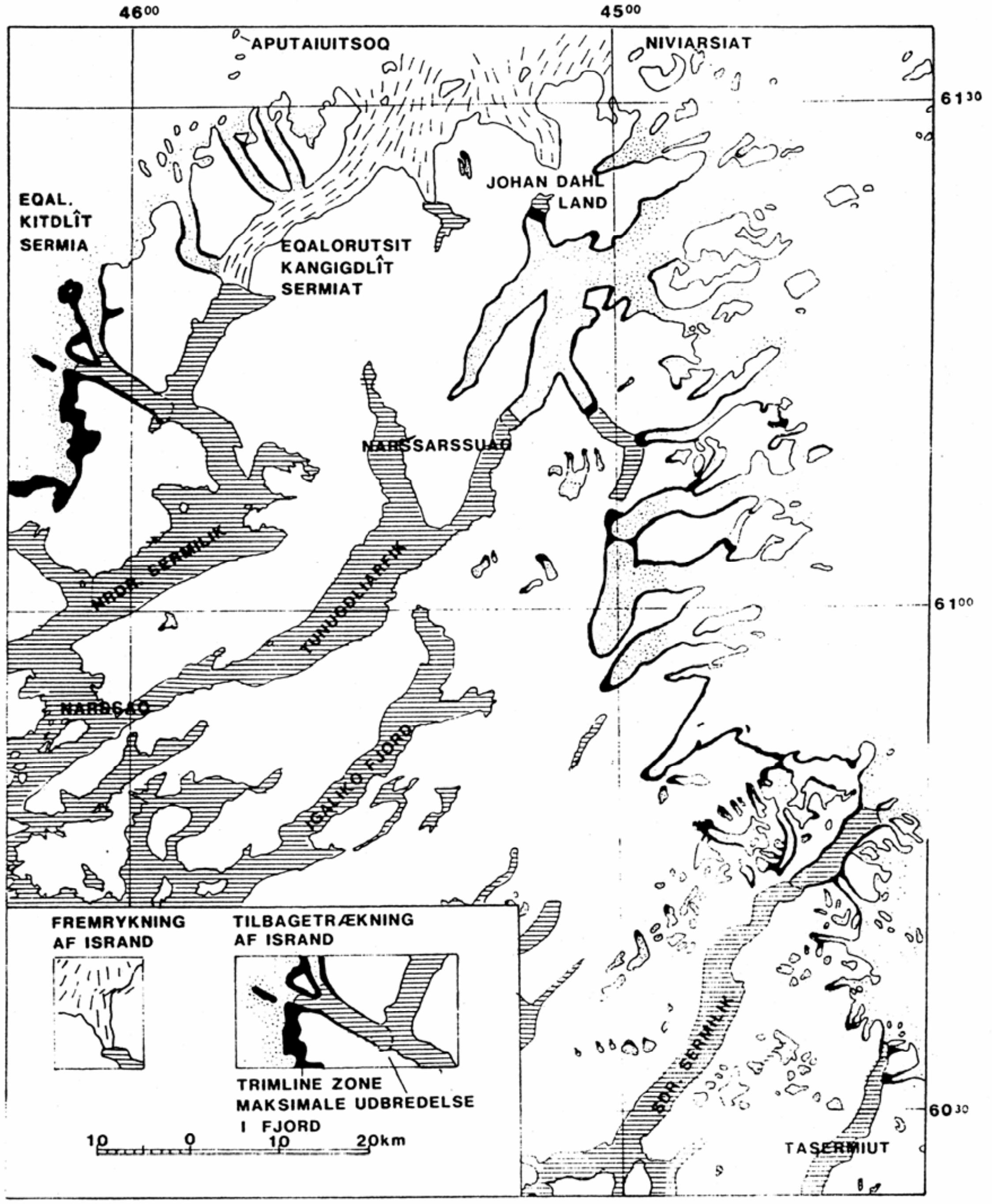


Figure 3.2 *Map showing position of the Inland Ice margin in South Greenland. Black areas indicate recession sectors while dashed ornament indicates sectors under expansion (from Weidick, 1982).*

4. Nordbogletscher

The plans for hydropower in Johan Dahl Land were based on the use of Nordbosø as reservoir. In this connection Nordbogletscher is the most important water resource, since the drainage from the glacier contributes with 60–70% of the drainage volume from the Nordbosø.

The survey of Nordbogletscher was started by GGU in 1977, when a camp (Base Camp) at the east side of the glacier was set up 850 m a.s.l. Since then, an extended network of stakes was set up on the glacier to cover all elevation intervals from the frontal area to the other parts of the accumulation area. Data and results were published as reports from GGU (Olesen & Weidick 1978; Clement 1980, 1981, 1982 and 1983).

4.1 The front conditions at Nordbosø

Nordbogletscher flows directly into Nordbosø, 660 m a.s.l. Due to the insignificant calf-ice production to the Nordbosø and the front’s characteristic, convex profile it was presumed that the front was not floating.

Depth and sediment conditions in Nordbosø have been surveyed by Larsen (1981). The depth at the advancing glacier front varies from 50 m to 150 m. The distribution of sediment in the lake showed that the bottom sediments primarily were deposited from the east, and most likely originates from an earlier period, when a glacier advance from east (Østgletscher) pushed into the valley between Hullet og Nordbosø (Weidick 1963). No deposition cone was found from Nordbogletscher, and no sign of drowned end moraines was found. The observations indicate that Nordbogletscher has been under constant advance for a long time (up to 1983), so that a major part of the glacier sediments (from Nordbogletscher) is constantly passed over by the advance ice front.

The oldest information about Nordbogletscher is an aerial photo from the Geodetic Institute (now the National Survey and Cadastre, KMS) from 1942. Since the photo does not show a trim line zone, it must be presumed that the glacier at this time is advancing. When this advance started is not known, but probably the Nordbogletscher has been more or less constantly advancing since the beginning of the 19th century (Weidick 1982). A more recent aerial photo from 1953 shows that during the period 1942–1953 the glacier advanced *c*. 360 m (32.7 m/yr). The advance continues the following years and amounts to further 265 m (11 m/yr) for the period 1953–1977. An aerial photo from 1981 showed that the front had advanced 40 m (10 m/yr) since 1977. This is a total advance of 665 m between 1942 and 1981, or an annual, average advance of 17 m.

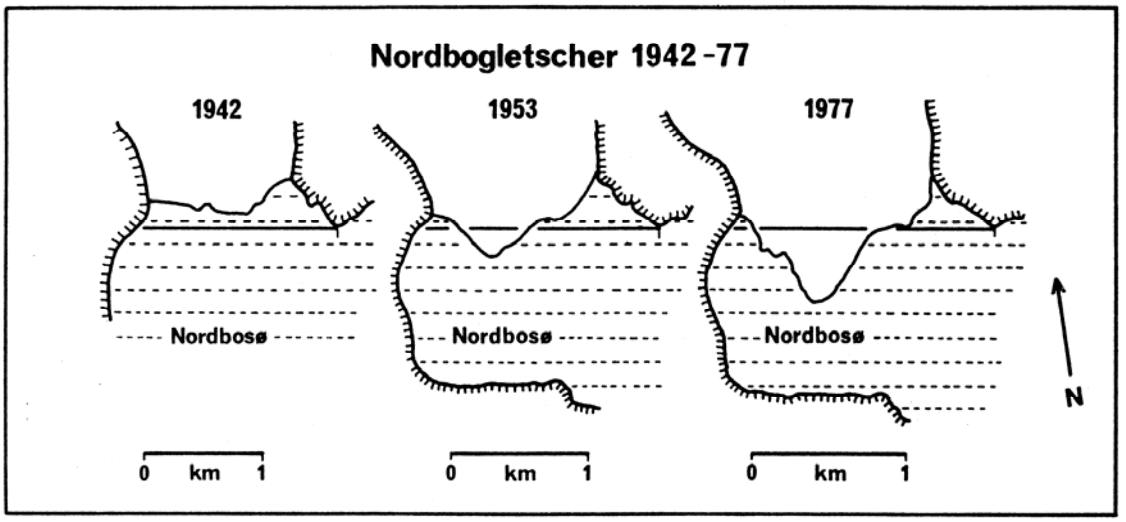


Figure 1. *Sketch map of the snout area of Nordbogletscher at shown on aerial photographs from the Geodetic Institute (1942 and 1953) and Aerokort A/S (1977).*

Nordbogletscher also expands along its sides and in several places it can be seen that the glacier erodes into old areas of vegetation. At the Base Camp station the glacier side had moved 10 m closer in between 1981 and 1983. There were also several indications that the glacier thickness had increased during these later years of the survey.

In 1983, the frontal position of Nordbogletscher seemed to be the most advanced in historical time. During the period 1942–1981 Nordbosø has been reduced with 0.4 km^2 (4%). If this advance velocity continues it may influence the suitability of the lake as a reservoir.

4.2 Delineation issues on Nordbogletscher

Nordbogletscher is an outlet glacier from the inland ice sheet, implying that it does not have well defined boundaries. Delineation towards the neighbouring glaciers is difficult, especially at higher elevations. The investigations at Nordbogletscher have shown that it is necessary to distinguish between two kinds of catchment delineation, depending on the intended application:

1) Topographical catchment
The topographical catchment of Nordbogletscher is defined as the catchment from which the <u>ice</u> is assumed to flow towards Nordbosø. The topographical catchment is based on the map sheets of the Geodetic Institute and is delineated under the assumption that ice flows perpendicular to the elevation contours. Additionally, the glaciological principle that every ablation area has its accumulation area is applied. The topographical catchment of Nordbogletscher is approx. 208 km^2.

2) Hydrological catchment
The hydrological catchment of Nordbogletscher is defined as the catchment from which <u>water</u> is assumed to flow towards Nordbosø. The hydrological catchment is based on in-

formation derived from satellite imagery, radio-echo soundings and field observations, as well as knowledge of the refreezing process in the firn area. The hydrological catchment of Nordbogletscher is approx. 57 km^2.

One of the main aims of the investigations on Nordbogletscher was to calculate its mass balance. However, this proved difficult. A stake network was established in the topographical catchment of the glacier, making it possible to determine the mass balance parameters. However, calculations showed a relatively large inconsistency between the ablation and the discharge from Nordbosø, as the ablation turned out to be 40-60% higher than the measured discharge (Clement 1982, 1983).

The inconsistency does not necessarily imply that the mass balance is wrong, but might rather indicate that the water follows another routing system than the topographical catchment. The water might for example flow internally in the ice along directions different from the ice movement. Water reaching the bottom of the glacier will move along the bedrock topography which might be different than the surface topography, subglacial thresholds might redirect water into neighbouring basins, and so on. In other words, Nordbogletscher might have more exits for the water than the one at the glacier front. This also implies that the concept of mass balance is not immediately applicable to Nordbogletscher as the glacier is not residing in a well-defined basin.

The inconsistency between ablation and discharge is also affected by the fact that previous calculations have not included refreezing of meltwater in the accumulation zone.

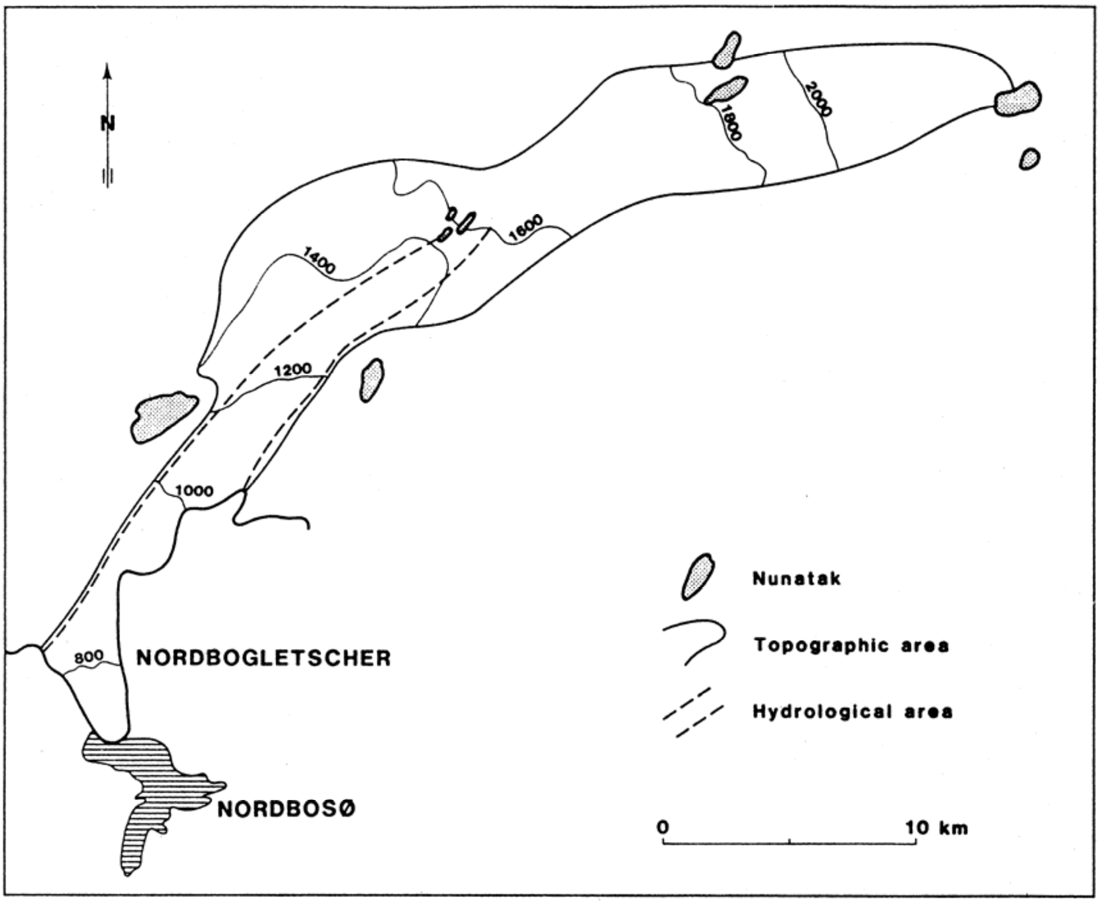


Figure 4.2 *Sketch map of Nordbogletscher showing the topographical and hydrological catchments, respectively.*

When estimating the influence of Nordbogletscher on the discharge from Nordbosø, it is necessary to know how much water stems from the glacier. This is the reason for introducing the term ‘hydrological catchment’. This catchment cannot be identified through ordinary map studies, but has to build on, among other things, the sub-surface topography.

4.3 Subglacial conditions

A limited amount of knowledge has been obtained regarding the subglacial conditions of Nordbogletscher and a preliminary map of the bedrock is drafted as Fig. 4.3. The map information is based on interpretation of satellite images and radio-echo soundings.

a) Interpretation of satellite images
Interpretation was carried out on Landsat imagery, digitally enhanced on the IDIMS-system (installed at the Technical University of Denmark) by Henrik Højmark Thomsen, GGU. The method which included geometrical correction and contrast enhancement is described in Thomsen (1983). The Landsat images are well suited to identification and mapping of surface structures on the Inland ice, which in a damped form represent basal topography. Thus, it is easy to trace striking flow lines and subglacial ridges.

It turns out that upstream from the nunataks in the Nordbogletscher region, one finds extensive areas with relatively shallow ice.

b) Radio-echo sounding
GGU had a radar system developed in collaboration with the Institute for Electromagnetism, DTH, to measure the thickness of the ice. A 300 MHz radar, installed on a helicopter or dragged on a sledge after a snow scooter, was applied to Nordbogletscher. Data was collected on videotape. Fieldwork was conducted with the instrument in autumn 1982 and spring 1983, collecting data from several hundred kilometres of profile lines. However, results did not quite match expectations, since no echo was received in some regions (especially crevasse fields) and interpretation was difficult in several instances.

The depths shown in Fig. 4.3 were derived from distinct echoes, presumed to originate from the bottom. The measurements were cross-checked since similar results were obtained from helicopter and snow-scooter. The ice thickness was approx. 180-260 m in the majority of the area, but reached 700 m in the northern part (outside the nunatak area). In the central part of the front of Nordbogletscher, the depth was measured to be approx. 400 m (with 60 MHz). Results should be considered preliminary, as the interpretation difficulties for the echoes located were never completely resolved.

The subglacial conditions in the Johan Dahl Land region are rather complicated due to the many nunataks and the subglacial thresholds connecting them. The nunataks only constitutes the highest parts of an ice-covered, rugged terrain. The majority of the ice moves towards the great valley containing Eqalorutsit kangigdlît sermiat and the flow lines of this glacier can be traced all the way up to an elevation of 1600 m a.s.l. The subglacial thresholds can be identified in the field as heavily crevassed terrain and as icefalls. The subglacial conditions are significant for delineation of the hydrological catchment of Nordbogletscher.

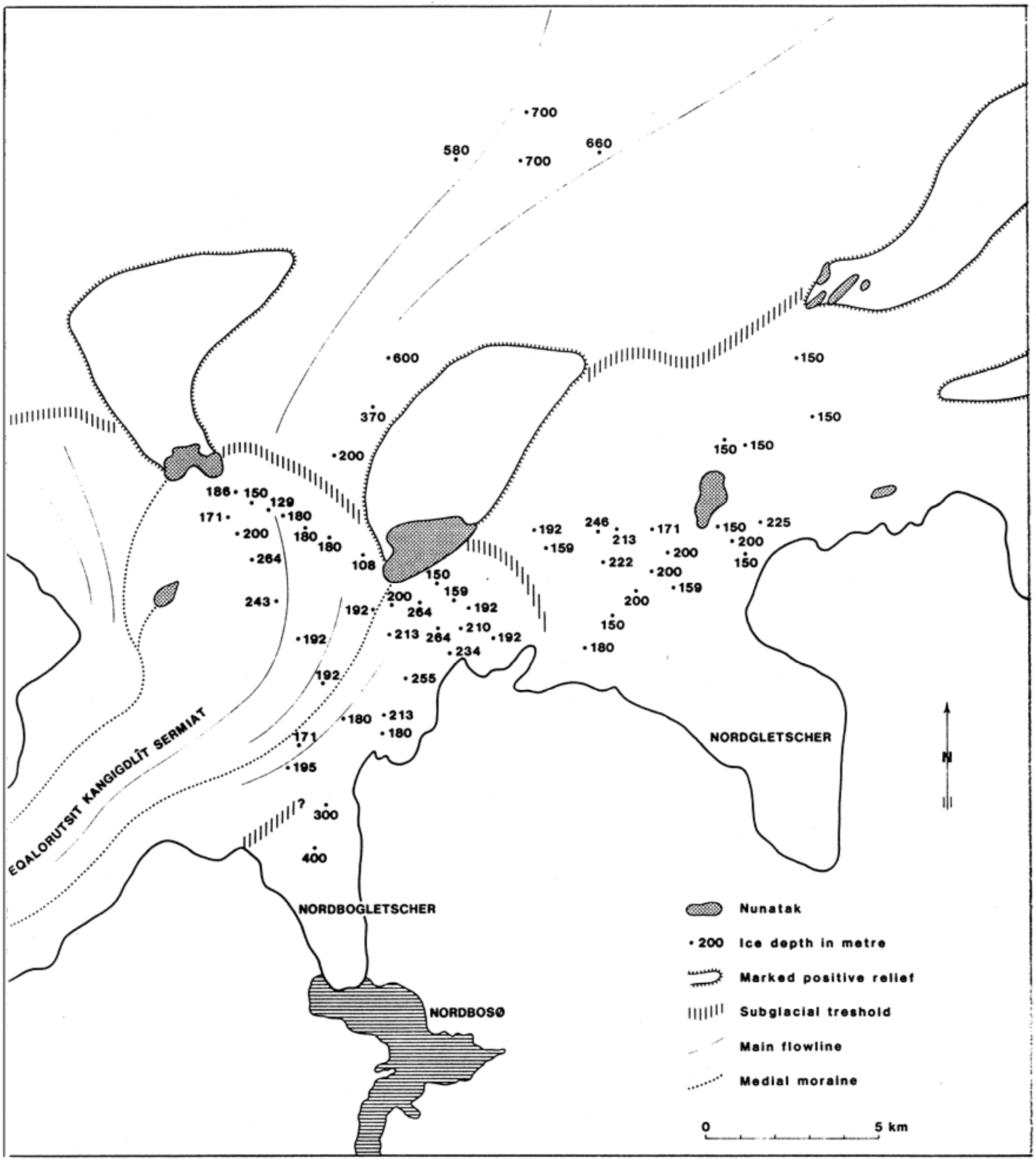


Figure 4.3 *Preliminary map showing subglacial conditions around Nordbogletscher based on satellite images and radio-echo soundings.*

4.4 Glacier movement

The glacier movement on Nordbogletscher was determined by forward intersection to stakes from fixed points on the cliff. All measurements were done with a 400° theodolite Carl Zeiss Jena 010.

The annual mean centre line velocity of the lower reaches of Nordbogletscher (750–900 m a.s.l.) was found to be approx. 90 m/yr, decreasing towards the sides. There was a tendency that the velocity increased to just over 100 m/yr closer to the front. The velocity in the elevation interval 1050–1100 m a.s.l. was significantly higher (Fig. 4.4), increasing from the valley side towards the 1370 nunatak. For example, halfway between the valley side and the nunatak the velocity was 1 m a day or four times higher than at the frontal area itself. Presumably, the divide between Eqalorutsit kangigdlît sermiat and Nordbogletscher is found between the velocity points 245 m and 358 m (Fig. 4.4).

The velocity of Eqalorutsit kangigdlît sermiat was measured at 600 m a.s.l. using terrestrial photogrammetry, obtaining a value of approx. 1500 m/yr (Knudsen, 1983). The velocity pattern of the area fits well with the subglacial pattern, outlined in Fig. 4.3.

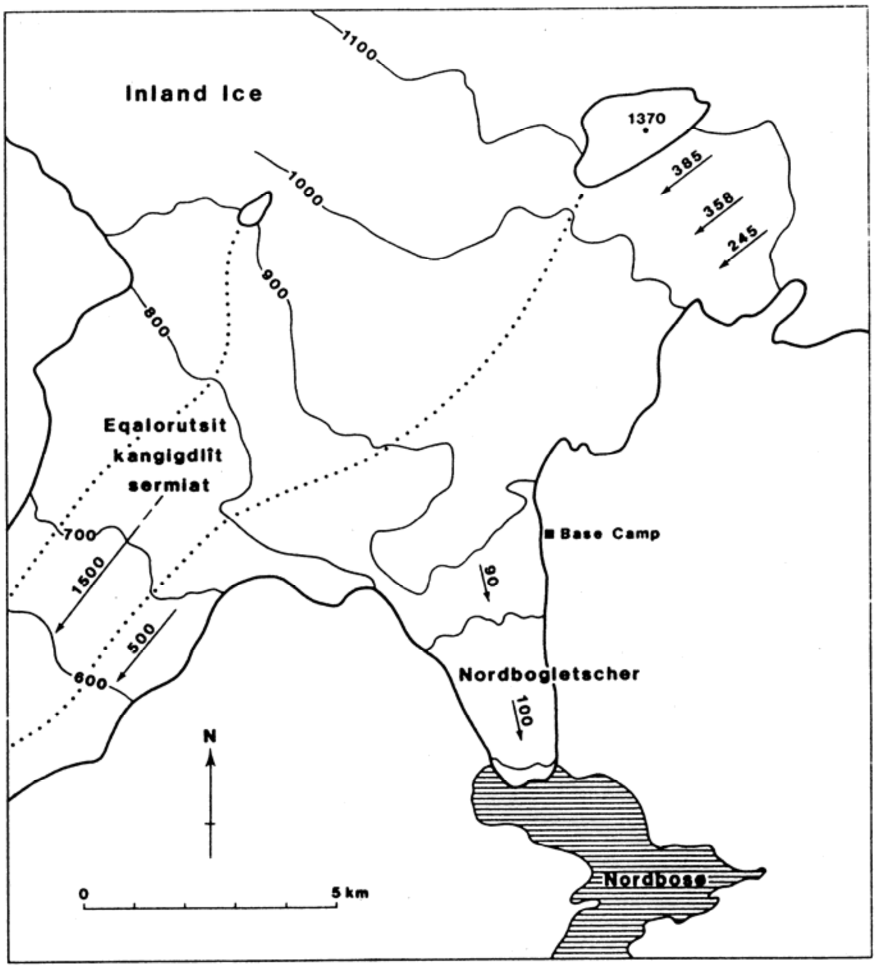


Figure 4.4 *Map showing the measured velocities (metres/year) on Nordbogletscher and Eqalorutsit kangigdlît sermiat. The tongue of Nordbogletscher can be regarded as an overspill from the main drainage system entering the deep valley containing Eqalorutsit kangigdlît sermiat.*

4.5 Zonation and temperature conditions of the accumulation area

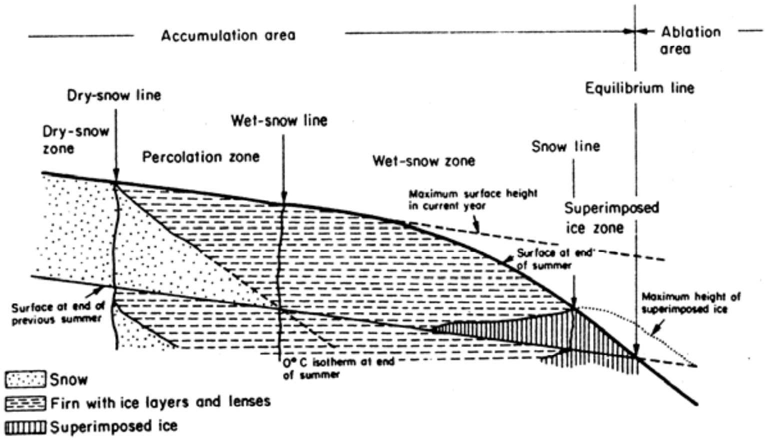
The accumulation area can be separated into a number of characteristic zones, divided primarily by differences in temperature. The division of the accumulation area in zones was developed by Benson (1961) following a series of traverses across the inland ice, and expanded by Müller (1962) after investigations on Axel Heiberg Island. The terminology used here is the one used in Paterson (1981), see also Fig. 4.5.

From a mass balance perspective, it is important to know whether the entire winter snowpack reaches 0°C during the summer period, as this is a necessary prerequisite for ablation to occur from the dry-snow zone and the percolation zone.

The most efficient mechanism for heating the snowpack is refreezing of meltwater in the snow. Both the percolation zone and the wet-snow zone experiences snow melt in the summer; the meltwater seeps into the snow and refreezes when it attains a depth where the snow temperature is below 0°C. Refreezing of 1 g of water releases enough latent heat to warm up 160 g of snow or firn by 1°C (Paterson, 1981). The process of refreezing is far more important than heat conduction as a warming mechanism. In the wet-snow zone, the entire winter snowpack is heated to 0°C, eventually allowing meltwater to penetrate further and either leave the area as ablation or refreeze in deeper firn layers.

In May 1983, thermistors were drilled down to 10 m depth on Nordbogletscher at stake 15 (1500 m a.s.l.) and stake 17 (1740 m a.s.l.), respectively. The positions of the stakes are shown in Fig. 4.7. The drilling was accomplished with a 3” SIPRE ice drill. The thermistors were mounted on a cable and lowered into the drill hole where they were left to freeze in, eventually allowing the temperature to be measured at a variety of depths by recording the resistance on a multimeter. A conversion table was established between resistance and temperature. Once frozen in, the temperature was recorded on May 23 and again at the end of the summer period on August 30. Results are shown in Fig. 4.6.

Stake 15 was located approx. at the equilibrium line altitude. Winter accumulation in the winter season 1982/1983 was approx. 2 m snow, accumulated on top of pure glacier ice. The temperature profile from May 1983 shows that the temperature dropped from -2.3°C near the surface to -4.8°C at 4 m depth, only to rise again slowly to -3.0°C at 10 m depth. The temperature profile from August 30 shows that the snow was warmed to 0°C while negative temperatures persisted in the underlying glacier ice. At 10 m depth the ice temperature was -2.2°C. The meltwater from the snow cannot penetrate the ice; either it runs off along the ice surface to lower elevations, or it refreezes on the ice surface as superimposed ice. The region around stake 15 should for this year (i.e. 1983) be considered as being in the lower part of the wet-snow zone, while in earlier years it was a pronounced super-imposed ice region.



Zone designation	Characteristics	Boundary designation
Dry-snow zone	No melting at all. Negative snow temperatures all year round. Only found on the central part of the Inland Ice, where the annual mean temperature is below –25°C.	
		Dry-snow line
Percolation zone	A certain surface melting but no discharge from the area takes place, as the meltwater refreezes in the snow. The volume of snow during the winter does not reach 0°C during the summer period.	
		Wet-snow line
Wet-snow zone	In this zone the total amount of winter snow is warmed to 0°C during the summer, so that an ablation can occur. Some of the meltwater can be withheld in the deeper-lying firn layer, if negative temperatures occur there.	
		Firn or snow line
Superimposed-ice zone	Occurs where the entire snow pack is transformed into a coherent mass of ice lenses, which is super-imposed on the underlying glacier ice. Often a narrow zone, in terms of height.	
		Equilibrium line
Ablation zone	Here the entire winter snow volume melts away, and an ablation from the exposed glacier ice occurs.	
		Glacier front

Figure 4.5 *Distribution of zones in the accumulation area, from Paterson (1981).*

Stake 17 (1740 m a.s.l.) was situated in the accumulation area proper, where the material of the upper 10 m consists of ice lenses, snow and firn. Winter accumulation was also approx. 2 m here. During drilling, several large ice lens formations were encountered, e.g. at the depth of 7–9 m, formed from strong seepage/refreezing of meltwater from the surface. The minimum snowpack temperature of -8.7°C was measured in May 1983 at the depth of 4 m. By August 30, 1983, the temperature profile was remeasured. The upper 6 m of snow had been warmed to 0°C during the summer, while negative temperatures still prevailed at 10 m depth (-1.5°C). Stake 17 belongs to the wet-snow zone. Even if the total snow volume of the winter was warmed to 0°C, there was no or only limited discharge from the area, as the meltwater refreezes in the deeper-lying, colder firn layers.

The temperature profiles at stakes 15 and 17 revealed characteristic variations. At stake 17 the winter temperatures were lower, but on the other hand the warming during the summer was higher than at stake 15; for instance the snow was warmed at stake 17 at a depth of 4 m by 8.7°C, while the warming of the ice at stake 15 at a depth 4 m was only 4.0°C. At stake 17 the warming was mainly caused by refreezing, while the warming of the ice at stake 15 was caused by heat conduction, a process which is very inefficient.

In 1981, at 2060 m on the Nordbogletscher a 19 m deep firn drilling was made. The drill showed that at this height there was melt, but the meltwater refreezed in the firn and therefore the area had no discharge (Braithwaite *et al*. 1982). The area was therefore considered as belonging to the upper part of the wet-snow zone.

Based on the temperature measurements, Nordbogletscher was divided into the following zones:

1. Ablation zone	From the glacier front to *c*. 1400 m a.s.l.
2. Superimposed-ice zone	In the elevation interval from *c*. 1400 to 1600 m a.s.l.
3. Wet-snow zone	From *c*. 1600 m a.s.l. to *c*. 2200 m a.s.l.

The height of the zones can vary from year to year depending on the climatic conditions.

Even though the entire accumulation area of Nordbogletscher belongs to the wet-snow zone, the discharge from this area will be minimal due to the refreezing in the deeper-lying firn layers. When calculating the amount of discharge (ablation) from Nordbogletscher to Nordbosø it is only necessary to consider the ablation area, i.e. the area below the equilibrium line.

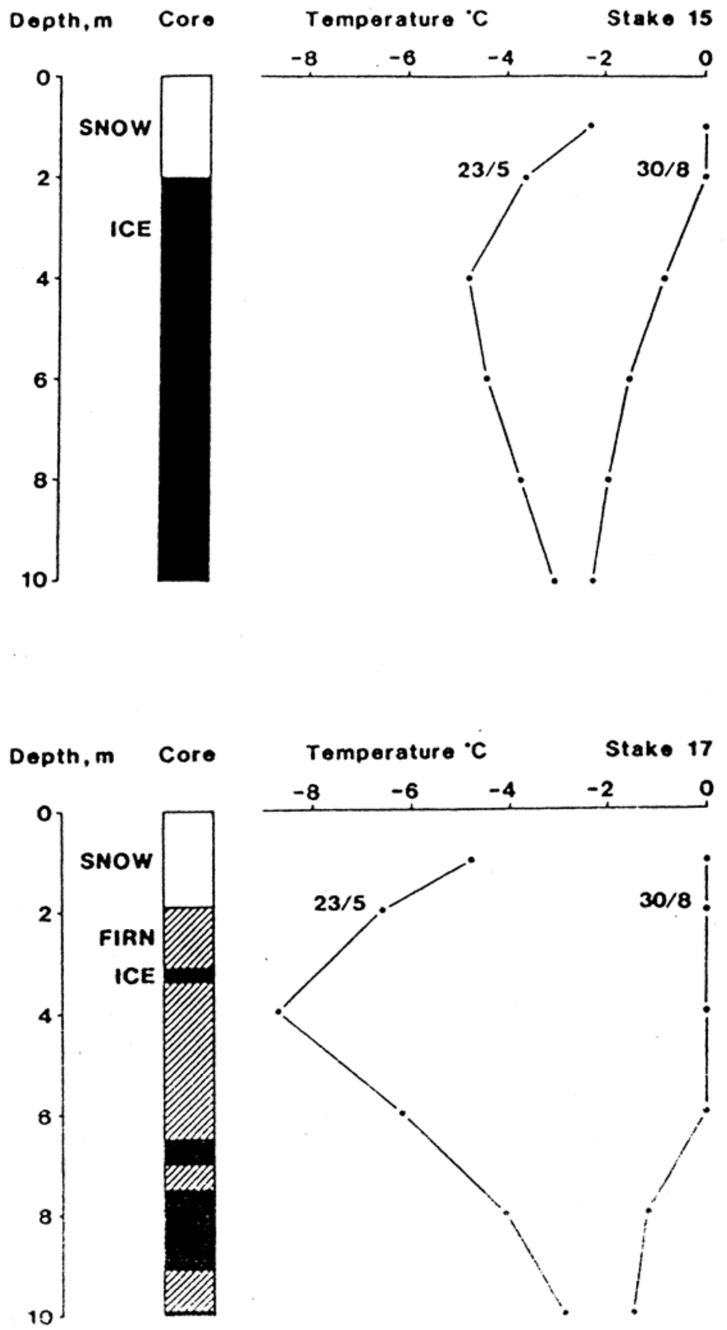


Figure 4.6 *Temperature measurements in the accumulation area of Nordbogletscher 1983. At the top the results from stake 15 (1500 m a.s.l.) are shown and at the bottom the results from stake 17 (1740 m a.s.l.). Positions of the stakes are shown in fig. 4.7. The core shows the situation in May 1983.*

4.6 The hydrological catchment area of Nordbogletscher

Based on the knowledge of the sub-glacial conditions, including especially the existence of sub-glacial thresholds between the nunataks and the refreezing of the accumulation area, an outline of the hydrological catchment area of Nordbogletscher can be made (figs 4.2, 4.7). The hydrological catchment area has an extent of 57 km^2 and reaches from the front of Nordbogletscher to the area at the equilibrium line at 1500 m a.s.l. The upper limit is not fixed, but can vary from year to year depending on the climatic conditions. The height–area distribution is shown in table 4.1.

Højdeinterval m o.h.	Areal km^2
600- 700	0.35
700- 800	5.32
800- 900	4.57
900-1000	9.91
1000-1100	7.01
1100-1200	12.11
1200-1300	6.74
1300-1400	8.59
1400-1500	2.30
600-1500	56.90

Table 4.1 *Elevation–area distribution of the hydrological area of Nordbogletscher (Højdeinterval m o.h. = Elevation interval m a.s.l., Areal km^2 = Area km^2).*

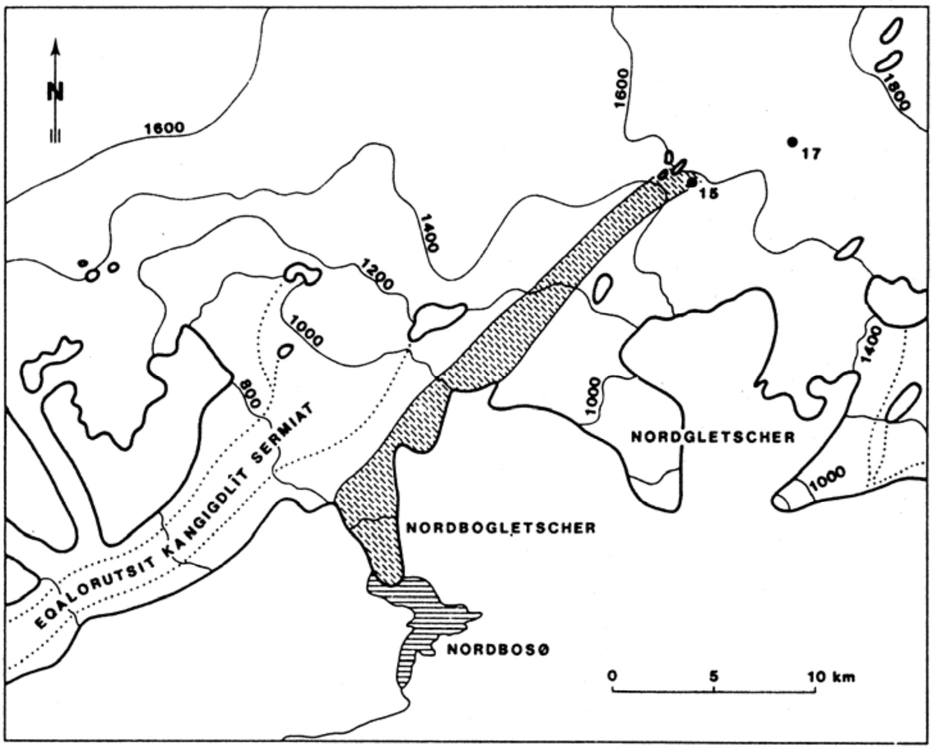


Figure 4.7 *Map showing the hydrological area of Nordbogletscher. From this area the ablation amounts to Nordbosø were calculated. Also shown are the locations of stakes 15 and 17, where englacial temperature measurements were made.*

5. The ablation conditions on Nordbogletscher

The ablation on Nordbogletscher was measured at the stakes drilled into the ice. The stakes are 5 m long aluminium tubes with an inner diameter of 32 mm. The distance from the top of the stake to the glacier surface was measured in centimetres and the difference between two consecutive measurements indicates the size of the ablation (or accumulation). All values were converted into water equivalents. If the glacier surface consisted of snow, the water equivalent was found by determination of the density in a nearby snow pit; if the glacier surface consisted of ice, the density was fixed at 0.90 g/cm^3.

5.1 Ablation conditions in the elevation interval 800–900 m

A total of 24 stakes (fig. 5.1) was drilled into Nordbogletscher in the elevation interval 800–900 m. The stake network must be said to be dense (5 stakes per km^2) and can be used for investigation of the ablation conditions within a limited elevation interval. As the general climate is largely the same for all the stakes in this elevation interval, the ablation variations between the stakes will reflect local conditions on the glacier surface, and the representativity of a single stake can be estimated.

Table 5.1 gives an overview of the average ablation at the stakes and the standard deviation during the period 1978–1983. The ablation has on average been 2.4 m water equivalent, the highest value being in 1980 and the lowest in 1983 (2.8 m and 1.6 m water equivalents). The standard deviation in the individual years was rather large with ablation variations of up to 1 m between the stakes. In the elevation interval mentioned, the surface of Nordbogletscher is slightly undulating with ridges and valleys, and a stake placed on the top of a ridge yields a higher ablation than a stake situated in a valley. Just how representative a single stake measurement is highly depends on the location of the stake and on the topography of the surface of the glacier.

5.2 Ablation versus elevation

Besides the stakes on the frontal area of the Nordbogletscher, stakes were drilled at the various elevation intervals to upwards of 2000 m a.s.l., which means a distance of *c*. 40 km from the front. The highest located stakes were visited a couple of times a year by snow scooter or helicopter. With increasing elevation the surface topography of Nordbogletscher becomes more even and the individual stakes' representativity becomes better.

Temperature measurements in the firn area have shown that even though there is melt from the snow surface, the meltwater refreezes in the deeper-lying firn layers (see section 4.5) and the area therefore has no discharge. The equilibrium line on Nordbogletscher is situated in the elevation interval 1400–1600 m; thus no proper ablation will occur above *c*. 1500 m. Nordbogletscher's ablation area (or hydrological catchment area) is shown on fig. 4.7.

Figure 5.2 shows the size of the summer balance (ablation) as a function of the elevation in the ablation area. The table shows the specific values (b_s) and total values (B_s) for the individual elevation intervals for the period 1979–1983. The figure also shows the average ablation value and the relevant standard deviations. The ablation decreases from a value of *c*. 2.8 m water near the frontal area to *c*. 0.6 m water near the equilibrium line.

Knowing the elevation–area distribution of the ablation area, the total ablation can also be calculated.

År	Antal stager	Ablation m vand	Måleperiode
1978	23	2.55 ± 0.22	26/5 - 24/9
1979	24	2.12 ± 0.36	27/5 - 18/9
1980	24	2.83 ± 0.47	17/5 - 15/9
1981	23	2.70 ± 0.24	16/5 - 13/9
1982	16	2.33 ± 0.25	19/5 - 19/9
1983	15	1.59 ± 0.23	15/5 - 13/9

Table 5.1 *Ablation on Nordbogletscher at an elevation of 800–900 m, 1978–1983 (år = Year, Antal stager = Number of stakes, Ablation m vand = Ablation m water, Måleperiode = Measurement period).*

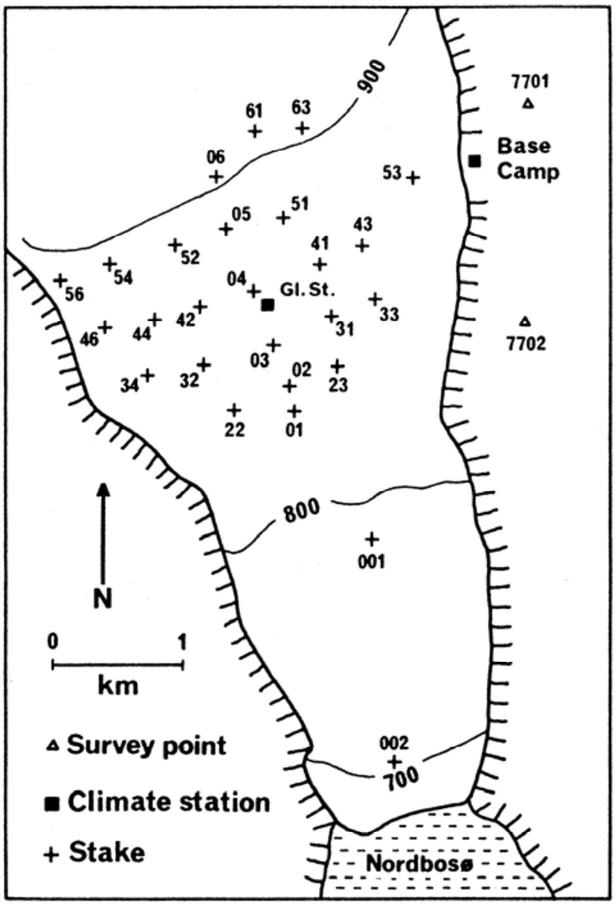


Figure 5.1 *Distribution of stakes on the tongue of Nordbogletscher.*

Højdeinterval m o.h.	Areal km²	1979 b_s m	1979 B_s 10^6 m³	1980 b_s m	1980 B_s 10^6 m³	1981 b_s m	1981 B_s 10^6 m³	1982 b_s m	1982 B_s 10^6 m³	1983 b_s m	1983 B_s 10^6 m³
600- 700	0.35	2.60	0.91	3.20	1.12	3.17	1.11	3.00	1.05	2.00	0.70
700- 800	5.32	2.35	12.50	3.00	15.96	2.98	15.85	2.75	14.63	1.80	9.58
800- 900	4.57	2.12	9.69	2.83	12.93	2.70	12.34	2.33	10.65	1.59	7.27
900-1000	9.91	1.85	18.33	2.15	21.31	2.39	23.68	2.04	20.22	1.30	12.88
1000-1100	7.01	1.55	10.87	1.67	11.71	2.25	15.77	1.60	11.22	1.15	8.06
1100-1200	12.11	1.32	15.99	1.25	15.14	1.63	19.74	1.23	14.90	0.90	10.90
1200-1300	6.74	1.10	7.41	0.91	6.13	1.28	8.63	0.91	6.13	0.65	4.38
1300-1400	8.59	0.85	7.30	0.96	8.25	1.20	10.31	0.65	5.58	0.42	3.61
1400-1500	2.30	0.55	1.27	0.83	1.91	1.06	2.44	0.45	1.04	0.19	0.44
600-1500	56.90		84.27		94.46		109.87		85.42		57.82

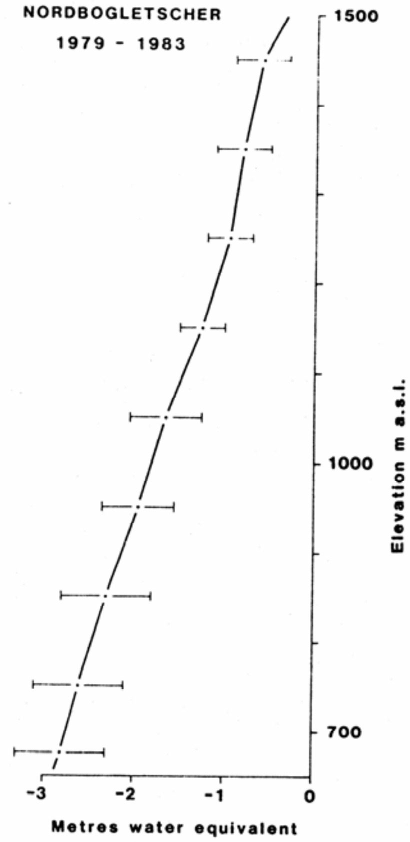


Figure 5.2 *Ablation on Nordbogletscher in relation to elevation, 1979–1983 (Højdeinterval m o.h. = Elevation interval m a.s.l.)*

5.3 The temperature influence on the ablation

The temperature is the climate parameter which best describes the ablation on Nordbogletscher. This applies on a daily as well as on an annual basis. Figure 5.3 shows the correlation between the total ablation on Nordbogletscher and the summer mean temperature

(June–August) at Base Camp and Narssarssuaq. The correlation coefficients are relatively high at both climate stations, which means that the ablation amount can be calculated based on climate data.

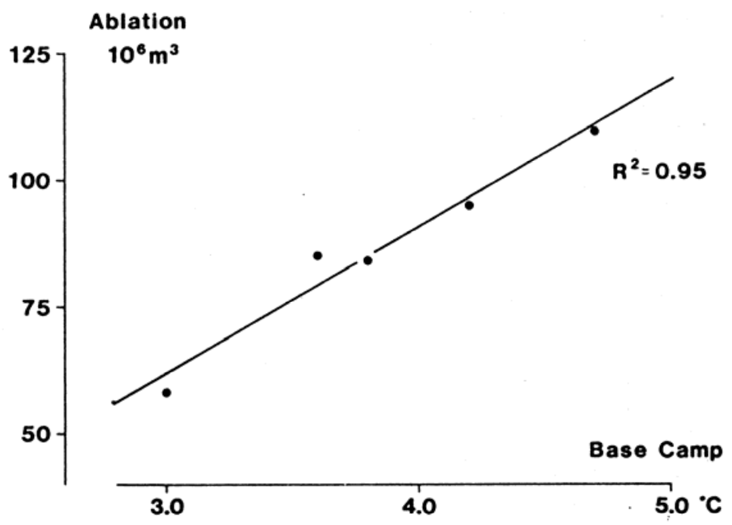
The correlation between the total ablation at Nordbogletscher and the summer temperature in Narssarssuaq is given by

$$ABL = 23.2\ T - 120.5 \quad (r^2 = 0.88)$$

Where ABL = total ablation on Nordbogletscher, $10^6\ m^3$

and T = the mean temperature in Narssarssuaq (June–August), °C

	Ablation on Nordbogletscher		Mean temperature °C	
	10^6 m^3	mm	Base Camp	Narssarssuaq
1979	84.3	1480	3.7	9.3
1980	94.5	1660	4.2	9.2
1981	109.9	1930	4.7	9.7
1982	85.4	1500	3.6	8.7
1983	57.8	1010	3.0	7.7



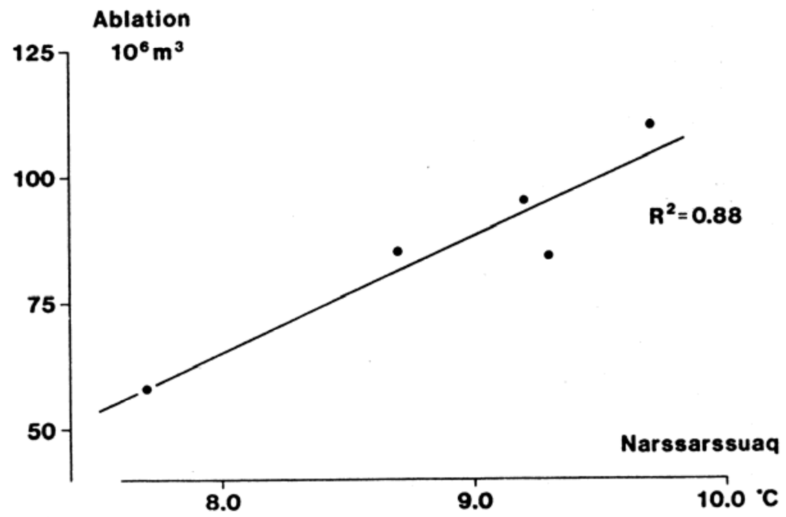


Figure 5.3 *Total amounts of ablation from Nordbogletscher and mean summer temperature (June–August) at Base Camp and Narssarssuaq.*

5.4 Ablation conditions for the period 1962–1983

Based on the correlation equation in section 5.3 the total ablation on Nordbogletscher can be calculated for the period 1962–1983 (fig. 5.4). The average total ablation has in this period been 95 million m^3 with a standard deviation of 17 million m^3 (18%). The largest ablation is calculated to have taken place in 1974 (130 million m^3). The summer of 1983 was on the other hand the coldest in the period, and the ablation was as low as 58 million m^3.

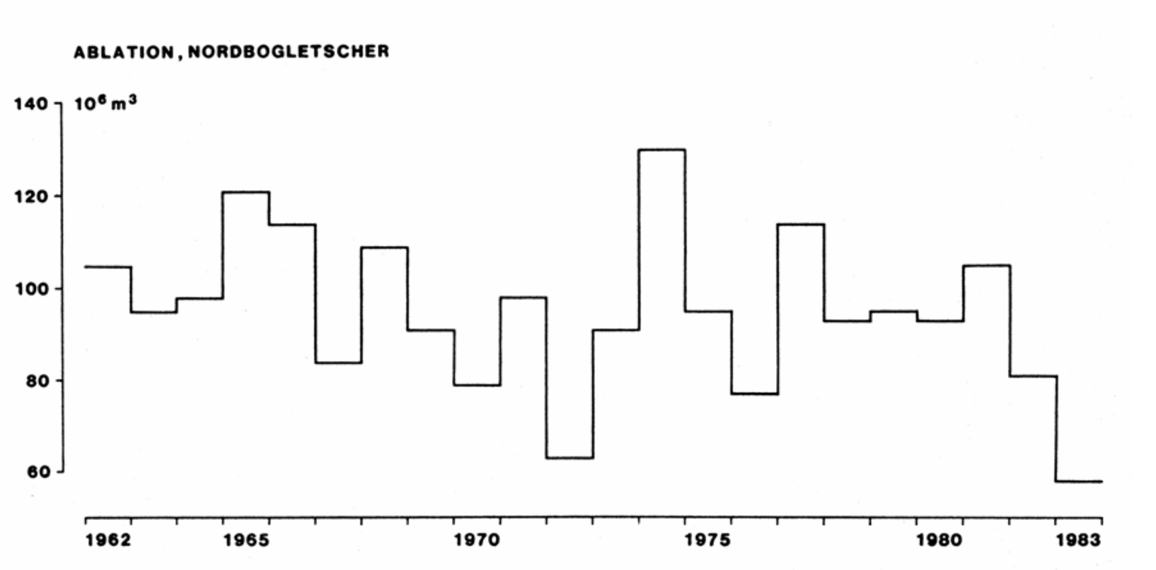


Figure 5.4 *Calculated total ablation from Nordbogletscher 1962–1983.*

6. Mass balance conditions on Valhaltindegletscher

6.1 Valhaltindegletscher

Valhaltindegletscher is one of the local glaciers in the Johan Dahl Land area, situated on the northern slopes of Valhaltinde in the elevation interval 1050–1640 m a.s.l. The glacier was mapped by means of aerial photos made in August 1977 at a scale of 1: 20 000 (Aerokort A/S). The glacier can be divided into two basins: an upper basin in the elevation interval 1350–1640 m a.s.l., and a lower basin in the elevation interval 1050–1550 m a.s.l. (fig. 6.1). It is not known if there is an actual connection (ice movement) between the two basins; it is likely that they are two separate glaciers, but in this report the glaciers are considered as one. In the lower basin the glacier ice is normally exposed during the summer to a height of c. 1400 m a.s.l., while the upper basin is snow covered all year round. Valhaltindegletscher can be seen as minor ice cap with a total area of 1.9 km^2. Discharge from the glacier takes place towards north, later ending in the ice-dammed 'Base Camp Sø' near Nordbogletscher.

Valhaltindegletscher was presumably in recession during the majority of the 20^{th} century. In the area in front of the present front, several old end moraines systems are found, but when these were made is not known. Along the entire western margin, a very high and fully developed side moraine, possibly 'ice-cored', is found. Glacier movement was measured at the stakes in the lower basin in a single season (1979/1980). The annual velocity at stakes 03 and 04 was only 3 m per year, i.e. the glacier is almost immobile.

To measure the mass balance a total of seven stakes were drilled into Valhaltindegletscher covering various elevation intervals (fig. 6.1). In this connection, the glacier serves a two-fold purpose, as the results can be transferred to Nordbogletscher, for which it is logistically and delimitation-wise extremely difficult to make mass balance measurements.

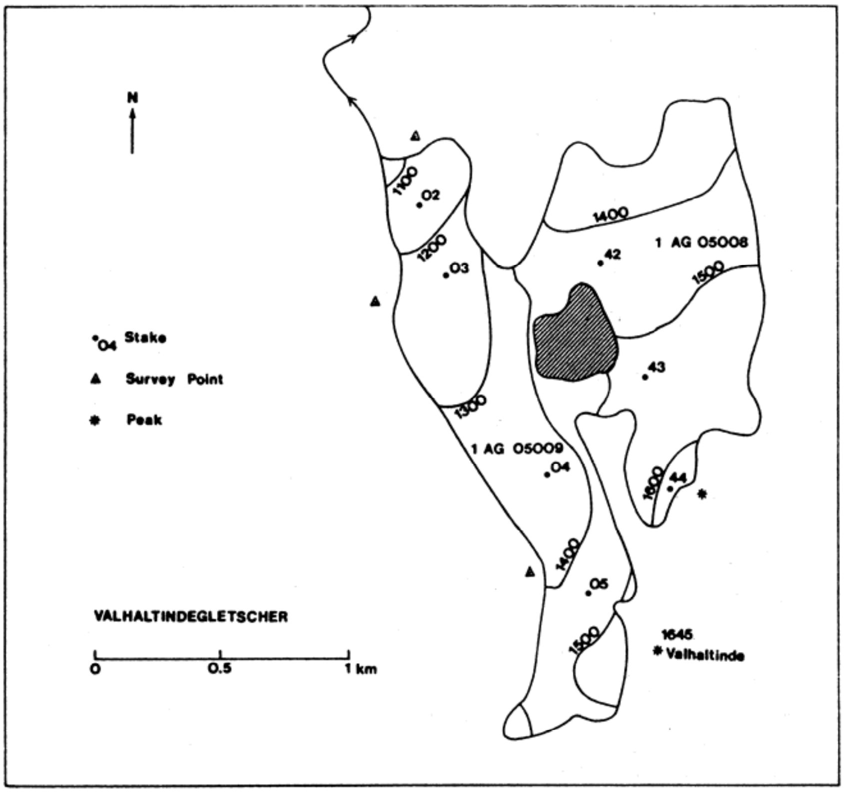


Figure 6.1 *Map of Valhaltindegletscher showing positions of the inserted stakes.*

6.2 Mass-balance measurements

At the present, mass-balance data from Valhaltindegletscher for a period of five years are available, which – even though it is a short period – is a long time span from a glacier in Greenland as such. The results are shown in table 6.1.

Budgetår	1978/79	1979/80	1980/81	1981/82	1982/83
Winter balance, B_w, 10^6 m^3	1.18	0.84	1.07	0.52	1.04
Winter balance, b_w, m	0.63	0.45	0.57	0.28	0.55
Summer balance, B_s, 10^6 m^3	-1.21	-1.26	-2.02	-1.03	-0.72
Summer balance, b_s, m	-0.64	-0.67	-1.07	-0.55	-0.38
Net balance, B_n, 10^6 m^3	-0.02	-0.42	-0.95	-0.51	0.32
Net balance, b_n, m	-0.01	-0.22	-0.50	-0.27	0.17
Equilibrium line, m a.s.l.	1375	1440	1440	1440	1340

Table 6.1 *Summary of mass-balance results from Valhaltindegletscher during the period 1978/79–1982/83 (Budgetår = Budget year).*

The winter balance in the individual years was measured in May in snow pits and by snow soundings. The average snow density normally was at 0.38–0.42 g/cm^3. At the times of investigation the glacier was always completely snow covered and with negative snow temperatures, and the accumulation was relatively evenly distributed with the height. The winter balance in the individual years varied between 0.28 m and 0.63 m water equivalent (table 6.1). The winter balance variation followed the variation of the winter precipitation in Narssarssuaq, given in the following equation:

$$b_w = 0.87\ P + 0.17 \quad (r^2 = 0.82)$$

where b_w = specific winter balance on Valhaltindegletscher, m

and P = winter precipitation (October to April) in Narssarssuaq, m

The summer balance was measured at the turn of the month August/September at the inserted stakes. In this case the variations were higher, as regards the height and year by year, than those of the winter balance. The specific summer balance in the individual years varied from –0.38 m to –1.07 m water equivalent.

The net balance showed three years of negative balance, one year with equilibrium and a year with positive balance. The equilibrium line varied from 1340 m a.s.l. to 1440 m a. s. l.

6.3 Mass balance conditions in the period l962–1983

It is well known that there is some correlation (however in no way simple) between the mass balance of a glacier and the climate in the relevant area. The net balance (b_n) is the difference between the winter balance (b_w) and the summer balance (b_s). It often turns out that the winter balance can be correlated with the winter precipitation, measured at a nearby meteorological station. The summer balance, on the other hand, is more of a problem, as it is influenced by several meteorological parameters, such as air temperature, radiation, wind, air humidity, and albedo conditions on the surface of the glacier, the temperature being the most dominant parameter.

Calculations of the net balance conditions on glaciers based on climate observations at nearby stations was carried out in Norway (Liestøl 1967 and Twede 1979) and in Canada (Young 1981). The equation used has often been of the type

$$b_n = c_1 + c_2\ P + c_3\ T$$

where bn = the net balance of the investigated glacier
P = the winter precipitation measured at the nearby meteorological station
T = mean summer temperature measured at the nearby meteorological station
c = constants

The correlation equation formulated can in this way be used for determination of the net balance in the past or in the future, if a time series of data is concluded, as it can be used for completing an incomplete measuring series. The prerequisite for using the equation is however

(1) that the equation is determined well enough,
(2) that the area distribution of the glacier is approximately the same as for the period for which the equation was formulated.

The first prerequisite can among other things be estimated from the correlation coefficient found and other statistical prerequisites (e.g. that both positive and negative balances occur in the calibration period). The second prerequisite is more problematic, if the calculations are made over several decades, as glaciers are characterized by adjusting to changes in the mass balance conditions by changing their areal extent.

For Valhaltindegletscher the following equation between the net balance and climate parameters can be formulated:

$$B_n = 151. + 0.81\ P - 22.3\ T \quad (r^2 = 0.78)$$

where b_n = net balance in cm water equivalent

P = winter precipitation (October to April) in Narssarssuaq, cm

T = mean summer temperature (June –August) in Narssarssuaq, °C

The equation was formed on the basis of data from five years, which is probably not quite permissible. In Norway corresponding equations were formed on the basis of at least 10 years of measurements. On the other hand, the correlation coefficient (r^2 = 0.78) is reasonable, and both positive and negative net balance values have occurred in the calibration period (1979–1983), which gives a certain dispersion. In table 6.2 a correlation between the measured and the calculated net balance was made. Considering that the measuring uncertainty of the net balance is estimated to be 10 cm, the result can be said to be promising.

On the basis of climate data from the Danish Meteorological Institute in Narssarssuaq, a calculation of the net balance of Valhaltindegletscher for the period 1962–1983 was made. The results are shown in fig. 6.2. The net balance was in general for the entire period negative, where only four years showed a positive balance. It should be noted, that 1983 was the most positive year, as the summer of 1983 was the coldest in Narssarssuaq for the entire period 1962–1983. The average net balance for the whole period was on an annual basis –0.26 m water equivalent.

The calculated absolute values should be taken with reservation, as only 5 years of measured data are available for the calibration. But it is very likely that the net balance was negative in South Greenland for at least the 20 years preceding the survey reported here. The hydrological consequence has been that watercourses originating in basins with extensive glacier cover have had an extra influx of water in the same period, while the ice reservoir has been reduced.

Budgetår	Nettobalance, cm Målt	Beregnet
1978/79	-1	-14
1979/80	-22	-31
1980/81	-50	-33
1981/82	-27	-27
1982/83	17	22

Table 6.2 *Calculated net balance (b_n) on Valhaltindegletscher in comparison with the measured value (Budgetår = Budget year, Nettobalance = Net balance, Målt = Measured, Beregnet = Calculated).*

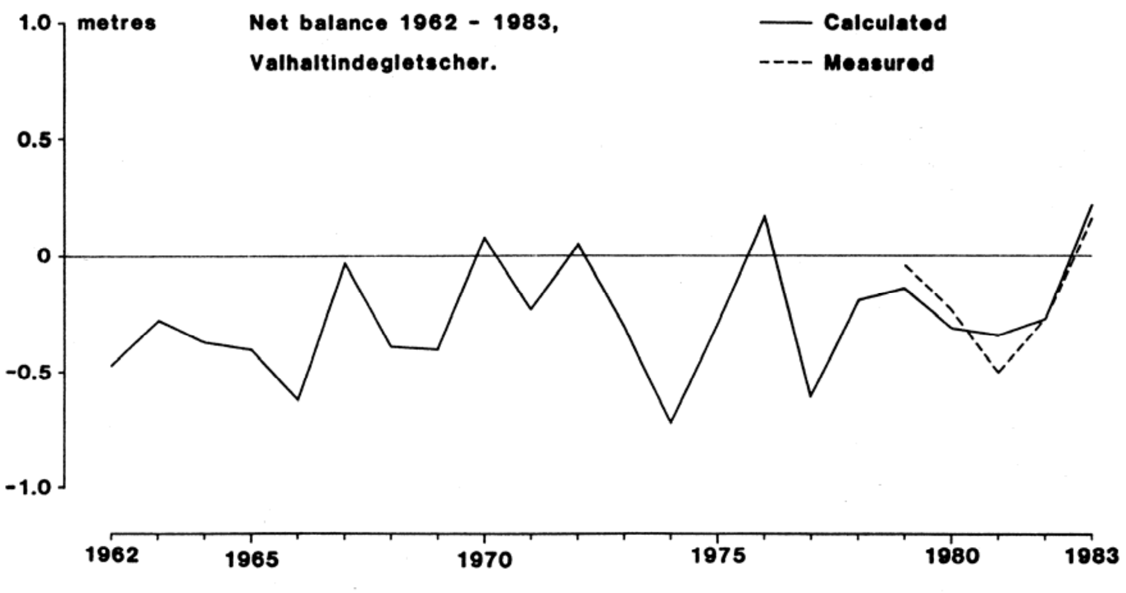


Figure 6.2 *Calculated net balance on Valhaltindegletscher 1962–1983.*

7. The influence of Nordbogletscher on the discharge

The Nordbosø basin can be divided into to very different catchment areas, the Indland Ice (Nordbogletscher) and the ice-free catchment area (fig. 7.1).

The Inland Ice's catchment area for Nordbosø is unknown, since we do not have sufficient information about the extent of the accumulation area of Nordbogletscher. The hydrological catchment area of Nordbogletscher has, however, been determined to be 57 km^2 (see fig. 4.7). The hydrological catchment area can be used for determination of volume of water from Nordbogletscher to Nordbosø, but it would be incorrect to calculate a specific discharge from this area.

The ice-free catchment area for Nordbosø is identical with the entire Valhaltinde massif. The term 'ice-free catchment area' is however, not strictly correct, as there are local glaciers in the area. The local glaciers only account for 5% of the ice-free catchment area, so they can be disregarded, assuming that the mass balance is in equilibrium. The ice-free catchment area is 100 km^2. Contrary to the Inland Ice, the topographical delimitation of the ice-free catchment area is identical to its hydrological delimitation.

The total hydrological catchment area of Nordbosø can therefore be composed by a catchment area from the Inland Ice of 57 km^2 and an ice-free catchment area of 100 km^2.

The discharge from Nordbosø was measured by the Greenland Technical Organisation (GTO) during the period 1976–1983, which is a long discharge series in Greenland. The annual mean discharge was 170 million m^3 with a coefficient of variation of 11% (table 7.1).

In table 7.2 the measured discharge from Nordbosø is divided into two catchment areas, Nordbogletscher and the ice-free catchment area. The discharge from Nordbogletscher is calculated on the basis of the measured ablation of the hydrological catchment area and the summer precipitation (rain), measured at Base Camp, over the same catchment area. The discharge from the ice-free catchment area is found by simple subtraction.

The discharge from Nordbogletscher was on average found to be 61% of the total discharge from the Nordbosø basin. It should be noted that 1983 was an unusual year where precipitation was dominant. Nordbogletscher has stabilising effect on the discharge. If the year is dry and warm, the ablation volume will increase in importance, but if the year is cold and wet (1983) the ablation will be small, but the amount of precipitation will be high. It is thus characteristical that the discharge coefficient of variation from Nordbogletscher is only 14%, while the variation for the ice-free catchment area amounts to 46%.

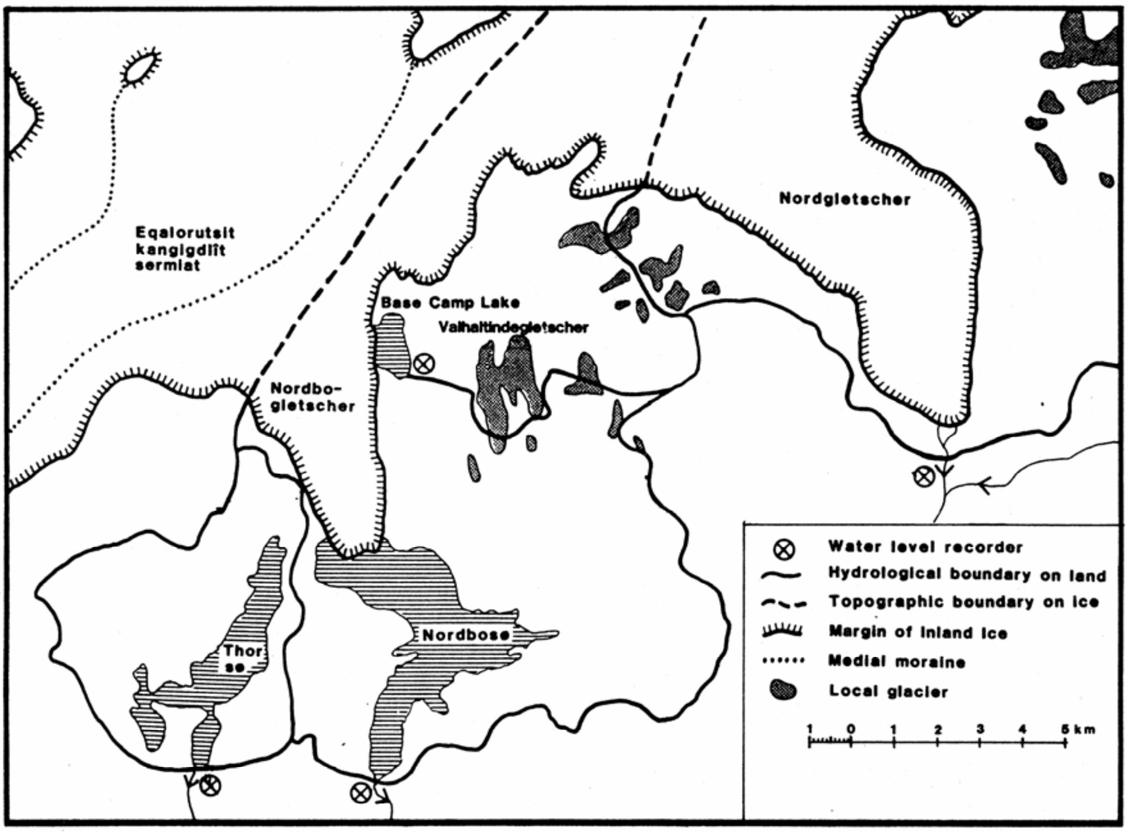


Figure 7.1 *The Johan Dahl Land area with Nordbogletscher and Nordbosø. Discharge from Nordbosø and Thor Sø was measured by the Greenland Technical Organisation. The different basin boundaries are shown on the map.*

År	Afstrømning 10^6 m^3
1976	190.6
1977	167.3
1978	174.4
1979	155.6
1980	162.7
1981	171.1
1982	139.1
1983	195.4
Middel	169.5
Variation %	11

Table 7.1 *Annual discharge from Nordbosø 1976–1983. Data from the Greenland Technical Organisation (År = Year, Afstrømning = Discharge, Middel = Mean, Variation = Coefficient of Variation).*

	Nordbosø (157 km^2)		Nordbogletscher (57 km^2)		Isfrit opland (100 km^2)	
År	10^6 m^3	%	10^6 m^3	%	10^6 m^3	%
1979	155.6	100	95.9	62	59.7	38
1980	162.7	100	104.1	64	58.6	36
1981	171.1	100	121.9	71	49.2	29
1982	139.1	100	102.4	74	36.7	26
1983	195.4	100	81.9	42	113.5	58
Middel	164.8	100	101.2	61	63.5	39
Variation %	13		14		46	

Table 7.2 *Discharge from Nordbosø and the subbasins (Nordbogletscher and the ice-free catchment area) (Isfrit opland = Non-glaciated catchment, Middel = Mean, Variation = Coefficient of Variation).*

7.1 Comparison between GGU's and GTO's measurements

The Nordbosø basin was unique in Greenland at the time, as all the hydrological parameters were measured. GGU measured the 'input' of water, while GTO measured the 'output' of water from Nordbosø. This means that a comparison between the two data sets can be made (table 7.3).

The discharge from Nordbosø is composed of the discharge from Nordbogletscher and the discharge from the ice-free catchment area. The discharge from Nordbogletscher is calculated as the summer balance (the ablation) plus the liquid precipitation in the summer period, measured at Base Camp (the ablation term includes melt of winter precipitation). It is assumed that the evaporation from Nordbogletscher is insignificant. The discharge from the ice-free catchment area is calculated as precipitation minus evaporation. The precipitation is calculated on the basis of the precipitation in Narssarssuaq from October to October, and is transferred to the area by means of the precipitation correlation (section 2). The evaporation is presumed to be 50% of the measured, potential evaporation at Base Camp.

The calculated discharge from Nordbosø agrees with the measured discharge (table 7.3); the average annual deviation is only 8%. So the data from GGU and GTO must be said to be in full agreement.

ÅR	Nordbogletscher		Isfrit opland		Afstrømning fra Nordbosø bassinet		
	Ablation +	Nedbør	Nedbør +	Fordampning	GGU (beregnet)	GTO (målt)	Forskel i %
1979	84.3	11.6	85.7	10.5	171.1	155.6	9
1980	94.5	9.6	46.0	9.3	140.8	162.7	-16
1981	109.9	12.0	70.8	9.3	183.4	171.1	7
1982	85.4	17.0	46.3	8.7	140.0	139.1	1
1983	57.8	24.1	104.4	7.3	179.0	195.4	-9
Middel	86.4	14.9	70.6	9.0	162.9	164.8	-1

Table 7.3 *Comparison between GGU's calculated and GTO's measured discharge form the Nordbosø basin. Data in million m^3. (År = Year, Isfrit opland = Non-glaciated catchment, Afstrømning fra Nordbosø bassinet = Discharge from the Nordbosø catchment, Nedbør = Precipitation, Fordampning = Evaporation, Beregnet = Calculated, Målt = Measured, Forskel i % = Difference in %).*

7.2 The importance of Nordbogletscher

The most important feature of Nordbogletscher as regards the discharge is its stabilising effect on the annual variations. If it had been purely a precipitation basin, the discharge variation from Nordbosø would have been 46%, but due to the existence of Nordbogletscher the variation is only 13% (table 7.2). This is very important when it comes to hydrological power generation. In dry and warm years the ablation quantities will increase and compensate for the lack of precipitation, and the other way round in cold and wet years.

The mass balance conditions of Nordbogletscher were not fully investigated. The mass balance for the nearby Valhaltindegletscher, however, was determined for the period 1962–1983 (section 6). The mass balance was in general found to be negative, and it must be assumed that the mass balance for Nordbogletscher followed the same pattern. This means that the discharge from the Nordbosø basin in the same period was larger, than if it had been purely a precipitation basin. When modelling the discharge conditions of Nordbosø, a correction for the mass balance should be carried out.

It should be noted that the found, generally negative mass balance conditions in the area do not necessary conflict with the general advance of Nordbogletscher in the same period.

8. Observations of ice-dammed lakes

Ice-dammed lakes are frequent in Johan Dahl Land along the Inland Ice margin. The lakes vary in size from local water accumulations with no practical importance to lakes that are several km^2 with almost disastrous discharge conditions. The two largest lakes will be described in brief below. They are 'Base Camp Sø' at Nordbogletscher and 'Hullet' at Sydgletscher.

8.1 Base Camp Sø

Base Camp Sø is situated very close to GGU's camp at the eastern flank of Nordbogletscher. When filled, the lake is 0.8 km^2 and it is emptied each year (at least up to 1983) into Nordbosø.

The water-level variations in the lake were registered between 1978 and 1983. The lake is filled in the beginning of the ablation period (May–June) to a critical level, which is reached in the beginning of July. Then drainage starts. It takes place partly under and partly along the flank of Nordbogletscher. The drainage itself happens relatively slowly and gradually and takes 6–7 weeks. Contrary to other ice-dammed lakes (e.g. Hullet) Base Camp Sø is emptied from top to bottom as the discharge canal erodes the ice surface.

The time for maximum water level was more or less the same year by year, just as the maximum level seemed to be rather stable (ca. 826 m a.s.l.). Larger variations were seen in the minimum level. In 1980 the lake was totally drained. This was also the case in 1953 (aerial photo); the other years the minimum level was *c*. 785 m a.s.l.).

Base Camp Sø has a relatively large catchment area (*c*. 40 km^2) and it drains the entire northern part of the Valhaltinde massif and part of Nordbogletscher (fig. 7.1). The major part of the influx is a single water stream (Main stream), running into the eastern part of the lake (fig. 8.1), while a minor water stream (Glacier stream) transports some meltwater from Nordbogletscher to the lake. Other streams are insignificant.

Water-flow measurements of the Main Stream and the Glacier stream were made and the daily discharges were calculated. The total influx to Base Camp Sø can then be calculated as the sum of the discharge from the two water streams. As the lake has proved to be 'leak-tight' during the filling period (Clement 1983), and as the height–volume distribution is known, the daily discharge from the lake can be calculated, on the basis of the water-level variations in the lake, given in the following equation

$$\text{Discharge} = \text{influx} \pm \text{volume change in lake}$$

The annual discharge from Base Camp Sø constitutes 21% of the discharge from Nordbosø (table 8.2). The annual storage of the lake is very limited and only constitute ± 1% of the discharge from Nordbosø.

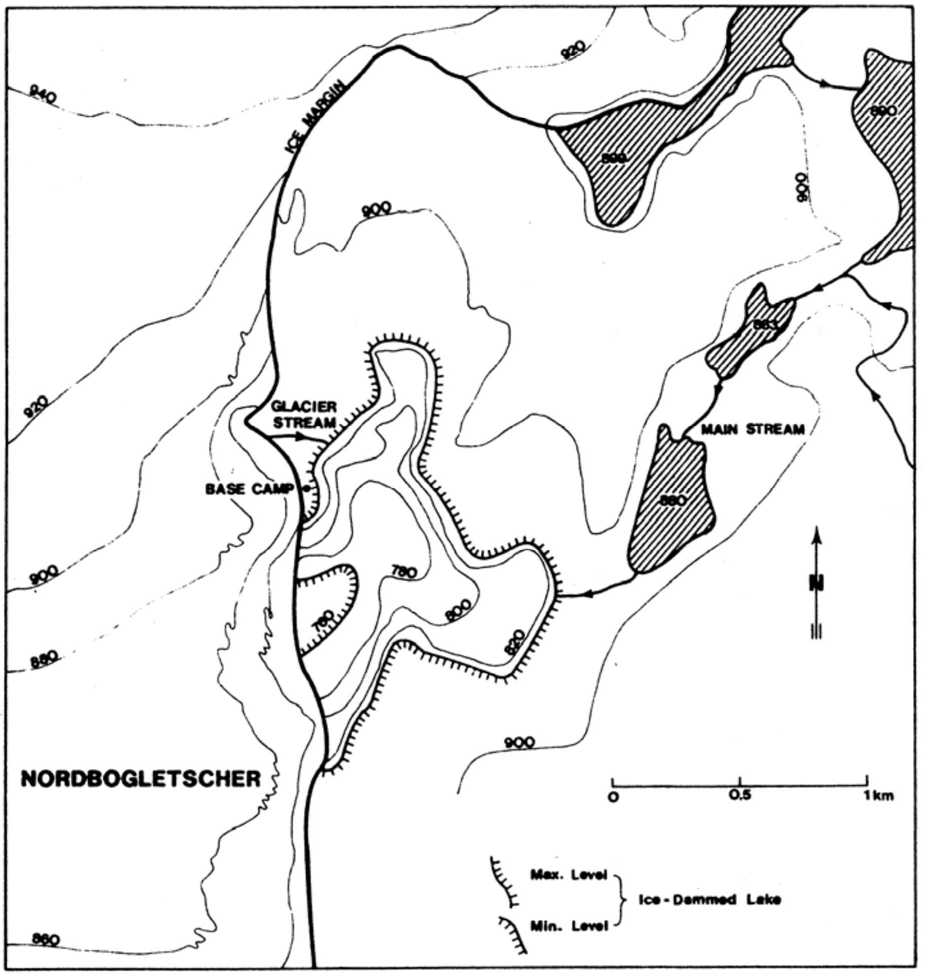


Figure 8.1 *Position of the ice-dammed lake at Nordbogletscher (Base Camp Sø). Maximum and minimum levels are shown.*

Base Camp sø	1978	1979	1980	1981	1982	1983
Dato for max vandstand	12/7	2/7	3/7	2/7	14/7	23/6
Max højde, m o.h.	827	822	827	830	826	825
Min højde, m o.h.	785	780	763	787	786	788
Vandstandsvariation, m	42	42	64	43	40	37
tapningstid, dage	39	47	78	39	49	44

Table 8.1 *Water-level variations in Base Camp Sø 1978–1983. (Dato for max vandstand = Date of max water level, Max højde, m o.h. = Max elevation, m a.s.l., Min højde, m o.h. = Min elevation, m a.s.l., Vandstandsvariation, m = Water-level variation, m, Tapningstid, dage = Drainage time, days).*

	1980	1981	1982
Tilstrømning	31.8	37.1	28.6
Afstrømning	33.8	34.8	30.2
Opmagasinering	-2.0	2.3	-1.6
Base Camp sø´s andel i afstrømningen fra Nordbosø, %	21	20	22

Table 8.2 *Water balance for Base Camp Sø 1980–1982 in million m^3. (Tilstrømning = Influx, Afstrømning = Discharge, Opmagasinering = Accumulation, Base Camp sø's andel I afstrømningen fra Nordbosø, % = Base Camp Sø percentage of the discharge from Nordbosø, %).*

Base Camp Sø works as an inserted reservoir in the catchment area of Nordbosø. During May and June an accumulation of water occurs in the lake, during July and August the accumulated water is slowly drained, after which the lake works as a normal lake with influx and discharge. During winter the discharge canal is closed due to ice formation and a new cycle is started the year after.

Seen from a water-power-generation perspective Base Camp Sø does not constitute any major problems or hazards, contrary to other ice-dammed lakes. The lake is emptied every year in a steady and calm discharge, and the annual accumulation of the lake is limited compared to the total discharge.

8.2 The lake Hullet

Hullet, one of the largest ice-dammed lakes in South Greenland, is located *c*. 28 km northeast of Narssarssuaq (fig. 3.1). Hullet is dammed towards south by Sydgletscher, which is an outlet from the main glacier Qôrqup sermia. Drainage from Hullet takes place subglacially via Sydgletscher og Kiagtut sermiat to Narssarssuaq, a distance under ice cover of 22 km.

Hullet has a relatively large catchment area and receives meltwater from Nordgletscher, Østgletscher and Sydgletscher. The maximum or critical water level is at *c*. 530 m a.s.l. At outburst the water level drops *c*. 110 m in Hullet. At maximum water level the area of the lake is 6.5 km^2, and based on a volume determination the discharge volume at each outburst can be set to be *c*. 600 million m^3.

Outburst from Hullet has been reported several times. Table 8.3 has an overview of existing observations between 1957 and 1983. For the period 1957–1978, the table is far from being complete, as outbursts must be expected to have taken place several more times than reported – not until 1978 the series of observations was continuous.

Based on the existing observations the frequency of outburst from Hullet can be said to be 1–2 years, depending on the time of year of the last outburst and the amount of precipitation and meltwater during the filling period, i.e. the climate. The outburst time seems to be at the end of the summer period (August–November), but an outburst in February has been seen. The outburst itself takes a few weeks.

When Hullet is drained, it has been observed that the entire riverbed at Narssarssuaq is flooded, just as Tunugdliarfik Fjord's hydrography is influenced by the sudden discharge of these huge amounts of freshwater. After the outburst in October 1981, the inner parts of the fjord for instance froze quickly due to the generated pycnocline effect, and the ice cover this year was thicker and its extent larger than normally.

Figure 8.2 shows the registered water-level observations in Hullet, as observed by GTO and GGU in the period 1978–1983. As can be seen, changes of water level only occur during the summer period; during winter the lake is frozen. It should also be noted that in 1981 the lake was emptied only one year after the last discharge. The summer of 1981 was warmer than usual, and the ablation volume the largest registered for the period 1978–1983; so the lake had a large input of water and was able to fill itself within one year. Furthermore, it must be noted that the maximum level (530 m a.s.l.) and the minimum level (420 m a.s.l.) has more or less been the same for all the outbursts.

The last outburst from Hullet recorded during the survey took place in the autumn of 1983. At the turn of the months August/September, the water level was registered to be 530 m above sea level, i.e. at the critical level. On 17 September the water level in the river at Narssarssuaq started to increase dramatically, and a water-level observation in Hullet on 20 September was 509 m a.s.l., this means that the outburst had started. On 12 October the water level in Hullet was registered to be 424 m a.s.l. by personnel from Iscentralen in Narssarssuaq; the outburst had finished, and the water level had dropped more than 100 m in less than a month.

Year	Month	Source
1957	June (?)	Leighty & Poulin 1960
1960	June (?)	Weidick 1963
1964	September	Ellitsgaard-Rasmussen, personal communication
1968	February	Brathay Exploration Group 1969
1970	August	Brathay Exploration Group 1969
1971	November	Brathay Exploration Group 1969
1978	November	Langager, GTO, personal communication
1980	September	The author
1981	October	The author
1983	September	The author

Table 8.3 *Known outbursts from the ice-dammed lake Hullet.*

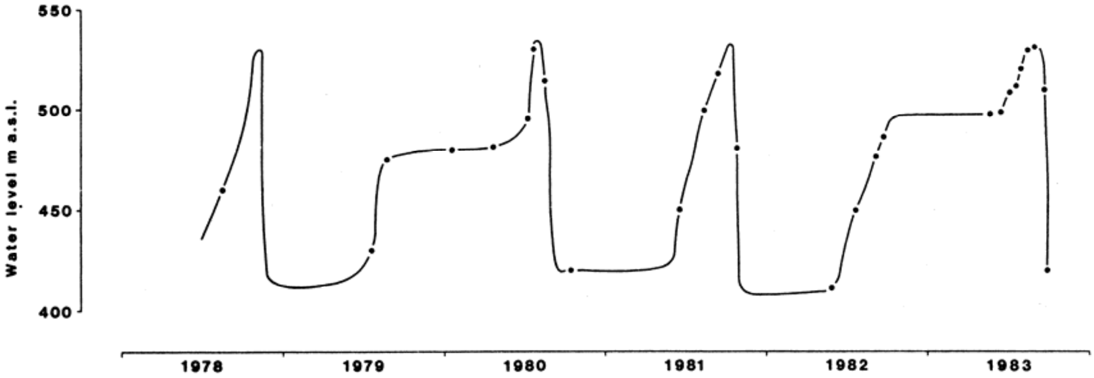


Figure 8.2 *Water-level variations in the lake Hullet 1978–1983.*

9. Concluding remarks

The investigations in Johan Dahl Land in 1977-1983 indicate that the Nordbosø basin seems to be suited for hydropower production. The annual power production from Nordbosø alone was estimated to be on average *c*. 250 GWh/year. The production can later be more than doubled by including neighbouring basins. It must, however, be pointed out that unsolved questions remain as regards the impact of glacial conditions on hydropower production in the area. Especially the glacial-dynamic conditions, including the causes of the advance of Nordbogletscher and its consequences need to be investigated. Furthermore, the sub-glacial conditions should be investigated in more detail to clarify the many delineation and mass balance aspects.

In a historical perspective the Johan Dahl Land project was an important as a test site for developing a comprehensive survey of hydropower feasibility. The Nordbosø basin was the first hydropower area to be investigated in Greenland, and all aspects of hydropower were included in the investigation programme. The hydrological conditions were measured from the top of the accumulation area of Nordbogletscher to the mouth of Qingua river in Tunugdliarfik fjord. The investigations were not only of specific interest to a local hydropower project; results and experience was transferred to and used in similar investigations at other locations. In many ways the Johan Dahl Land was a test area, in which ideas and methods were tested and developed. Johan Dahl Land was at the time the only area in Greenland where the ablation from the Inland Ice and its discharge had been measured simultaneously, leading to the realisation of the complex delineation problems of the Inland Ice.

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