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GLACIERS AND HYDROPOWER FOR NUUK/GODTHÅB WEST GREENLAND

Roger J. Braithwaite

May 1989

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RESUMÉ (DANSK)

Undersøgelser til vandkraftforsyning af Nuuk/Godthåb, Vestgrønland er udført af Grønlands Tekniske Organisation (GTO) siden 1981. Vandmængderne til kraftproduktionen kommer fra bassinet Kangerluarsunnguaq (KNNQ) syd for Nuuk/Godthåb. I en tidlig fase af undersøgelserne blev tillige vurderet mulighederne for ekstra vandtilførsel fra et nabobassin, Isortuarsuup Tasia (ISTA). Gletscherdækket i KNNQ-bassinet er begrænset, hvorimod ISTA-bassinet har et stort gletscherdække omfattende en sektor af Indlandsisen samt store isdæmmede søer. Glaciologiske undersøgelser er udført af Grønlands Geologiske Undersøgelse (GGU) ved Qamanârssûp sermia nordøst for området samt i KNNQ- og ISTA-bassinerne. Den foreliggende rapport vurderer gletschernes mulige effekt på afstrømningen fra begge bassiner.

Hovedkilden for afstrømningen fra KNNQ-bassinet er nedbøren, og afstrømningen er ikke signifikant påvirket af gletscherne. I modsætning hertil er hovedafstrømningen fra ISTA-bassinet smeltevand fra gletschere, og afstrømningsvariationer er stærkt influeret af variationen i ablation og opfyldning og dræning af isdæmmede søer. GTO's afstrømningsimuleringer for KNNQ-bassinet kan derfor ignorere effekten af gletschere, men et problem med homogeniteten af nedbørsdata fra Nuuk/Godthåb er opstået ved en flytning af målestationen og bør løses. Hensyntagen til effekten af gletschere, specielt bidraget fra Indlandsisen, er derimod nødvendig ved afstrømningssimuleringer for ISTA-bassinet.

GGU`s målinger af akkumulationen på en gletscher i KNNQ-bassinet kan anvendes til afstrømningsprognoser for bassinet og bør derfor fortsætte og muligvis udvides, hvis vandkraftudnyttelse bliver aktuel.

ABSTRACT

Investigations have been made by the Greenland Technical Organization (GTO) since the early 1980s on the feasibility of hydropower for Nuuk/Godthåb, West Greenland. The main source of water would be the Kangerluarsunnguaq (KNNQ) basin to the south of Nuuk although the possibility of transferring extra water from another basin, the Isortuarsuup Tasia basin (ISTA), was considered at an early stage of planning. The KNNQ basin contains only a sparse glacier cover while the ISTA basin has an extensive glacier cover, including sectors of the Inland Ice, and contains large ice-dammed lakes. Glaciological measurements have been made by the Geological Survey of Greenland (GGU) at Qamanârssûp sermia to the north-east of the area, and in both the KNNQ and ISTA basins, and the present report assesses the possible effects of glaciers on runoff from both basins.

Runoff from the KNNQ basin is not significantly influenced by glaciers and the basin is essentially a precipitation basin. By contrast, glaciers are the main source of runoff from the ISTA basin and strongly influence runoff variations through both ablation variations and the filling/draining of ice-dammed lakes. Runoff simulations for the KNNQ basin by GTO can therefore ignore glacier effects but there is a serious problem with the homogenuity of the precipitation data from Nuuk which is caused by the relocation of the measuring station and must be solved. Runoff simulations for ISTA must include glacier effects, and especially runoff from the Inland Ice.

GGUs measurements of accumulation on a glacier in the KNNQ basin can be used to forecast runoff from the basin, and should be continued, and possibly extended, as a contribution to the operation of the hydropower station if it is ever built.

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1. PLANNING HYDROPOWER

1.1 Locations

Investigations have been made since the mid-1970s on the feasibility of hydropower in Greenland. At first, emphasis was put upon large, or regional, basins that could supply new energy-intensive industries (GTO, 1975). For example, the Johan Dahl Land area was investigated in the years 1977-1983 as a possible power source for mining in South Greenland. During the 1980s, the emphasis changed to the so-called "town basins" where hydropower would be developed to supplement the existing energy supplies in 12 towns (11 in West Greenland and 1 in East Greenland) according to the requirements of the energy plan for Greenland (Ølgaard, 1987). The locations of possible hydropower stations and the towns to be supplied are shown in Fig. 1.1.

1.2 Planning stages

The planning of hydropower for Greenland towns is divided into 3 "feasibility" stages whose overall aim is to produce a basis for decisions on where, when, and how hydropower stations should be built (MFG, 1982).

Pre-feasibility study: stage 1. The purpose of this stage is to find out if basic hydrological, topographical, and constructional conditions are such that a hydropower station can be built and operated in a specific area with an acceptable economy. This stage includes technical reconnaissance of the area, preliminary evaluation of possible power station sites and first estimations of annual runoff. If the results are favourable, automatic recording stations are installed to collect hydrological and climatological data. This stage is completed by a report (*projektskitse*) which is used to decide whether to continue with planning the hydropower station.

Preliminary design: stage 2. This stage involves more intensive investigations in the area, including measurement of runoff, climate, basic glaciological measurements, environmental surveys, and technical investigations for the hydropower plant and transmission lines to the town where power will be used. This stage is completed by a report (*dispositionsforslag*) in which alternative layouts of the hydropower station are evaluated.

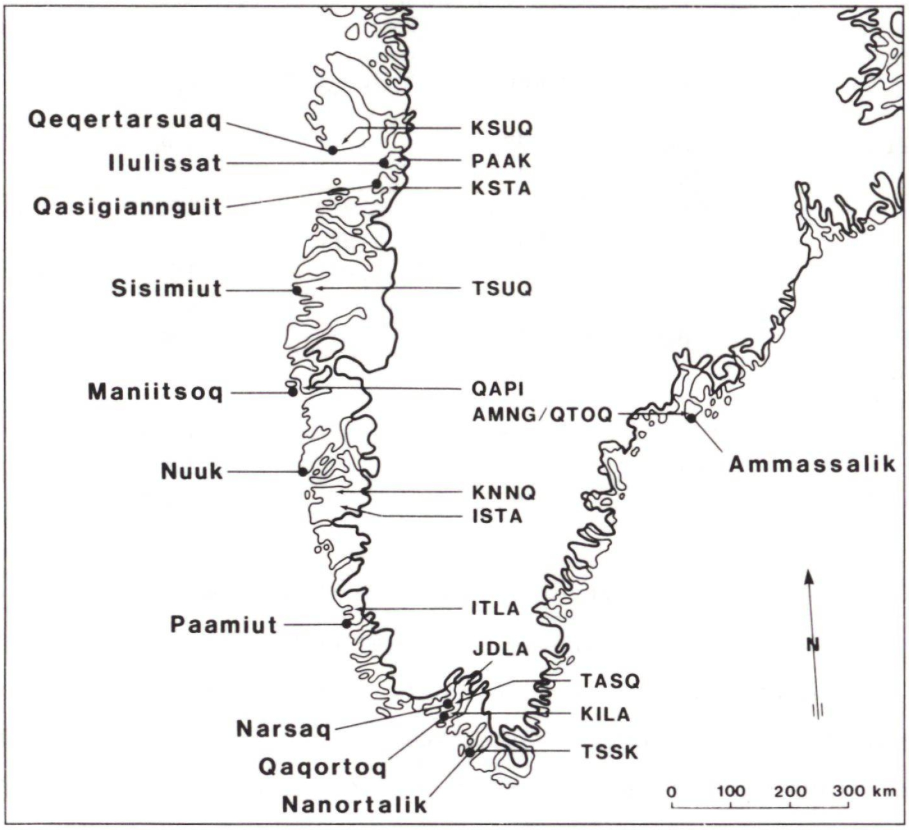

Fig. 1.1. Locations of possible hydropower stations

Feasibility study: stage 3. This stage comprises continued hydrological, climatological and routine glaciological data collection, and possibly detailed glaciological investigations, detailed studies of on-site construction problems, and investigations of load potentials in the town where power will be used. This stage is completed by a report (*projektforslag*) which assesses the overall feasibility of the hydropower project including estimates of its economy. The report is used to decide whether to build a hydropower station for the place in question.

1.3 Status

The status of the hydropower projects in fig. 1.1 are shown in Table 1.1 by the completion dates for the different planning stages for hydropower together with completion dates of the energy plan for the town in question: stage 1 is pre-feasibilty study; stage 2 is preliminary design; stage 3 is feasibility study.

Table 1.1. Completion dates for planning hydropower

Town	Stage 1	Stage 2	Stage 3	Energy Plan
Nanortalik	1980	1983		1985
Qaqortoq	1981			1985
Narsaq	1980	1981	1981	1985
Paamiut	1980	1984	1986	1985
Nuuk	1981	1983	1986	1985
Maniitsoq	1981			1985
Sisimiut	1980	1983/1985	?	1985
Qasigiannguit (+ Aasiaat)	1980/1983	1984		1988
Ilulissat	1981	1983	1986	1984
Qeqertarsuaq	1982			1988
Ammassalik	1981	1984		1988

The progress of each project through the planning stages depends upon decisions made at each stage of planning. For example, the most attractive sites for hydropower have reached stage 3 while less attractive sites were terminated after stage 1 or stage 2. The exception to this is the Narsaq project where the planning stages were accelerated on a different basis to the other projects and where hydropower now has zero priority.

1.4 Energy Plan

The hydropower investigations are part of the energy plan (GTO, 1987a) which attempts to plan energy supplies into the next century. According to the plan, hydropower stations will be built at sites which are favourable while energy will be supplied to other places by continuing with oil or by converting to coal. The town-by-town recommendations of the Energy Plan (GTOa, 1987, Table 6.1) are coal for Qaqortoq (Julianehåb), Narsaq & Maniitsoq (Sukkertoppen) while hydropower is recommended for Nanortalik, Paamiut (Frederikshåb), Nuuk (Godthåb), Sisimiut (Holsteinsborg), Qasigiannguit (Christianshåb), Aasiaat (Egedesminde), Ilulissat (Jakobshavn), Qeqertarsuaq (Godhavn) & Ammassalik (Angmagssalik). The inclusion of Qeqertarsuaq as a possible hydropower site contradicts the termination of hydropower investigations after stage 1. Continuation of oil power is recommended for Uummannaq (Umanak), Upernavik, Qaanaaq (Thule), and Ittoqqortoormiit (Scoresbysund) which were not included in hydropower investigations.

1.5 Priorities

Priorities are matters of politics and economics but GTO (1987a, p. 6-9) recommend building four hydropower stations by AD 2000 to cover all electricity for lighting & power, and some electricity for heating. The four towns are Ilulissat (to come on-line in 1991), Nuuk (1994), Sisimiut (1997) and Paamiut (2000). The remaining five towns, i.e. Nanortalik, Qasigiannguit, Aasiaat, Qeqertarsuaq, and Ammassalik, are still considered as possible hydropower sites but obviously with extremely low priority.

The hydropower station at Ilulissat could have involved severe glaciological problems and GTO requested GGUs assistance at an early stage of the feasibility study, as acknowledged by Thomsen & Jørgensen (1984). Intensive glaciological investigations were therefore made (Braithwaite & Thomsen, 1984 & 1989a: Thomsen *et al.*, 1986, 1988 & 1989) as a contribution to the successful completion of the feasibility study (stage 3). By contrast, the next-highest priority hydropower station for Nuuk involves few glaciological problems and no intensive glaciological investigations were requested by GTO for the feasibility study (stage 3). However, background glaciological investigations have been made over a number of years in the Nuuk area and are described in the following.

2. HYDROPOWER FOR NUUK

2.1 Introduction

A very brief summary of the background to hydropower for Nuuk is given in the feasibility study (GTO, 1986c, p. 7-8). Locations of the main features of the KNNQ basin are shown in Fig. 2.1, including hydrological boundaries of basins and sub-basins. The glacier cover of the KNNQ and ISTA basins is described by Weidick & Thomsen (1983).

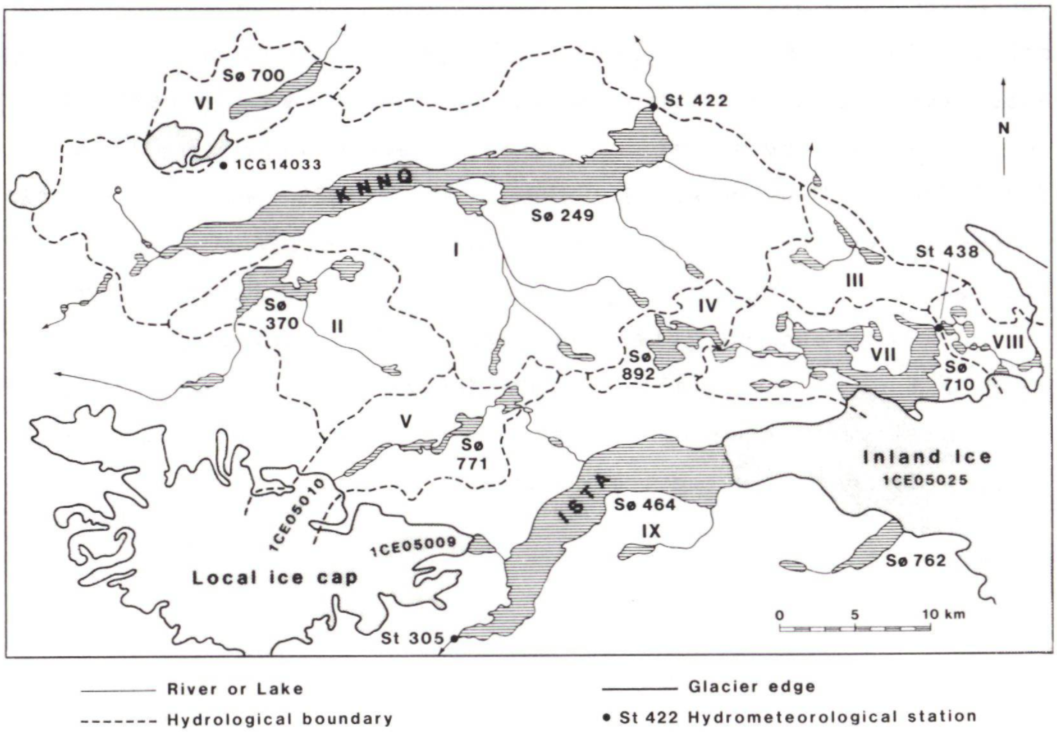

Fig. 2.1 Map of KNNQ and ISTA basins

2.2 Reconnaissance

Reconnaissance studies for hydropower were first made in Greenland in the 1970s to identify 16 basins with large hydropower potentials, i.e. 110-2100 GWh a^{-1}, which could be developed to supply new energy-intensive industries (GTO, 1975). The Kangerluarsunnguaq (KNNQ) and Isortuarsuup Tasia (ISTA) basins were among these with estimated potentials of 120 and 960 GWh a^{-1} respectively.

No runoff data were available from either basin so GTO (1975) had to estimate runoff (procedure not clearly described). The mean annual runoff for the KNNQ basin was estimated to be 220 Mm^3 a^{-1} which seems in remarkable agreement with the 7-year mean of 233 Mm^3 a^{-1} for observed runoff in Table 3.1. However, the 1975 estimate refers to an assumed basin area of 710 km^2, corresponding roughly to sub-basins I & II in Fig. 2.1, while the runoff measurements correspond to sub-basin I with an area of 582 km^2. Adjusting the estimated runoff in GTO (1975) to this smaller basin area gives a figure of only 180 Mm^3 a-1 which is 23 percent too low. The corresponding correction of the estimate of 330 Mm^3 a^{-1} by Braithwaite (1982), also without using runoff data, gives 278 Mm^3 a^{-1} which is 19 percent too high.

For the ISTA basin, the estimated mean annual runoff is 950 Mm^3 a^{-1} which is in surprisingly good agreement with the 11-year mean of 845 Mm^3 a^{-1} in Table 3.1. (The value 1240 Mm^3 a^{-1} estimated by Braithwaite (1982) is not so good although the error is still less than 50 percent).

With the hindsight granted by a few years of measurements, it can be seen that the runoff estimates for KNNQ and ISTA by GTO (1975) were reasonably realistic but this could not have been recognized at the time because of the lack of description of the method used.

The estimated hydropower potential of the ISTA basin was judged sufficiently promising for industrial hydropower that runoff measurements were started in the basin in 1976, i.e. at St. 305, while the KNNQ basin was obviously not regarded as promising.

2.3 Pre-feasibility study

By the late-1970s, planning of hydropower production for industry was downgraded in favour of hydropower to supply the domestic needs of Greenland towns, the so-called town-basins (*bynære bassiner*), as described in Chapter 1. In the case of Nuuk, the KNNQ basin, already identified as a potential site for industrial hydropower, was converted to a town-basin and runoff and climate measurements were started in 1981 at the outlet of Sø 249 (St. 422).

A crucial difference between developing the KNNQ basin for industrial hydropower and for electricity supply to Nuuk is that the latter requires power to be carried over Ameralik Fiord. If this was done by a suspended cable it would be a new world record. This is probably the largest single problem for Nuuk hydropower using the KNNQ basin while hydrological (and glaciological) problems are secondary.

The early investigations are summarized in GTO (1981) which envisaged several possible lay-outs: using sub-basin I alone with an estimated production of 144 GWh a^{-1}; sub-basins I & II with 166 GWh a^{-1}; or sub-basins I & II together with transfer of water from the ISTA basin (sub-basins III to IX, excluding VI) to give around 400-450 GWh a^{-1}. The estimated power production figures were based on only 1 year of runoff measurements for KNNQ (sub-basin I). However, the runoff for that year, i.e. 240 Mm^3 a^{-1}, was only slightly less than the 7-year mean given in Table 3.1. and the hydrological assumptions of the pre-feasibility study are therefore not unrealistic.

The pre-feasibility study pointed out that the few local glaciers have little effect on the hydrology of the KNNQ basin while the ISTA basin is much more complicated as it contains a sector of the Inland Ice as well as the two ice-dammed lakes, Sø 710 & Sø 762. Artificial variations of water level in the main ISTA lake, Sø 464, connected with transfer of water to KNNQ, would also have an uncertain effect on the tongue of the Inland Ice sector which calves into that lake. GTO (1981, p. 33) therefore suggested mass balance measurements of both local glaciers and Inland Ice sectors, studies on the filling/draining cycle of ice-dammed lakes, and studies of the reaction of calving glaciers to water level variations.

2.4 Preliminary design

On the basis of the pre-feasibility study (GTO, 1981), the KNNQ basin was judged to be an attractive site for hydropower for Nuuk, and hydrological and technical investigations by the GTO were intensified in the basin (GTO, 1983b). Ablation studies were also started by GGU in 1982 on one glacier in the basin (Braithwaite & Thomsen, 1989b), i.e. on Glacier 1CG14033 (see Fig. 2.1).

The new data from the basin were used to assess various lay-outs, e.g. using water from sub-basins I-VI, but the published preliminary design for Nuuk hydropower (GTO, 1983a) only envisaged using water from sub-basins I-V with an estimated power production of 220 GWh a^{-1}. In particular, the preliminary design dropped the idea of using water from the main part of the ISTA basin (sub-basin IX). There was therefore no recommendation for glaciological work on the Inland Ice in the ISTA basin although it was pointed out that sub-basin V in the western part of the ISTA basin contains a large sector of a local ice cap.

2.5 Feasibility study

At an early stage of the feasibility study (GTO, 1986c), the planned exploitation of sub-basins II-V was dropped in favour of transferring water from sub-basin VIII. GTO therefore established a new automatic station (St. 438) to measure runoff from this area and, as this sub-basin includes a sector of the Inland Ice, requested GGU to make a preliminary estimate of runoff. The result was an estimated runoff of 60-80 Mm^3 a^{-1} (Braithwaite & Thomsen, 1984b). In addition, GGU established stakes on the Inland Ice above sub-basin VIII in June 1984 to measure ablation while the GTO installed an automatic climate station to measure air temperature.

It was realized during the preparation of the final feasibility study that the runoff from sub-basin VIII was lower than estimated and it was therefore decided to switch back to a lay-out using sub-basins II-V as extra sources of runoff, coming on-line in the period AD 2003-2006. However, there were no technical investigations of the sub-basins II-V and they are only considered cursorily in the feasibility study (GTO, 1986c). This change of plans also explains why ablation measurements were never started on the local ice cap draining into sub-basin V.

The power production using sub-basin I is estimated to be 145 GWh a^{-1} with an extra 85 GWh a^{-1} from sub-basins II-V. These figures assume a design runoff of 252 Mm^3 a^{-1} for the KNNQ basin which was obtained by runoff simulation (GTO, 1986b).

2.6 Recent developments

The energy plan for Greenland (GTO, 1987a) recommends hydropower for Nuuk as the alternative to oil. However, a district heating plant using garbage for fuel has recently come on-line (Anonymous, 1988). The plant can burn 12 kt $a^{-1}$of garbage with a heat output of 27 GWh a^{-1} which is enough to supply heat to the suburb of Nuussuaq at a considerable saving in oil fuel costs. The construction of this plant was apparently not foreseen in the energy plan. This development has implications for hydropower planning as it supplies heat to one of the districts for which hydropower is intended according to the feasibility study (GTO, 1986c). A revised feasibility study is therefore needed to take account of this.

3. HYDROLOGICAL BACKGROUND

3.1 Introduction

The runoff from any basin is the volume of water flowing out of the basin. For a conventional hydrological basin like KNNQ, the only input of water is by precipitation and there is only one outflow. The runoff is then a balance between water supply by precipitation, loss by evaporation, and changes of storage within the basin. On a seasonal basis, these storage changes include snow accumulation, melting of snow and glacier ice, and storage changes in lakes. The latter are small on a year-to-year basis while changes in glacier balance can be significant for basins with extensive glacier cover.

The above hydrological concepts are still valid for basins like ISTA which contain a sector of the Greenland ice sheet but must be applied with caution. For example, in discussion of a similar basin in Johan Dahl Land, Braithwaite & Olesen (1988a) suggest that a distinction has to be made between hydrological and glaciological basins where the former refers to the unit supplying liquid water to the basin outlet. The ISTA basin also contains large ice-dammed lakes which take many years to fill and drain quickly.

Table 3.1: Annual runoff from the KNNQ and ISTA basins.

Year	KNNQ 422	ISTA 305	ISTA 438
1976		826*	
1977		854*	
1978		775*	
1979		766*	
1980		961*	
1981	281*	849*	
1982	150	646*	
1983	329	756*	
1984	282		39*
1985	138	964*	28*
1986	207	1029	34*
1987	241*	873	33*
Mean	233	845	34
c.v.	31%	13%	13%

Units are $Mm^3\ a^{-1}$.

* = Including periods with missing data

The runoff and climate data from the KNNQ and ISTA basins are from GTO (1985, 1986a & 1987b) or are unpublished GTO data kindly provided by C. Kern-Hansen and O. Smith.

3.2 Runoff

The longest runoff measurements in the two basins are KNNQ 422 and ISTA 305 which are supplemented by a newer station ISTA 438. The locations of these stations are shown in Fig. 2.1. The available annual runoff data (September-August) for these stations are summarized in Table 3.1 together with the mean and coefficient of variation (c.v.) of the respective series (the latter is the mean of the series divided by the standard deviation and expresses the relative variability of the series).

KNNQ 422. The recordings were started in 1981 as part of pre-feasibility studies for hydropower for Nuuk (GTO, 1981). GTO (1986a, p. 76-87) summarize the data up to 1985. According to that source, the drainage area includes 574 km^2 of ice-free land and 8 km^2 of local glaciers, i.e. a total area of 582 km^2. It is clear from Table 3.1 that there have been few breaks in the record. There are also many points on the discharge-rating curve which is used to calculate the runoff from the recorded water levels. The quality of the runoff data is therefore high.

ISTA 305. The recordings were actually started in 1976 as a follow-up of reconnaissance hydrological studies for development of large-scale hydropower (GTO, 1975). GTO (1986a, p. 64-75) summarize the data up to 1985. According to that source, the drainage area includes 441 km^2 of ice-free land, 95 km^2 of local glaciers, and an unknown area of the Inland Ice which H.H. Thomsen (pers. comm.) estimates to be about 260-310 km^2. The basin therefore has about 45-48 percent glacier cover.

It is clear from Table 3.1 that there have been many breaks in the record making it necessary to estimate runoff subjectively for certain periods. From experience in the Påkitsoq basin, this usually involves underestimation (Braithwaite & Thomsen, 1984a) but this problem was largely solved in July 1985 when the old mechanical limnigraph was replaced with a more reliable electronic limninlogger. However, the quality of the runoff data is lower than for KNNQ 422 because there are relatively few points on the discharge-rating curve. This is mainly due to the difficulties (and dangers!) of making discharge measurements in the basin outlet. The solution is to install a permanent bridge or cableway to mount the discharge equipment.

ISTA 438. The recordings were started in 1984 in response to a suggestion to transfer water from the northernmost part of the ISTA basin to the KNNQ basin. i.e. from sub-basin VIII. According to GTO (1986a, p. 64) the basin includes 36 km² of ice-free land and 1 km² of local glacier as well as an unknown area of the Inland Ice. As for ISTA 305, the reliability of the data is questionable because of lack of sufficient calibration points on the discharge-rating curve.

Table 3.2. Estimated runoff for smaller sub-basins near the KNNQ basin

Sub-basin	Basin	Area km²	Runoff $Mm^3\ a^{-1}$	Comment
I	KNNQ	582	233	Measured 1981-1987
II	Sø 370	114	46	Estimated
III		52	21	Estimated
IV	Sø 892	37	15	Estimated
V	Sø 731	106	42	Estimated
I-V		891	357	

Ungauged basins. The KNNQ 422 basin corresponds to sub-basin I in the feasibility study (GTO, 1986c) which also envisages using water from sub-basins II to V, see Fig. 2.1 for locations. Runoff from these sub-basins has not yet been measured but is estimated in Table 3.2 assuming that their specific runoff is the same as specific runoff from the KNNQ basin. If it is seriously intended to use water from these sub-basins in later extensions of the hydropower scheme, i.e. sub-basin II to come on-line in AD 2003, sub-basins III & IV in AD 2005, and sub-basin V in AD 2006, runoff measurements should be started by the GTO. Sub-basin V would be of glaciological interest to GGU as it is fed by sectors (1CE05009 & 1CE05010) of a local ice cap while the other basins only have scattered glacier cover. However, new glaciological work in that sub-basin will have little value until runoff measurements are available.

Table 3.3: Annual precipitation and summer mean temperature in the basins.

	Annual precipitation (m water a^{-1})			Summer mean temperature (deg C)		
Year	St. 422	St. 305	St. 438	St. 422	St. 305	St. 438
1982	0.23			7.8		
1983	0.35			5.8		
1984	0.35			7.0		
1985	0.26			9.0		4.9
1986		0.92		7.7	4.9	3.8
1987	0.23	0.52	0.30	8.5	6.0	4.6

3.3 Climate in the basins

The available data for annual precipitation (September to August) and summer mean temperature (June to August) in the two basins are summarized in Table 3.3. The locations of the stations are shown in Fig. 2.1.

KNNQ 422. Climate recordings by an unattended automatic climate station were started in 1981 as part of pre-feasibility studies for hydropower for Nuuk (GTO, 1981). Data are summarized by GTO (1987b, p. 134-161 & 183-208). The precipitation gauges are shielded but the data suffer from the usual measurement problems, especially those for unattended gauges. All things equal, the annual precipitation is probably somewhat underestimated but the precipitation here is much less than in Nuuk. In contrast to the precipitation measurements, temperature readings by the GTO-type automatic climate station are reasonably accurate (Braithwaite, 1983a).

ISTA 305. Although runoff recordings were started in 1976, the early readings were made with a mechanical recorder and it was only in July 1985 that an automatic recorder was installed to collect climate data parallel to the runoff readings. Other comments as above.

ISTA 438. The recordings were started in 1984 but there are many breaks in the precipitation record while temperature readings are almost complete. Other comments as above.

3.4 Climate at Nuuk

Precipitation and temperature have been measured at Nuuk since 1873 although the measurements are not entirely homogeneous due to changes of procedures and station locations, and the precipitation suffers from the usual measurement problems. The data are reasonable well documented in annual summaries published up to 1981 by the Danish Meteorological Institute but are unpublished thereafter. Data are presently available to the author only up to 1986.

Unfortunately for the homogeneity of records, the meteorological station was moved again in 1981. Data during the period of runoff record from KNNQ , i.e. from 1981, are therefore not comparable with longer term data. The problem is particularly serious for precipitation. This is demonstrated by comparing mean precipitation in Nuuk with mean precipitation calculated for 4 other stations (Narsarssuaq, Qaqortoq, Paamiut & Sisimiut) which all have continuous series for 1961-1986. The results are shown in Table 3.4.

Table 3.4. Mean precipitation for Nuuk and 4 other stations.

Period	Years	Nuuk Mean S.D.	4 Stations Mean S.D.	Difference Mean S.D.
1961-1981	21	0.79±0.12	0.67±0.12	0.12±0.14
1982-1986	5	0.57±0.22	0.62±0.23	-0.05±0.08
1961-1986	26	0.75±0.16	0.66±0.15	0.09±0.15

Units are m water a^{-1}

The mean precipitation for the 4 stations in the second period is only 7 percent less than in the first period, indicating a small reduction in precipitation by climate fluctuation. By contrast, mean precipitation at Nuuk is 28 percent less. The mean precipitation for the two periods at each station were compared using Student's t-test to see if they could be drawn from the same populations (Kreyszig, 1970, p. 209-212). For Nuuk, the difference between the mean values of 0.57 and 0.79 m water a^{-1} is too large for them both to come from the same population (with 95 percent confidence). By contrast, the difference between 0.62 and 0.67 m water a^{-1} for the 4 stations is small enough to arise from the same population (with 95 percent confidence).

An alternative approach is to compare time-trends in the two samples, i.e. for Nuuk and for the 4 stations. Annual precipitation at Nuuk has a moderately negative correlation with a linear trend (R=-0.57 for 26 years) which is unlikely to arise by chance (with 95 percent confidence). By contrast, the linear trend is very weakly correlated with the 4-station mean precipitation, i.e. R=-0.08.

The difference between mean precipitation for the two periods at Nuuk, or alternatively the trend of decreasing precipitation, cannot be explained by statistical fluctuations and must be due, in part at least, to relocation of the station. Mean precipitation at Nuuk after 1981 is 0.722 times mean precipitation in the earlier period while 4-station precipitation is 0.925 times precipitation in the earlier period. Assuming the latter figure is also appropriate for climate fluctuations at Nuuk, the station relocation can be estimated as reducing precipitation by a factor of 0.22 (1 - 0.722/0.925). For further analyses, the pre-1982 precipitation values are therefore corrected with this factor. By comparison, GTO (1983b) estimate that station relocation reduced precipitation by 15 percent.

The mean and standard deviation of corrected precipitation at Nuuk for 1961-1981 is thereby reduced to 0.61 ±0.10 compared with 0.79 ±0.12 m water a^{-1} in Table 3.4. The mean and standard deviation of the difference between precipitation at Nuuk and for the 4 stations is now -0.06 ±0.13 compared with 0.12 ±0.14 m water a^{-1} in Table 3.4.

Ideally, precipitation should be measured at both the old and new station sites for a few years so that the true correction can be found.

3.5 Runoff variations

The variability of runoff means that runoff must be measured for many years to get a representative picture of average and extreme conditions. The question of how many years of runoff data are needed for any given level of information involves statistics and information theory, but depends approximately upon the runoff variability, i.e. standard deviation of the runoff series, and the square root of the length of the runoff series.

The fact that runoff varies with season and from year to year means that hydropower stations must be equipped with reservoirs to store surplus water until it is needed to offset low runoff. For example, if runoff and electricity demand were both absolutely constant no reservoir would be needed but most energy is needed in winter while most runoff occurs in a short 4-5 month season as well as varying from year to year. A reservoir is therefore needed to provide both seasonal and carryover storage (McMahon & Mein, 1978, p. 15). Large reservoirs are expensive while small reservoirs cannot use all available water: optimum dimensions can only be found by knowing the runoff variability.

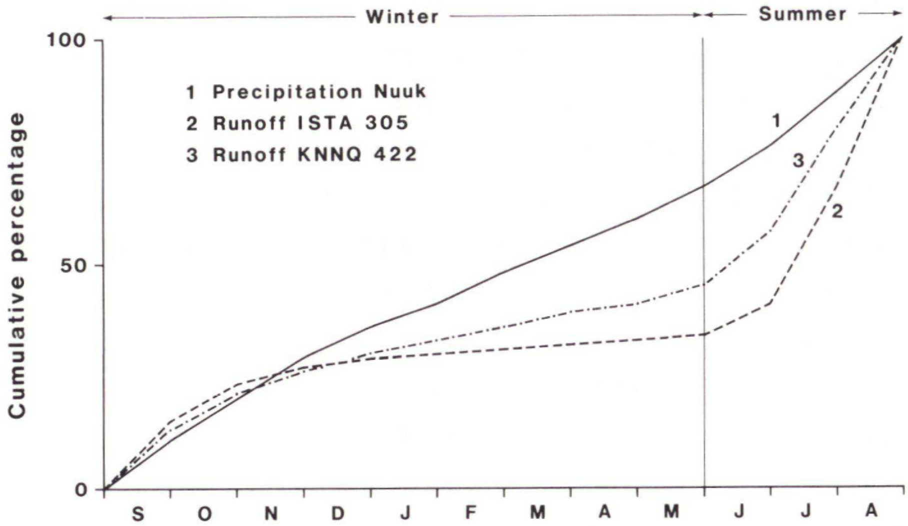

Fig. 3.1. Seasonal variations of runoff and precipitation.

Figure 3.1 shows seasonal variations of runoff for KNNQ 422 and ISTA 305 compared with seasonal variations of precipitation in Nuuk. The data refer to cumulative averages of monthly runoff or precipitation which, for purposes of comparison, are expressed as percentages of the respective averages of annual runoff and precipitation. The precipitation curve is fairly straight through the winter but curves slightly upwards in the summer. This indicates that precipitation is reasonably evenly distributed throughout the year but has a slight maximum in the summer. By contrast, the runoff curves for both KNNQ and ISTA only have gentle upwards slopes through the winter followed by steep rises in the summer. Comparing slopes of the runoff and precipitation curves, indicates that most precipitation in November-May falls as snow and is stored until released by melting in June-August while runoff and precipitation variations are fairly parallel in September and October. There are differences between the two runoff curves for KNNQ and ISTA which are partly due to effects of glaciers but these are fairly small compared with the large difference between runoff and precipitation curves. This shows that the accumulation/melting cycle is the main control on seasonal variations of runoff.

Figure 3.2 shows year-to-year variations of runoff for KNNQ 422 and ISTA 305 compared with precipitation in Nuuk. The data refer to percentage deviations of annual runoff and precipitation from their respective longer-term averages, i.e. for 1981-1986. The KNNQ runoff and precipitation

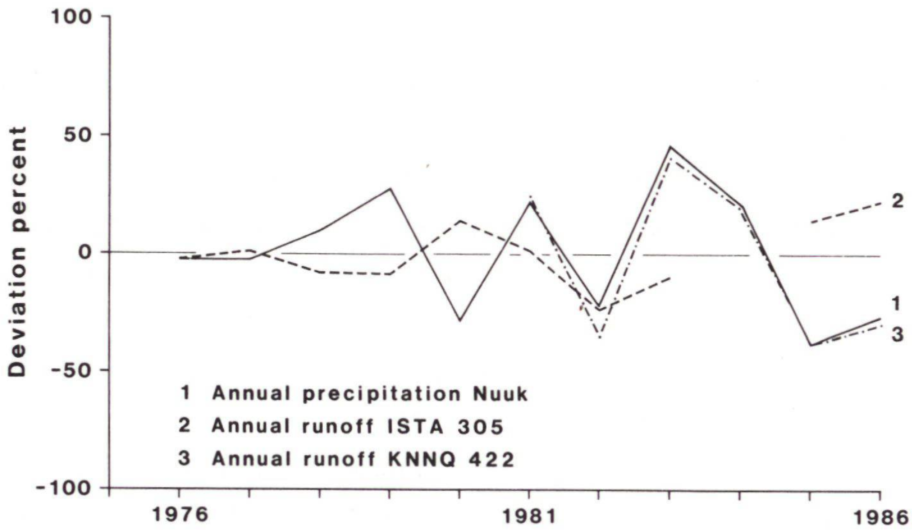

Fig. 3.2. Year-to-year variations of runoff and precipitation.

curves are quite similar, confirming that the KNNQ basin is essentially a precipitation basin. This is in contrast with the runoff curve for ISTA whose variations appear to be in anti-phase to precipitation variations and to have a lower amplitude. These differences between ISTA runoff and precipitation are caused by glaciers and are described in Chapter 5.

3.6 Conclusions

Runoff and climate data for the KNNQ basin are reasonably adequate while runoff data from the ISTA basin require updating with an improved discharge rating curve. There are no hydrological data from sub-basins II-V which might be included in a later phase of hydropower for Nuuk. The meteorological station in Nuuk was moved and the long-term precipitation record may not be homogeneous. Precipitation measurements should be made at the old station site for a few years to overlap with records at the new site.

4. GLACIOLOGICAL BACKGROUND

4.1 Introduction

The present studies of ablation in Greenland were started with the good intention of following the standard international guidelines (Anonymous, 1969) but they were found too difficult to apply. For example, modern mass balance concepts include both the mass balance at a point, specific balance, and the mass balance of the whole glacier. The second concept is difficult to apply because it requires: (1) specific balance variations over the whole glacier which can only be obtained by dense stake networks and (2) the areal distribution of the glacier which is usually unknown for sectors of the Inland Ice which means that mass balances cannot be calculated for whole "glaciers" represented by sectors of the Inland Ice. There are also serious problems in measuring mass balance in the lower accumulation zone because of the difficulties in measuring refreezing of meltwater in the limited time available for the measurements.

For the present discussion ablation data from four glaciers are considered: Glacier 1CG14033 in the KNNQ basin; 1CE05025 in the ISTA basin; Qamanârssûp sermia in Godthåbsfjord; and Nordbogletscher in South Greenland. The locations of these glaciers are shown in Fig. 4.1.

4.2 Glacier 1CG14033

Although glaciers only occupy 1.8 percent of the area of the KNNQ basin (Weidick & Thomsen, 1983, p. 56), ablation measurements have been made on one glacier in the basin since 1982 (Braithwaite & Thomsen, 1989b) to investigate the possible effects of glaciers on runoff from KNNQ, and to contribute to GGUs programme of regional glaciology. The glacier has an area of only 1.1 km^2 in the elevation range 1100-1450 m a.s.l.

Eight aluminium stakes were drilled into the glacier in 1982 in the elevation range 1260-1360 m a.s.l. and have been used for rudimentary mass-balance measurements during twice-yearly visits of a few hours by helicopter. The winter snow accumulation is determined in May by measuring snow depths at all stakes and measuring snow density in snowpits of 1-3 m depth at some stakes. The summer ablation is determined in late August or early September at the lowest stakes by measuring the ice surface relative to the stakes. However, snow ablation at higher stakes is more difficult to measure as most water from snow melt refreezes at depth in the snowpack, possibly a few metres below the surface.

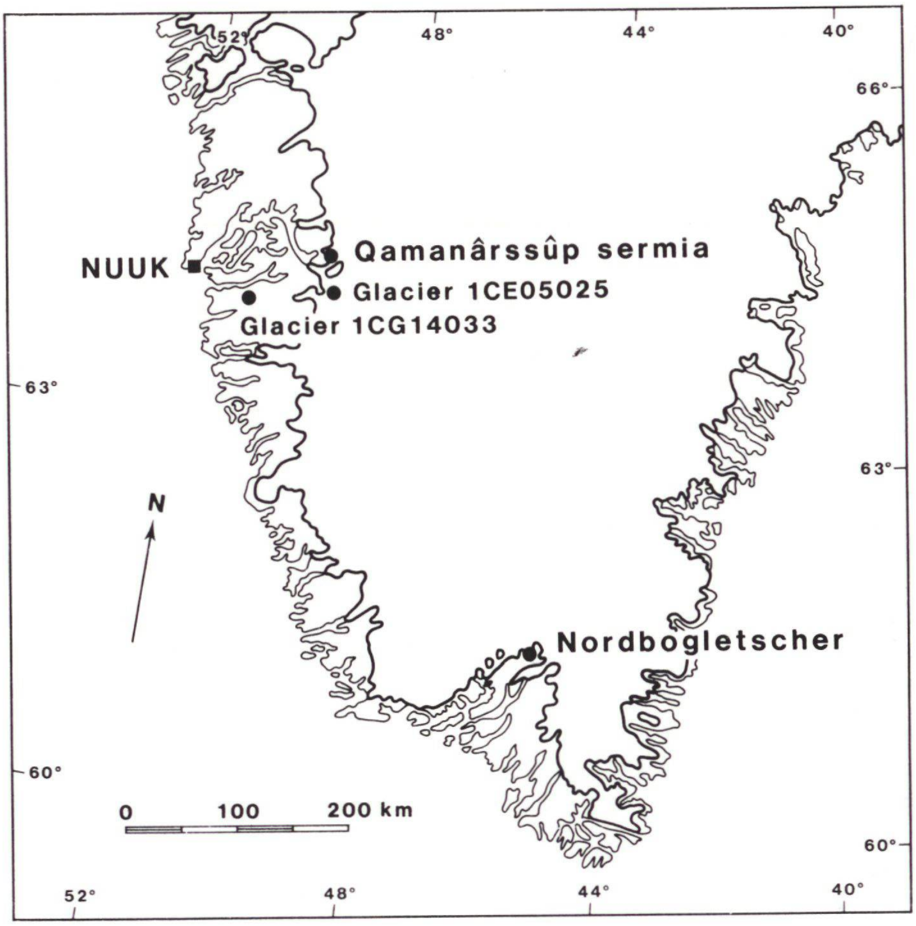

Fig. 4.1. Locations of 4 glacier with ablation measurements

Brief twice-yearly visits made in the period 1982-1987 never allowed enough time to dig or core throughout the whole wet snow layer but the reduction in activity at Qamanârssûp sermia since 1986 (Braithwaite, 1987) made it possible to plan a longer stay on the glacier in May 1988 to improve the accumulation measurements. Three deep snow pits were dug for density measurements which is a great improvement on earlier years. Another improvement was the use of a ramsonde to measure hardness profiles in the snowpack, and especially the hard summer surface of 1987.

The available data for 7 years for winter accumulation and net ablation are summarized in Table 4.1. Winter accumulation is calculated for all stakes where snow depths were measured. For most years, snow densities are extrapolated from a single snow pit compared with three snow pits in 1988. The data for many stakes in 1986, and for stake 8 in two other years, are missing because these stakes were buried by deep snow. Stake 3 has totally disappeared, presumably due to burial. Net ablation data are only available for stakes in the ablation area (stakes 1 & 7) or for situations where snowpits and/or cores were made sufficiently deep to measure refreezing (stakes 2 & 4).

Table 4.1. Mass-balance measurements on Glacier 1GC14033.

	Stakes							
	1	2	3	4	5	6	7	8
Elev. (m a.s.l.)	1260	1300	1320	1330	1320	1300	1270	1360
Winter accumulation:								
1981/82	0.48							
1982/83		0.74			0.91	0.83	0.67	
1983/84		0.70	0.73	0.76	0.93	0.89	0.56	
1984/85	0.59	0.68	0.39	0.46	0.43	0.51	0.37	0.38
1985/86	0.56	0.96					0.65	
1986/87		0.50		0.23	0.82	0.86	0.69	0.90
1987/88	0.82	0.78		0.81	0.88	0.95	0.31	0.98
Net ablation:								
1981/82	0.60							
1982/83	-0.03	-0.59	-0.60	-0.62			-0.38	
1983/84	0.02	0.09	-0.27	-0.03			0.36	
1984/85	1.62	1.06		0.68			1.58	
1985/86	0.58	-0.30		-0.14			0.44	
1986/87	0.47	0.36		0.03			1.04	
1987/88	-0.05	-0.07		-0.21			0.22	

Units are m water a^{-1}

The variations of accumulation and net ablation are best described by indices which are averages of the available data (Braithwaite & Olesen, in press). For Glacier 1CG14033, the accumulation index is the average accumulation at stakes 2, 5, 6 & 7 with a mean elevation of 1300 m a.s.l. (missing data for 1986 at stakes 5 & 6 are interpolated by correlations with data at stakes 2 & 7), and the ablation index is the average net ablation at stakes 1, 2, 4 & 7 with a mean elevation of 1290 m a.s.l.

Ablation is generally positively correlated with temperature and negatively correlated with variations in snow accumulation (Braithwaite & Olesen, 1989). The latter is very important for glacier hydrology. For Glacier 1CG14033 there is a strong negative correlation between ablation and accumulation indices which is illustrated in Fig. 4.2. The relation is quite similar to that found for Nordbogletscher and reflects the lower thermodynamic efficiency of snow ablation compared with ice ablation at the same temperature (Braithwaite & Olesen, 1988b).

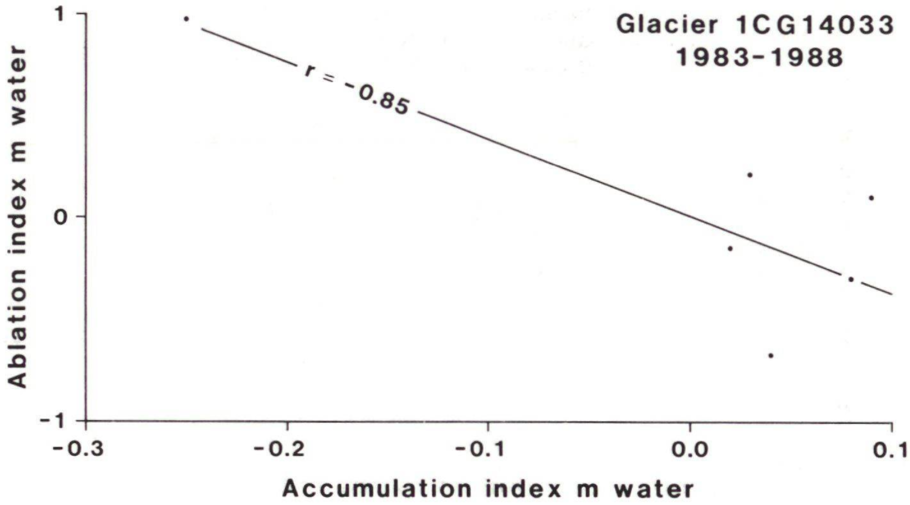

Fig. 4.2. Ablation index versus accumulation index, Glacier 1CG14033

4.3 Glacier 1CE05025

In response to the suggestion of transferring water from sub-basin VIII to the main reservoir in the KNNQ basin (see map in Fig. 2.1), ablation stakes were established in 1984 on the Inland Ice sector thought to drain into sub-basin VIII; coded 1CE05025 in the West Greenland glacier inventory (Weidick, in preparation).

Table 4.2. Annual ablation on Glacier 1CE05025

	IST 2/3	IST 35	IST 37	QAM
Elev. m	1140	1110	1190	1090-1200
1983/84	2.0*			0.5
1984/85	1.9	2.1	2.2	1.8
1985/86	1.8	1.5	1.8	1.6
1986/87	2.2	1.8		
1987/88	1.7			

Units are m water a^{-1}
* Estimated

Three stakes were established in the altitude range 1110-1190 m a.s.l., the first being drilled in June 1984 and the other two in September 1984. The stakes were remeasured every year in late May and early September, i.e. immediately before and immediately after fieldwork at Qamananârssûp sermia. There is little or no winter snow cover at stakes IST 35 and IST 2/3 while IST 37 was mistakenly established in a location which was found to be subject to snow drifting such that measurements in May were dangerous

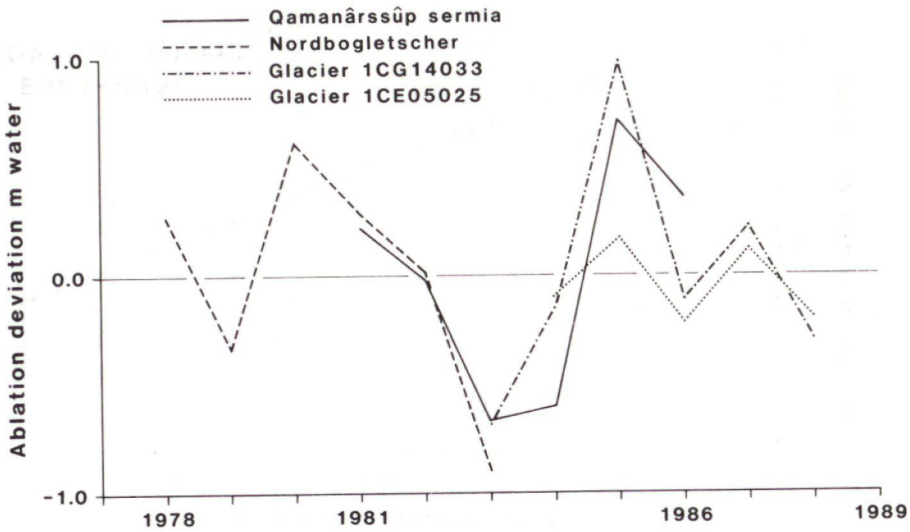

Fig. 4.3 Ablation variations on 4 glaciers

because of snow-covered crevasses. In general the quality of the measurements suffered because the location is at the limit of range of the Bell-206 helicopter used for the operation. The available data for net ablation are shown in Table 4.2 where QAM refers to the average ablation of stakes 12 & 13 at 1090-1200 m a.s.l. on Qamanârssûp sermia.

4.4 Qamanârssûp sermia

Glaciological and climatological measurements were started in 1979 at Qamanârssûp sermia which is an outlet of the Inland Ice located at the end of Godthåbsfjord (Olesen, 1981). The site itself was not of immediate interest for hydropower but was chosen as representative of ablation conditions in both the ISTA basin and at Imarssuaq north of Qamanârssûp sermia. The station was manned for seven summers 1980-86 (Olesen & Braithwaite, 1982: Braithwaite, 1983b, 1984, 1985, 1986 & 1987) and the field programme included collection of daily climate data at the base camp, measurements of daily ablation at the glacier edge, maintenance of auxiliary climate stations on the glacier, energy balance studies, and seasonal measurements of mass balance and ice movement in a sparse network of ablation stakes extending up to 1410 m a.s.l. on the Inland Ice. In addition, a GTO-type automatic climate station was tested (Braithwaite, 1983b) and has been used almost continuously for year-round data collection.

The field programme for 1987 & 1988 was drastically reduced to twice-yearly visits to measure ablation at only a few stakes (Braithwaite, 1989).

4.5 Nordbogletscher

Glaciological, climatological, and hydrological studies were started in 1977 at Nordbogletscher, an outlet of the Inland Ice, in connection with the planning of the Johan Dahl Land hydropower project. The station was manned for six summers 1978-1983 (Olesen, 1978: Clement, 1981, 1982, 1983 & 1984a) until plans for hydropower were dropped in 1983. The field programme included collection of daily climate data at the base camp, measurements of daily ablation at the glacier edge, maintenance of auxiliary climate stations on the glacier, and seasonal measurements of mass balance and ice movement in a sparse network of ablation stakes extending up to 2100 m a.s.l. on the Inland Ice. Mass balance measurements were also made on a local glacier Valhalatinde Gletscher. Other work included an outstanding study of the water balance of an ice-dammed lake (Clement, 1984b).

Table 4.3. Ablation variations on 4 glaciers.

Year	Glacier 1CG14033	Glacier 1CE05025	Qamanârssûp sermia	Nordbo-gletscher
1978				0.27
1979				-0.33
1980				0.61
1981			0.22	0.29
1982			-0.02	0.02
1983	-0.67		-0.67	-0.89
1984	-0.15	-0.10	-0.60	
1985	0.98	0.17	0.71	
1986	-0.11	-0.21	0.36	
1987	0.22	0.12		
1988	-0.29	-0.19		
s.d.	±0.56	±0.18	±0.55	±0.54

Units are m water a^{-1}

4.6 Ablation variations

Ablation variations on the four glaciers are shown in Table 4.3 in the form of deviations from mean ablation for the respective series. The values for Glacier 1CG14033 are 4-stake averages, for Glacier 1CE05025 1-3 stake averages, for Qamanârssûp sermia 8-stake averages (Braithwaite & Olesen, in press), and for Nordbogletscher 14-stake averages (Braithwaite & Olesen, 1988a).

For convenience the ablation variations are also plotted in Fig. 4.3. Despite differences in location and local conditions, 3 of the 4 series are fairly similar, e.g. ablation was very low in 1983 and very high in 1985, while there are problems with the data for Glacier 1CE05025 whose variations seem to be anomalously low although they generally follow ablation at the other sites.

The similarities in Fig. 4.3 hint at a broad regional pattern of ablation variations, e.g. due to regional correlation of temperature and radiation variations, while differences reflect differences in local conditions, e.g. local variations of precipitation and exposure. Both of these will be further investigated as part of GGUs regional programme of glaciology.

5. EFFECT OF GLACIERS ON RUNOFF

5.1 Introduction

The main hydrological problem in the early stages of planning hydropower, e.g. in the reconnaissance and pre-feasibility stages, is to estimate the mean runoff and thereby the expected power production. However, after a few years of runoff data have been collected, i.e. in the preliminary design and feasibility study stages, the main problem is the assessment of runoff variability. Glaciers can effect both mean runoff and runoff variations.

Runoff variability from year to year is expressed by the standard deviation of runoff series which, for convenience of comparing basins, is often divided by the mean of the runoff series to give the coefficient of variation (c.v.). The relation between runoff variability and amount of glacier cover is still a subject of debate in the literature, e.g. see Tvede (1983), Collins (1985), Ferguson (1985), Fountain & Tangborn (1985), and Röthlisberger & Lang (1987).

According to Braithwaite & Olesen (1988a & 1988b), the important mechanism is the negative correlation between ablation and precipitation, caused by the fact that increased snow accumulation reduces ice ablation. For a basin with little or no glacier cover, runoff variations are essentially driven by precipitation variations. For basins with a moderate glacier cover, runoff variations are smoothed because precipitation variations are to a greater or lesser extent offset by ablation variations. For highly glacierized basins, runoff variations are essentially driven by ablation variations.

5.2 The KNNQ 422 basin

For a conventional hydrological basin like KNNQ, the effect of glaciers on mean basin runoff is represented by the mean balance of glaciers in the basin. As stated in Chapter 4, it is not possible to give a figure for the mean balance of glaciers in either basin. However, from studies elsewhere (documented in the publications of the *Permanent Service on the Fluctuations of Glaciers*) it is known that long-term mean balances are seldom outside the range ±0.5 m water a^{-1}, and that ±1.0 m water a^{-1} would be very exceptional, corresponding to very large retreat or advance. Applying the latter figures to the KNNQ basin with a glacier cover of 10.1 km^2 gives a maximum glacier effect of ±10.5 Mm^3 a^{-1} which is quite negligible compared with the mean runoff of 233 Mm^3 a^{-1} (Table 3.1). Glaciers cannot therefore have a large effect on mean runoff from KNNQ.

KNNQ runoff and Nuuk precipitation have similar variability, i.e. coefficients of variation of ±31 and ±33 percent respectively for the period 1981-1986. There is a strong positive correlation between runoff and precipitation (r= 0.96) and a moderately negative correlation (r=-0.72) between runoff and ablation variation on Glacier 1CG14033 which is illustrated in Fig. 5.1. Note that the ablation record measured on Glacier 1CG14033 since 1983, see Table 4.2, has been extended back to the start of runoff records in 1981 by correlation with ablation at Qamanârssûp sermia.

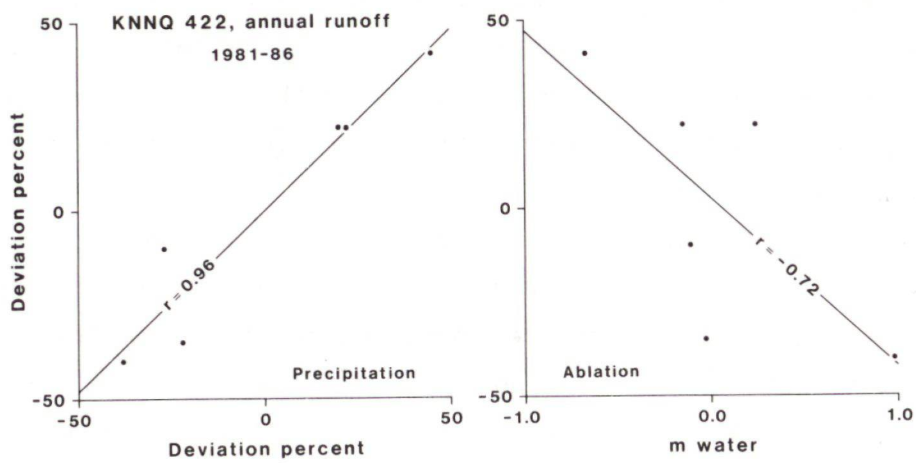

Fig. 5.1. Annual runoff for KNNQ 422 versus annual precipitation and ablation

This pattern of relatively high runoff variability, high runoff-precipitation correlation, and negative runoff-ablation correlation is characteristic of a basin with little or no glacier cover (Braithwaite & Olesen, 1988a). There is therefore no evidence that glaciers influence runoff variations in the KNNQ basin.

5.3 The ISTA 305 basin

The effect of glaciers on runoff can be estimated by separating the total runoff for the whole basin into contributions from ice-free and glacier parts. This is done by assuming that specific runoff, i.e. runoff per unit area, for the ice-free part of the ISTA 305 basin (441 km^2) is the same as the specific runoff from KNNQ 422 (584 km^2). The ice-free runoff is then

(441/584) times the runoff from KNNQ 422, and the glacier runoff equals the runoff from the whole ISTA 305 basin minus (441/584) times the runoff from KNNQ 422. The data for the calculation are given in Table 3.1 and the results are shown in Table 5.1.

According to this rough estimate, about 80 percent of the mean runoff from the ISTA 305 basin comes from glaciers, i.e. from precipitation on glaciers and from glacier melting. As there is no repeated mapping of the Inland Ice sector in the ISTA basin it is not possible to say if this runoff volume is significantly influenced by volume change of the Inland Ice sector, i.e. if some meltwater is drawn from long-term storage. However, photogrammetric measurement of volume change at Qamanârssûp sermia shows that it was nearly stationary (slight retreat) in the period 1968-1980 (Knudsen, 1983) while Weidick (pers. comm.) suggests that the ice margin in the ISTA basin is in a state of slow advance.

Table 5.1 Estimated runoff for ice-free and glacier parts of ISTA 305

Year	Total	Glacier	Ice-free
1981	849	639	212
1982	646	533	113
1983	756	508	248
1984			
1985	964	860	104
1986	1029*	873*	156
1987	873	691	182
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Mean	853	684	169
c.v.	16%	23%	33%
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Units are $Mm^3\ a^{-1}$.
* Ice-dammed lake drainage

A strong negative mass balance (-1 m water a^{-1} operating on an estimated glacier area of 260-310 km^3) would increase mean runoff by about 260-310 $Mm^3\ a^{-1}$ which represents a 30-36 percent increase over present basin runoff (853 $Mm^3\ a^{-1}$).

The glacier part of ISTA runoff from Table 5.1 is plotted against precipitation and ablation in Fig. 5.2. The ablation data in this case refers to ablation at Qamanârssûp sermia.

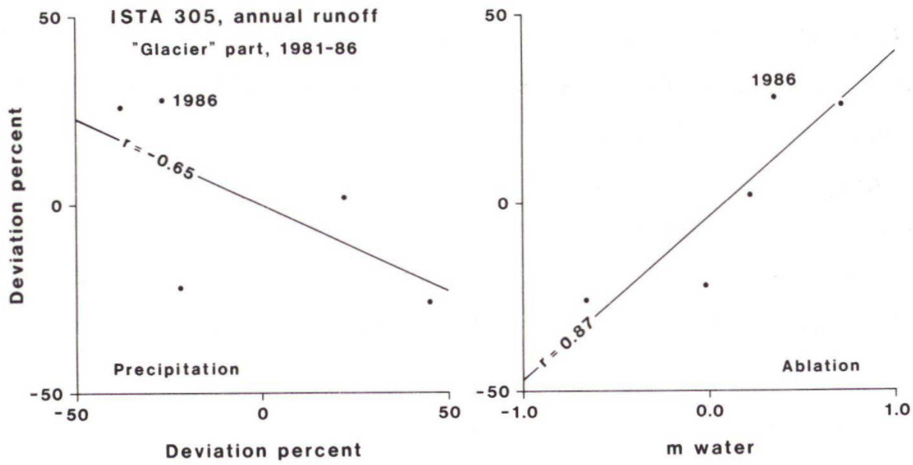

Fig. 5.2. Annual runoff for ISTA 305 versus annual precipitation and ablation

Runoff from the ISTA basin has a low coefficient of variation, i.e. only 13-16 percent, compared with Nuuk precipitation. From Table 5.1, it appears this is caused by a combination of glacier and ice-free runoff components which each have higher variability but tend to compensate each other. This is illustrated in Table 5.2 which shows the runoff-precipitation and runoff-ablation correlations for total runoff from ISTA as well as for glacier and ice-free runoff components. The moderate negative correlation between total runoff and precipitation (r=-0.41) is the result of a more negative correlation (r=-0.65) for the glacier component and a high positive correlation (r= 0.96) for the ice-free component. In a similar way, the moderate positive correlation between total runoff and ablation (r= 0.67) is a result of a strong positive correlation (r= 0.87) for glacier runoff and a negative correlation (r=-0.71) for ice-free runoff.

Table 5.2 Correlations coefficients for runoff from the glacier and ice-free parts of ISTA 305

	Total	Glacier	Ice-free
Runoff-precipitation	-0.41	-0.65	0.96
Runoff-ablation	0.67	0.87	-0.71

Sample size of 6 years

The pattern of relatively low runoff variability, negative runoff-precipitation correlation, and positive runoff-ablation correlation is characteristic of a moderately to highly glacierized basin. (Braithwaite & Olesen, 1988a). Runoff variations in the ISTA 305 basin are therefore strongly influenced by ablation variations.

In addition to the effects of ablation, runoff from the ISTA basin is also influenced by the sporadic tapping of a large ice-dammed lake which drained in 1975 (before records started), in October 1980, and in August 1986. This means that observed runoff for 1976-1979, and 1981-1985 is reduced in comparison with ablation and precipitation while runoff in 1980 and 1986 is increased, e.g. note the high runoff for 1986 in Fig. 5.2 compared with low precipitation and only moderately high ablation. This probably has the effect of reducing the correlations between runoff and precipitation, and runoff and ablation compared with what they would be if there were no ice-dammed lake.

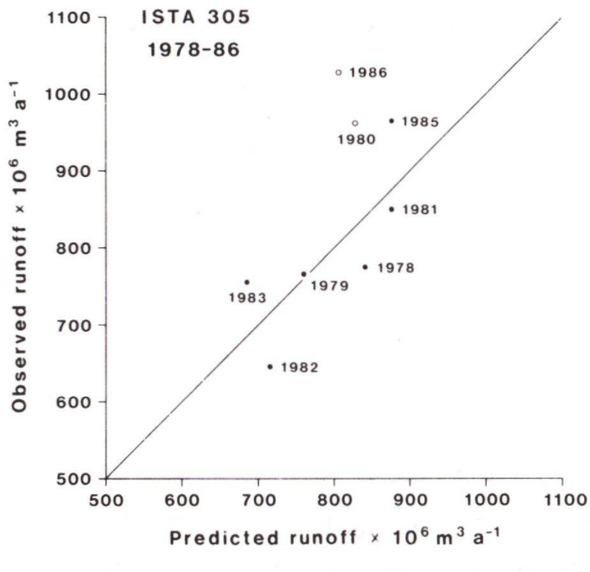

Fig. 5.3 Observed runoff versus runoff predicted from precipitation and ablation

The effect of ice-dammed lake drainage is also illustrated in Fig. 5.3 which shows the relation between observed runoff and the runoff predicted by a regression equation using ablation and precipitation. (Note that ablation at Qamanârssûp sermia was extended back to 1978 for this calculation by correlation with ablation at Nordbogletscher). The runoff values for 1980 and 1986 were not used in the calculation of the regression equation so the location of the two points well above the straight line in Fig. 5.3 reflects the effect of higher runoff due to ice-dammed lake drainage in those two years, superimposed onto the usual random errors associated with regression equations. From the differences between observed and predicted runoff for the two years, the ice-dammed lake drainage is estimated to give 130-220 Mm^3 of water compared with 230 Mm^3 estimated by GTO (1983b).

5.4 The ISTA 438 basin

The effect of glaciers on runoff from the ISTA 438 basin can be roughly estimated in the same way as for ISTA 305. In this case, specific runoff from the KNNQ basin (582 km^2) is applied to the ice-free part of ISTA 438 (36 km^2) so that ice-free runoff is (36/582) times the runoff from KNNQ 422, and the glacier runoff equals the runoff from the whole ISTA 438 basin minus (36/582) times the runoff from KNNQ 422. The data for the calculation are given in Table 3.1 and the results are shown in Table 5.3.

Table 5.3 Estimated runoff for ice-free and glacier parts of ISTA 438

Year	Total	Glacier	Ice-free
1984	39	22	17
1985	28	19	9
1986	34	21	13
1987	33	18	15
Mean	34	20	14
c.v.	13%	9%	25%

Units are $Mm^3\ a^{-1}$

According to this rough estimate, about 60 percent of the mean runoff from the ISTA 438 basin comes from glaciers. However, the total runoff is much less than the 60-80 $Mm^3\ a^{-1}$ estimated by Braithwaite & Thomsen (1984b) and the idea of using water from this area has been dropped in the feasibility study (GTO, 1986c). The low runoff is presumably caused by a sub-glacial sill which limits the drainage area on the Inland Ice but there is a further problem in that runoff variations do not follow ablation variations, e.g. runoff was lower in 1985 & 1987 when ablation was high.

5.5 Conclusions

Runoff from KNNQ 422 is not significantly influenced by glaciers. By contrast, glaciers are the main source of runoff from ISTA 305 and strongly influence runoff variations through ablation variations and through the filling/draining of an ice-dammed lake. Glaciers appear to be the main source of runoff from ISTA 438 but otherwise their effects are obscure.

6. RUNOFF SIMULATION

6.1 Introduction

Hydropower planners are naturally reluctant to measure runoff for many years before attempting any planning, and instead use runoff simulation to artificially extend short series of runoff data. However, the simulation method must take account of effects of glaciers if there are any. For example, a simple runoff-precipitation correlation is good enough for a basin with little or no glacier cover while a heavily glacierized basin also needs an ablation model.

GGU has developed an ablation model for annual runoff simulation (Braithwaite & Thomsen, 1984a & 1989a) and has also helped GTO to modify their NAM-II model to include ablation (Thomsen & Jørgensen, 1984: Kern-Hansen, 1989). The modified NAM-II model was used for GTOs runoff simulation at Påkitsoq near Ilulissat but has not been used for the KNNQ basin because the GTO regards the KNNQ basin as a precipitation basin.

6.2 The KNNQ 422 basin

According to Chapter 5 the KNNQ basin is essentially a precipitation basin and runoff simulations do not need to take account of glaciers and GTO (1986b) have already made a simulation using their (unmodified) NAM-II model which treats the basin as a pure precipitation basin. The GTO simulation used four years of runoff record 1981-1984 together with longer climate series from Nuuk to extend the runoff record to the 26-year period 1959-1984. The error standard deviation of the simulation was only ± 9 $Mm^3\ a^{-1}$ for the four years used for model calibration (GTO, 1986b, p. 35). The simulated runoff for 26 years is 252 $Mm^3\ a^{-1}$ compared with 262 $Mm^3\ a^{-1}$ for the calibration period.

The GTO simulation, using the highly sophisticated NAM-II model, gives detailed information down to simulated daily runoff which can be used for planning power station operation (*driftsimulation*). However, if only annual runoff is needed, a much simpler simulation can be made using annual precipitation in Nuuk.

The simple simulation uses September-August precipitation in Nuuk multiplied by the area of the KNNQ basin, i.e. 582 km^2. This precipitation volume is correlated with observed runoff for KNNQ to give a regression equation linking runoff to precipitation:

$$Q_{ob} = -17.3 + 0.692 \times P_{Nk}$$

where Q_{ob} is observed runoff from the KNNQ basin and P_{Nk} is precipitation volume (annual precipitation in Nuuk multiplied by 582 km^2). The simulated runoff is calculated from the precipitation volume using the regression equation. The error is the difference between simulated and observed runoff with a standard deviation of ± 22 Mm^3 a^{-1} for the 6 years which is larger than found by GTO (1986b). The data and results of the calculation are shown in Table 6.1.

Table 6.1. Observed and simulated runoff for the KNNQ basin

	Precipitation Volume	Observed Runoff	Simulated Runoff	Error
1981	437	281	281	0
1982	279	150	182	32
1981	437	281	281	0
1982	279	150	182	32
1983	518	329	332	3
1984	431	282	277	-5
1985	221	138	145	7
1986	262	207	171	-36
----	---	---	---	---
Mean	358	231	231	0
s.d.	±120	±78	±75	±22
c.v.	33%	34%	32%	---
----	---	---	---	

Units are Mm^3 a^{-1}

The correlation coefficient is 0.96 for the six years of record 1981-1986 and is statistically significant at less than 1 percent according to Student's t-test (Kreyszig, 1970, p. 343).

The regression coefficient is less than unity, i.e. 0.627, which partly accounts for evaporation but also indicates that precipitation in the KNNQ basin is less than precipitation in Nuuk. This fits with the precipitation data in Table 3.3.

The runoff simulation for 1961-1986 is problematic because of the inhomogenuity of the precipitation data in Nuuk, as described in Chapter 3. For example, using uncorrected precipitation data for Nuuk, the mean runoff for the 26 years is 279 Mm^3 a^{-1} which is 11 percent higher than the GTO value of 252 Mm^3 a^{-1}. However, using the suggested precipitation correction, the mean runoff is only 227 Mm^3 a^{-1} which is 10 percent less than the simulation by GTO (1986b).

In the second part of GTO (1986b) the runoff simulation is extended into the future by extrapolation of a claimed 110-year periodicity in the precipitation data at Nuuk since 1875. This is a very dubious procedure in view of all the measurement problems with precipitation, gaps in record, and relocations of the climate station.

6.3 The ISTA 305 basin

The runoff from the Inland Ice sectors in the ISTA basin was simulated using the same MB1 runoff model as used for Påkitsoq near Ilulissat (Braithwaite & Thomsen, 1984a & 1989a). The model uses monthly temperature and precipitation data extrapolated from Nuuk to calculate specific runoff from ablation and rainfall as a function of elevation. Volumetric runoff is then calculated by applying these specific runoff values to the supposed area-elevation distribution of the Inland Ice sector in the basin. The latter information were provided by H.H. Thomsen (pers. comm.) for maximum and minimum estimates of the glacier areas based upon analyses of low-angle satellite images (Thomsen, 1986: Thomsen & Braithwaite, 1987). The maximum and minimum delineations are shown in Fig. 6.1 (kindly provided by H.H. Thomsen).

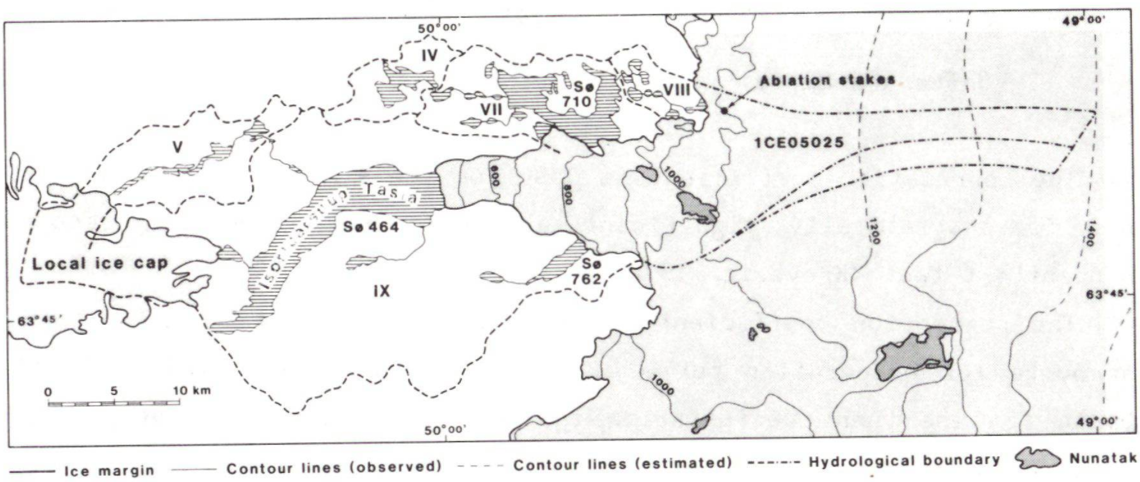

Fig. 6.1. Delineation of Inland Ice sector in the ISTA basin

The simulated runoff from the Inland Ice part of the basin is shown in Table 6.2 together with the estimated glacier runoff from Table 5.1. Because of the uncertainties in the observed runoff due to shortcomings of the discharge-rating curve and in the procedures for estimating the glacier runoff, as well as the effect of the ice-dammed lake draining, no calibration is made of the simulated runoff. However, two conclusions can still be made. First, the uncertainty in area of the Inland Ice part of the basin has a fairly small effect on the simulated runoff and, second, simulated runoff for the short period 1981-1986 is only a little less than simulated runoff for the longer period 1961-1986. Presumably the observed runoff is similarly representative of a longer period.

Table 6.2. Simulated runoff versus estimated glacier runoff from ISTA 305

Year	Estimated glacier	Simulated Inland Ice
1981	639	637-695
1982	646	507-551
1983	756	409-432
1984		548-594
1985	964	861-950
1986	1029	725-796
1981-86 Mean	807	615-670
1961-86 Mean		636-691

Units are $Mm^3\ a^{-1}$

6.4 Conclusion

The runoff simulation for KNNQ by GTO (1986b) with only 4 years of data (1981-1984) should be repeated with the present 8 years of record (1981-1988) which include both a very wet year (1983) and the driest year since at least 1961 (1985). The simulation does not need to include glacier effects but, in view of the economic importance of runoff simulation, the problem with Nuuk precipitation data must be solved. For example, new measurements should be made for a few years at the site of the old station in Nuuk to overlap with data from the new station so that a proper correction can be made.

7. RUNOFF FORECASTING

7.1 Introduction

Runoff forecasting is important for operating hydropower stations, i.e. for reservoir management, as decisions must be made continuously during the runoff season about either storing incoming water for later use or releasing it for power production. Energy for light and power has the highest price and it is beneficial to save water for this purpose except that lower priced energy must be provided for heating. A conservative policy of water release will misfire when the reservoir is nearly full and more water arrives, while it will be correct if most of the available runoff has already arrived in the reservoir. Seasonal forecasting of runoff would help reduce such uncertainties.

The planned reservoir is rather large compared with the design runoff for the project, i.e. 1000 Mm^3 compared with 252 $Mm^3\ a^{-1}$ (GTO, 1986c). One might therefore argue that seasonal forecasting for reservoir management is not critical as water deficits for several years can be supplied by continued drawdown of the reservoir. However, even if the storage volume is available, excessively low water levels should be avoided for aesthetic reasons and to avoid bank erosion.

7.2 The KNNQ 422 basin

As shown in the previous Chapter, glacier cover in the KNNQ basin is too sparse for glaciers to have any effect on runoff in the sense of Braithwaite & Olesen (1988a). There is, however, a positive correlation between runoff measured by GTO (1986a) and winter snow accumulation on Glacier 1CG14033 which is shown in Fig. 7.1 where "runoff" refers to total runoff for the period June-October. This is similar to the situation in Johan Dahl Land (Braithwaite & Olesen, 1988b).

The correlation coefficient is 0.72, but with only 5 years of record, this is only statistically significant at the 10 percent probability level according to Student's t-test (Kreyszig, 1970, p. 343). A further 2-3 years data must be collected to confirm the relation claimed in Fig. 7.1.

The correlation between winter snow accumulation and June-October runoff for the five years suggests that accumulation measurements made in May can forecast runoff in the following summer. This is useful because June-October runoff constitutes nearly 80 percent of the total basin runoff. This correlation between runoff and accumulation does not contradict the claim

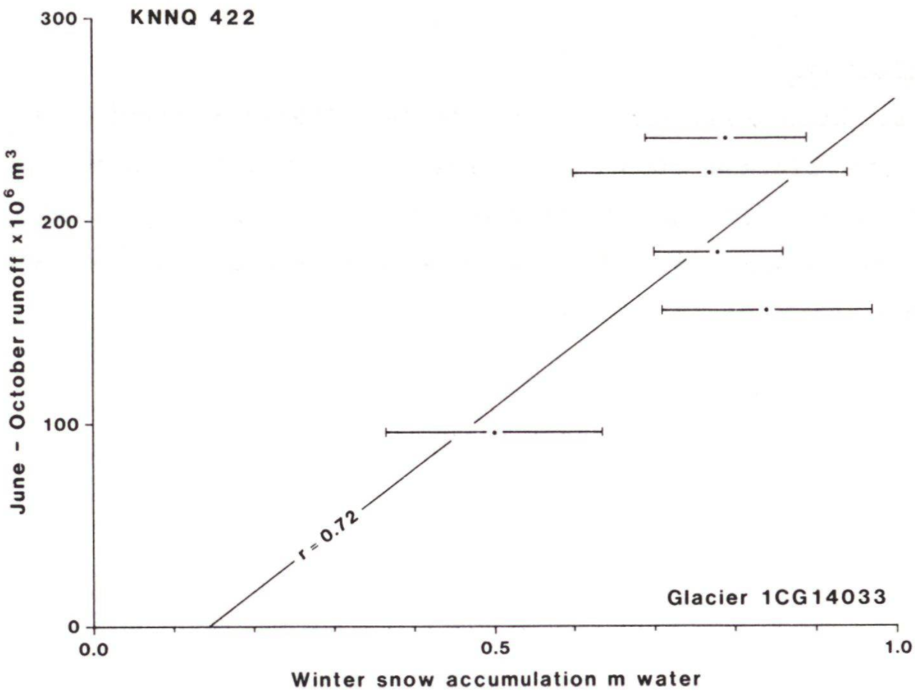

Fig. 7.1. June-October runoff from KNNQ 422 versus snow accumulation

that glaciers have no effect on runoff from KNNQ but occurs because snow accumulation on the glacier is an index of snow accumulation elsewhere in the basin, i.e. the glacier acts as a giant snow gauge.

7.3 The ISTA 305 basin

There is very little snow accumulation on the margin of the Inland Ice in the ISTA basin and there is therefore no possibility of forecasting seasonal runoff from snow accumulation as for the KNNQ basin. However, shorter term runoff forecasts of 1-5 days may be possible because present ablation can be calculated from air temperature data, or simulated energy balance (Braithwaite & Olesen, submitted), while it may take several days for meltwater in the higher parts of the basin to reach the outlet of the ISTA basin. This possibility should be investigated if the ISTA basin ever achieves a higher priority.

It should also be possible to forecast the tapping of the ice-dammed lakes in the ISTA basin if their filling/draining cycle is monitored. More accurate topographic data on the volumes of these lakes is probably required as available low level airphotos only show high water levels (H.H. Thomsen, pers. comm.).

7.4 Conclusions

Accumulation measurements on Glacier 1CG14033 should be continued to confirm the claimed runoff-accumulation correlation which can be used to forecast runoff if the hydropower station is ever built. Measurements should also be extended to 1-2 further glaciers sampling other parts of the KNNQ basin.

8. OTHER BASINS

Runoff from other basins (Fig. 1.1) were analysed in a similar way to the KNNQ and ISTA basins and the results are presented for comparison.

Out of a total of 19 basins there are 12 with at least 4 years of record up to and including 1985 (GTO, 1986a). Annual runoff data for these basins were used for calculating coefficients of variation, runoff-precipitation correlations and runoff-temperature correlations with the latter serving as substitutes for runoff-ablation correlations as ablation is measured in few of the basins. The climate data for the correlations are taken from the nearest weather station to the basin in question. The precipitation data refer to September-August total precipitation while the temperature data refer to June-August mean temperature. The results are given in Table 8.1 versus the amount of glacier cover where R(Q,P) and R(Q,T) are correlation coefficients for the runoff-precipitation and runoff-temperature correlations respectively.

Table 8.1. Effects of glacier cover on runoff

Basin	Years	c.v. %	R(Q,P)	R(Q,T)	Glacier cover %
TSSK 428	4	22	0.64	0.26	0
KILA 419	4	19	0.95	-0.80	0
TASQ 431	4	38	0.57	-0.93	0
ITLA 420	4	35	0.87	0.19	0
KNNQ 422	7	31	0.85	-0.48	2
TSUQ 106	9	17	0.41	0.05	3
AMNG 426	4	26	0.98	-0.24	9
TSSK 124	4	25	0.91	-0.27	15
QAPI 113	5	19	0.21	0.56	31
ISTA 305	11	13	0.08	0.56	45-48
KSTA 421	5	15	-0.92	0.96	48-73
PAAK 437	5	25	-0.73	0.92	89-96

The present results, with 4-9 years of record, have a very sparse statistical base compared with similar studies in other areas, e.g. Tvede (1983). Statistical results can therefore be unduly influenced by errors and by chance. There are also three basins (ISTA 305, KSTA 421 and PAAK 437) with uncertain amounts of glacier cover because they contain Inland Ice sectors but the results in Table 8.1 are probably arranged in correct order of increasing glacier cover.

The results generally indicate high values of the coefficient of variation c.v. and runoff-precipitation correlation for low amounts of glacier cover together with low positive, or large negative, runoff-temperature correlations. For example, of the first 8 basins in Table 8.1 with small amounts of glacier cover (0 to 15%) there are 6 basins that fit this pattern reasonably well, notably including the KNNQ 422 basin. The other two basins (KILA 419 & TSUQ 106) both have low coefficients of variation despite their lack of glacier cover.

There are three basins (QAPI 113, ISTA 305 and KSTA 421) with moderate to large glacier cover which have low coefficients of variation, low or negative runoff-precipitation correlations and reasonably high runoff-temperature correlations. There is a fourth basin (PAAK 437) with a relatively high coefficient of variation which may be caused by the high (estimated!) glacier cover as predicted by Braithwaite & Olesen (1988a).

9. CONCLUSIONS

The possibility of supplementing runoff from the KNNQ basin with water from the Inland Ice in the ISTA basin, sub-basins VIII or IX, was considered at an early stage of planning but was dropped in favour of using extra water from sub-basins II-V. If this is to be taken seriously, hydrological measurements should be started in all these sub-basins. Glaciological measurements should also be started in sub-basin V, containing part of a local ice cap.

Runoff and climate data for the main KNNQ basin are reasonably adequate for planning purposes but the long-term precipitation record in Nuuk is inhomogeneous because the meteorological station was moved in 1981.

Runoff from the KNNQ basin is not significantly influenced by glaciers while glaciers are the main source of runoff from the ISTA basin and strongly influence runoff variations.

The runoff simulation for KNNQ by GTO with only 4 years of data (1981-1984) should be repeated with the present 8 years of record (1981-1988). This simulation does not need to include glacier effects but, in view of the economic importance of runoff simulation, the problem with Nuuk precipitation data must be solved.

Accumulation measurements on Glacier 1CG14033 should be continued to confirm the claimed runoff-accumulation correlation which can be used to forecast runoff if the hydropower station is ever built.

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