DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE **RAPPORT 2021/45**

Evaluation of the water resource for sixteen hydropower potentials of industrial interest in Greenland

Andreas P. Ahlstrøm, Dorthe Petersen, Kenneth D. Mankoff, Signe H. Larsen, Robert S. Fausto, Signe B. Andersen, Peter L. Langen & Ruth H. Mottram

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Introduction

This report is a collaborative effort between GEUS and Asiaq, requested by the Ministry of Industry, Labour, Trade and Energy, Government of Greenland in consultation with Nukissiorfiit.

The aim is an updated evaluation of the water resources available to hydropower potentials with potential industrial interest in West and Southwest Greenland. This report is an extension of GEUS Report 2018/34 which dealt exclusively with the four largest hydropower potentials in Southwest Greenland, specifically the catchments 06.g, 07.d, 07e and 07.f. For completeness, the present report will include results from these catchments, while expanding to also include catchments 03.h, 03.j, 05.h, 05.j, 05.k, 06.b, 06.c, 06.d, 06.e, 06.f, 06.h, 12.j and 15.a, as numbered in the report Nukissiorfiit (2005).

The evaluation mainly covers the period 1980-2014 and is based on data collected by Asiaq (previously the Greenland Technical Organisation), supported by output from the regional climate model HIRHAM5 provided by the Danish Meteorological Institute, and glaciological/glacier hydrological data and methods employed by the Geological Survey of Denmark and Greenland.

An extension of the results up to 2020 has been obtained by application of the catchment scale model DETIM. As results from the period 2014-2020 has not been verified with observations from the catchments, focus remains on the period 1980-2014 where validation data is available.

Background

Hydropower is a key element in the transition of the Greenlandic energy supply towards sustainable energy. The continued expansion of the hydropower capacity in Greenland will be crucial for combining economic growth of the Greenlandic society with sustainable development. On the global scale, hydropower is growing, with an additional 31.5 GW installed worldwide in 2016, out of which hydropower serving as a reservoir for the more variable solar and wind power consisted of 6.4 GW (IHA, 2017).

The potential for hydropower in Greenland is intimately related to the amount of meltwater from the Greenland ice sheet as well as the amount of precipitation. The ongoing changes in global climate thus have immediate economic consequences for Greenland and must be taken into account when developing a strategy for the future energy supply. Climate change is accelerated in the Arctic, where the temperature is increasing nearly twice as fast as for the global mean, and the atmospheric circulation patterns appear to be shifting (AMAP, 2017). The increased contribution to sea level rise of the Greenland ice sheet is causing concern globally, but climate change is also important for the Greenlandic society on the local scale.

Climate change implies that the existing survey of the hydropower potential of Greenland presented in the Nukissiorfiit report (in Danish) ”Grønlands vandkraftressourcer. En oversigt – August 2005” (Nukissiorfiit, 2005) most likely underestimates the actual present size of the hydropower potentials. Climate change also implies that the variability from year to year has become more important – this parameter was not included in the report from 2005. The hydropower potential of partially ice-covered catchments is primarily affected by changes in meltwater runoff, while for ice-free catchments it is mainly affected by changes in precipitation patterns.

The Greenland Government supports the collection of fundamental data from a range of the larger hydropower potentials, permitting the derivation of actual discharge. For obvious reasons, data from the period after 2005 is not included in the report from Nukissiorfiit from 2005. There is therefore clearly merit in carrying out an updated analysis of the hydropower potential of Greenland, exploiting available discharge measurements and the various extensive recent datasets made available from the intense research on the contribution of the Greenland ice sheet to sea level rise.

For completeness, this report includes results from both the second and third phase of an effort to update the existing survey from 2005 of the hydropower potentials in Greenland from Nukissiorfiit. The first phase was a preliminary analysis, presented in GEUS-Notat 10-NA-17-01 (Ahlstrøm and others, 2017), while results from the second phase was previously reported in (Ahlstrøm and others, 2018). In this report we initially present results from the first phase preliminary analysis for Southwest Greenland, followed by an evaluation of the hydropower potentials of industrial interest, named 03.h, 03.j, 05.h, 05.j, 05.k, 06.b, 06.c, 06.d, 06.e, 06.f, 06.g, 06.h, 07.d, 07.e, 07.f,12.j and 15.a, all situated in Southwest Greenland, with names derived from Nukissiorfiit (2005). Many of these catchments are dominated by meltwater runoff from the Greenland ice sheet and over the ice, the delineation carried out in this analysis will be based on the current ice sheet surface. Thus, we will present no risk evaluation of catchment changes or variability due to ice sheet retreat or changes in the internal hydrological drainage of the ice sheet.

We will provide an estimate of the development of the water resource of the hydropower potentials over the period 1980-2014, based on a combination of data collected in the field and results from numerical models. This period was determined from the available output from the regional climate model (RCM) used at the onset of the evaluation as well as availability of processed field data. Field data are available for varying durations of this period for only some catchments presented.

By agreement with the Greenland Government, the initial results were complemented in Phase 3 with results from an additional model, capable of downscaling the RCM output also to smaller catchments with no available field data. This model covers 1981-2020, thus extending results somewhat further in time.

Evolution of the water resource in Southwest Greenland

A first step in establishing a sufficient foundation for policy-making on the possible future development of hydropower in Greenland is to determine the impact of the climate change which has already occurred. A preliminary analysis of this change was provided in GEUS-Notat 10-NA-17-01 (Ahlstrøm and others, 2017) and we reiterate the results in the following as they provide a relevant framework for the analysis of the individual hydropower potentials.

For the preliminary analysis we employed a regional climate model designed to utilize measured meteorological parameters and which provides results for the ice sheet meltwater runoff as well as the runoff from ice-free terrain driven by precipitation. This division makes it possible to obtain an overview of the industrial-size hydropower potentials primarily depending on ice sheet meltwater runoff, as well as the smaller hydropower potentials in the vicinity of populated areas which depend primarily on precipitation over the ice-free terrain.

We have employed results from a model experiment with the regional climate model HIRHAM5 of the Danish Meteorological Institute (DMI), which meets the requirements stated above, and used the data over the most relevant region for hydropower in Greenland (the model domain is shown in Figure 1).

Figure 1. Map showing the chosen model domain (red polygon) in Southwest Greenland of the regional climate model experiment with HIRHAM5.

The vast majority of Greenlands exploitable hydropower potential is situated between Ilulissat in West Greenland and Nanortalik in the far south. Accordingly, this region is chosen for further analysis of the evolution of the runoff from the ice sheet and the ice-free terrain, respectively, as estimated by the regional climate model HIRHAM5 of DMI. The model was run using so-called re-analysis data from the ERA-Interim dataset over the period 1980-2014, which implies that the numerical modelling was, as far as possible, based on observed data. The model operates on a horizontal resolution of 5.5 km, providing output every 90 seconds and is described in more detail in Ahlstrøm & Petersen and others (2017). For this analysis, we have chosen to focus on the difference in runoff between the first 12 years (1980-1991) and the last 12 years (2003-2014) of the period investigated for the ice sheet and ice-free terrain, respectively. The latter 12-year period is chosen because the region appears to have experienced an abrupt shift in climate since 2003 (Ahlstrøm & Petersen and others, 2017), whereas the first 12-year period is chosen as the earliest possible 12-year interval in the model experiment. The difference between the two 12-year periods is subsequently shown partly with a colour-coded map of Southwest Greenland and partly with a plot illustrating the difference in the monthly mean runoff from the entire model domain delineated in Figure 1.

The result of the model experiment for ice sheet runoff is shown in Figure 2. Here, Figure 2a shows how the difference in runoff between the two 12-year periods is distributed geographically over an area approaching 100 km in width from the ice margin and inwards, with an annual mean difference reaching above 800 mm water equivalent (that is, the amount of water corresponding the ice melted away). Figure 2b shows the same result, with the difference illustrated as additional runoff (in percent) going from the former 12-year period to the latter. The red colour in Figure 2b illustrates the expansion of the area experiencing melt. At higher elevations on the ice sheet, meltwater refreezes in the underlying snow, which is below the freezing point, keeping the meltwater from leaving the ice sheet as runoff.

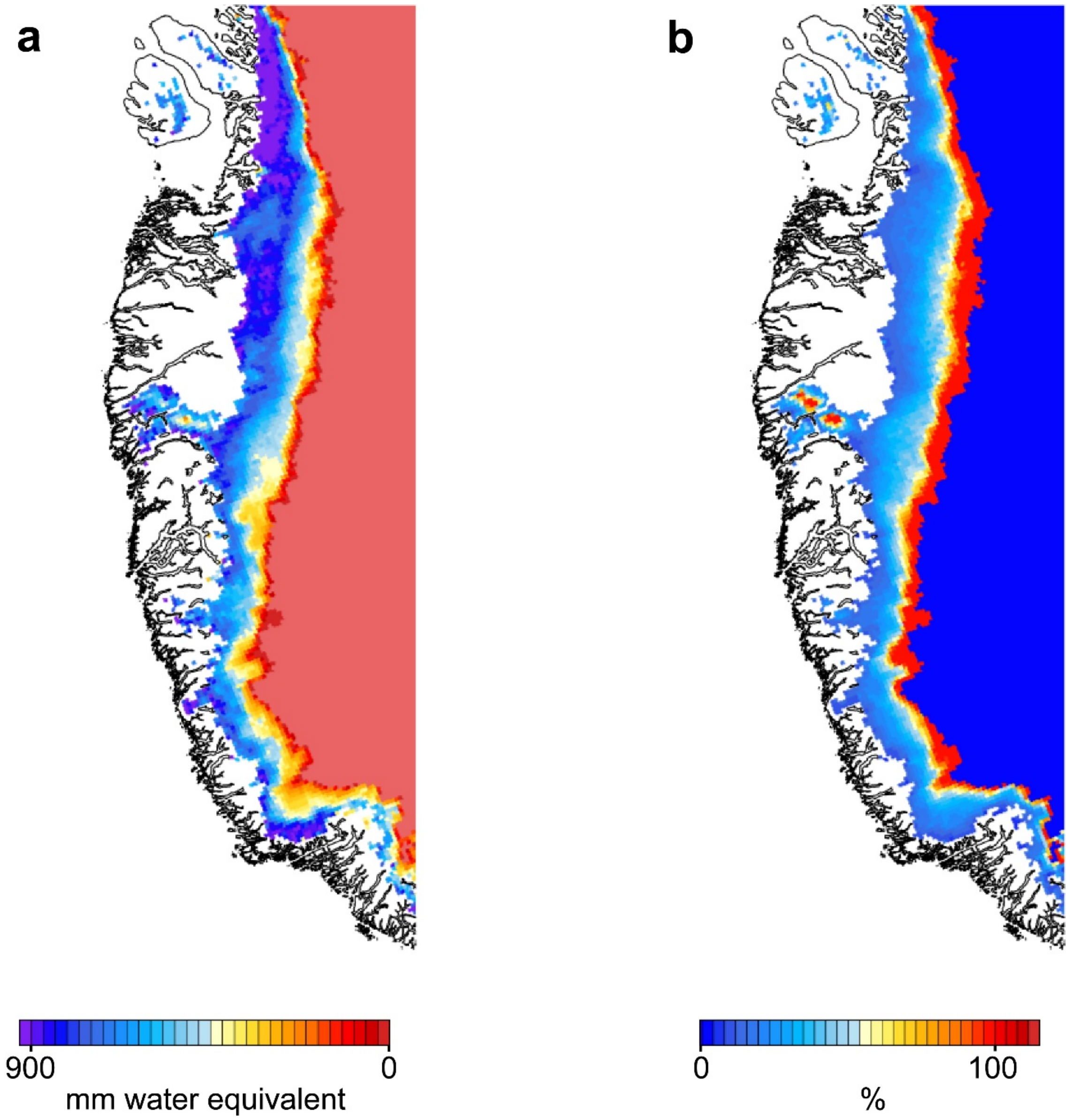

Figure 2. Results from the regional climate model over the ice-sheet covered part of Southwest Greenland. Panel a) The difference in runoff between 1980-1991 and 2003-2014 given in mm water equivalent (that is, the amount of water corresponding the ice melted away). Panel b) The same difference given in percent increase from the first period to the next.

Summing up the results from the regional climate model on a monthly basis within the model domain marked in Figure 1 allows a quantification and evaluation of the total difference and its seasonal distribution (see Figure 3). Figure 3 illustrates that the relative difference is larger in the early and late parts of the melt season, as the latter is expanding, but also that the difference in terms of volume is larger from June to August. The total increase in the ice sheet meltwater runoff in Southwest Greenland is estimated to be 54% between the two 12-year periods 1980-1991 and 2003-2014.

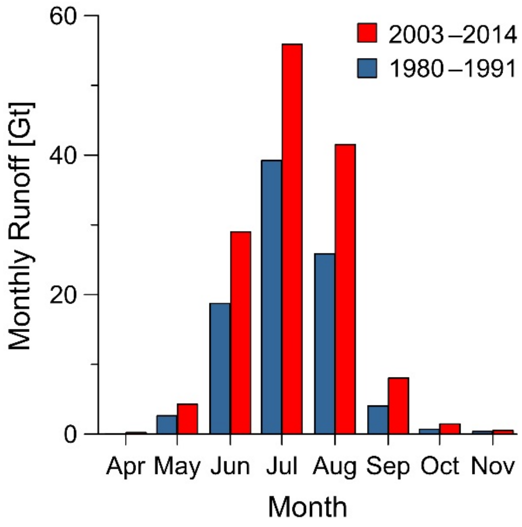

Figure 3. The estimated monthly mean runoff from the regional climate model for the ice-sheet covered part of the model domain (delimited in red in Figure 1). The blue colour represents the period 1980-1991 and the red colour represents the period 2003-2014.

Model results from the ice-free terrain, illustrated in Figure 4, are more relevant for the smaller catchments, often situated in the vicinity of populated areas. Figure 4a shows a minor increase in the runoff from the ice-free terrain, typically varying between +1 and -1 mm water equivalent. The change in percent, shown in Figure 4b, exhibits the same geographical distribution as seen in Figure 4a.

Evidently, the difference in runoff between the two 12-year periods is significantly smaller for the ice-free area than for the ice-sheet covered area, and varies over the region. The area in the vicinity the ice margin north of Nuup Kangerlua/Godthåbsfjorden has become more dry, while the area closer to the coast has become more wet. The area south of Nuup Kangerlua/Godthåbsfjorden has primarily become more dry, with a few exceptions.

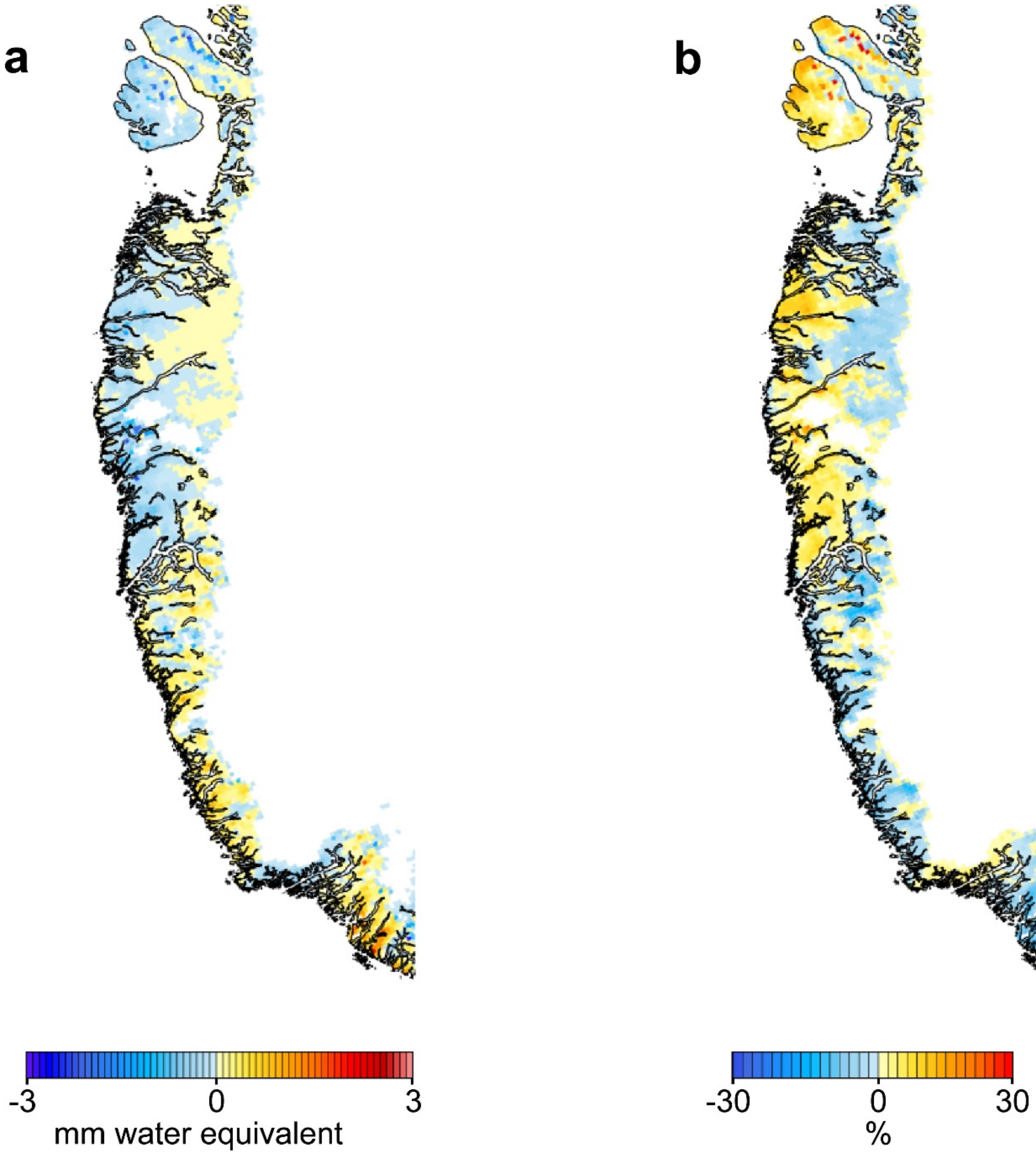

Figure 4. Results from the regional climate model over the ice-free part of Southwest Greenland. Panel a) The difference in land runoff between 1980-1991 and 2003-2014 given in mm water. Panel b) The same difference given in percent increase from the first period to the next.

Summing up instead the results from the regional climate model on a monthly basis for the ice-free part of the within the model domain marked in Figure 1, it is evident that values are more than an order of magnitude smaller than for the ice-covered part (see Figure 5). Meanwhile, we know from examining Figure 4 that these values represent the sum of both negative and positive numbers and might thus cover potentially larger differences, which may be either positive or negative on local basis. However, the total shows an estimated increase in the runoff from the ice-free terrain of 33% between the two 12-year periods 1980-1991 and 2003-2014.

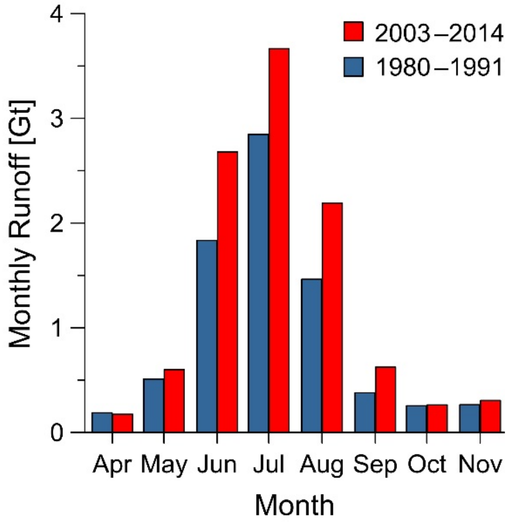

Figure 5. The estimated monthly mean runoff from the regional climate model for the ice-free part of the model domain (delimited in red in Figure 1). The blue colour represents the period 1980-1991 and the red colour represents the period 2003-2014. While the numbers are more than an order of magnitude lower than for the ice-covered part of the model domain shown in Figure 3, they specifically convey the total integrated difference over the entire ice-free part of the model domain, hiding possible local variations that may be either positive or negative (see Figure 4).

Evaluation of the water resource for 16 hydropower potentials of industrial interest

The focus of this report will be an assessment the available water resource and its evolution over time for sixteen industrial-size hydropower potentials (shown in Figure 6), to provide a starting point for a new assessment of the hydropower potential of Greenland.

Some of the hydropower potentials assessed in this report are based on the assumption that several natural catchments will be connected in the development phase. In this assessment, we examine datasets retrieved from these natural catchments which are initially analysed separately and then subsequently combined in a final analysis of the evolution of the potentials.

Initially, we present the methods employed by Asiaq to calculate the discharge and by GEUS to delineate the catchments on the ice sheet and the ice-free terrain, respectively.

Subsequently, we present for each catchment the data coverage and proceed to establish a uniform time series of the estimated water resource from each catchment, covering 1980-2014. The period 1980-2014 was chosen because it provides an adequate data coverage for intercomparison of the potentials. For establishing a complete time series, measured data provided the starting point, supplemented with bias-adjusted measured data from nearby catchments, or from the regional climate model HIRHAM5.

Some of the catchments assessed have not been observed at all, have no neighbouring catchments and are too small to be meaningfully assessed with the relatively coarsely gridded RCM output from HIRHAM5. To estimate the water resource from these, we employ a catchment scale model, DETIM, designed for partly glaciated mountain catchments. DETIM requires temperature and precipitation to be specified in a point within the catchment, and subsequently distributes these parameters over the catchment according to a digital elevation model, using assumed rates of change with elevation. As *in situ* observations of temperature and precipitation are lacking, the point input is derived from another RCM, Modèle Atmosphérique Régional (MAR).

DETIM is set up for all sixteen catchments, in order to evaluate model performance against observations where available and to extend the time series from 2014 up to 2020.

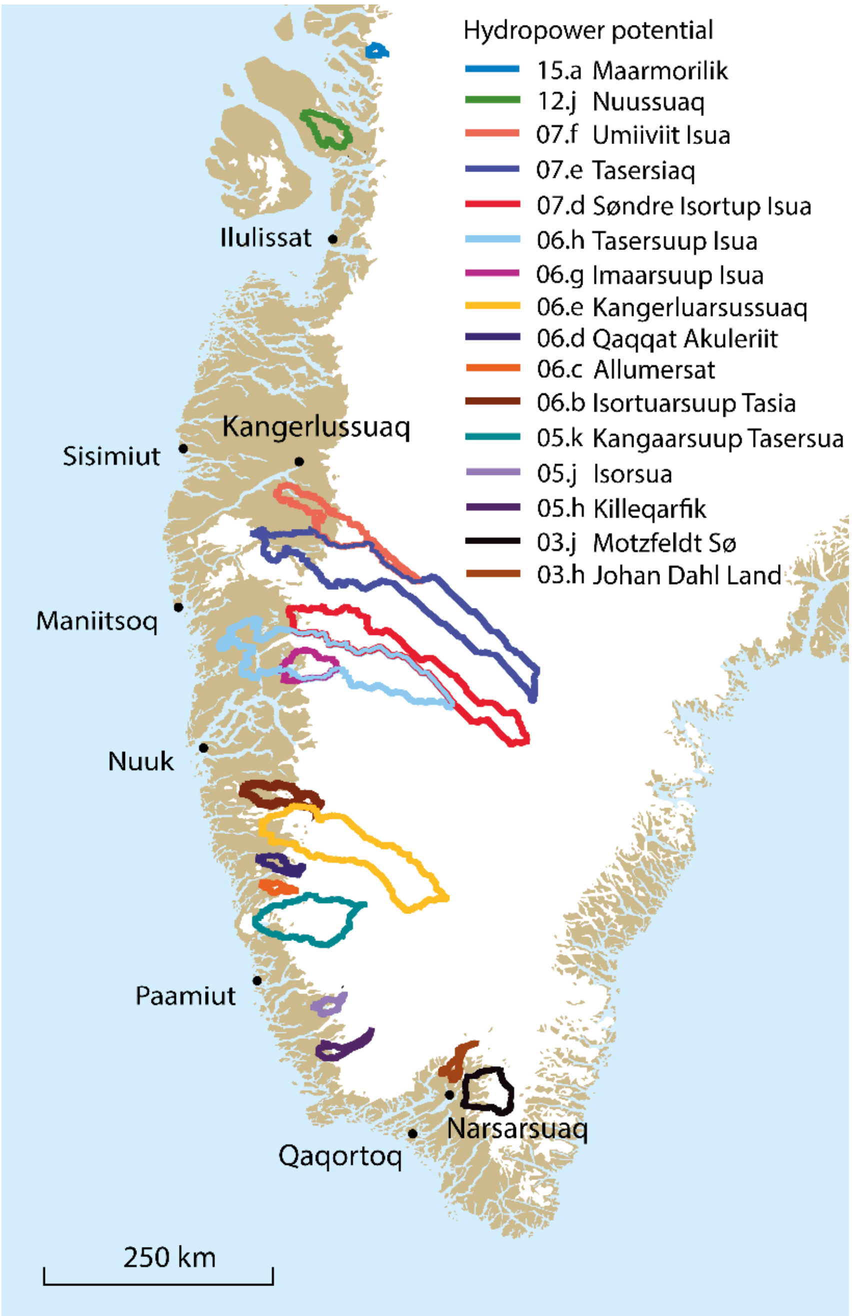

Figure 6. Sixteen hydropower potentials with capacity for industrial use.

Method

Measuring the water resource

The water resource at a catchment is evaluated as the mean annual discharge for that catchment, and is thus calculated from the discharge time series. The discharge time series is not measured directly but calculated indirectly from continuously measured water level and a stage-discharge relation, termed the Q/h-relation, specific to the location. The stage or water level is the absolute elevation of the water surface which varies according to the inflow of water. For lakes in Greenland, the water level is generally high during the summer and low during the winter. The difference between the water level in the summer and in the winter typically amounts to 1 to 3 metres, but for some lakes, the difference can be as large as 10 metres.

Water level registration

Water depth is monitored at an automatic measuring station by pressure transducers placed on the lake or river bottom. A picture of the hydrometric station monitoring catchment 07.d.I is shown in Figure 7 as example. The water depth is measured daily or sub-daily. The water level of the lake or river is measured relative to a reference point (gauge datum) by levelling every time the station is visited. Based on the result of the leveling and the water depth measured simultaneously by the pressure transducer the position (height) of the sensor can be found. A time series of water level can thus be found from the sensor position and the measured water depth.

Figure 7. Hydrometric station monitoring catchment 07.d.I. Stations measures the water depth as well as selected climatic parameters (air temperature, wind speed and precipitation). The station is powered by solar panels and batteries. Data are stored in a data logger on site and transferred on a daily basis to Asiaqs office via an iridium satellite modem. Photo: Asiaq.

Stage-discharge relation

A stage-discharge relation is an empirical relation describing the discharge as a function of the height of the water surface (the water level). In general it is recommended to base the stage-discharge relation on at least 12 to 15 manual discharge measurements evenly distributed over the interval of water levels occurring at the site (ISO 1100-2). As a stage-discharge relation is an empirical relation extrapolation beyond the interval of manually measured discharges has a higher degree of uncertainty and should always be evaluated and used with great care. Especially extrapolation beyond the maximum manually measured discharge (upward extrapolation) can be problematic, whereas extrapolation to low values (downward extrapolation) is less problematic due to the lower constrain of zero discharge.

Manual discharge measurements

Discharge is measured manually by the velocity-area method (ISO 748). At a cross section of the river the water velocity is measured in a number of points in a number of verticals distributed over the cross section, see Figure 8 for an example. Generally, measurements are carried out in 15-20 verticals with measurements of water velocity in 1-4 points in each vertical depending on the water depth. The discharge is calculated by integration of the velocities over the cross-sectional area.

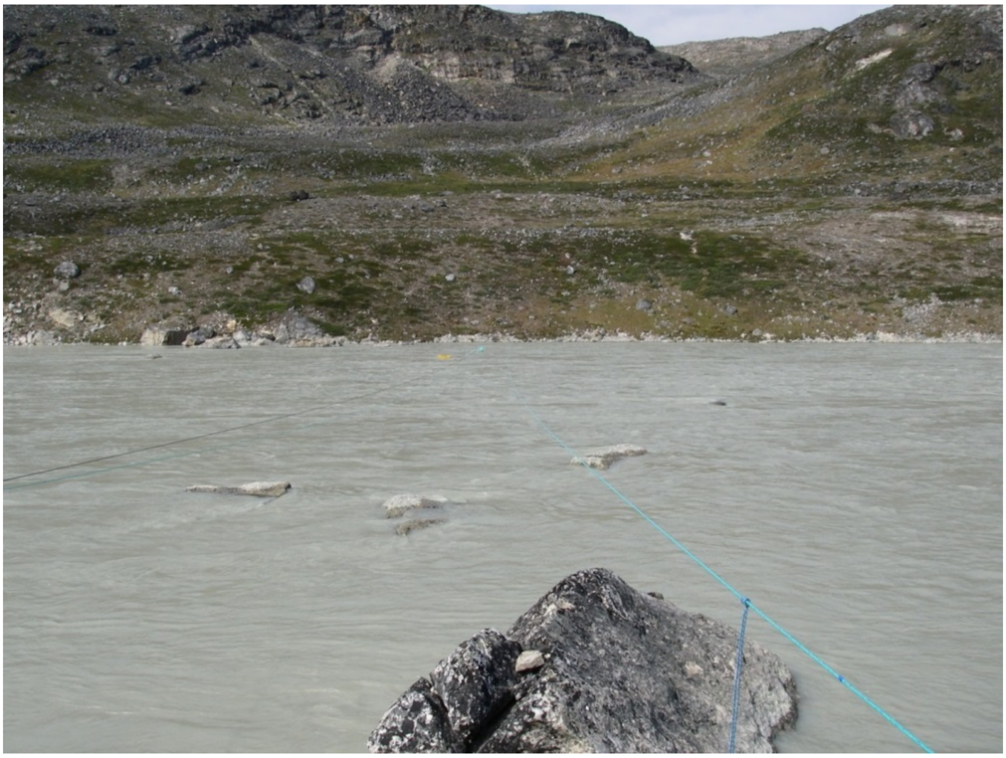

Figure 8. Measurement of discharge at the outlet river from catchment 07.d.I. A wire is set up across the river at the measuring cross section and water velocity is measured by an acoustic Doppler current meter (ADCP) mounted on a small yellow catamaran boat, which can be seen near the opposite shore. Photo: Asiaq.

Time series of the water resource

Based on the time series of water level and the stage-discharge relation, a time series of discharge is calculated. Minor data gaps in the time series have been filled by linear interpolation. Data gaps outside of the melt-season have been filled by a mean basis runoff curve for the catchment. Outside of the melt season the discharge is generally very low and decreasing during the winter as the water storages (e.g. lakes) within the catchment are depleted. The discharge time series thus have a similar form each year although it can be somewhat shifted in time depending on the intensity of the melt season of that year.

The discharge time series is integrated to give annual discharge values. As the annual discharge can vary considerably from year to year depending on the climate it is recommended to base an evaluation of the water resource for a potential hydropower plant on a discharge time series covering 25 years (Nukissiorfiit, 2005). In this report we establish discharge time series for the 35-year period 1980-2014.

Filling of data gaps in measured time series

Regional climate models are not yet precise enough to be used to evaluate the water resource on catchment level directly (e.g. Teutschbein and Seibert (2012), Ehret et al.

(2012)). It is therefore necessary to adjust the model output, based on measured discharge for the catchment.

Annual model runoff values are compared with annual measured discharge values. For catchments where an adequate number of years of data is available, a linear regression is used as an adjustment function to adjust the annual model runoff values. For these catchments, it is found that HIRHAM5 typically captures the year-to-year variation well (correlation coefficients of 0.80-0.95), but overestimates the magnitude of the year-to-year variations (slope of 0.2-0.7, i.e. less than 1). Furthermore, the linear regressions have non-zero offsets.

For some catchments the measured discharge time series is too short to base a linear regression on. In these cases, the ratio of measured annual values to modelled annual runoff are calculated for each year and the mean ratio is used to adjust the annual model runoff values.

Statistical evaluation

The Spearman's Rho test is a rank-based, non-parametric statistical test for detecting monotonic trends in time series. The Spearman's Rho test has similar power in detecting a trend as the Mann-Kendall test, which has often been used to test hydro-meteorological time series (Yue et al., 2002).

While non-parametric tests do not require the data to be normal distributed, they do require data to be serial independent (no autocorrelation). The disadvantage of the Spearman's Rho test is that it does not determine the size of the trend. To this end we have used the Theil-Sen slope estimator, which is a method that is robust and insensitive to outliers.

Delineation of catchments

The catchments are defined by the drainage area above the outlet, calculated using a standard GIS tools implemented in GRASS GIS (Neteler et al., 2012). The prior information used to calculate the catchments consists of a coordinate list of the outlets (Table 1), an elevation model of the Greenland ice sheet with a resolution of 30 m (GIMP DEM; Howat et al., 2014) and an elevation model of the area without ice, with a resolution of 5 m (ArcticDEM; Morin et al., 2016).

The first step when defining catchments, was to calculate the flow direction of an area enclosing all catchments, both the ice-covered area and the areas without ice, using the GIMP elevation model. The algorithm used to calculate the flow direction provides placement of streams as a raster file (a grid) and the flow direction of all grid cells in the GIMP elevation model.

The raster file containing the streams was converted into a vector format and exported as a KML-layer to be used in Google Earth. The calculated placement of the streams was compared to visible streams using Google Earth as the background. In areas where the comparison shows disagreement between the calculated and visible streams, the GIMP elevation model is manually edited by adding blockades, forcing the calculation to provide more realistic streams. Subsequently, the original outlet positions (Table 1) were shifted to be located in a grid cell with a calculated stream. The shift in outlet position was made to be congruent with the nearest significant stream. The shift was in general between 0-5 grid cells (0-200 m). The outlines of the catchments were then derived using the shifted outlet positions and calculations of flow direction. The process was repeated iteratively, until the calculated outlet positions were reasonably correct, and the catchments were comparable to existing manually drawn maps.

The next step involved improving the calculation of the catchment areas without ice, as the 30 m resolution provided by the GIMP elevation model is not sufficient to define the catchment outlines in landscapes with highly varying topography. The process outlined in the section above was repeated for the areas without ice, this time using the ArcticDEM elevation model, which has a resolution of 5 m. Again, the outlet positions were shifted to fit the calculated streams before deriving the upstream catchment.

Each catchment was then divided into an ice-covered part and land part (ice free) using an ice/land mask (Citterio & Ahlstrøm, 2013). The catchment based on the ArcticDEM was cut to fit the land part and the catchment based on the GIMP was cut to fit the ice part. The land part of the catchment (5 m resolution) was then resampled to 30 m resolution. The high resolution of 5 m gives a better calculation of the catchment outlines in the highly varying terrain but is unnecessary after the calculation is done and has a very limited effect on the final result.

Catchment ID	Longitude (°W)	Latitude (°N)
03.h.I	45.3712	61.35320
03.h.II	45.4514	61.35431
03.h.III	45.5571	61.34053
03.h.IV	45.3771	61.33118
03.h.V	45.2165	61.34723
03.h.VI (lake)	45.1546	61.39625
03.j.I	44.9876	61.10327
03.j.II	45.0678	61.08162
05.h.I	48.0746	61.37707
05.h.II	48.0518	61.49629
05.h.III	48.1376	61.42657
05.j.I	48.3678	61.83424
05.k.I (lake)	49.5675	62.51004
06.a.IV (canal)	50.0904	63.92034
06.a.IV	50.0091	63.89992
06.a.VII (lake)	49.7857	63.87349
06.b.I	50.3548	63.74094
06.b.II (lake)	49.7863	63.78951
06.b.V	50.2743	63.87199
06.c.I	49.8412	62.91105
06.c.II	49.6631	62.95284
06.d.I	49.7132	63.22964
06.d.II	49.6448	63.11211
06.d.III	49.5120	63.22245
06.e.I	50.0265	63.46737
06.e.II	49.8344	63.44065
06.e.III	49.8560	63.49877
06.g.I	50.2143	64.93224
06.g.II	50.1553	65.15175
06.g.III	50.1466	65.15954
06.g.IV	49.9203	64.93000
06.h.I	50.7222	64.95566
07.d.I	50.3326	65.53874
07.d.II	50.2881	65.47091
07.e	51.3134	66.30535
07.f.I	51.1173	66.67358
07.f.II	49.7830	66.62143
12.j.I	52.4170	70.40098
15.a.I	51.1177	71.09967
15.a.II	51.0629	71.10137

Table 1. Geographical coordinates of the outlet positions of each catchment.

The catchment outlines were calculated using an 8-direction (D8) single flow direction model (SFD), which implies that all the water in one grid cell is assigned a single flow direction towards the steepest downslope neighboring grid cell. The assigned flow direction can only be towards one of the 8 neighboring grid cells. A comparison of the results from the SFD to a calculation using a multiple flow direction model (MFD) showed that the difference between the two was insignificant, remaining within a few grid cells at the edge of each catchment.

The results of the process explained above, were two masks for each catchment: a land mask and an ice mask. The next step was to use the masks to deduce the discharge from the regional climate model.

Error analysis of the catchment delineation

A catchment calculated with the method defined above is not necessarily the exact catchment for a given outlet. For the ice-covered part, the catchment will change when the ice surface changes. Additionally, the delineation of a catchment on the Greenland ice sheet will depend on the internal hydrological system of the ice, which in turn depends on the ice thickness and a number of other parameters such as the amount of added meltwater per time and the time-dependent evolution of the hydrological system at the base of the ice throughout the melt season.

Despite these shortcomings, we consider a delineation of the ice-covered part of the catchment based on the 30 m resolution GIMP elevation model to be a good approximation. This assumption is based on the currently available science (e.g. Ahlstrøm & Petersen and others, 2017) and visual comparison to surface meltwater streams visible in the Google Earth image layer. The visible meltwater rivers followed the above delineated catchments fairly well.

An alternative would be to utilize the best existing ice thickness model (Morlighem et al., 2017) in the analysis. However, this does not have an adequate resolution and underlying data coverage to be sufficient on catchment scale (Morlighem, personal communication; Ahlstrøm & Petersen and others, 2017).

The land sector delineation within the catchments had large and significant errors in the first derivation based on the 30 m resolution GIMP elevation model, leading to the implementation of the ArcticDEM with its higher resolution of 5 m. Using the ArcticDEM generally improved the catchment delineation but introduced other problems. Specifically, certain parts of the ArcticDEM contains no grid cell values (”NULL” values) which in our derivation were set to 0 m elevation. When these occur outside the catchment, they have no influence on the result; when occurring inside the catchment boundaries, they have no influence either, as the flow direction algorithm treats these gaps as lakes which in turn have no influence on the total water balance of the catchment (as described in the following section). However, when a data gap is connected to the actual catchment boundary, the algorithm will derive the flow around this. A comparison between ArcticDEM and the delineated catchment boundaries showed that this occurred in one instance, resulting in an error of approx. 100 grid cells, corresponding to 2.5 km^2, which was an insignificant part of the catchment in question.

Model-based discharge

Discharge derived from HIRHAM5 regional climate model output

The discharge through the outlet of each catchment was calculated for the period 1980-2014 based on the results from the regional climate model HIRHAM5 (Langen et al., 2017), which provide the following variables on a daily time scale:

- Surface discharge (ice, ice + land)
- Rain
- Snowfall
- Snowmelt
- Evaporation

The model output was recalculated from its original 0.5° x 0.5° resolution to grid with a 5.5 km resolution in the same map projection as the GIMP and ArcticDEM elevation models. We mainly used the modelled surface discharge, but also calculated the precipitation over the ice-covered part of each catchment as:

Precipitation = evaporation + rain + snowfall

The projected 5.5 km grids of the ice-covered part with the HIRHAM5 output containing respectively surface discharge and precipitation were further regridded into the 30 m resolution GIMP elevation model. The coarser resolution of the HIRHAM5 model implies that its ice mask will not fit the 30 m resolution ice mask used in this analysis. To fill out the missing values of modelled discharge and precipitation occurring when applying the high resolution ice mask, a 3 x 3 grid cell box filter was used, where the cells without a value were given the mean of the valid neighboring cells (up to a maximum of 8 cells).

This method will provide a conservative estimate of the discharge, as the missing cells are situated at the part of the ice margin at the lowest elevation, where melting is expected to be more pronounced compared to the cells at higher elevation from which the boundary values are extrapolated.

Precipitation was only calculated for the ice-covered part of the catchments, as the HIRHAM5 precipitation output from the (generally small) areas without ice yielded rather noisy datasets of minimal importance for the compiled discharge. This again is a conservative choice, resulting in a slightly smaller calculated discharge.

An ice fraction value between 0 and 1 was assigned to each 5.5 km cell by evaluating the area with ice cover using the high-resolution ice mask (30 m). The discharge of each 30 m cell was subsequently scaled to fit the area-based ice fraction. This provided another conservative estimate, as a 50/50 split of the area between ice/land will be scaled with 0.5 even though the largest part of the discharge in such conditions are likely to originate from the ice-covered part. Yet, the number of cells containing both ice and land is rather limited compared to the total number of cells in a catchment, making the influence on the calculated discharge relatively small.

Using the above-mentioned choices, the model-based daily total discharge was calculated for 12 of the 16 catchments, as a combination of surface discharge and precipitation. The remaining catchments 03.j, 05.h, 05.j and 05.k had no observations of discharge and where deemed unfit for discharge calculation directly from a regional climate model.

In the measured time series of the remaining other 12 catchments, years without measurements occur. These data gaps were filled by the HIRHAM5-derived time series, as described in the next section. To this end, a correlation between the measured and model-derived time series was established in order to calibrate the latter with observations. Therefore, it is not crucial if the absolute values of the modelled discharge are correct, as long as the model is able to catch the variability of the time series.

Discharge derived from DETIM local distributed model output

In order to assess the longer-term water resource also from the smaller catchments, and specifically for catchments 03.j, 05.h, 05.j and 05.k, we modelled the discharge daily for the period 1981-2020 using a local distributed model, effectively downscaling output from an RCM to the catchment terrain.

With this local modelling approach, discharge estimations were based on a well-established model for calculating meltwater runoff in glaciated mountainous areas, namely the “Distributed Enhanced Temperature-Index Model” (DETIM) described in detail in Hock (1999). Basically, we used DETIM to calculate daily meltwater runoff values for each grid cell in a digital elevation model; here a 30 m x 30 m resolution version of the GIMP DEM is used (Howat et al., 2014). DETIM requires at least temperature and precipitation input from within a selected catchment, either from a weather station or from a regional climate model. Since the smaller catchments investigated are scarcely monitored from *in situ* instrumentation, climate variables were extracted from the regional climate model MAR version 3.11, which is driven by the ERA5 reanalysis data (Hersbach et al., 2020) along the boundary of the domain (see description of MAR in Fettweis et al., 2017). The MAR data has a resolution of 6 km; thus, the input temperature and precipitation are average values for the 6x6 km grid cell covering the central area of the catchment.

In order to evaluate the validity of using output values from a single grid cell in MAR, we compared the extracted temperature and precipitation from MAR to the observed equivalents at DMI weather stations in SW Greenland.

There are 17 DMI weather stations in southwest Greenland, and all of them record temperature, but only two of them record precipitation. Correlating temperature observations against temperatures extracted from MAR yielded r^2-values between 91 % and 96 %. Thus, the MAR temperature was considered valid for use as input data to the local distributed model DETIM. For the two precipitation stations r^2-values were 40 % and 50 % and thus it is likely that precipitation is less well constrained. However, measuring precipitation is generally regarded as notoriously difficult and is associated with greater uncertainties. Based on the comparison between modelled precipitation output from MAR with observations from the two DMI precipitation gauges in Southwest Greenland, the MAR precipitation was reduced to only 1/3 of the initial RCM model output before being used as input to the catchment model DETIM.

DETIM has four main model parameters, determining how the input temperature and precipitation is turned into catchment discharge: the lapse rates of temperature and precipitation, respectively, and the melt-factors for snow and ice, respectively, defining how much melt is caused in one day with a temperature of 1 °C (corresponding to one positive degree-day).

Lapse-rates are topographically dependent changes in temperature and precipitation employed to distribute the input temperature and precipitation, extracted from a single grid cell in MAR, to the DEM grid. Here we employ a general temperature lapse-rate of -0.5 °C per 100 m, based on a mean value for the wet adiabatic lapse-rate.

Precipitation is, however, far more complicated to extrapolate, as it depends on other parameters than just elevation, for example wind direction. As such, the lapse-rate constitute an unknown that we cannot quantify with the current amount of observational data. There is a general tendency for precipitation to increase with elevation until a certain level and thus we employ a moderate lapse-rate that increase precipitation by 3% per 100 m until a limit of 1500 m where the precipitation is kept constant with elevation. The sensitivity to this value is not tested due to the lack of available observations of precipitation in the region. More certainty on this parameter could be obtained by adding precipitation gauges at different elevations within the investigated catchments.

Melt factors describe the statistical relationship between air temperature and snow/ice melt rates. From studies in Greenland and arctic Scandinavia (Janssens and Huybrechts, 2000; Hock, 1999) values of 7 mm ice per degree Celsius and 3 mm snow per °C are reasonable assumptions. The melt-factors for snow and ice differ mainly to take into account the difference in albedo of the two surfaces. We run the catchment model DETIM using these melt factors and as part of the uncertainty assessment use ±1 mm per °C for both melt factors.

In summary, the discharge is calculated daily for the period 1981-2020. Uncertainty estimates are found by varying the DETIM input temperatures by ±10 % and input precipitation by ±50 % as well as using ±1 mm per °C for both melt factors.

Hydropower potential 03.h

The hydropower potential 03.h Johan Dahl Land is based on five-six natural catchments (see Figure 9). Catchment 03.h.I constitutes the main catchment of the hydro power potential. Additional water can be drawn from the catchments 03.h.II, 03.h.III, 03.h.IV and 03.h.V. Some reports furthermore suggest utilizing the water from the ice-dammed lake of catchment 03.h.VI. This requires that the water from the ice-dammed lake is pumped up to the lake Nordbo Sø (catchment 03.h.I) (GTO 1980, ACG 1981).

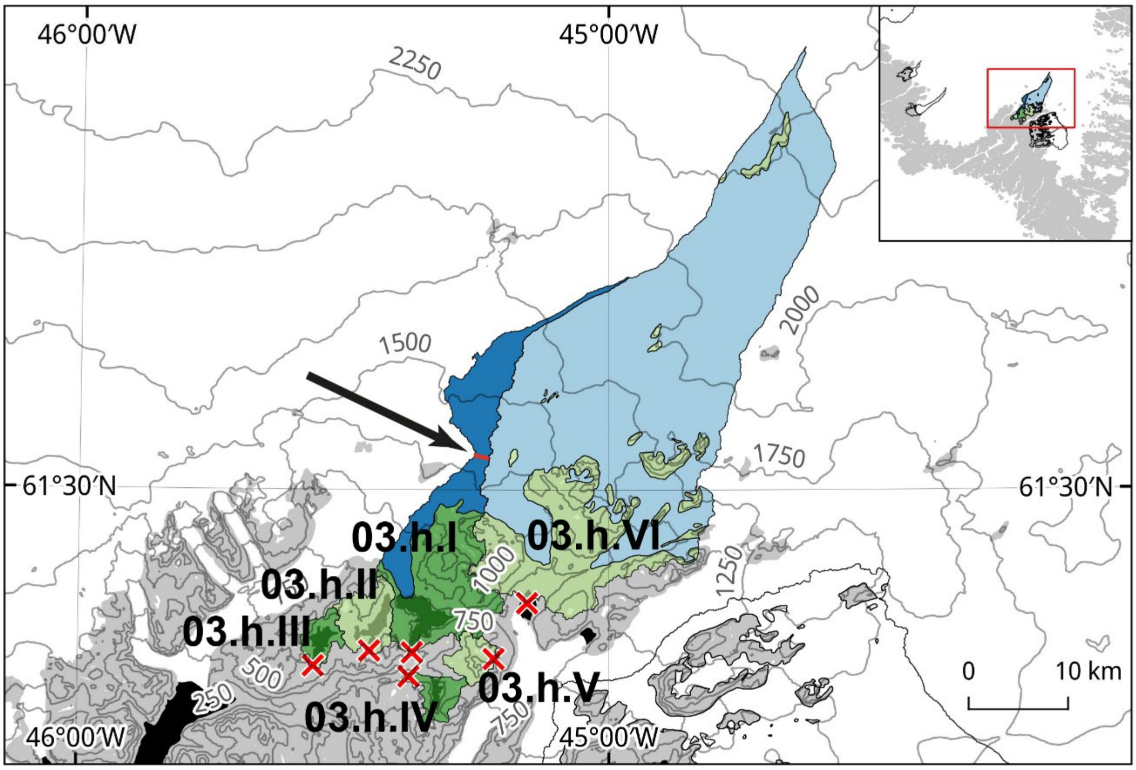

Figure 9. Map showing the catchments. Light shades and dark shades indicate separate sub-catchments, while blue signifies ice cover and green is ice-free land. Red crosses mark outlets, listed in Table 1. The black arrow shows an unresolved delineation, where the part of the catchment above the red line is uncertain.

Monitoring of the water resource

The hydro power potential 03.h was identified by map studies in 1975 (GTO, 1975). Monitoring of the water resource of the main catchment, catchment 03.h.I, was initiated in 1976 by the Greenland Technical Organization (GTO). In 1978 the monitoring program was expanded with monitoring of catchment 03.h.II. The measurements were terminated in 1992. In 2011 monitoring of the water resource of catchment 03.h.I was resumed on initiative of Greenland Minerals and Energy A/S as a possible energy supply to their planned mine at Kvanefjeld near Narsaq. The monitoring program was continued until autumn 2013.

The stage-discharge relation for catchment 03.h.I is based on a large number of manual discharge measurements that to a high degree covered the range of discharge; extrapolation of the stage-discharge relation amount to less than 4 % of the total discharge volume (Table 2).

Similarly, the stage-discharge relation for catchment 03.h.II is based on a large number of manual discharge measurements that to a high degree covered the range of discharge; extrapolation of the stage-discharge relation amount to less than 1 % of the total discharge volume (Table 2).

Catchment 03.h.VI is the catchment of the ice-dammed lake Hullet. The lake empties under the glacier in a glacial lake outburst flood (GLOF) once every year or every second year. The amount of water released has been estimated for four recent GLOF events. Each estimate consists of two parts: the volume of water from the open/visible part of the lake and the volume of water under the floating glacier tongue in the southern part of the lake. The volume of water released from the open part of the lake is estimated based on a digital elevation model of the empty lake and information about the water level in the lake just before the GLOF event. The water level in the lake before GLOF has been obtained via the lake outline from Landsat images after the method described in Larsen et al. (2013). The digital elevation model (DEM) of the lake at very low water level was established from a 2m ArcticDEM (DEM(s) created by the Polar Geospatial Center from DigitalGlobe, Inc., imagery) from October 2012 combined with a UAS derived DEM (DEM created by Asiaq during S:GLA:MO project) from October 2014. The glacier in the southern part of the lake has a floating tongue. The volume of water under the glacier tongue was estimated based on 2m ArcticDEM's from just before and just after the GLOF in 2012.

An overview of the data coverage of the discharge time series for each catchment is given in Figure 10.

Catchment	Manual discharge measurements	Part of total discharge volume found by extrapolation of stage-discharge relation or gap filling, %		
		Upward extrapolation	Downward extrapolation	Gap filling
03.h.I	51	0.9 %	2.4 %	1.5 %
03.h.II	49	0 %	0.5 %	0.6 %

Table 2 Basis for the stage-discharge relation for each catchment and part of total discharge volume found by extrapolation of the stage-discharge relation or gap filling.

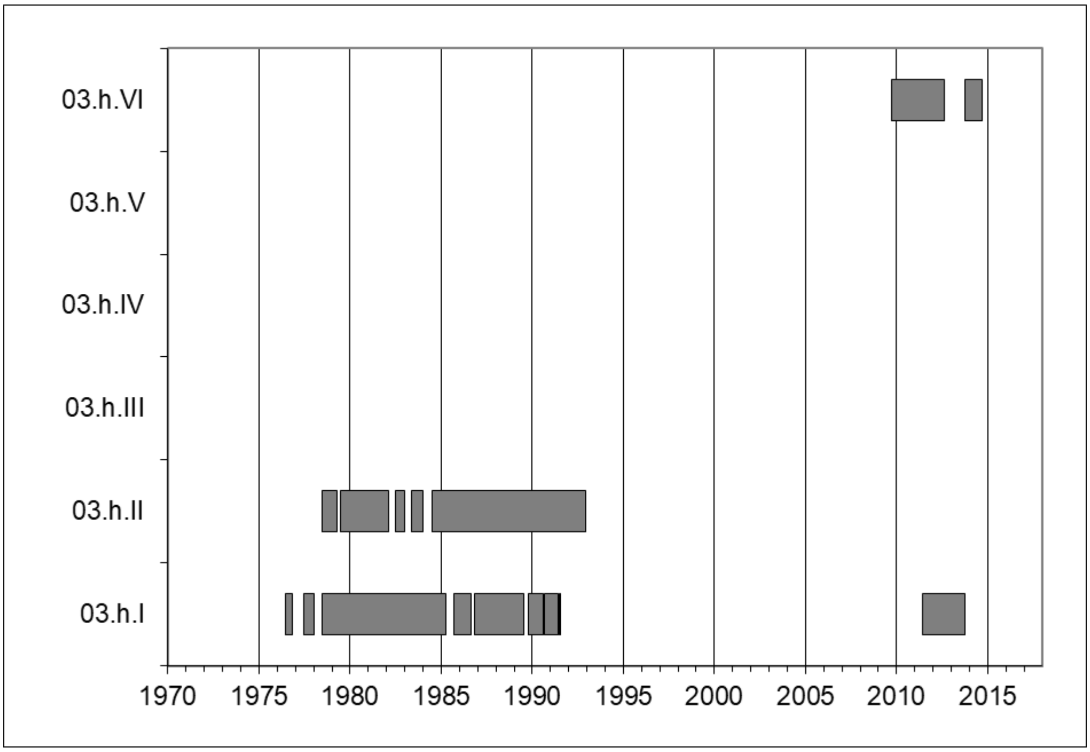

Figure 10. Data coverage of measured discharge time series for the catchments in hydro power potential 03.h. Periods with measured data are shown as dark grey bars, periods with larger, filled data gaps are shown with light grey bars (for description of gap filling method see method section).

Establishing the 1980-2014 time series

The measured discharge time series does not cover the entire period from 1980 to 2014 for any of the catchments (see Figure 10). Therefore, HIRHAM5 runoff data is used to supplement the measured discharge time series.

For catchment 03.h.I, runoff from the ice-free parts of the catchment constitutes 56% of the total runoff according to HIRHAM5. The measured time series for catchment 03.h.I has seven years overlapping with the HIRHAM5 time series and the correlation is good (R^2 = 0.89). The 1980-2014 yearly discharge time series is constructed with the measured data supplemented with HIRHAM5 yearly runoff values adjusted linearly by the regression formula.

Catchment 03.h.II has nine years of measured runoff overlapping with the HIRHAM5 time series, and the correlation is reasonable (R^2 = 0.79). The 1980-2014 yearly discharge time series is constructed with the measured data supplemented with HIRHAM5 yearly runoff values adjusted linearly by the regression formula.

For catchment 03.h.II, 03.h.III, 03.h.IV and 03.h.V land runoff constitutes the water resource; there is no contribution from glacial runoff. As the catchments are situated close to one another and in similar terrain, time series of yearly runoff values for catchment 03.h.III, 03.h.IV and 03.h.V have been constructed from the catchment 03.h.II, adjusted with the ratio between the catchment areas.

For catchment 03.h.VI, runoff from the ice-free parts of the catchment constitutes 41% of the total runoff according to HIRHAM5. For Catchment 03.h.VI we have estimates of the volume of water released during four GLOF events. The correlation with the HIRHAM5 run-off between GLOF events (i.e. the water accumulated in the lake and released during the GLOF) is good ($R^2 = 0.93$). The 1980-2014 yearly water resource series is constructed with HIRHAM5 yearly runoff values, adjusted linearly by the regression formula.

Water resource

Based on the 1980-2014 discharge time series for the catchments 03.h.I – 03.h.V, the mean yearly water resource at hydro power potential 03.h has been calculated to 0.25 km^3, see Table 3. An additional 0.56 km^3 can be drawn from catchment 03.h.VI. However, part of the produced electricity would then be used to pump water from lake Hullet to the reservoir of catchment 03.h.I. The yearly water resource does not show a statistically significant trend in a Spearman Rho test.

Catchment	**Yearly water resource, km^3**			**Contribution to water resource, %**
	Mean	**Maximum**	**Minimum**	
03.h.I	0.19	0.26	0.13	76
03.h.II	0.023	0.040	0.007	9.3
03.h.III	0.012	0.020	0.004	4.6
03.h.IV	0.013	0.022	0.004	5.0
03.h.V	0.013	0.022	0.004	5.1
03.h total	**0.25**	**0.35**	**0.14**	
03.h.VI	*0.56*	*0.68*	*0.50*	

Table 3. Water resource at hydro power potential 03.h. The water resource from 03.h.VI has not been added to the total.

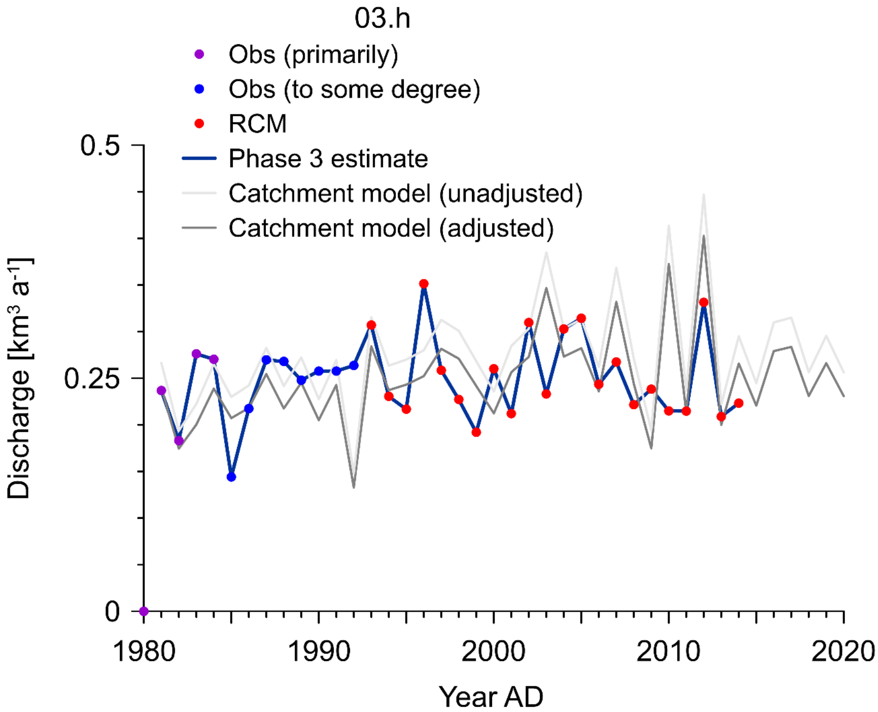

Figure 11. The annual discharge ("Phase 3 estimate") from the hydropower potentials 06.h.I-V with the following labelling of data sources; "Obs (primarily)": mainly based on measured data, "Obs (to some degree)": partially based on measured data, "RCM": based on regression between results from climate models and measured data from other years. Catchment model results are shown in both the original unadjusted and bias-corrected adjusted versions.

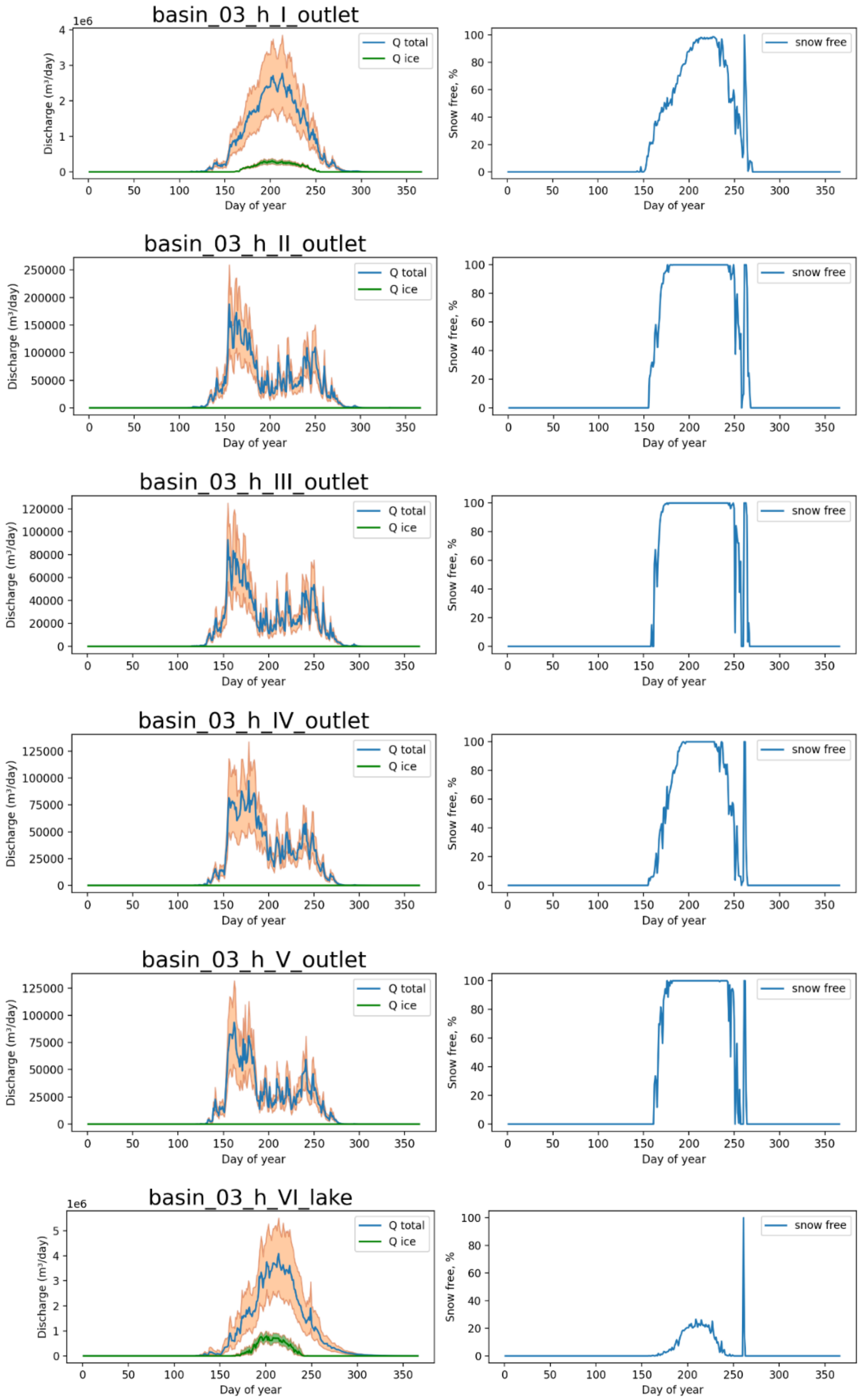

Figure 12. Left graphs: seasonal variation of the total daily discharge from the catchment, averaged over 1981-2020 (blue line "Q total"), including uncertainty interval (light brown) with the daily discharge from the glaciated part of the catchment (green curve "Q ice") specified, also including uncertainty interval (light green). Right graphs: daily percentage of the total catchment (ice-covered and ice-free) experiencing snow-free conditions.

Hydro Power Potential 03.j

The hydro power potential 03.j Motzfeldt Sø is based on the natural catchment of the lake Motzfeldt Sø; catchment 03.j.I, see Figure 13 (top panel). An alternative project design further suggests a dam on the river downstream of Motzfeldt Sø, and intake tunnels both at Motzfeldt Sø and at the dam. This alternative design utilizes the water resource of catchment 03.j.II, which includes 03.j.I, see Figure 13 (bottom panel).

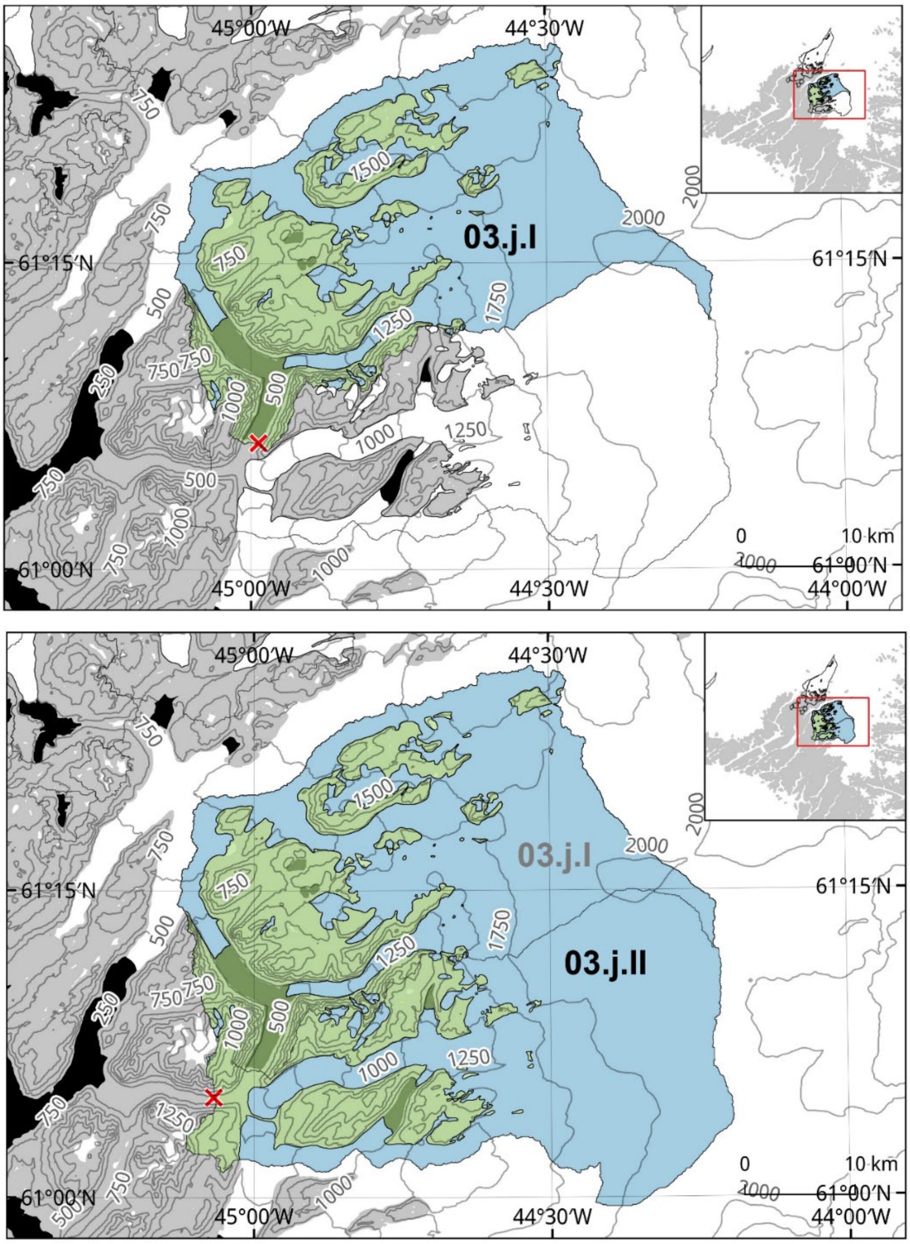

Figure 13. Map showing the catchments. Top panel shows sub-catchment 03.j.I while bottom panel shows 03.j.II which represents the total catchment considered, including 03.j.I. Blue signifies ice cover and green is ice-free land. The red cross marks the outlet, listed in Table 1.

Monitoring of the water resource

The hydro power potential 05.h was identified by map studies in 1975 (Nukissiorfiit, 1995). No monitoring of the water resource has been carried out.

Establishing a 1981-2020 time series

As no observations exist from this catchment, a time series of discharge was derived solely from the catchment model DETIM, with no bias-correction applied. To estimate the uncertainty of this approach, the model input parameters (air temperature and precipitation) and the melt-factors used in the model were varied within reasonable bounds as detailed in the model description section. For comparison with the catchments with observations, the period 1981-2014 was chosen to match as closely as possible the 1980-2014 period used for these.

Water resource

The water resource of hydropower potential 03.j was estimated solely from results of the catchment model DETIM, with no validation or bias-correction available from measurements in the catchment. The mean yearly water resource is 1.70 km^3, see Table 4.

Catchment	Yearly water resource, km^3		
	Mean	Maximum	Minimum
03.j	1.70	3.08	0.97

Table 4. Water resource at hydro power potential 03.j.

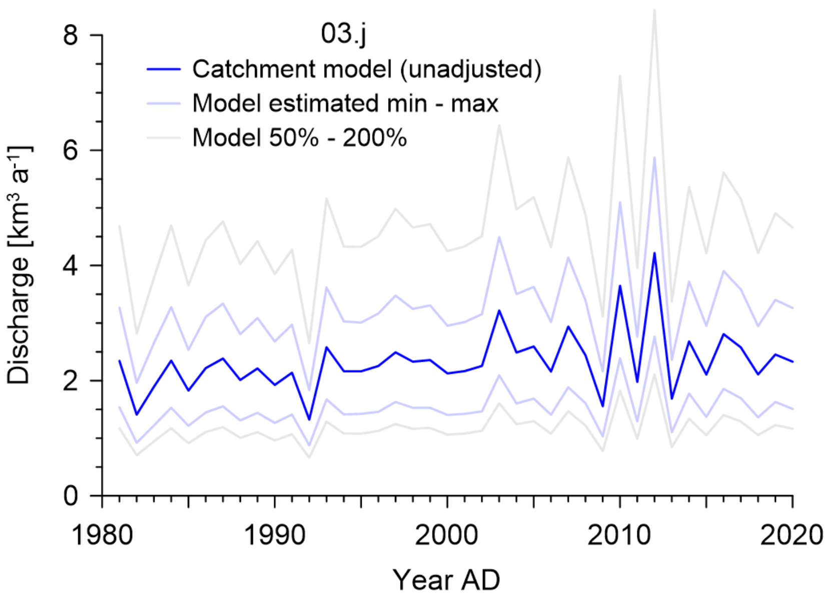

Figure 14. The annual discharge derived from the catchment model DETIM (dark blue line), along with estimated model uncertainty bounds (light blue lines) and a range derived from comparing unadjusted DETIM results to observed discharge in all the catchments where these are available (grey lines).

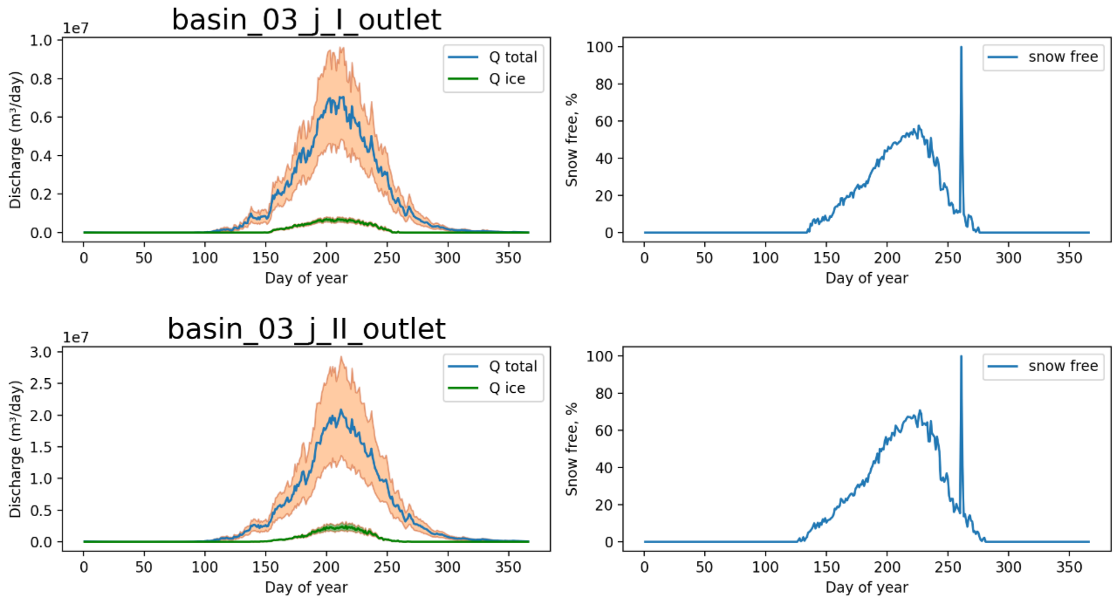

Figure 15. Left graphs: seasonal variation of the total daily discharge from the catchment, averaged over 1981-2020 (blue line "Q total"), including uncertainty interval (light brown) with the daily discharge from the glaciated part of the catchment (green curve "Q ice") specified, also including uncertainty interval (light green). Right graphs: daily percentage of the total catchment (ice-covered and ice-free) experiencing snow-free conditions.

Hydro Power Potential 05.h

The hydro power potential 05.h Killeqarfik is based on three natural catchments (see Figure 16). Catchment 05.h.I constitutes the main catchment of the hydro power potential. Additional water can be drawn from the catchment 05.h.II directly or through catchment 05.h.III.

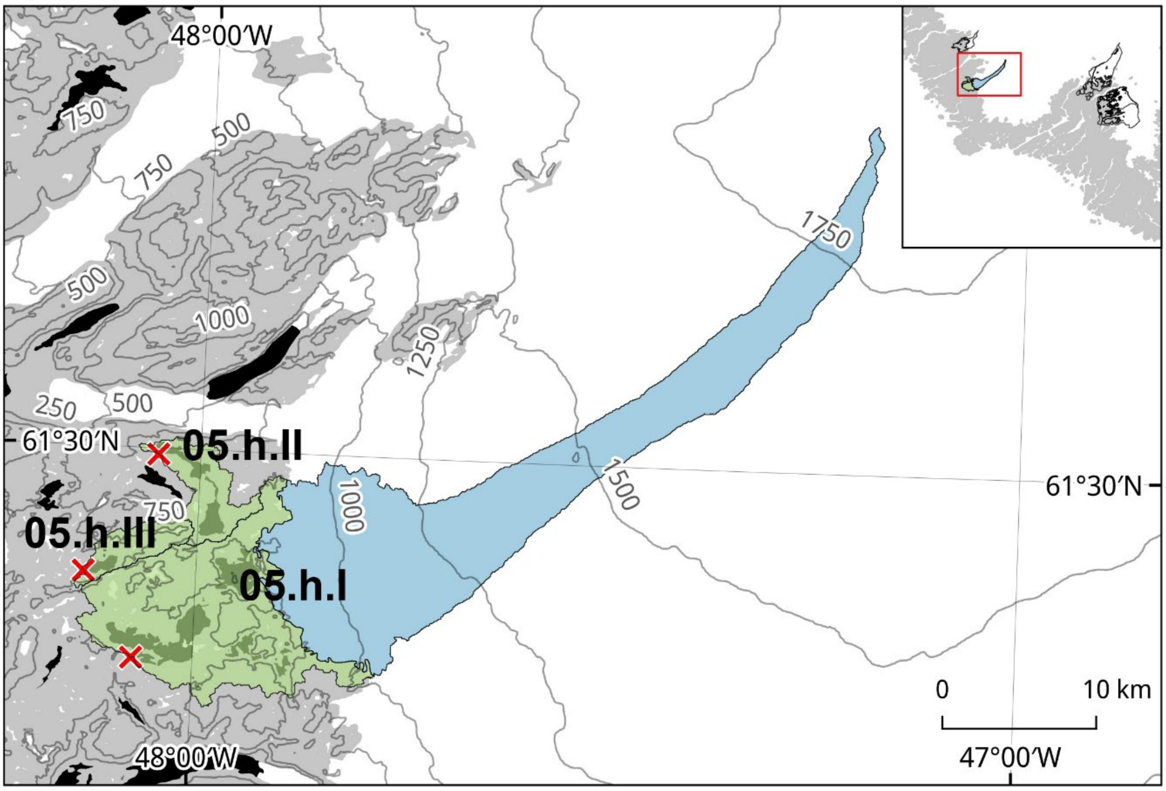

Figure 16. Map showing the catchments. Blue signifies ice cover and green is ice-free land. Red crosses mark outlets, listed in Table 1.

Monitoring of the water resource

The hydro power potential 05.h was identified by map studies in 1975 (Nukissiorfiit, 1995) and has since then not been investigated further. Monitoring of the water resource has not been carried out.

Establishing a 1981-2020 time series

As no observations exist from this catchment, a time series of discharge was derived solely from the catchment model DETIM, with no bias-correction applied. To estimate the uncertainty of this approach, the model input parameters (air temperature and precipitation) and the melt-factors used in the model were varied within reasonable bounds as detailed in the model description section. For comparison with the catchments with observations, the period 1981-2014 was chosen to match as closely as possible the 1980-2014 period used for these.

Water resource

The water resource of hydropower potential 05.h was estimated solely from results of the catchment model DETIM, with no validation or bias-correction available from measurements in the catchment. The mean yearly water resource is 0.30 km^3, see Table 5.

Catchment	**Yearly water resource, km^3**		
	Mean	**Maximum**	**Minimum**
05.h.I	0.28	0.51	0.17
05.h.II	0.014	0.021	0.008
05.h.III	0.010	0.017	0.006
05.h total	**0.30**	**0.55**	**0.19**

Table 5. Water resource at hydro power potential 05.h.

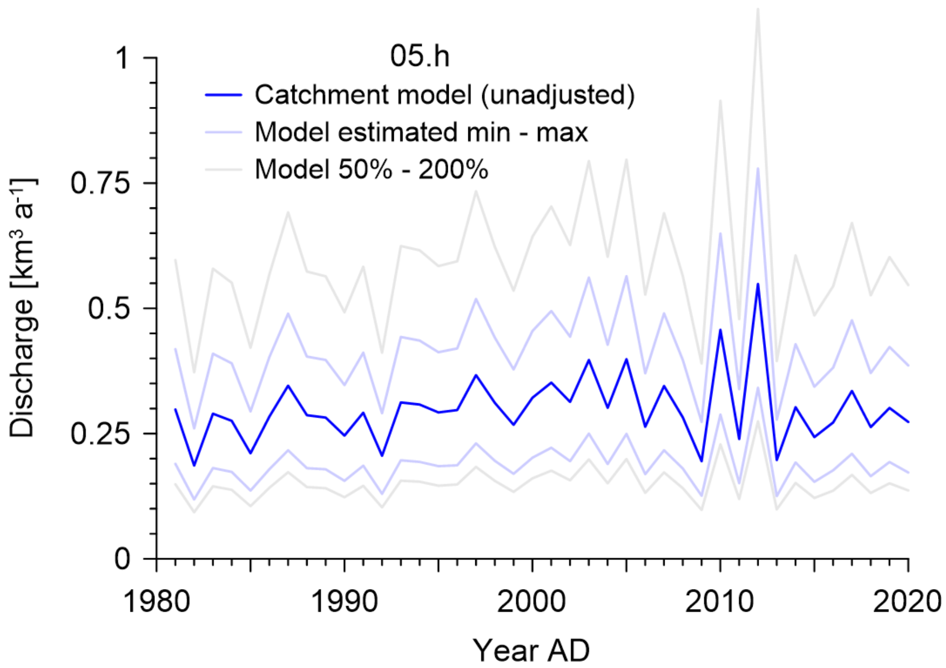

Figure 17. The annual discharge derived from the catchment model DETIM (dark blue line), along with estimated model uncertainty bounds (light blue lines) and a range derived from comparing unadjusted DETIM results to observed discharge in all the catchments where these are available (grey lines).

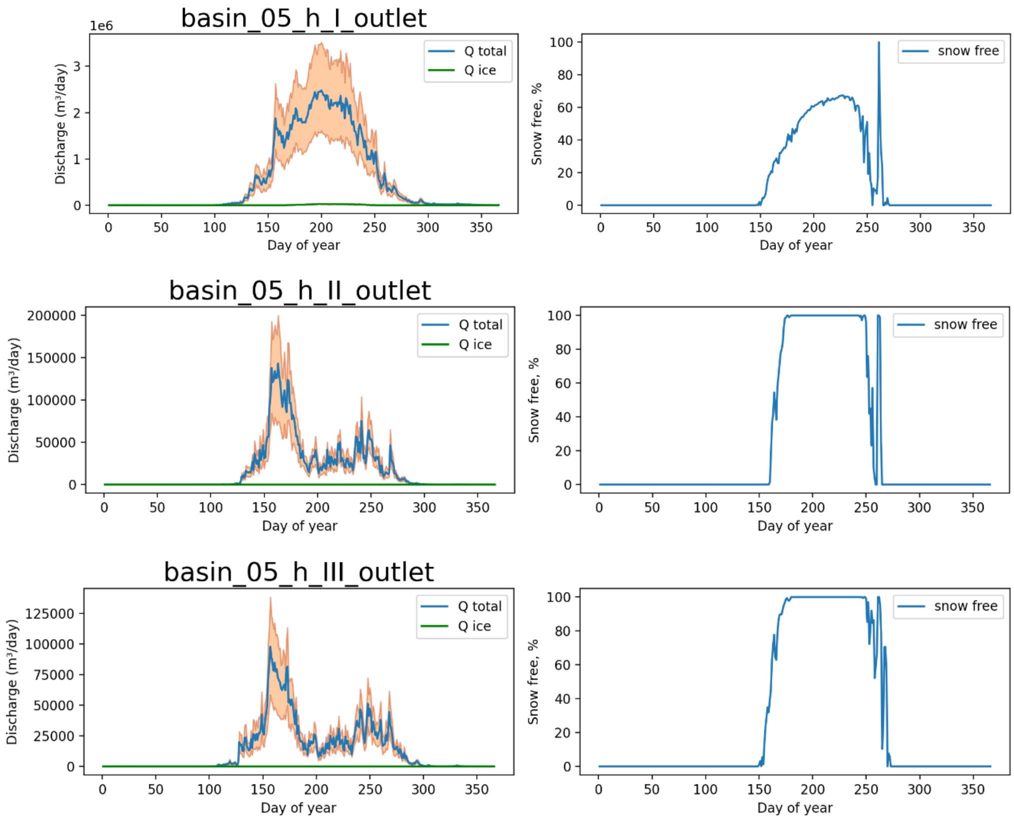

Figure 18. Left graphs: seasonal variation of the total daily discharge from the catchment, averaged over 1981-2020 (blue line “Q total”), including uncertainty interval (light brown) with the daily discharge from the glaciated part of the catchment (green curve “Q ice”) specified, also including uncertainty interval (light green). Right graphs: daily percentage of the total catchment (ice-covered and ice-free) experiencing snow-free conditions.

Hydro Power Potential 05.j

The hydro power potential 05.j Isorsua is based on the natural catchments of lake Isorsuup Tasersua, catchment 05.j.I (see Figure 19).

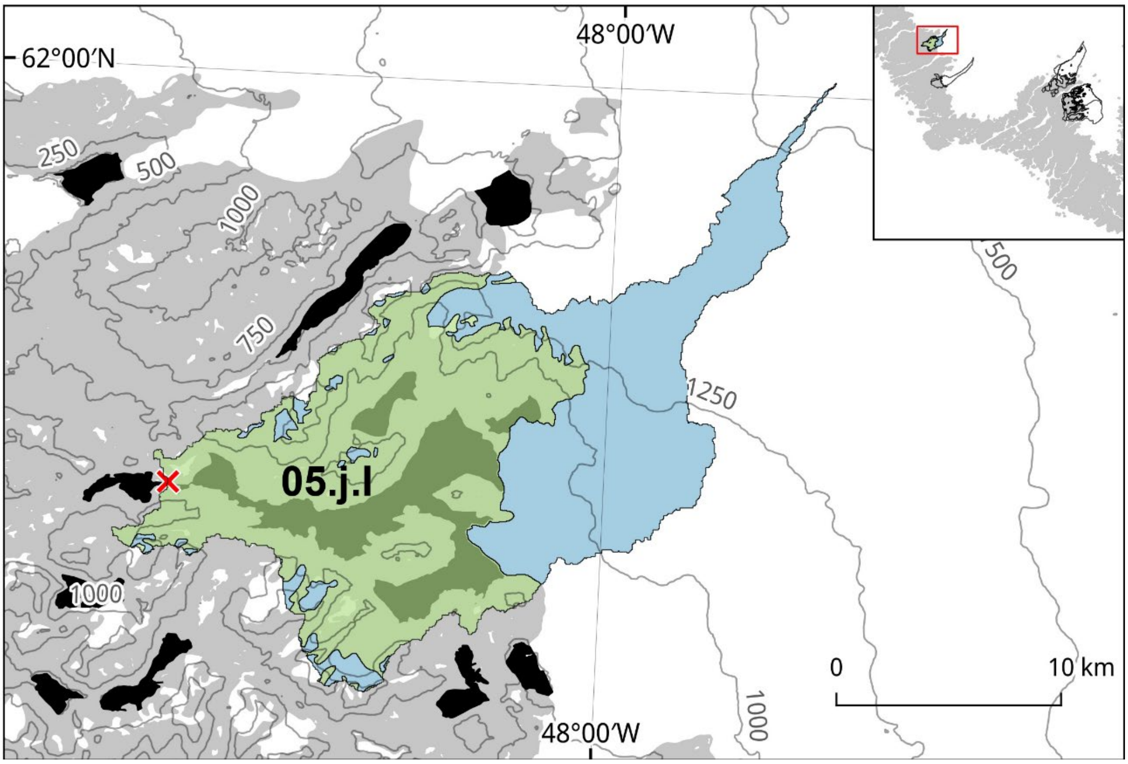

Figure 19. Map showing the catchment. Blue signifies ice cover and green is ice-free land. The red cross marks the outlet, listed in Table 1.

Monitoring of the water resource

The hydro power potential 05.j was identified by map studies in 1975 (Nukissiorfiit, 1995) and has since then not been investigated further. Monitoring of the water resource has not been carried out.

Establishing a 1981-2020 time series

As no observations exist from this catchment, a time series of discharge was derived solely from the catchment model DETIM, with no bias-correction applied. To estimate the uncertainty of this approach, the model input parameters (air temperature and precipitation) and the melt-factors used in the model were varied within reasonable bounds as detailed in the model description section. For comparison with the catchments with observations, the period 1981-2014 was chosen to match as closely as possible the 1980-2014 period used for these.

Water resource

The water resource of hydropower potential 05.j was estimated solely from results of the catchment model DETIM, with no validation or bias-correction available from measurements in the catchment. The mean yearly water resource is 0.21 km^3, see Table 6.

Catchment	Yearly water resource, km^3		
	Mean	Maximum	Minimum
05.j	0.21	0.33	0.14

Table 6. Water resource at hydro power potential 05.j.

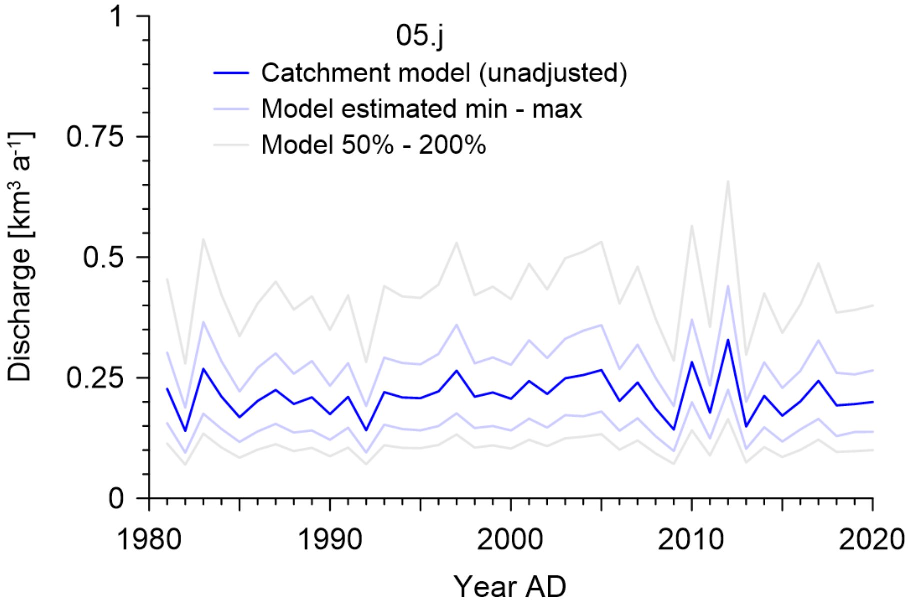

Figure 20. The annual discharge derived from the catchment model DETIM (dark blue line), along with estimated model uncertainty bounds (light blue lines) and a range derived from comparing unadjusted DETIM results to observed discharge in all the catchments where these are available (grey lines).

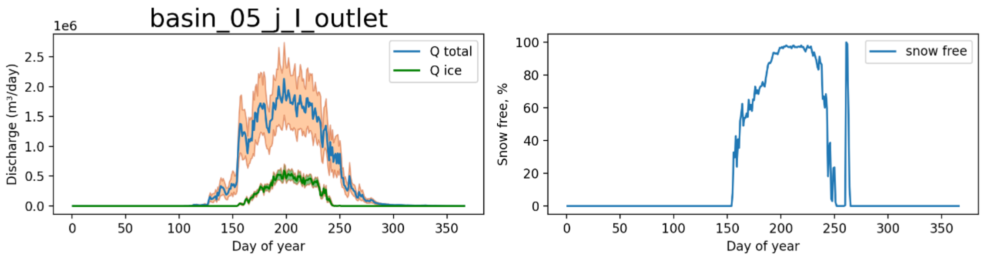

Figure 21. Left graph: seasonal variation of the total daily discharge from the catchment, averaged over 1981-2020 (blue line "Q total"), including uncertainty interval (light brown) with the daily discharge from the glaciated part of the catchment (green curve "Q ice") specified, also including uncertainty interval (light green). Right graph: daily percentage of the total catchment (ice-covered and ice-free) experiencing snow-free conditions.

Hydro Power Potential 05.k

The hydro power potential 05.k is based on the natural catchments of lake Kangaarsuup tasersua, catchment 05.k.I (see Figure 22).

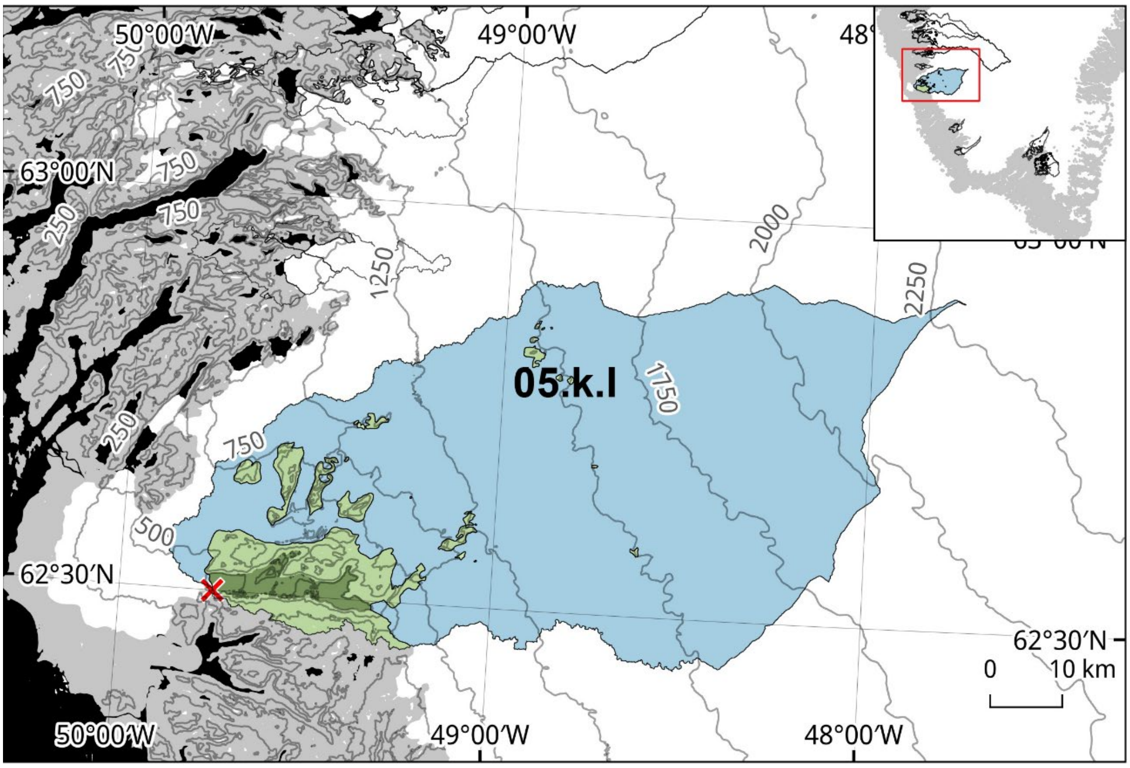

Figure 22. Map showing the catchment. Blue signifies ice cover and green is ice-free land. The red cross marks the outlet, listed in Table 1.

Monitoring of the water resource

The hydro power potential 05.k was identified by map studies in 1975 (Nukissiorfiit, 1995) and has since then not been investigated further. Monitoring of the water resource has not been carried out.

Establishing a 1981-2020 time series

As no observations exist from this catchment, a time series of discharge was derived solely from the catchment model DETIM, with no bias-correction applied. To estimate the uncertainty of this approach, the model input parameters (air temperature and precipitation) and the melt-factors used in the model were varied within reasonable bounds as detailed in the model description section. For comparison with the catchments with observations, the period 1981-2014 was chosen to match as closely as possible the 1980-2014 period used for these.

Water resource

The water resource of hydropower potential 05.k was estimated solely from results of the catchment model DETIM, with no validation or bias-correction available from measurements in the catchment. The mean yearly water resource is 2.9 km^3, see Table 7.

Catchment	Yearly water resource, km^3		
	Mean	Maximum	Minimum
05.k	2.91	5.32	1.69

Table 7. Water resource at hydro power potential 05.k.

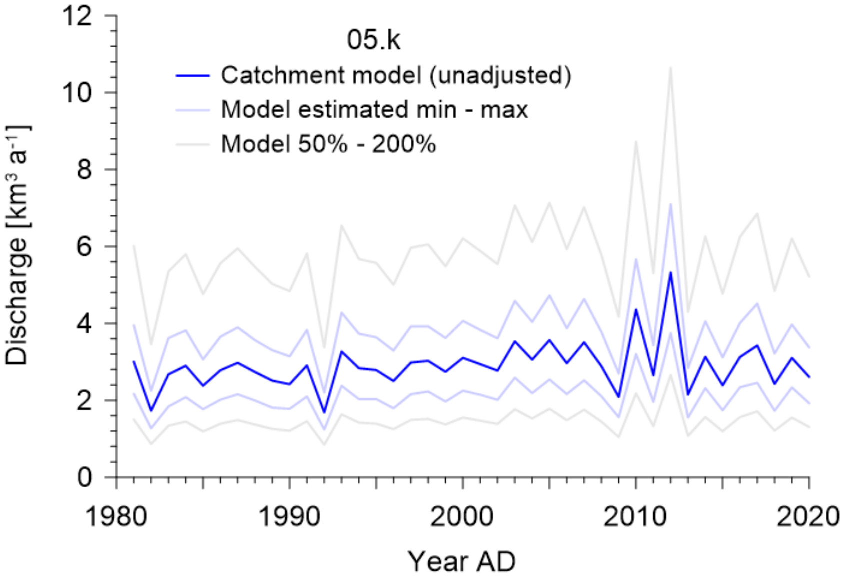

Figure 23. The annual discharge derived from the catchment model DETIM (dark blue line), along with estimated model uncertainty bounds (light blue lines) and a range derived from comparing unadjusted DETIM results to observed discharge in all the catchments where these are available (grey lines).

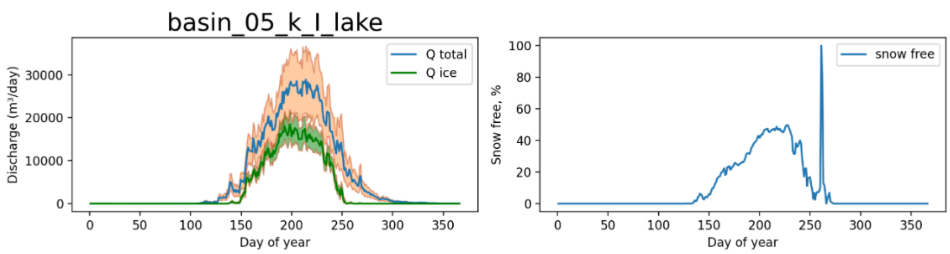

Figure 24. Left graph: seasonal variation of the total daily discharge from the catchment, averaged over 1981-2020 (blue line "Q total"), including uncertainty interval (light brown) with the daily discharge from the glaciated part of the catchment (green curve "Q ice") specified, also including uncertainty interval (light green). Right graph: daily percentage of the total catchment (ice-covered and ice-free) experiencing snow-free conditions.

Hydro Power Potential 06.b/06.f

The hydro power potentials 06.b and 06.f are two different technical designs to utilize the same water resource; that is from the catchment 06.b of lake Isortuarsuup Tasia (ISTA). The catchment of ISTA borders the natural catchment of the lake Kangluarsunnguup Tasersua (Hydro power potential 06.a). A hydro power plant at site 06.a has been in operation since October 1993. Since that time the water from two smaller sub-catchments in the ISTA catchment has been diverted to the 06.a hydro power plant. Thereby the natural catchment of ISTA was artificially reduced (see Figure 25).

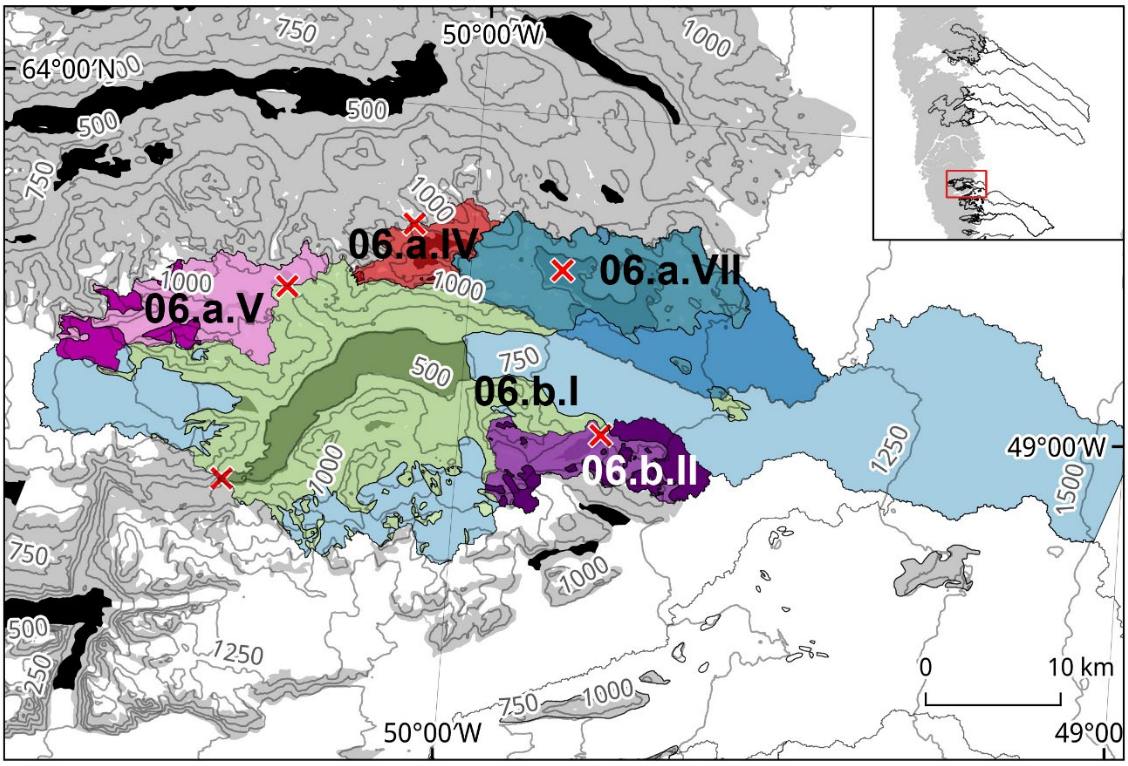

Figure 25. Map showing the catchments. The largest sub-catchment 06.b.I is in light shades of blue (ice-covered) and green (land or lake) and is truncated at c. 1500 m elevation to obtain a delineation more in line with expected subglacial drainage patterns. Within the other sub-catchments, dark shades indicate ice-cover. Red crosses mark outlets, listed in Table 1. Sub-catchments 06.a.V and 06.a.IV were diverted northwards in 1993. Sub-catchments 06.b.II and 06.a.VII both feed glacier-dammed lakes, periodically draining into 06.b.I, creating peaks in the discharge.

Monitoring of the water resource

Investigations of hydro power potential 06.b were initiated in 1975 by the Greenland Technical Organization (GTO) and have continued ever since. Today the monitoring is run by Asiaq – Greenland Survey.

The stage-discharge relation for catchment 06.b is derived from a combination of 8 manual discharge measurements and calculated discharge for very high water levels. Lake 710 at position N66°09', W050°54' is an ice-marginal lake that every 9-10 years empties under the glacier in a glacial lake outburst flood (GLOF). Lake 710 is emptied in a matter of 5 days and the water released during the GLOF amounts to twice the mean yearly runoff from lake ISTA. The released water enters lake ISTA causing the water level to rise around 18 meters. When Lake 710 has emptied the water level in lake ISTA starts to drop towards normal levels. During the upper part of the recession curve the inflow of water to lake ISTA is negligible compared to the outflow. Thus, discharge can be calculated from the time series of water level, a digital elevation model of the flooded terrain and a simple volume balance.
The stage-discharge relation for catchment 06.b is well documented and covers the range of discharge very well; extrapolation of the stage-discharge relation amount to less than 1 % of the total discharge volume, Table 8. An overview of the data coverage of the discharge time series for lake ISTA is given in Figure 26.

Catchment	Manual discharge measurements	Part of total discharge volume found by extrapolation of stage-discharge relation or gap filling, %		
		Upward extrapolation	Downward extrapolation	Gap filling
06.b	8 + recession curve*	0.8 %	0.1 %	2 %

Table 8. Basis for the stage-discharge relation for the catchment and part of total discharge volume found by extrapolation of the stage-discharge relation or gap filling. * see explanation in the text.

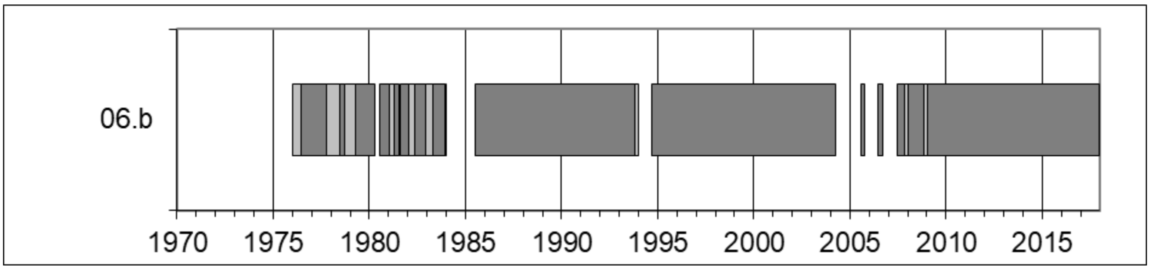

Figure 26. Data coverage of measured discharge time series for the catchment of ISTA in hydro power potential 06.b. Periods with measured data are shown as dark grey bars, periods with larger, filled data gaps are shown with light grey bars (for description of gap filling method see method section).

Establishing the 1980-2014 time series

Although catchment 06.b have been monitored since 1976 some data gaps occur in the discharge time series, and these have to be filled in order to generate the 1980-2014 time series. Therefore, HIRHAM5 runoff data is used to supplement the measured discharge time series.

The discharge time series from catchment 06.b is dominated by the yearly melt peak, but beside this the discharge time series show occasional short-term peaks that can occur on all times of year but are most common in the autumn. The source is glacial lake outburst floods (GLOFs) from one of two upstream ice-dammed lakes: Lake 710 at position N66°09', W050°54' and Lake 760 at position N66°09', W050°54', relatively. The time between GLOFs is 9-10 years for Lake 710 and 4-6 years for Lake 760. This storage of meltwater from one year to another is not included in the HIRHAM5 model. Therefore, the volume of water released at the GLOF events have been removed from the measured discharge time series before comparing it with the modelled runoff for the area of the catchment not including the catchments of the GLOF lakes. The measured time series has 28 years overlapping with the HIRHAM5 ice runoff time series and the correlation is decent (R^2 = 0.75).

Missing yearly values are now found from HIRHAM5 yearly ice runoff values adjusted linearly by the regression formula and thereafter the volume of water released during any GLOF occurring in that year have been added. In the period 1980-2014 one GLOF event from lake 710 occurred that has not been measured. As the volume of water released is approximately the same for each event the median value has been used for the GLOF event not captured in the measured time series.

Water resource

Based on the 1980-2014 discharge time series the mean yearly water resource at hydro power potential 06.b has been calculated. The mean yearly water resource (excluding GLOF events) is 0.9 km^3, see Table 9.

Notable the six highest yearly resource values occur within the period 2000-2014. The yearly water resource (GLOF's excluded) shows a statistically significant, positive trend (significance level $p<0.02$) in a Spearman Rho test. The trend for the discharge time series of catchment 06.e.I is estimated to be a 0.005 km^3/year increase in discharge (Theil & Sen slope estimator).

Catchment	**Yearly water resource, km^3**		
	Mean	**Maximum**	**Minimum**
06.b (GLOF excl.)	0.88	1.3	0.52
06.b (GLOF incl.)	1.1	3.0	0.52

Table 9. Water resource at hydro power potential 06.b.

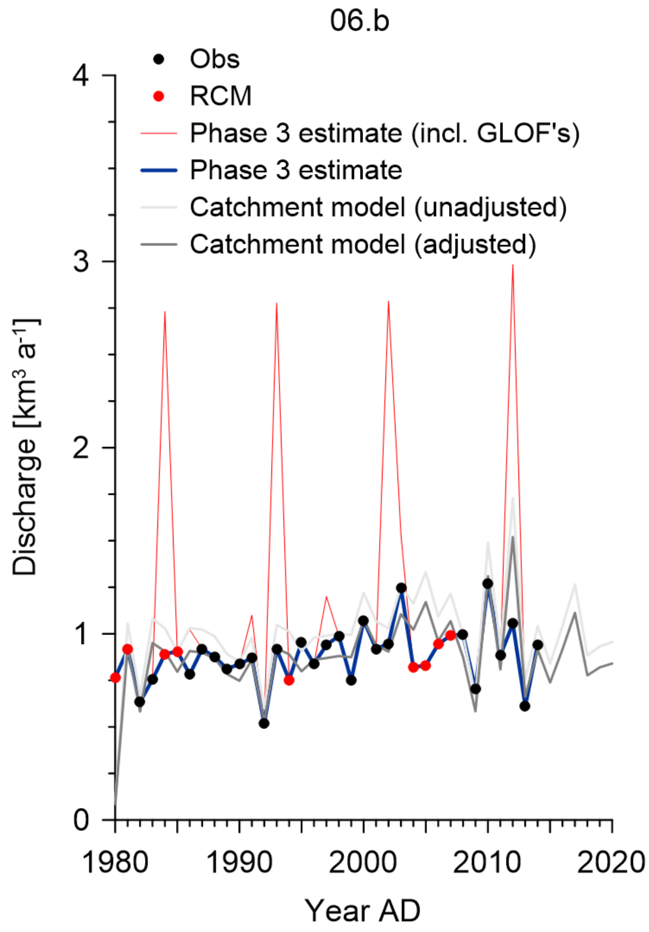

Figure 27. The annual discharge (“Phase 3 estimate”), with and without GLOF’s, from the hydropower potential 06.b with the following labelling of data sources; “Obs”: measured data, “RCM”: based on regression between results from climate models and measured data from other years. Catchment model results are shown in both the original unadjusted and bias-corrected adjusted versions.

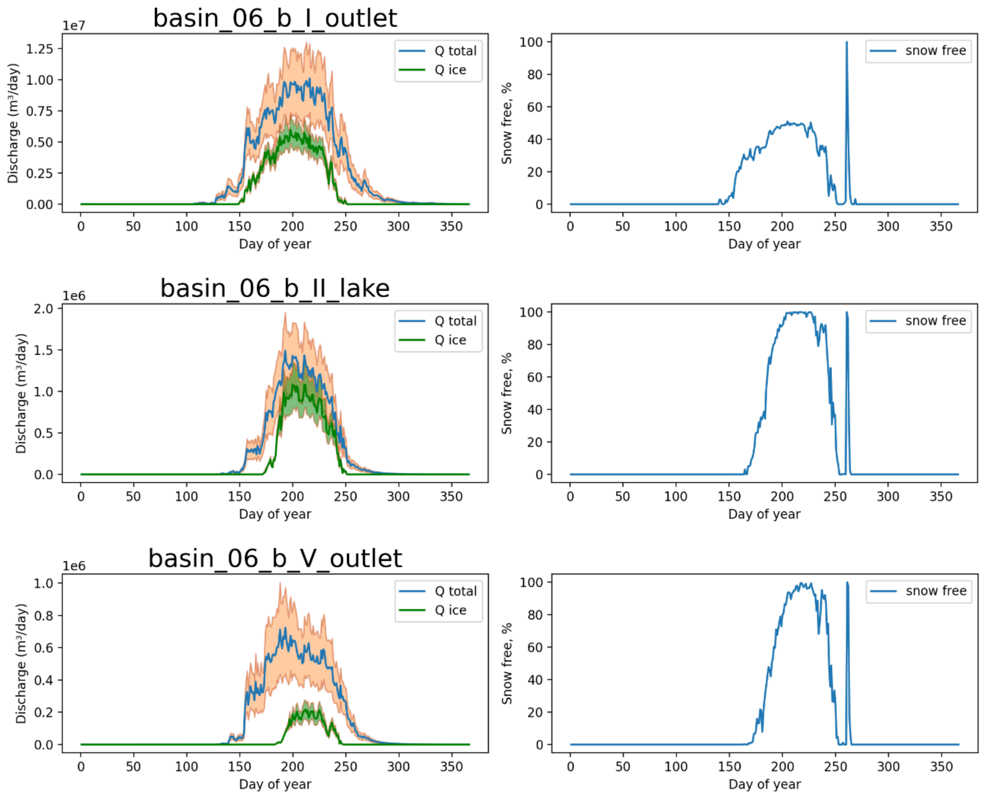

Figure 28. Left graphs: seasonal variation of the total daily discharge from the catchment, averaged over 1981-2020 (blue line "Q total"), including uncertainty interval (light brown) with the daily discharge from the glaciated part of the catchment (green curve "Q ice") specified, also including uncertainty interval (light green). Right graphs: daily percentage of the total catchment (ice-covered and ice-free) experiencing snow-free conditions.

Hydro Power Potential 06.c

The hydro power potential 06.c Allumersat is based on two natural catchments, figure 06cX1; Catchment 06.c.I and 06c.II. Catchment 06.c.I contributes with the main part of the water resource.

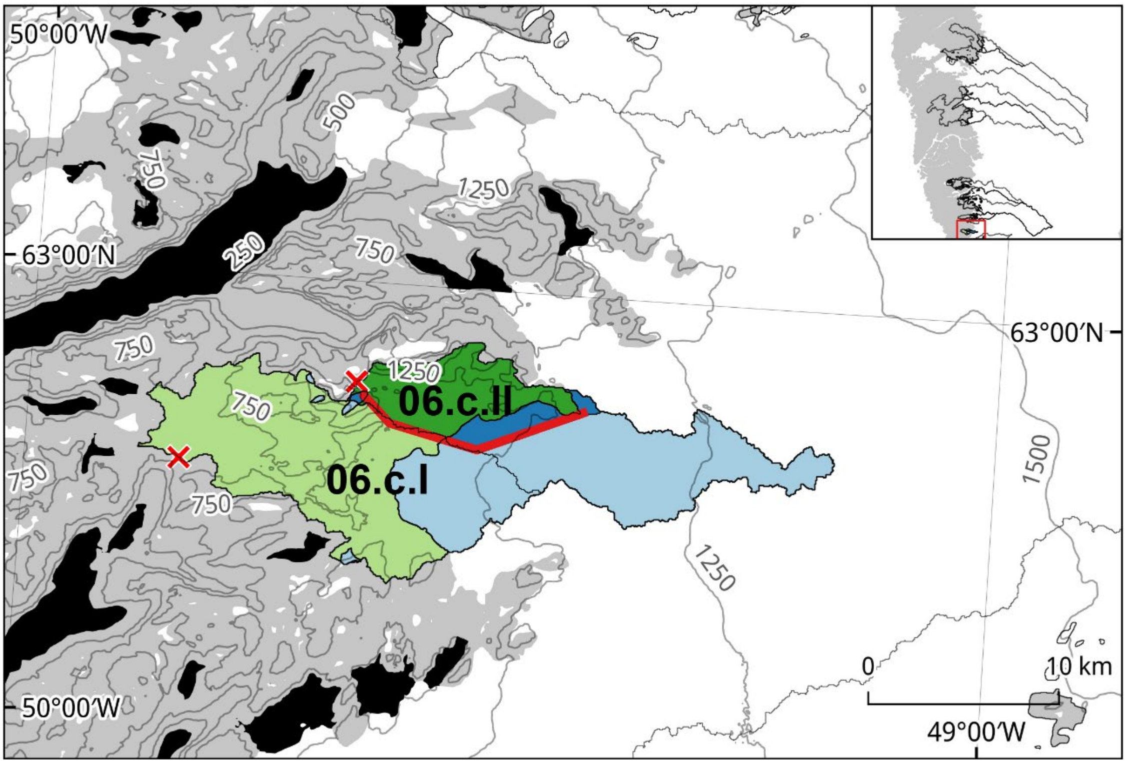

Figure 29. Map showing the catchments. Light shades and dark shades indicate separate sub-catchments, while blue signifies ice cover and green is ice-free land. Red crosses mark outlets, listed in Table 1. The thick red line indicates a barrier introduced artificially in the DEM prior to sub-catchment delineation, as earlier attempts got the division between the two sub-catchments wrong when compared to knowledge from site visits and inspection of sediment load in downstream lakes from visual satellite imagery.

Monitoring of the water resource

The hydro power potential 06.c was identified by map studies in 1975 (GTO 1975). In 2008 monitoring of the water resource was initiated by the Greenlandic energy supply company Nukissiorfiit. After a hydrological and technical reconnaissance trip to the site, a hydrometric station was established at catchment 06.c.I. The water resource from catchment 06.c.II has not been measured. The monitoring program is run by Asiaq – Greenland Survey and is still ongoing as of 2018.

The stage-discharge relation for catchment 06.c.I is based on a low number of manual discharge measurements that however covers the range of discharge reasonably well; extrapolation of the stage-discharge relation amount to 17% of the total discharge volume, Table

10. An overview of the data coverage of the discharge time series for each catchment is given in Figure 30.

Catchment	Manual discharge measurements	Part of total discharge volume found by extrapolation of stage-discharge relation or gap filling, %		
		Upward extrapolation	Downward extrapolation	Gap filling
06.c.I	6	6 %	11 %	0.1 %

Table 10. Basis for the stage-discharge relation for the catchment and part of total discharge volume found by extrapolation of the stage-discharge relation or gap filling.

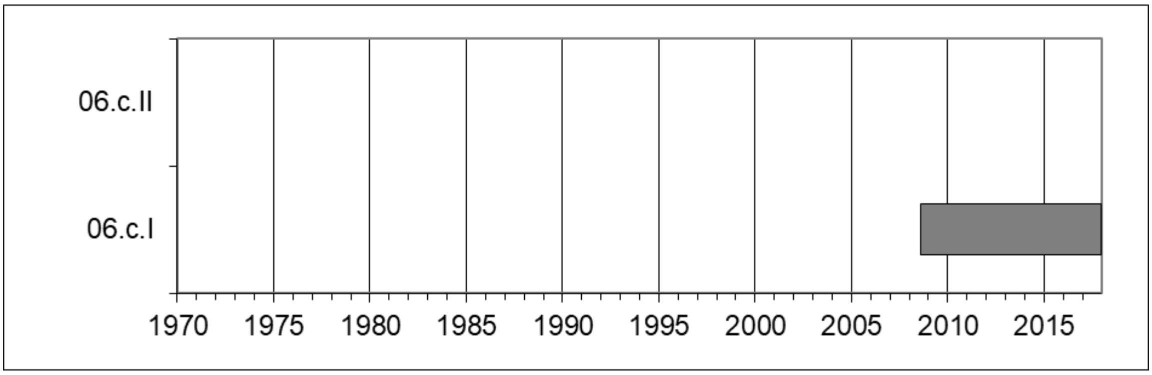

Figure 30. Data coverage of measured discharge time series for the catchments of hydro power potential 06.c. Periods with measured data are shown as dark grey bars.

Establishing the 1980-2014 time series

For none of the catchments the measured discharge time series covers the entire period from 1980 to 2014 (see Figure 30). Therefore, discharge data from the nearby catchment 06.d.I is used to supplement the measured discharge time series.

For catchment 06.c.I runoff from the ice-free parts of the catchment constitutes a significant part of the total runoff: 29% according to HIRHAM5. In this respect the catchment is similar to the nearby catchment 06.d.I. The measured time series for catchment 06.c.I has six years overlapping with the HIRHAM5 time series and the correlation is good (R^2 = 0.90). However, the correlation with the runoff time series from catchment 06.d.I is even better (R^2 = 0.98) and thus data from 06.d.I is used to fill data gaps. The 1980-2014 yearly discharge time series is constructed with the measured data supplemented with 06.d.I yearly runoff values adjusted linearly by the regression formula.

Water resource

Based on the 1980-2014 discharge time series for the two catchments the mean yearly water resource at hydro power potential 06.c has been calculated to 0.51 km^3, see Table 11. Notably, the six highest yearly resource values occur within the period 2000-2014.

Catchment	Yearly water resource, km^3			Contribution to water resource, %
	Mean	Maximum	Minimum	
06.c.I	0.49	0.84	0.38	96.1
06.c.II	0.020	0.026	0.013	3.9
06.c total	**0.51**	**0.87**	**0.39**	

Table 11. Water resource at hydro power potential 06.c.

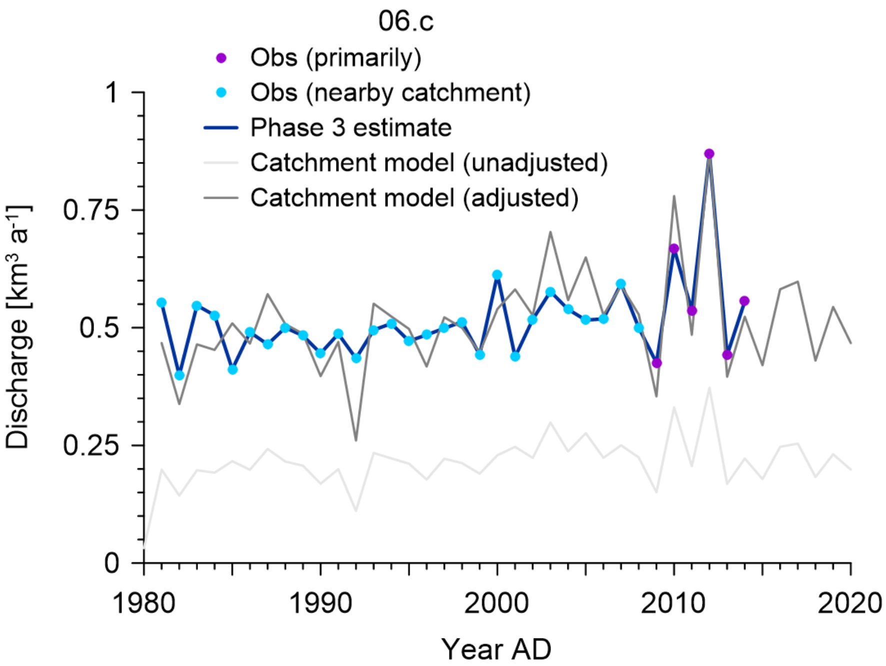

Figure 31. The annual discharge ("Phase 3 estimate") from the hydropower potentials 06.c with the following labelling of data sources; "Obs (primarily)": mainly based on measured data, "Obs (nearby catchment)": based on regression between measured data from catchments nearby and measured data from other years, "RCM": based on regression between results from climate models and measured data from other years. Catchment model results are shown in both the original unadjusted and bias-corrected adjusted versions.

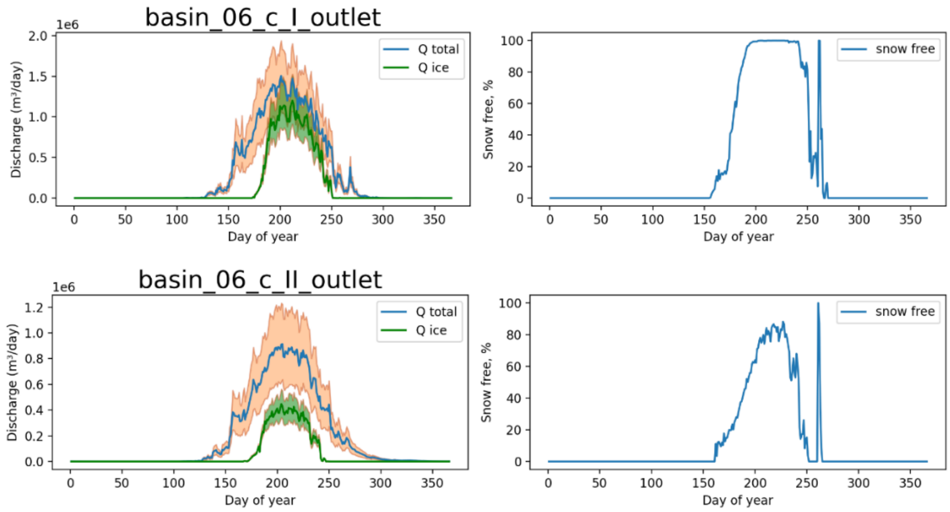

Figure 32. Left graphs: seasonal variation of the total daily discharge from the catchment, averaged over 1981-2020 (blue line “Q total”), including uncertainty interval (light brown) with the daily discharge from the glaciated part of the catchment (green curve “Q ice”) specified, also including uncertainty interval (light green). Right graphs: daily percentage of the total catchment (ice-covered and ice-free) experiencing snow-free conditions.

Hydro Power Potential 06.d

The hydro power potential 06.d is based on two natural catchments (see Figure 33). Catchment 06.d.I is the natural catchment of the lake Qajartoriaq and 06d.II is the natural catchment of the lake Ilulialik.

Until recently the Catchment 06.d.I included the catchment of the ice-marginal lake Norratallip Tasia (catchment 06.d.III). Due to recent thinning of the glacier lake Norratallip Tasia started to drain periodically as glacial lake outburst floods (GLOF events) under the glacier towards northwest bypassing lake Qajartoriaq. The first GLOF event occurred in August 2013 reducing the water level of lake Norratallip Tasia to a very low level. Following this event, the water level of lake Norratallip Tasia increased and from September 2015 water again spilled over to lake Qajartoriaq until another GLOF event occur during the winter 2015/2016.

With the predicted warming of the Arctic in the coming decades catchment 06.d.III will likely not be part of the catchment of lake Qajartoriaq in the future. In the following we have used the name 06.d.I for the old catchment of lake Qajartoriaq (including the sub-catchment 06.d.III), whereas we use the name 06.d.I-III for the current and probably future catchment of lake Qajartoriaq (not including sub-catchment 06.d.III).

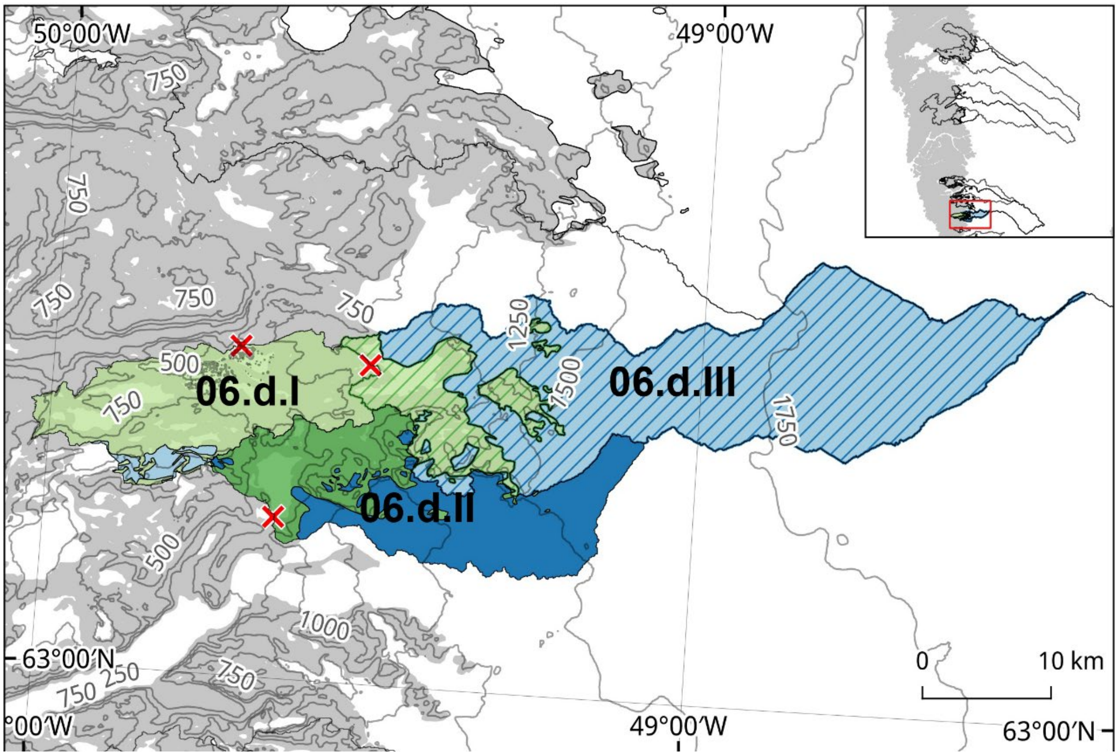

Figure 33. Map showing the catchments. Light shades and dark shades indicate separate sub-catchments, while blue signifies ice cover and green is ice-free land. Red crosses mark outlets, listed in Table 1. The sub-catchment 06.d.I includes 06.d.III (hatched part) which broke away as the ice-dam holding it in thinned sufficiently. Thus, the natural sub-catchment is now 06.d.I minus 06.d.III.

Monitoring of the water resource

The hydro power potential 06.d was identified by map studies in 1975 (GTO 1975). A reconnaissance trip to the site was conducted in the summer of 1975. During this visit some preliminary measurements was carried out, but no further investigations was started at that time. In 2008 monitoring of the water resource was initiated by the Greenlandic energy supply company Nukissiorfiit. Two hydrometric stations were established; one at catchment 06.d.I and one at catchment 06.d.II. The monitoring program is run by Asiaq – Greenland Survey and is still ongoing as of 2018.

The stage-discharge relation for catchment 06.d.I is based on a reasonable number of manual discharge measurements that to a reasonable degree covered the range of discharge; extrapolation of the stage-discharge relation amount to 20% of the total discharge volume (Table 12). However, after the sub-catchment 06.d.III stopped contributing with water the discharge from catchment 06.d.I-III is much lower and 92% of the total discharge volume is found by downward extrapolation of the stage-discharge relation. The measured discharge from catchment 06.d.I-III is thus somewhat uncertain, but as the extrapolation to low values has a lower constrain of zero discharge, the absolute uncertainty on these values is limited.

Similarly, the stage-discharge relation for catchment 06.d.II is based on a reasonable number of manual discharge measurements that to a high degree covered the range of discharge; extrapolation of the stage-discharge relation amount to less than 15% of the total discharge volume (Table 12).

An overview of the data coverage of the discharge time series for each catchment is given in Figure 34.

Catchment	Manual discharge measurements	Part of total discharge volume found by extrapolation of stage-discharge relation or gap filling, %		
		Upward extrapolation	Downward extrapolation	Gap filling
06.d.I	10	2 %	18 %	0 %
06.d.I-III		0 %	92 %	0 %
06.d.II	9	3 %	11 %	0 %

Table 12. Basis for the stage-discharge relation for each catchment and part of total discharge volume found by extrapolation of the stage-discharge relation or gap filling.

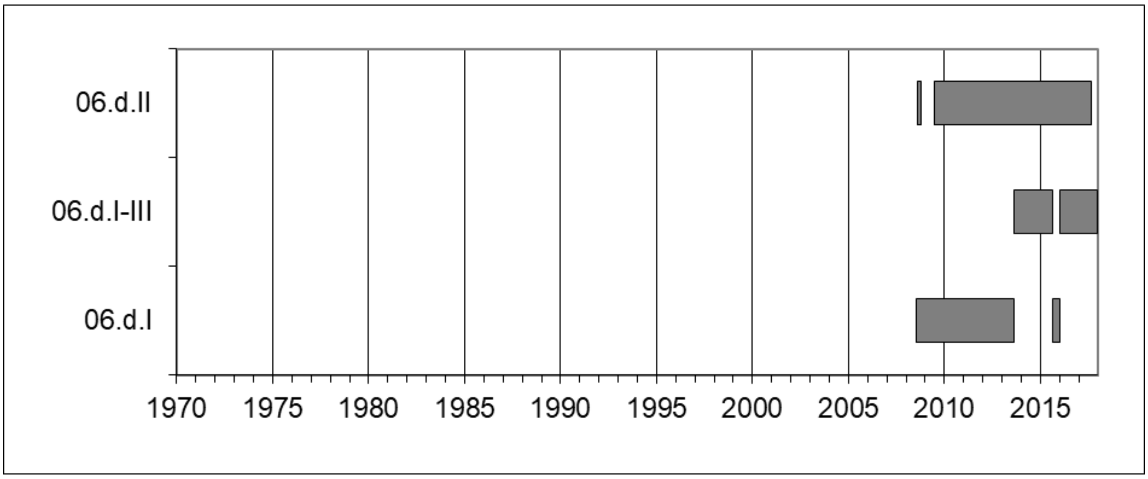

Figure 34. Data coverage of measured discharge time series for the catchments of hydro power potential 06.d. Periods with measured data are shown as dark grey bars.

Establishing the 1980-2014 time series

For none of the catchments the measured discharge time series covers the entire period from 1980 to 2014, Figure 34. Therefore, discharge data from HIRHAM5 is used to supplement the measured discharge time series.

As described above the natural catchment of lake Qajartoriaq is likely to be the catchment 06.d.I-III in future. Direct measurements of the runoff from catchment 06.d.I-III have been possible since August 2013 excluded the period in 2015 where lake Norratallip Tasia (catchment 06.d.III) again delivered water to lake Qajartoriaq. As the HIRHAM5 model output for land areas only covers 1980-2014, the hydrological year of 2014 is the only full years overlap between measured and model data for catchment 06.d.I-III. For 2014, the modelled yearly runoff value has to be increased with 35% to fit the measured value. Adjusting the HIRHAM5 land runoff values for all years with 35%, increased the correlation coefficient between measured and modelled runoff for catchment 06.d.I (from $R^2 = 0.98$ to $R^2 = 0.99$) thus justifying that this adjustment of the HIRHAM5 land runoff is generally applicable for catchment 06.d.I-III. The 1980-2014 yearly discharge time series is constructed with the measured data supplemented with yearly HIRHAM5 land runoff values increased by 35%.

For catchment 06.d.II meltwater from the Greenland ice sheet (GrIS) dominates the discharge: 83% of the total discharge according to HIRHAM5. The measured time series has 7 years overlapping with the HIRHAM5 ice runoff time series and the correlation is good ($R^2 = 0.87$). When including HIRHAM land runoff the correlation decreases ($R^2 = 0.80$). The 1980-2014 yearly discharge time series is constructed with the measured data supplemented with yearly HIRHAM5 ice runoff values adjusted linearly by the regression formula.

Water resource

Based on the 1980-2014 discharge time series for the two catchments the mean yearly water resource at hydro power potential 06.d has been calculated to 0.47 km3, see Table 13. The yearly water resource does not show a statistically significant trend in a Spearman Rho test.

Catchment	**Yearly water resource, km^3**			**Contribution to water resource, %**
	Mean	**Maximum**	**Minimum**	
06.d.I-III	0.21	0.32	0.09	45
06.d.II	0.26	0.42	0.17	55
06.d total	**0.47**	**0.65**	**0.34**	

Table 13. Water resource at hydropower potential 06.d. As the water resource at catchment 06.d.II is mainly meltwater from the GrIS, whereas the water resource at catchment 06.d.I-III is entirely from precipitation, high and low runoff years do not coincide for the two catchments. The maximum and minimum yearly water resource for the 06.d total is therefore not the sum of the values for each catchment.

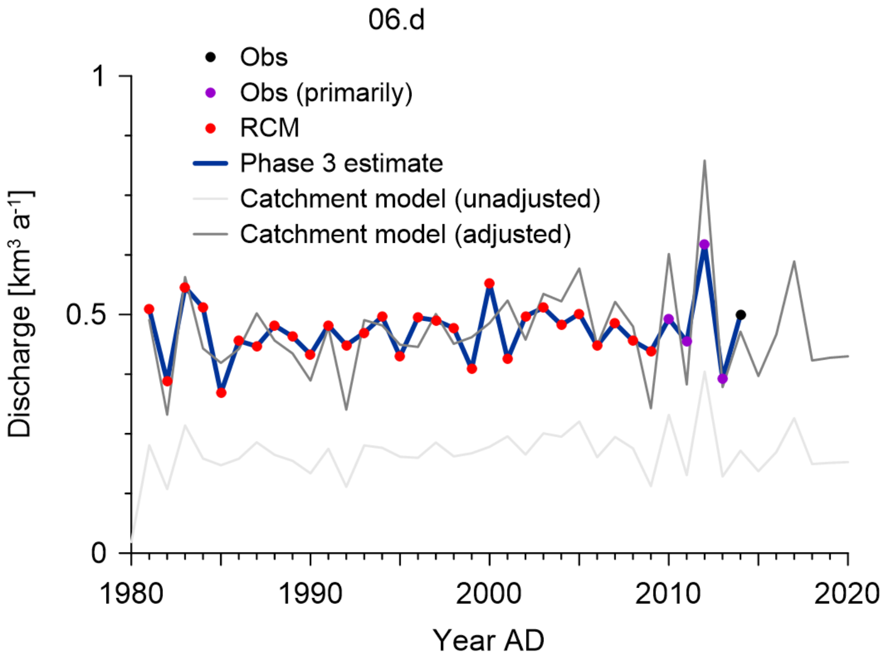

Figure 35. The annual discharge ("Phase 3 estimate") from the hydropower potential 06.d with the following labelling of data sources; "Obs": measured data, "Obs (primarily)": mainly based on measured data, "RCM": based on regression between results from climate models and measured data from other years. Catchment model results are shown in both the original unadjusted and bias-corrected adjusted versions.

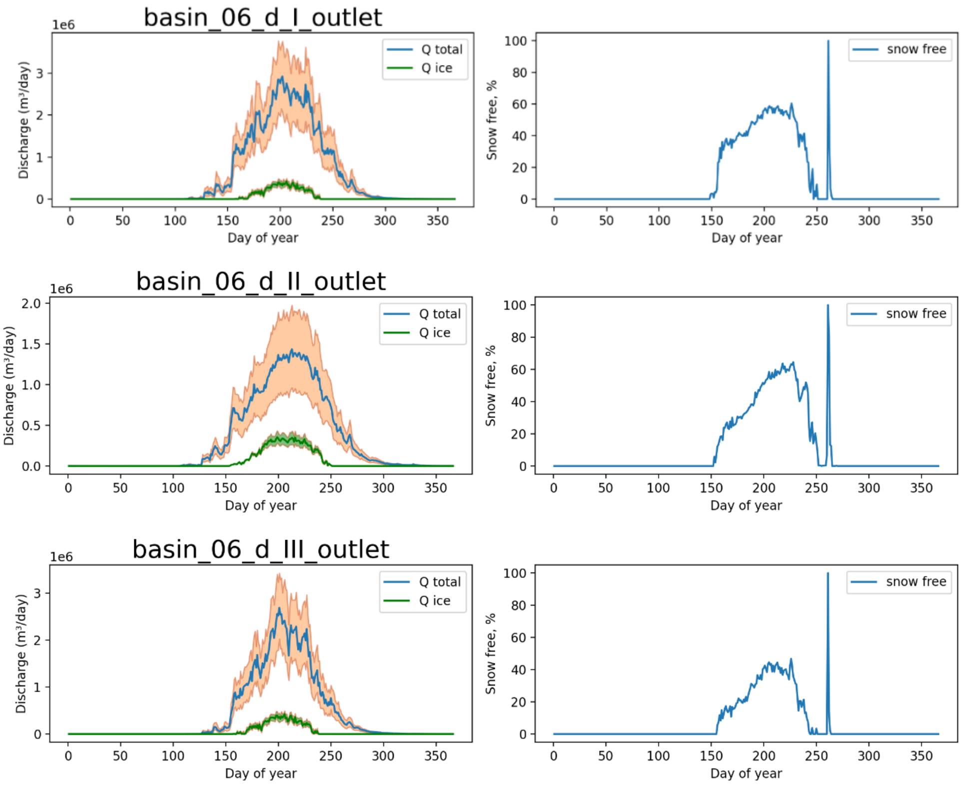

Figure 36. Left graphs: seasonal variation of the total daily discharge from the catchment, averaged over 1981-2020 (blue line “Q total”), including uncertainty interval (light brown) with the daily discharge from the glaciated part of the catchment (green curve “Q ice”) specified, also including uncertainty interval (light green). Right graphs: daily percentage of the total catchment (ice-covered and ice-free) experiencing snow-free conditions.

Hydro Power Potential 06.e

The hydro power potential 06.e is based on the natural catchment of Lake 348, catchment 06.e.I. The energy production can be increased by installing two additional power plants utilizing the height difference from sub-catchment 06.e.II and 06.e.III down to the main reservoir lake (see Figure 37).

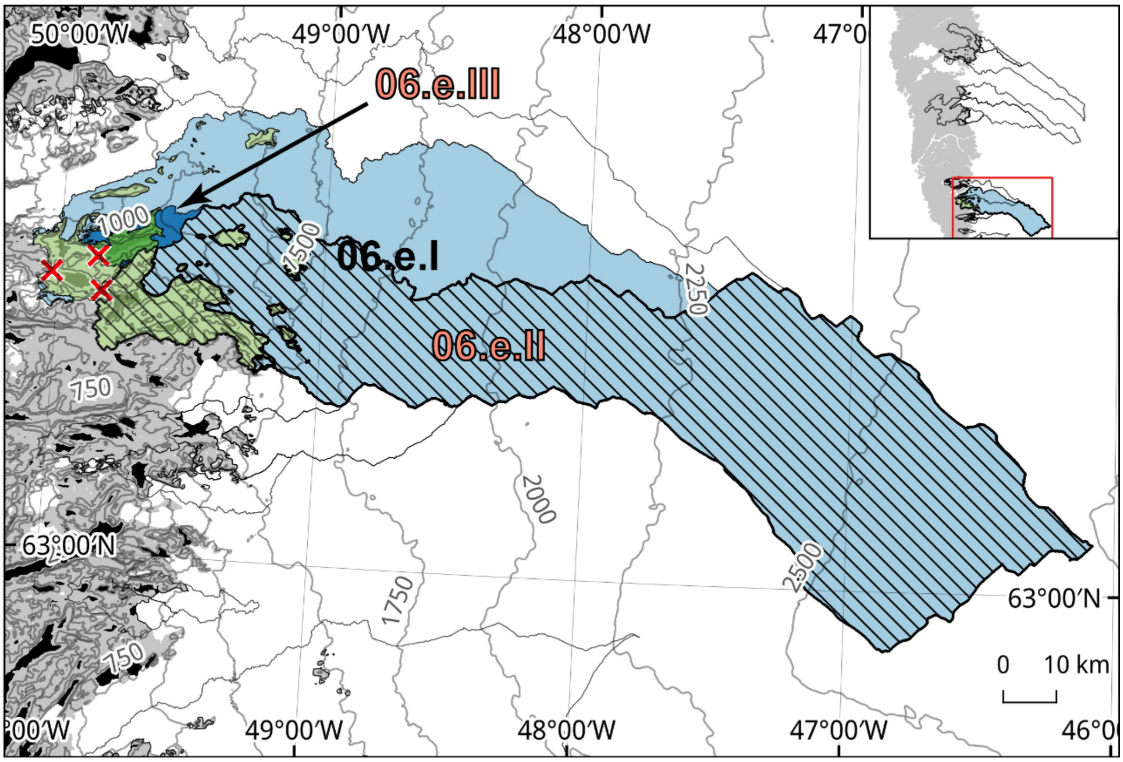

Figure 37. Map showing the catchments. Light shades and dark shades indicate separate sub-catchments, while blue signifies ice cover and green is ice-free land. Red crosses mark outlets, listed in Table 1. The catchment 06.e.I includes 06.e.II (hatched part) and 06.e.III (dark shaded part).

Monitoring of the water resource

The hydro power potential 06.e was identified by map studies in 1975 (GTO 1975). Monitoring of the water resource of catchment 06.e.I was initiated in 1976 by the Greenland Technical Organization (GTO). In 1978, the monitoring program was expanded with monitoring of catchment 06.e.II. The measurements were terminated in 1986 for catchment 06.e.I and in 1988 for catchment 06.e.II. In 2008, monitoring of the water resource was resumed on initiative of the Greenlandic energy supply company Nukissiorfiit. Three hydrometric stations were established; one at each of the catchments 06.e.I, 06.e.II and 06.e.III. The monitoring program is run by Asiaq – Greenland Survey and is still ongoing as of 2018.

The stage-discharge relation for catchment 06.e.I is based on a reasonable number of manual discharge measurements that to a high degree cover the range of discharge; extrapolation of the stage-discharge relation amount to 5% of the total discharge volume, see Table 14.

The stage-discharge relation for catchment 06.e.II is based on a reasonable number of manual discharge measurements that to a reasonable degree cover the range of discharge; extrapolation of the stage-discharge relation amount to 18% of the total discharge volume, Table 14.

The stage-discharge relation for catchment 06.e.III is based on a low number of manual discharge measurements that however covers the range of discharge reasonably well; extrapolation of the stage-discharge relation amount to 15% of the total discharge volume, and only downward extrapolation has been necessary, Table 14.

An overview of the data coverage of the discharge time series for each catchment is given in Figure 38.

Catchment	Manual discharge measurements	Part of total discharge volume found by extrapolation of stage-discharge relation or gap filling, %		
		Upward extrapolation	Downward extrapolation	Gap filling
06.e.I	14	2 %	3 %	0.5 %
06.e.II	12	8 %	10 %	0.3 %
06.e.III	7	0 %	15 %	0.1 %

Table 14. Basis for the stage-discharge relation for each catchment and part of total discharge volume found by extrapolation of the stage-discharge relation or gap filling.

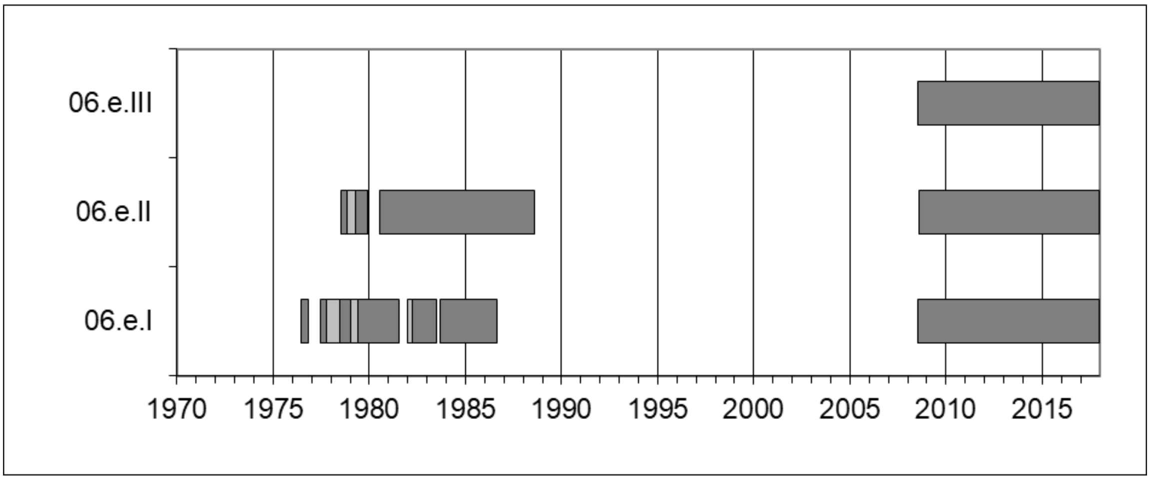

Figure 38. Data coverage of measured discharge time series for the catchments of hydro power potential 06.e. Periods with measured data are shown as dark grey bars, periods with larger, filled data gaps are shown with light grey bars (for description of gap filling method see method section).

Establishing the 1980-2014 time series

The measured discharge time series does not cover the entire period from 1980 to 2014 for any of the catchments (see Figure 38). Therefore, discharge data from HIRHAM5 is used to supplement the measured discharge time series.

The discharge time series for catchment 06.e.II has the largest time overlap with the HIRHAM5 runoff time series (15 years). Meltwater from the Greenland Ice Sheet (GrIS) contributes with the main part of the water resource and the correlation between the measured time series and the modelled ice runoff (R^2 = 0.98) is better than the correlation with the modelled runoff from land and ice (R^2 = 0.95). The 1980-2014 yearly discharge time series is constructed with the measured data supplemented with yearly HIRHAM5 ice runoff values adjusted linearly by the regression formula.

The discharge time series for catchment 06.e.I has 12 years overlapping the time series of catchment 06.e.II and the correlation between the two measured time series is very good (R^2 = 0.994) and better than the correlation with HIRHAM5 ice runoff (R^2 = 0.96). The 1980-2014 yearly discharge time series is constructed with the measured data supplemented with yearly runoff values from catchment 06.e.II adjusted linearly by the regression formula.

The discharge time series for catchment 06.e.III has eight years overlapping the time series of catchment 06.e.II and the correlation between the two measured time series is very good (R^2 = 0.98) and better than the correlation with HIRHAM5 ice runoff (R^2 = 0.93). The 1980-2014 yearly discharge time series is constructed with the measured data supplemented with yearly runoff values from catchment 06.e.II adjusted linearly by the regression formula.

Water resource

Based on the 1980-2014 discharge time series, the mean yearly water resource at hydropower potential 06.e has been calculated. The main catchment 06.e.I has a mean yearly water resource of 2.0 km^3, see Table 15.

Notably, the nine highest yearly resource values occur within the period 2000-2014. The yearly water resource shows a statistically significant, positive trend (significance level $p<0.01$) in a Spearman Rho test. The trend for the discharge time series of catchment 06.e.I is estimated to be a 0.017 km^3/year increase in discharge (Theil & Sen slope estimator).

Catchment	Yearly water resource, km^3		
	Mean	Maximum	Minimum
06.e.I	**2.0**	**4.1**	**1.3**
06.e.II	1.6	3.8	0.97
06.e.III	0.14	0.25	0.11

Table 15. Water resource at hydro power potential 06.e. Note that catchment 06.e.II and 06.e.III are sub-catchments of catchment 06.e.I.

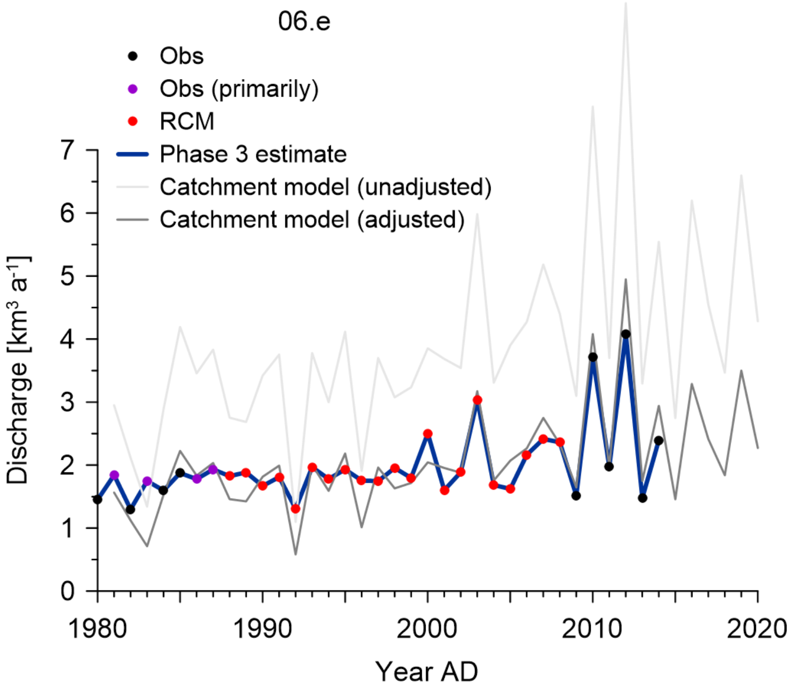

Figure 39. The annual discharge ("Phase 3 estimate") from the hydropower potential 06.e with the following labelling of data sources; "Obs": measured data, "Obs (primarily)": mainly based on measured data, "RCM": based on regression between results from climate models and measured data from other years. Catchment model results are shown in both the original unadjusted and bias-corrected adjusted versions.

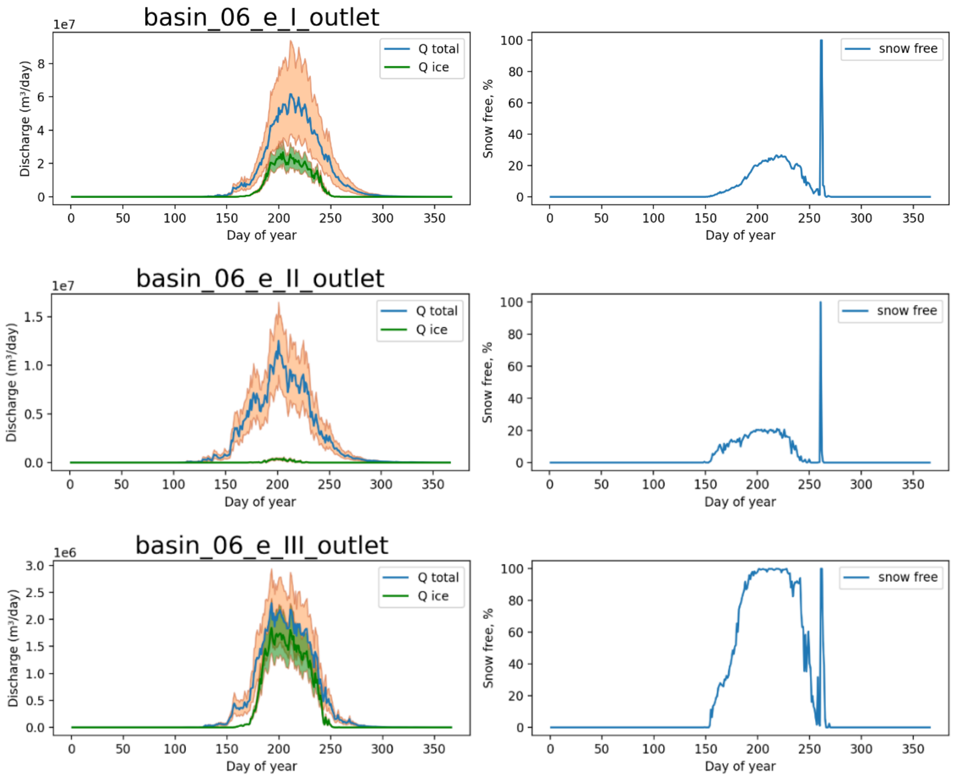

Figure 40. Left graphs: seasonal variation of the total daily discharge from the catchment, averaged over 1981-2020 (blue line "Q total"), including uncertainty interval (light brown) with the daily discharge from the glaciated part of the catchment (green curve "Q ice") specified, also including uncertainty interval (light green). Right graphs: daily percentage of the total catchment (ice-covered and ice-free) experiencing snow-free conditions.

Hydropower potential 06.g

The hydro power potential 06.g Imaarsuup Isua is based on four natural catchments marked as (I), (II), (III) and (IV) (see Figure 41).

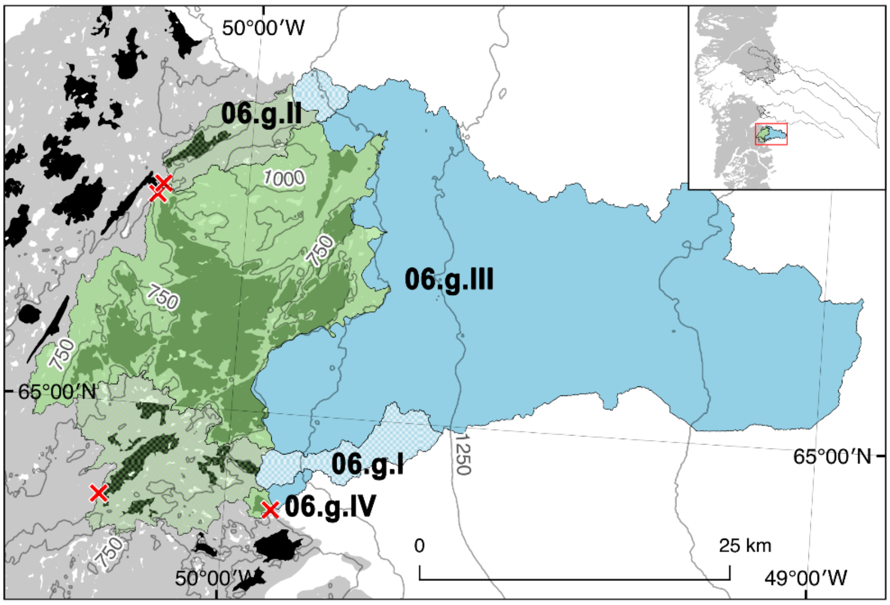

Figure 41. Map showing the four natural catchments marked with roman numerals I-IV, which combined represents the hydropower potential 06.g. All catchments are divided into a blue ice-covered area, a green area without ice and a red cross to mark the outlet.

Monitoring of the water resource

Investigations of hydropower potential 06.g were initiated in 1974 by Kryolitselskabet Øresund, as a possible power supply to a potential mine at the nearby iron ore at Isukasia (Kryolitselskabet Øresund 1984). Monitoring of the water resource was taken over by the Greenland Technical Organization (GTO) in 1985 and terminated in 1989. In 2008, monitoring of the water resource was started up again on initiative of the aluminium company Alcoa, due to a renewed interest in the hydropower potential as power supply for industry with high energy consumption. The monitoring was taken over by Asiaq – Greenland Survey in 2013 and is still ongoing as of 2018. The monitoring has focused on catchment (I) which contributes with around 82% of the total water resource for the hydropower potential (see Water resource section below).

Hydrometric stations have been established at each of the four catchments, but these have been operational for different periods of time. Stage-discharge relations have been established for each catchment based on manual discharge measurements (see Table 2). For catchments 06.g.I and 06.g.II, the stage-discharge relations are based on a reasonable number of discharge measurements that covers the range discharge reasonably (extrapolation of the stage-discharge relation amount to less than 15% of the total discharge volume). For catchments 06.g.III and 06.g.IV, the few discharge measurements form a weak basis for the stage-discharge relations and measurements at low discharge are specifically lacking for catchment 06.g.III. However, as catchments 06.g.III and 06.g.IV only contributes with around 10% of the water resource, the uncertainty of their stage-discharge relations does not influence the evaluation of the total water resource for the hydropower potential to any siginificant degree.

An overview of the data coverage of the discharge time series for each catchment is given in Figure 42.

Catchment ID	Manual discharge measurements	Part of total discharge volume found by extrapolation of stage- discharge relation or gap filling, %		
		Upward extrapolation	Downward Extrapolation	Gap filling
06.g.I	14	3%	10%	4%
06.g.II	13	9%	1%	1%
06.g.III	4	4%	31%	1%
06.g.IV	5	9%	2%	0%

Table 16. Basis for the stage-discharge relation for each catchment and part of total discharge volume found by extrapolation of the stage-discharge relation or gap filling.

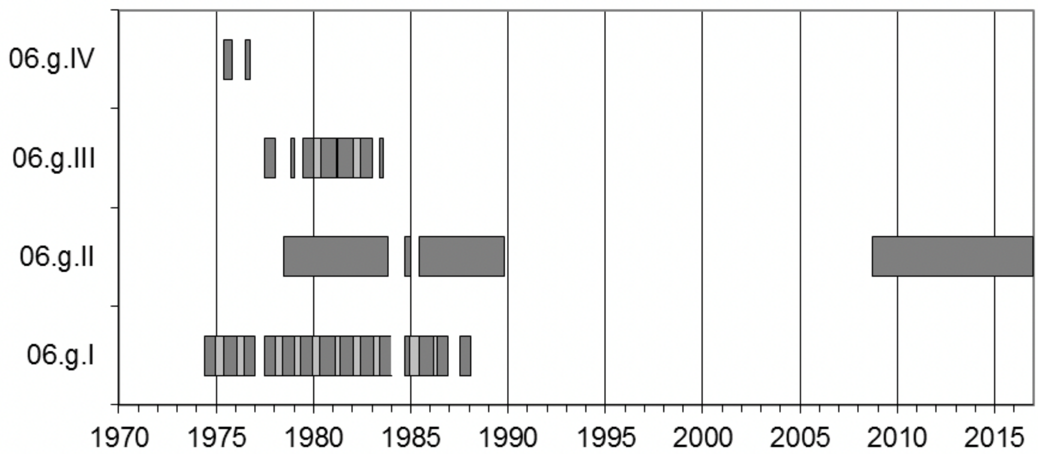

Figure 42. Data coverage of measured discharge time series for catchments in hydropower potential 06.g. Periods with measured data are shown as dark grey bars, periods with larger, filled data gaps are shown with light grey bars (for description of gap filling method, see method section).

Establishing the 1980-2014 time series

The measured discharge time series does not cover the entire period from 1980 to 2014 in any of the sub-catchments shown in Figure 41. Therefore, HIRHAM5 runoff data as well as discharge data from the nearby catchment 07.d.I is used to supplement the measured discharge time series.

For catchment 06.g.I, runoff from the ice-free parts of the catchment constitutes a significant part of the total runoff; 45% according to HIRHAM5. This is in contrast to the other catchments, where runoff from the ice-covered part is dominant. For this reason, annual discharge values from 06.g.I does not correlate well with data from the neighboring catchment 06.g.II. The measured time series has five years overlapping with the HIRHAM5 time series and the correlation is fair (R^2 = 0.40). The 1980-2014 annual discharge time series is constructed with measured data supplemented with HIRHAM5 annual runoff values adjusted linearly by the regression formula.

For catchment 06.g.II, meltwater from the Greenland ice sheet (GrIS) dominates the discharge. In order to base the correlation with HIRHAM5 data on as large a dataset as possible, only modelled runoff from the ice-covered part of the catchment is considered, since the model output from land areas only covers 1980-2014, whereas the model output from the glacier-covered areas covers 1980-2016. The measured time series has 17 years overlapping with the HIRHAM5 ice runoff time series and the correlation is very good (R^2 = 0.93). The measured discharge from the period 2008-2012 is a restricted dataset and not to be made public. The 1980-2014 annual discharge time series is constructed with the non-restricted measured data, supplemented with HIRHAM5 annual runoff values adjusted linearly by the regression formula.

The main part of the measured discharge time series for catchment 06.g.III is measured previous to the period covered by HIRHAM5 model output. Therefore, the overlap between measurements and HIRHAM5 output is limited to two years, which is not sufficient to establish a reliable regression. The discharge from catchment 06.g.III correlates very well (R^2 = 0.998) with discharge from the neighboring catchment 06.g.II (based on data from five years). The 1980-2014 annual discharge time series is constructed with measured data, supplemented with data from 06.g.II 1980-2014 discharge time series adjusted linearly by the regression formula.

The measured discharge time series for catchment 06.g.IV covers the summers of 1975 and 1976 (see Figure 42) and thus has no overlap with the HIRHAM5 output. The 06.g.IV data do overlap with measured discharge from catchment 06.g.I, but as the discharge from 06.g.IV is larger in 1975 than in 1976 (in contrast to the discharge from 06.g.I), it is unlikely that an adjusted 06.g.I time series will be a good estimator for the 06.g.IV discharge. This discrepancy is likely due to glacial meltwater being a much larger contribution to the discharge from 06.g.IV than from 06.g.I. We thus turn to catchment 07.d.I (see the section on Hydropower potential 07.d), which is situated around 40 km to the north of 06.g.IV. Here, the discharge in 1975 was larger than in 1976, as was the case at 06.g.IV. The mean ratio between annual discharge values has been used to adjust the 07.d.I annual time series to estimate the 1980-2014 annual discharge time series for catchment 06.g.IV.

The water resource

Based on the 1980-2014 discharge time series for the four catchments, the mean annual water resource at hydropower potential 06.g has been calculated to 1.08 km3 (see Table 17). Notably, the eight highest annual resource values occur within the period 2003-2014. The annual water resource shows a statistically significant, positive trend (significance level p=0.01) in a Spearman's Rho test. The trend for the discharge time series is estimated to be a 0.008 km^3/year increase in discharge (Theil & Sen slope estimator).

Catchments	**Annual water resource, km^3**			**Contribution to the water re-source, %**
	Average	**Maximum**	**Minimum**	
06.g.I	0.10	0.12	0.08	9
06.g.II	0.88	1.57	0.58	82
06.g.III	0.06	0.08	0.04	5
06.g.IV	0.04	0.08	0.03	4
06.g total	**1.08**	**1.85**	**0.75**	

Table 17. The water resource at hydropower potential 06.g.

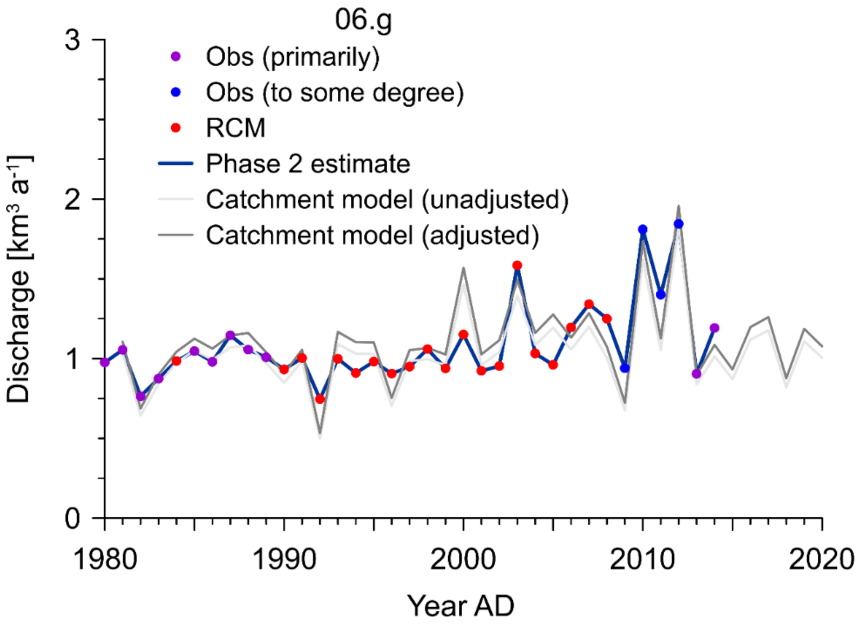

Figure 43. The annual discharge ("Phase 2 estimate") from the hydropower potentials 06.g with the following labelling of data sources; "Obs (primarily)": mainly based on measured data, "Obs (to some degree)": partially based on measured data, "RCM": based on regression between results from climate models and measured data from other years. Catchment model results are shown in both the original unadjusted and bias-corrected adjusted versions.

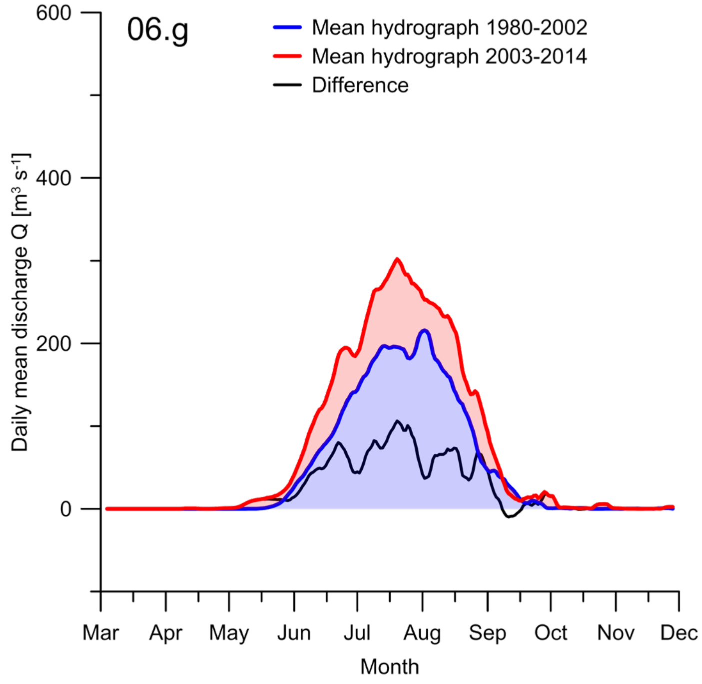

Figure 44. Mean hydrograph of the discharge from the hydropower potential 06.g during the periods 1980-2002 (blue) and 2003-2014 (red), respectively. The black curve illustrates the difference between the two periods.

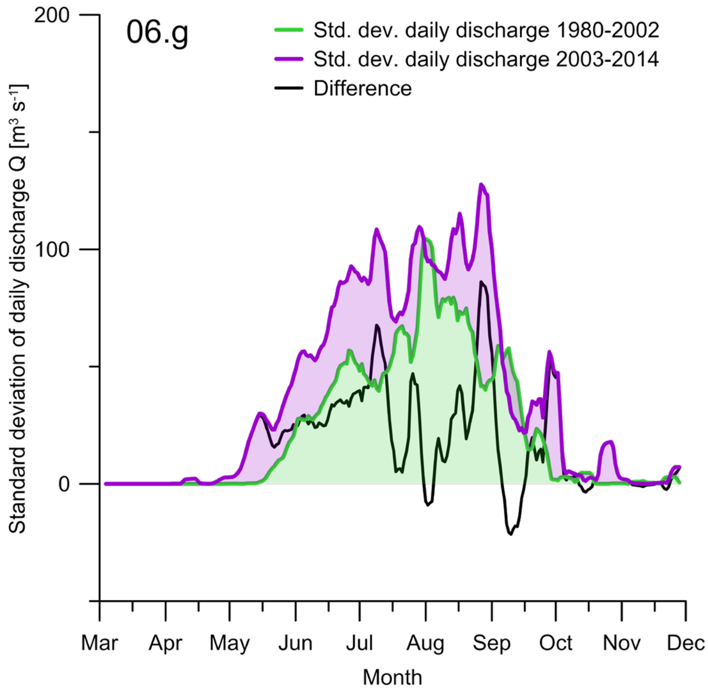

Figure 45. The standard deviation of the daily discharge (see Figure 44) on any given day during the periods 1980-2002 (green) and 2003-2014 (purple). The difference between the periods is marked by the black curve.

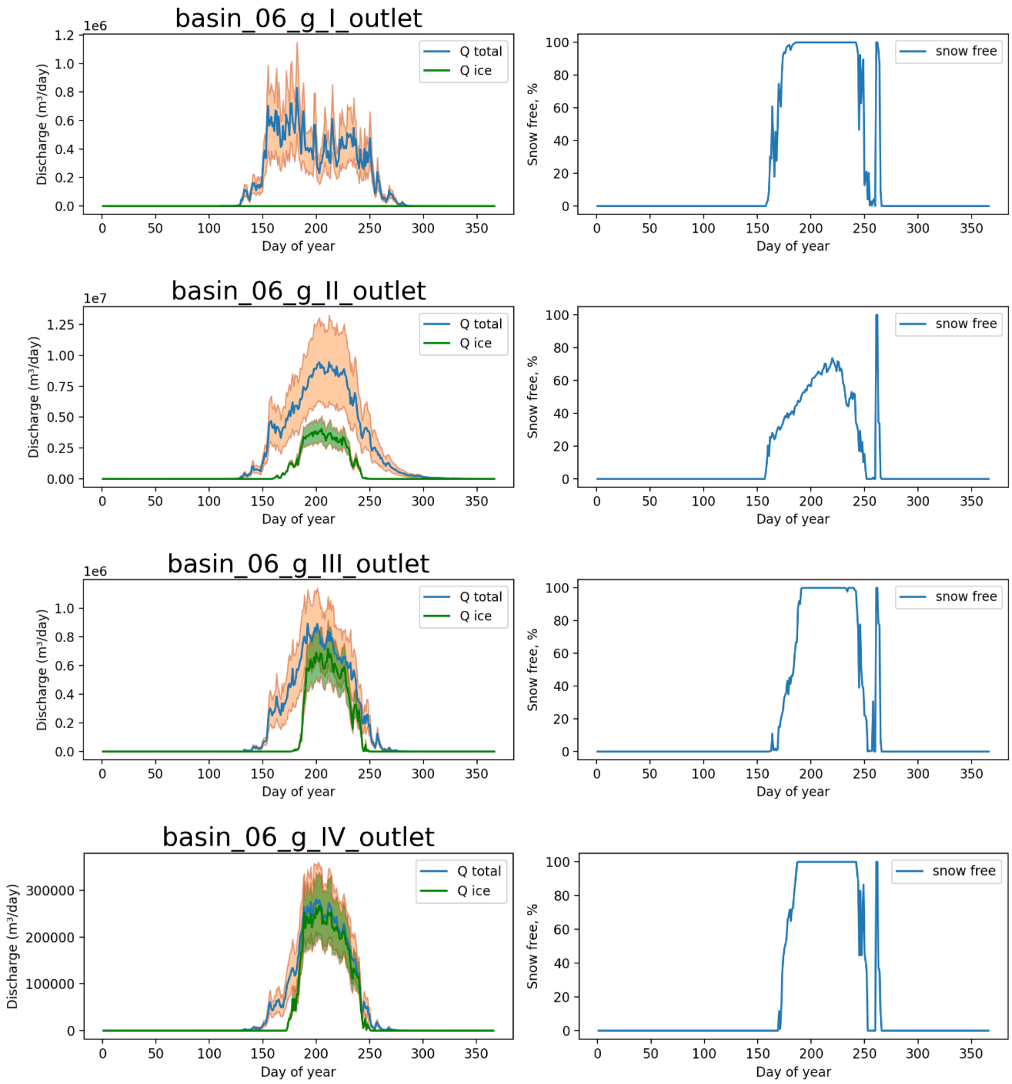

Figure 46. Left graphs: seasonal variation of the total daily discharge from the catchment, averaged over 1981-2020 (blue line “Q total”), including uncertainty interval (light brown) with the daily discharge from the glaciated part of the catchment (green curve “Q ice”) specified, also including uncertainty interval (light green). Right graphs: daily percentage of the total catchment (ice-covered and ice-free) experiencing snow-free conditions.

Hydro Power Potential 06.h

The hydro power potential 06.h is based on the natural catchment of the lake Tasersuaq,(see Figure 47).

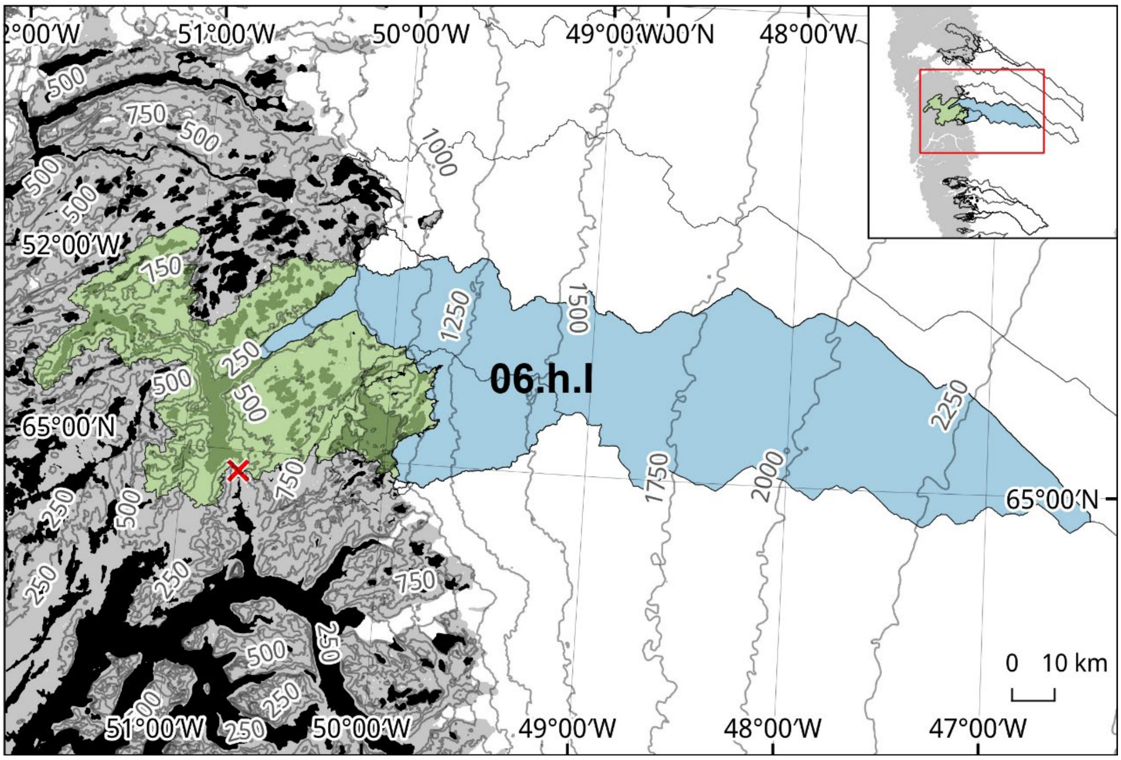

Figure 47. Map showing the catchment. Blue signifies ice cover and green is ice-free land. The red cross marks the outlet, listed in Table 1.

Monitoring of the water resource

Investigations of hydro power potential 6.h were initiated in 1974 by Kryolitselskabet Øresund as a possible power supply to a potential mine at the Iron ore at Isukasia (Kryolitselskabet Øresund 1984). These investigations were terminated in 1983. In 2008 monitoring of the water resource was started up again on initiative of Asiaq – Greenland Survey as part of a research project. The monitoring is still ongoing as of 2018.

The stage-discharge relation for catchment 06.h is based on a reasonable number of manual discharge measurements that to a high degree covers the range of discharge; extrapolation of the stage-discharge relation amount to less than 5% of the total discharge volume (Table 18).

An overview of the data coverage of the discharge time series for the catchment is given in Figure 48.

Catchment	Manual discharge measurements	Part of total discharge volume found by extrapolation of stage-discharge relation or gap filling, %		
		Upward extrapolation	Downward extrapolation	Gap filling
06.h	15	0.6 %	3 %	0 %

Table 18. Basis for the stage-discharge relation for the catchment and part of total discharge volume found by extrapolation of the stage-discharge relation or gap filling.

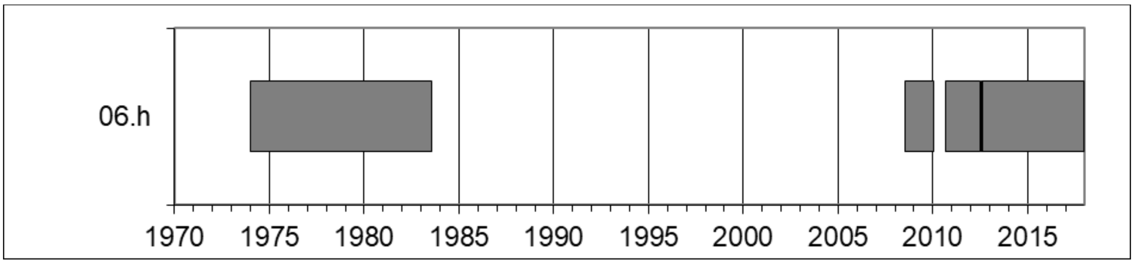

Figure 48. Data coverage of measured discharge time series for the catchment of hydro power potential 06.h. Periods with measured data are shown as dark grey bars.

Establishing the 1980-2014 time series

The measured discharge time series for the catchment does not cover the entire period from 1980 to 2014, Figure 48. Therefore, discharge data from the nearby catchment 07.e is used to supplement the measured discharge time series. The measured time series for catchment 06.h has 11 years overlapping with the measured time series from catchment 07.e and the correlation is good (R^2 = 0.94). The 1980-2014 yearly discharge time series is constructed with the measured data supplemented with yearly runoff values from catchment 07.e adjusted linearly by the regression formula.

Water resource

Based on the 1980-2014 discharge time series for the mean yearly water resource at hydro power potential 06.h has been calculated to 6.9 km^3, see Table 19. Notable the eight highest yearly resource values occur within the period 2003-2014. The yearly water resource shows a statistically significant, positive trend (significance level $p<0.001$) in a Spearman Rho test. The trend for the discharge time series is estimated to be a 0.10 km^3/year increase in discharge (Theil & Sen slope estimator).

Catchment	**Yearly water resource, km^3**		
	Mean	**Maximum**	**Minimum**
06.h	6.92	13.6	3.29

Table 19. Water resource at hydro power potential 06.h.

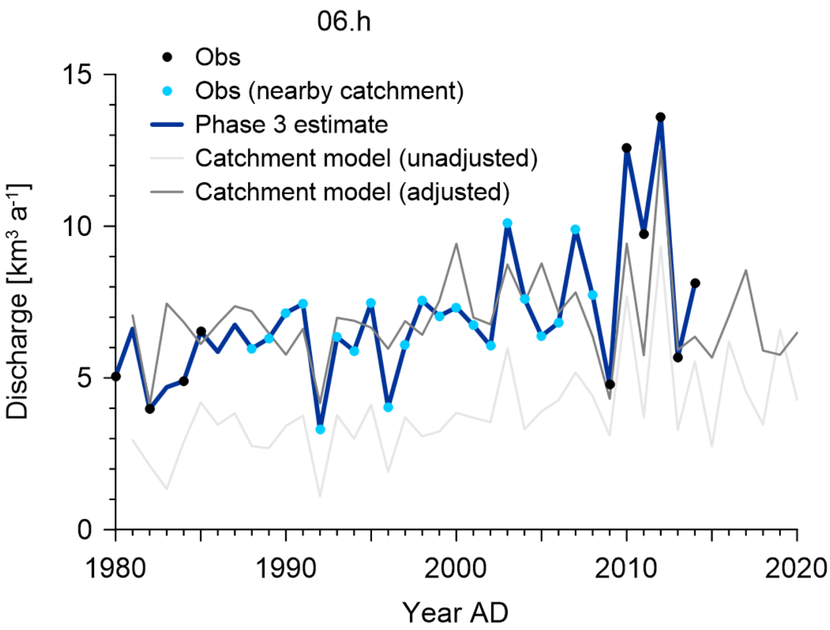

Figure 49. The annual discharge ("Phase 3 estimate") from the hydropower potentials 06.h with the following labelling of data sources; "Obs": measured data, "Obs (nearby catchment)": based on regression between measured data from catchments nearby and measured data from other years, "RCM": based on regression between results from climate models and measured data from other years. Catchment model results are shown in both the original unadjusted and bias-corrected adjusted versions.

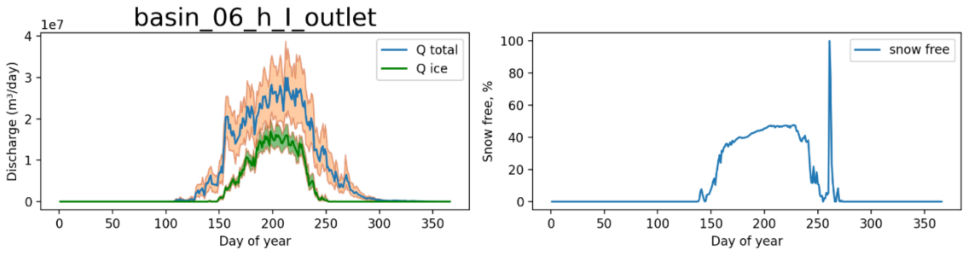

Figure 50. Left graph: seasonal variation of the total daily discharge from the catchment, averaged over 1981-2020 (blue line "Q total"), including uncertainty interval (light brown) with the daily discharge from the glaciated part of the catchment (green curve "Q ice") specified, also including uncertainty interval (light green). Right graph: daily percentage of the total catchment (ice-covered and ice-free) experiencing snow-free conditions.

Hydropower potential 07.d

The hydropower potential 07.d Søndre Isortup Isua is based on two natural catchments (I) and (II) (see Figure 51).

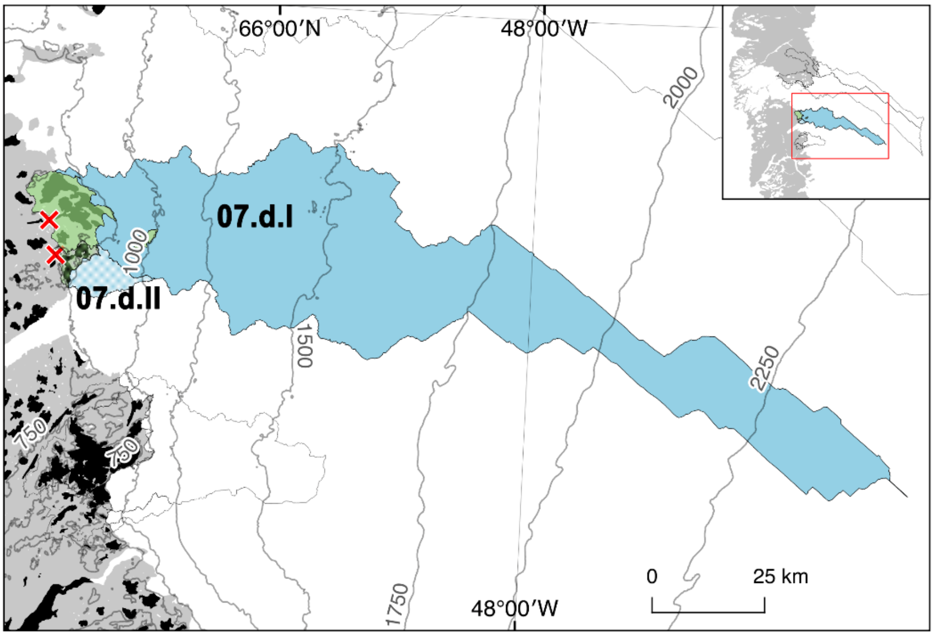

Figure 51. Map showing the two natural catchments marked with roman numerals I-II, which combined represents the hydropower potential 07.d. Both catchments are divided into a blue ice-covered area, a green area without ice and a red cross to mark the outlet.

Monitoring of the water resource

Investigations of hydropower potential 07.d were initiated in 1974 by Kryolitselskabet Øresund (Kryolitselskabet Øresund 1984) and terminated in 1983. In 2007, monitoring of the water resource was started up again on initiative of the aluminium company Alcoa, due to a renewed interest in the hydropower potential as power supply for industry with high energy consumption. The monitoring was taken over by Asiaq – Greenland Survey in 2009 and is still ongoing as of 2017.

In the early monitoring period from 1974-1983, only catchment 07.d.I. was included in the measuring program, whereas monitoring of both catchments, 07.d.I and 07.d.II, have been carried out since 2007. Stage-discharge relations have been established for each catchment based on manual discharge measurements (see Table 20). For catchment 07.d.I, the stage-discharge relation is based on a reasonable number of discharge measurements, although it would improve the accuracy of the resulting discharge time series if further manual discharge measurements at high discharge were carried out. This would reduce the derived amount of discharged water found by extrapolation of the stage-discharge relation to high values. For catchment 07.d.II, the number of discharge measurement forming the base for the stage-discharge relation is in the lower end, but the coverage of the normally occurring discharges is sufficiently extensive (less than 3% of the total volume found by extrapolation).

An overview of the data coverage of the discharge time series for each catchment is given in Figure 52.

Catchment ID	Manual discharge measurements	Part of total discharge volume found by extrapolation of stage discharge relation or gap filling, %		
		Upward extrapolation	Downward extrapolation	Gap filling
07.d.I	17	14%	2%	1%
07.d.II	9	0.3%	2%	0.3%

Table 20. Basis for the stage-discharge relation for each catchment and part of total discharge volume found by extrapolation of the stage-discharge relation or gap filling.

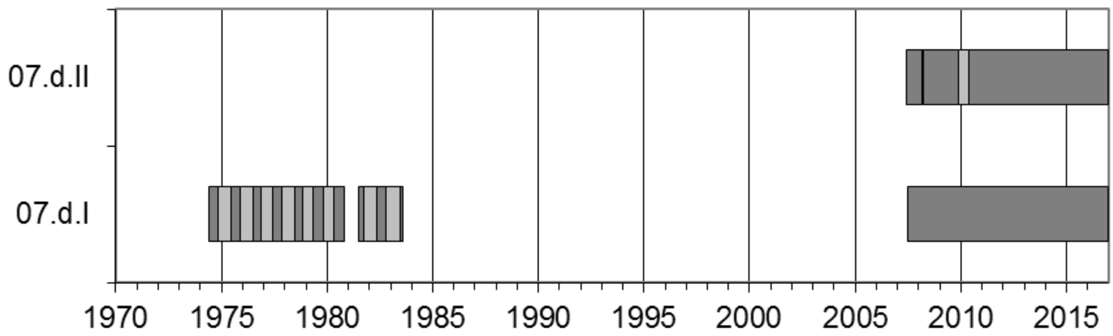

Figure 52. Data coverage of measured discharge time series for catchments in hydropower potential 06.g. Periods with measured data are shown as dark grey bars, periods with larger, filled data gaps are shown with light grey bars (for description of gap filling method, see method section).

Establishing the 1980-2014 time series

The measured discharge time series does not cover the entire period from 1980 to 2014 in any of the sub-catchments shown in Figure 51. Therefore, HIRHAM5 runoff data is used to supplement the measured discharge time series.

For catchment 07.d.I, meltwater from the Greenland ice sheet (GrIS) dominates the discharge. In order to base the correlation with HIRHAM5 data on as large a dataset as possible only modelled runoff from the ice-covered part of the catchment is considered since the model output from land areas only covers 1980-2014, whereas the model output from the glacier covered areas covers 1980-2016. The measured time series has 11 years overlapping with the HIRHAM5 ice runoff time series and the correlation is very good (R^2 = 0.95). The measured discharge in the period 2007-2008 2012 is a restricted dataset and not to be made public. The 1980-2014 annual discharge time series is constructed with the non-restricted measured data, supplemented with HIRHAM5 annual runoff values adjusted linearly by the regression formula.

For catchment 07.d.II, the measured data series covers 10 years. The correlation between 07.d.II and 07.d.I is slightly better (R^2 = 0.88) than the correlation between 07.d.II and HIRHAM5 (R^2 = 0.84) and thus data from 07.d.I is used to fill data gaps. The measured discharge in the period 2007-2008 is a restricted dataset. The 1980-2014 annual discharge time series is constructed with the non-restricted measured data, supplemented with 07.d.I annual runoff values adjusted linearly by the regression formula.

The water resource

Based on the 1980-2014 discharge time series for the two catchments the mean annual water resource at hydropower potential 07.d has been calculated to 1.17 km^3 (see Table 21). Notably, the eight highest annual resource values occur within the period 2003-2014. The annual water resource shows a statistically significant, positive trend (significance level p=0.001) in a Spearman's Rho test. The trend for the discharge time series is estimated to be a 0.009 km^3/year increase in discharge (Theil & Sen slope estimator).

Catchments	**Annual water resource, km^3**			**Contribution to the water resource, %**
	Mean	**Maximum**	**Minimum**	
07.d.I	1.00	1.94	0.71	86
07.d.II	0.17	0.28	0.13	14
07.d total	**1.17**	**2.22**	**0.84**	

Table 21. The water resource at hydropower potential 07.d.

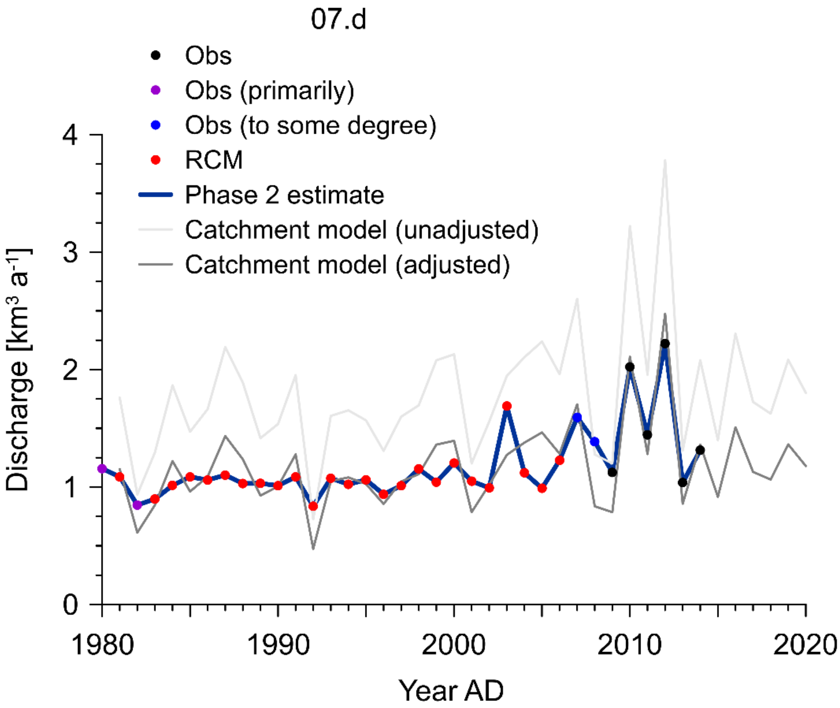

Figure 53. The annual discharge ("Phase 2 estimate") from the hydropower potential 07.d with the following labelling of data sources; "Obs": measured data, "Obs (primarily)": mainly based on measured data, "Obs (to some degree)": partially based on measured data, "RCM": based on regression between results from climate models and measured data from other years. Catchment model results are shown in both the original unadjusted and bias-corrected adjusted versions.

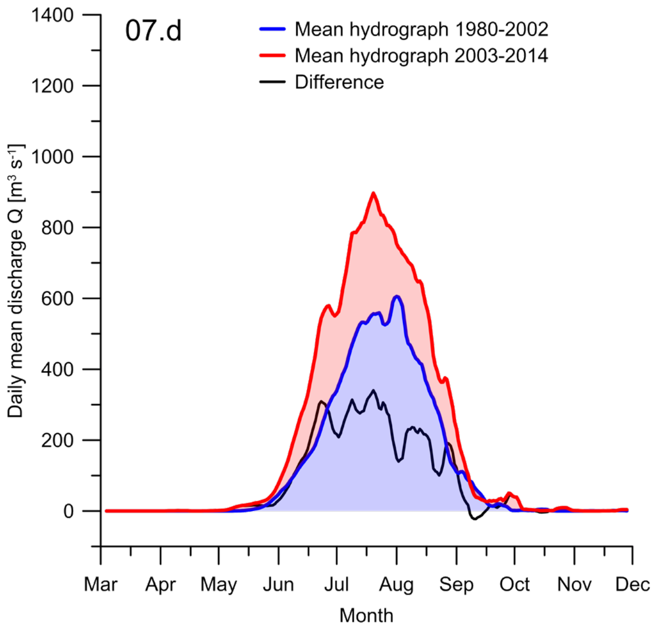

Figure 54. Mean hydrograph of the discharge from the hydropower potential 07.d during the periods 1980-2002 (blue) and 2003-2014 (red), respectively. The black curve illustrates the difference between the two periods.

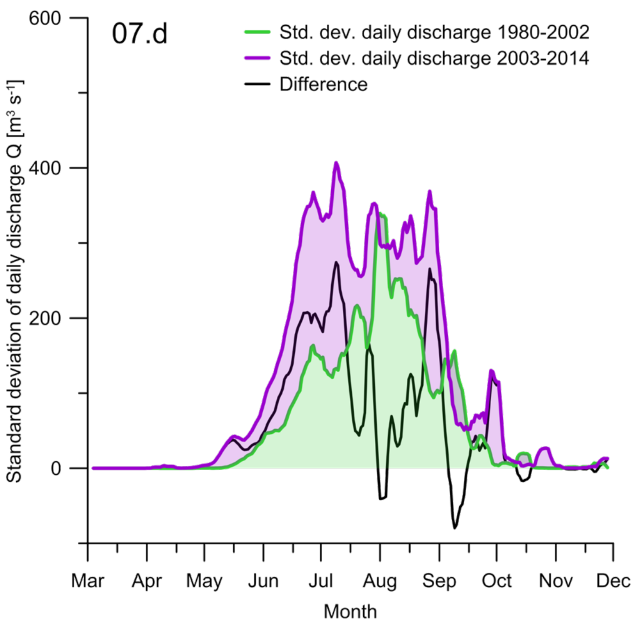

Figure 55. The standard deviation of the daily discharge (see Figure 54) on any given day during the periods 1980-2002 (green) and 2003-2014 (purple). The difference between the periods is marked by the black curve.

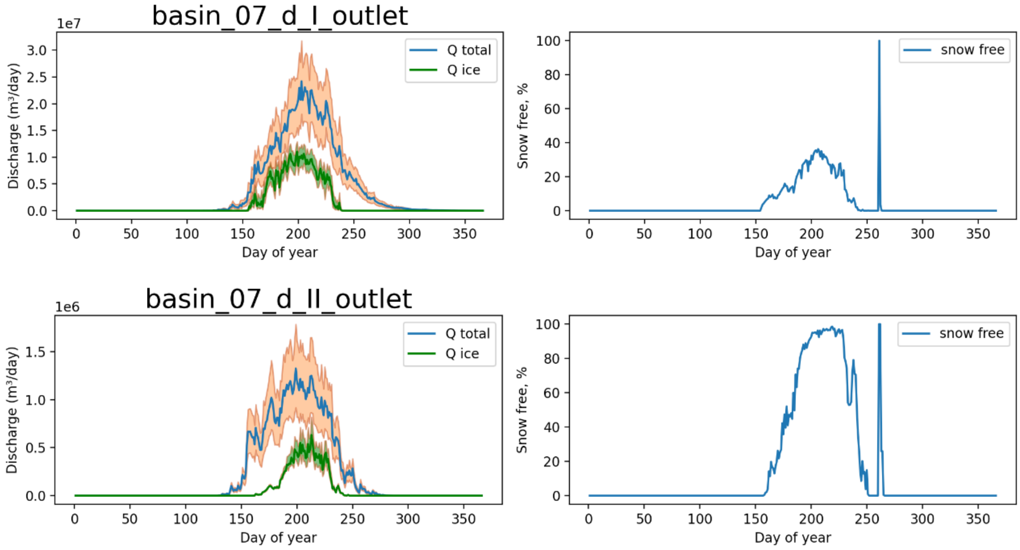

Figure 56. Left graphs: seasonal variation of the total daily discharge from the catchment, averaged over 1981-2020 (blue line “Q total”), including uncertainty interval (light brown) with the daily discharge from the glaciated part of the catchment (green curve “Q ice”) specified, also including uncertainty interval (light green). Right graphs: daily percentage of the total catchment (ice-covered and ice-free) experiencing snow-free conditions.

Hydropower potential 07.e

The hydropower potential 07.e is based on exploitation of the catchment of lake Tasersiaq (see Figure 57).

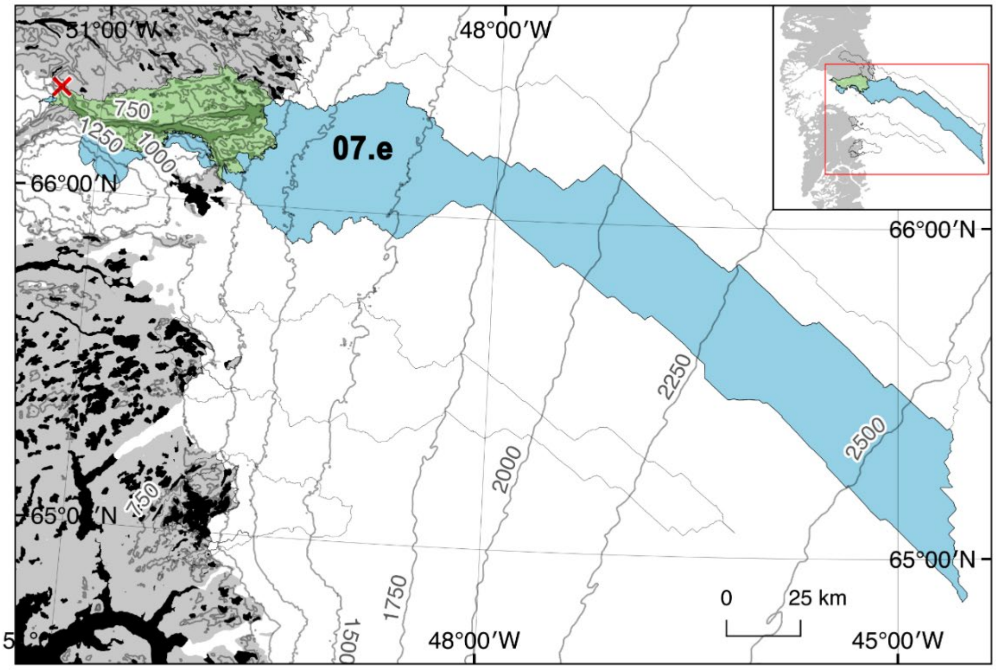

Figure 57. Map showing the hydropower potential 07.e. The catchment is divided into a blue ice-covered area, a green area without ice and a red cross to mark the outlet.

Monitoring of the water resource

Investigations of hydropower potential 07.e were initiated in 1975 by the Greenland Technical Organization (GTO) and is still ongoing as of 2018. Today the monitoring is run by Asiaq – Greenland Survey.

The stage-discharge relation for catchment 07.e is well-defined, as it is based on 37 manual discharge measurements, which covers the range of discharge from the catchment well (see Table 22). An overview of the data coverage of the discharge time series for each catchment is given in Figure 58.

Catchment ID	Manual discharge measurements	Part of total discharge volume found by extrapolation of stage-discharge relation or gap filling, %		
		Upward extrapolation	Downward extrapolation	Gap filling
07.e	37	6%	1%	1%

Table 22. Basis for the stage-discharge relation for the catchment and part of total discharge volume found by extrapolation of the stage-discharge relation or gap filling.

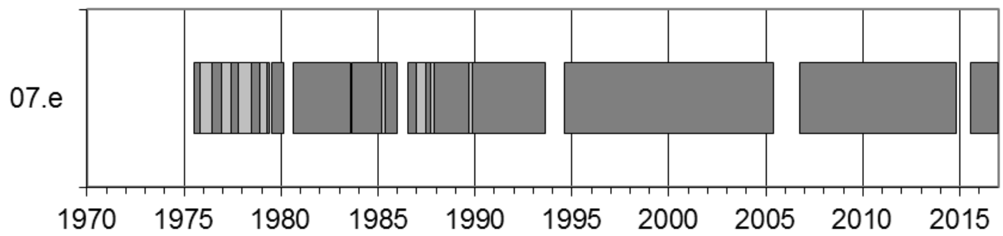

Figure 58. Data coverage of measured discharge time series for hydropower potential 07.e. Periods with measured data are shown as dark grey bars, periods with larger, filled data gaps are shown with light grey bars (for description of gap filling method, see method section).

Establishing the 1980-2014 time series

Although catchment 07.e has been monitored since 1975, some data gaps occur in the discharge time series, and these has to be filled in order to generate the 1980-2014 time series. Therefore, HIRHAM5 runoff data is used to supplement the measured discharge time series.

The discharge time series from catchment 07.e is dominated by the annual melt peak, but besides from this, the discharge time series exhibit occasional short-term peaks that occurs at all times of the year, but are most common in the autumn. The source is glacial lake outburst floods (GLOFs) from an upstream ice-dammed lake found at position N66°09', W050°54'. The time between GLOFs is normally a few years. This storage of meltwater from one year to another is not included in the HIRHAM5 model. Thus, the volume of water released at the GLOF events were removed from the measured discharge time series prior to the regression of measured and model annual values. The measured time series has 29 years overlapping with the HIRHAM5 ice runoff time series with a strong correlation (R^2 = 0.90).

Missing annual values were estimated from HIRHAM5 annual runoff values adjusted linearly by the regression formula, with subsequent addition of the volume of water released during a given GLOF occurring in that year. By utilizing the relation between GLOF volume and the sum of positive degree days between events together with Landsat images, it has been possible to clarify that two GLOF events have taken place, which are not documented in the Tasersiaq discharge time series due to data gaps. The volume of water released during GLOF events decreases over time (R^2 = 0.75) due to thinning of the glacier damming the source lake of the GLOFs. The volume of water released during the two GLOF events that were not captured in the measured discharge time series, were estimated based on this relation.

The water resource

Based on the 1980-2014 discharge time series, the mean annual water resource at hydropower potential 07.e has been calculated to 2.78 km^3 (see Table 23). Notably, the eight highest annual resource values occur within the period 2003-2014. The annual water resource shows a statistically significant, positive trend (significance level p<0.0005) in a Spearman's Rho test. The trend for the discharge time series is estimated to be a 0.056 km^3/year increase in discharge (Theil & Sen slope estimator).

Catchment	Annual water resource, km^3		
	Average	Maximum	Minimum
07.e	2.78	6.81	0.61

Table 23. The water resource at hydropower potential 7.e.

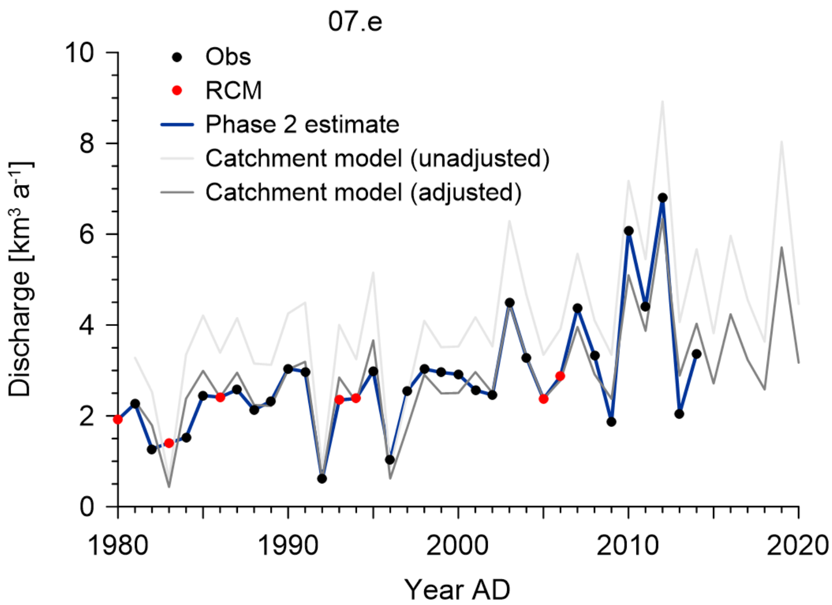

Figure 59. The annual discharge ("Phase 2 estimate") from the hydropower potential 07.d with the following labelling of data sources; "Obs": measured data, "RCM": based on regression between results from climate models and measured data from other years. Catchment model results are shown in both the original unadjusted and bias-corrected adjusted versions.

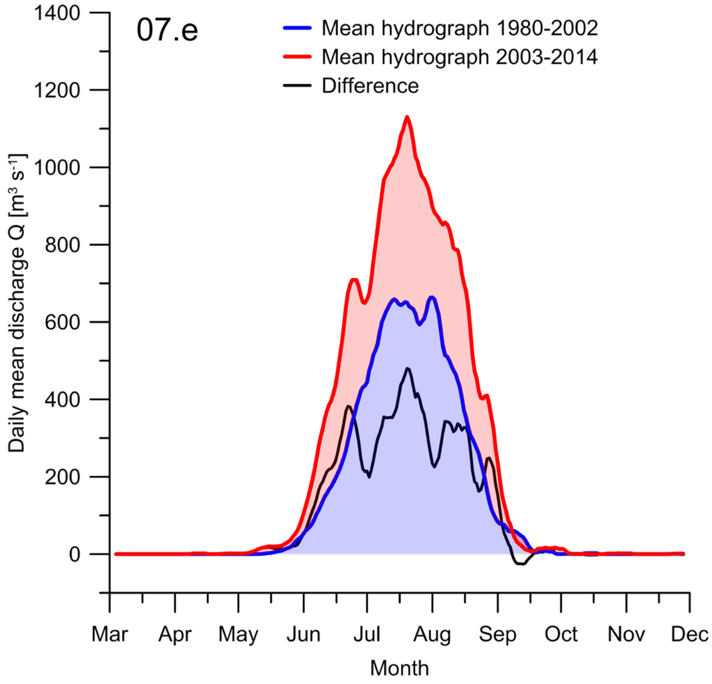

Figure 60. Mean hydrograph of the discharge from the hydropower potential 07.e during the periods 1980-2002 (blue) and 2003-2014 (red), respectively. The black curve illustrates the difference between the two periods.

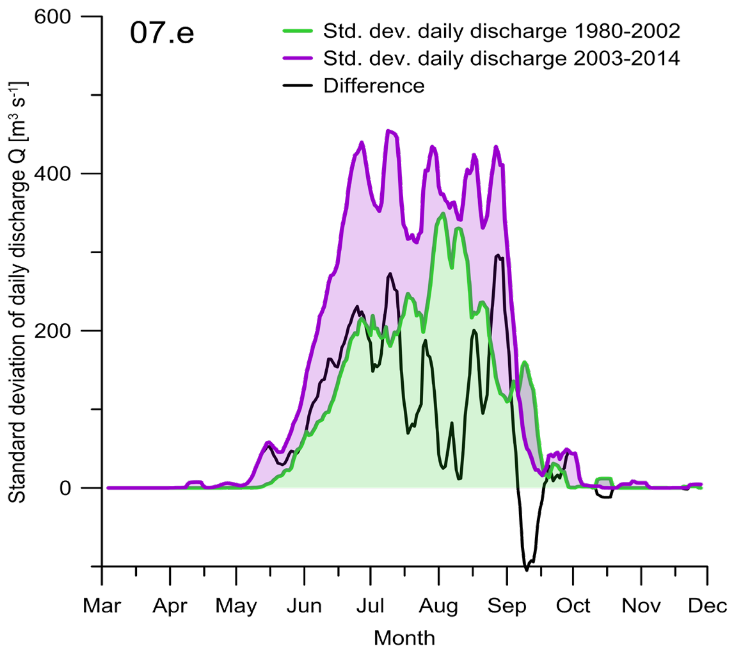

Figure 61. The standard deviation of the daily discharge (see Figure 60) on any given day during the periods 1980-2002 (green) and 2003-2014 (purple). The difference between the periods is marked by the black curve.

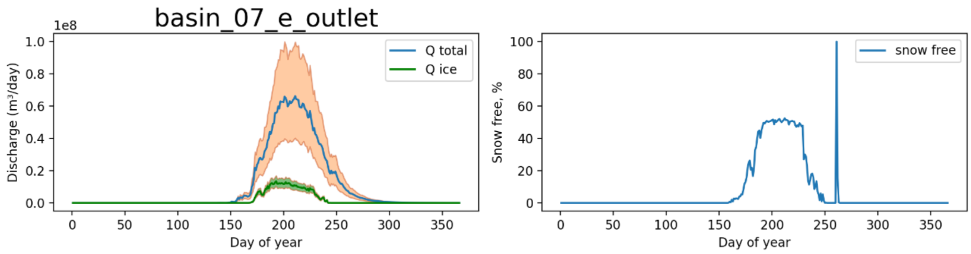

Figure 62. Left graph: seasonal variation of the total daily discharge from the catchment, averaged over 1981-2020 (blue line “Q total”), including uncertainty interval (light brown) with the daily discharge from the glaciated part of the catchment (green curve “Q ice”) specified, also including uncertainty interval (light green). Right graph: daily percentage of the total catchment (ice-covered and ice-free) experiencing snow-free conditions.

Hydropower potential 07.f

The hydro power potential 07.f Umiiviit Isua is based on two natural catchments marked as (I) and (II) (see).

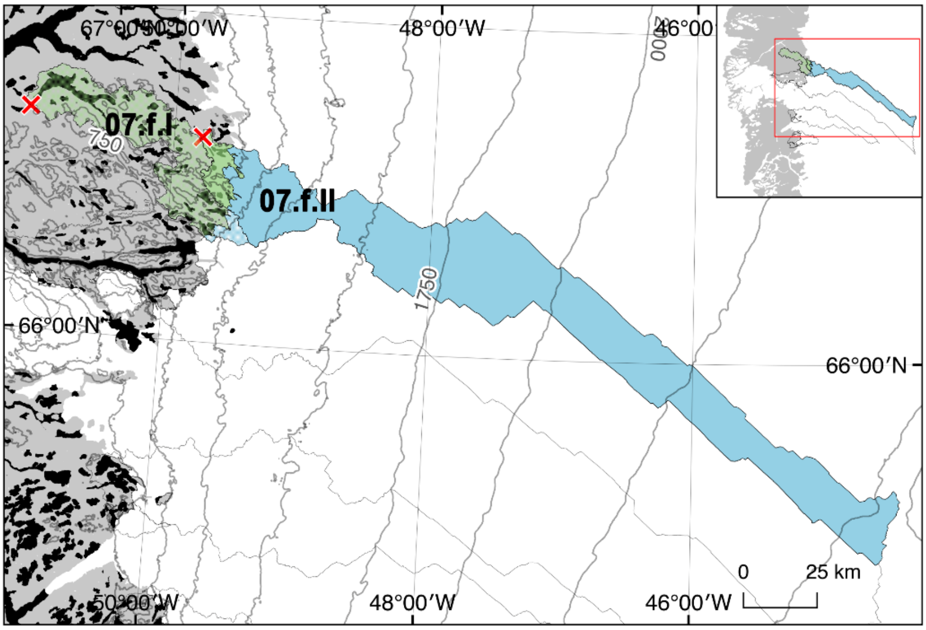

Figure 63. Map showing the two natural catchments marked with roman numerals I-II, which combined represents the hydropower potential 07.f. Both catchments are divided into a blue ice-covered area, a green area without ice and a red cross to mark the outlet.

Monitoring of the water resource

Investigations of hydropower potential 07.f were initiated in 1975 by the Greenland Technical Organization (GTO), when a hydrometric station was established at the river of catchment 07.f.II. The monitoring was closed down again in the autumn of 1976. Another hydrometric station was established at catchment 07.f.II in 1994 and kept in operation until 2002.

Stage-discharge relationships have been established for each catchment, based on manual discharge measurements (see Table 24). For both catchments, the stage-discharge relations are based on a very limited number of discharge measurements. Furthermore, catchment 06.f.I especially misses manual discharge measurements at low flow.

An overview of the data coverage of the discharge time series for each catchment is given in Figure 64.

Catchment ID	Manual discharge measurements	Part of total discharge volume found by extrapolation of stage- discharge relation or gap filling, %		
		Upward extrapolation	Downward extrapolation	Gap filling
07.f.I	6	6%	32%	3%
07.f.II	3	6%	2%	

Table 24. Basis for the stage-discharge relation for each catchment and part of total discharge volume found by extrapolation of the stage-discharge relation or gap filling.

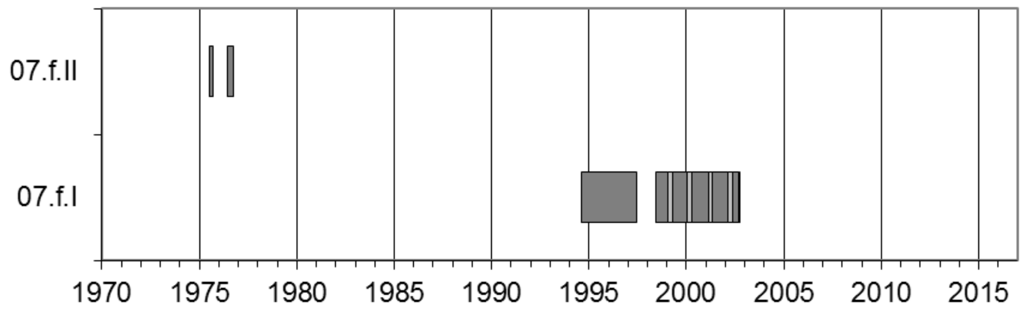

Figure 64. Data coverage of measured discharge time series for catchments in hydropower potential 06.g. Periods with measured data are shown as dark grey bars, periods with larger, filled data gaps are shown with light grey bars (for description of gap filling method, see method section).

Establishing the 1980-2014 time series

The measured discharge time series does not cover the entire period from 1980 to 2014 in any of the sub-catchments shown in Figure 63.

For catchment 07.f.I, runoff from the ice-free parts of the catchment constitutes a significant part of the total runoff; 52% according to HIRHAM5. This is in contrast to the neighboring catchment 07.e, where runoff from the ice-covered part is dominant. Consequently, annual discharge values from 07.f.I does not correlate at all with data from 07.e. The measured time series has six years overlapping with the HIRHAM5 time series, but the correlation is poor (R^2 = 0.04). A somewhat better correlation (R^2 = 0.42) can be obtained by combining HIRHAM5 runoff for the ice-covered part of the catchment, with an estimate of the land runoff (based on precipitation data from Kangerlussuaq) multiplied by the ice-free catchment area. While this indicates that the HIRHAM5 land runoff may be quite uncertain, the measured discharge time series for catchment 07.f.I is not ideal either, as it is based on a weak stage-discharge relation (see the previous chapter). We therefore chose to base the 1980-2014 annual discharge time series on measured data, supplemented with HIRHAM5 annual runoff values adjusted by the mean ratio of measured to model annual discharge values.

The measured discharge time series for catchment 07.f.II covers the summers of 1975 and 1976 (Figure 64) and thus has no overlap with the HIRHAM5 data. Fortunately, catchment 07.e (see the section on Hydropower Potential 07.e), which is situated around 40 km south of 07.f.II, has an overlapping time series. Furthermore, meltwater from the GrIS dominates the water resource for both catchments. The mean ratio between annual discharge values has been used to adjust the 07.e annual time series to estimate the 1980-2014 annual discharge time series for catchment 07.f.II.

The water resource

Based on the 1980-2014 discharge time series for the two catchments, the mean annual water resource at hydropower potential 07.f has been calculated to 1.35 km^3 (see Table 25). Note that the water resource for 07.f is based on a very short measured time series and that the stage-discharge relations used to calculate the discharge time series are not well documented.

Notably, the eight highest annual resource values occur within the period 2003-2014. The annual water resource shows a statistically significant, positive trend (significance level $p<0.0005$) in a Spearman's Rho test. The trend for the discharge time series is estimated to be a 0.025 km^3/year increase in discharge (Theil & Sen slope estimator).

Catchments	Annual water resource, km^3			Contribution to the water resource, %
	Average	Maximum	Minimum	
07.f.I	0.26	0.35	0.20	19
07.f.II	1.09	2.64	0.25	81
07.f total	1.35	2.99	0.49	

Table 25. The water resource at hydropower potential 07.f.

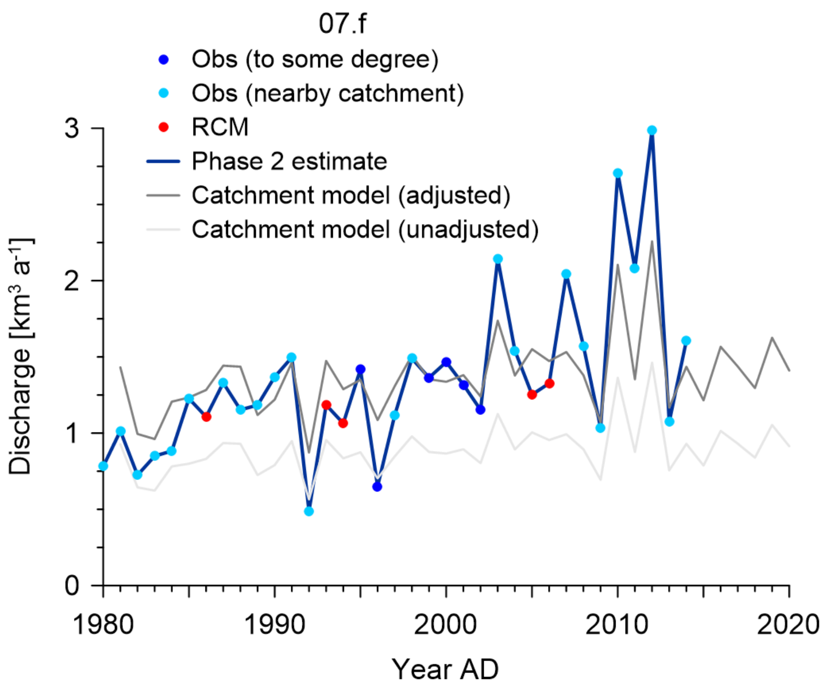

Figure 65. The annual discharge ("Phase 2 estimate") from the hydropower potential 07.d with the following labelling of data sources; "Obs (to some degree)": partially based on measured data, "Obs (nearby catchment)": based on regression between measured data from catchments nearby and measured data from other years, "RCM": based on regression between results from climate models and measured data from other years. Catchment model results are shown in both the original unadjusted and bias-corrected adjusted versions.

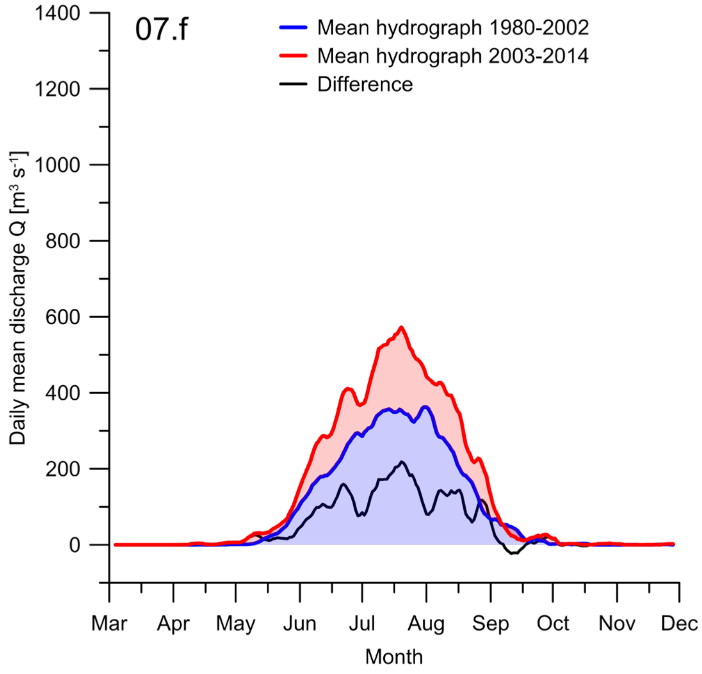

Figure 66. Mean hydrograph of the discharge from the hydropower potential 07.f during the periods 1980-2002 (blue) and 2003-2014 (red), respectively. The black curve illustrates the difference between the two periods.

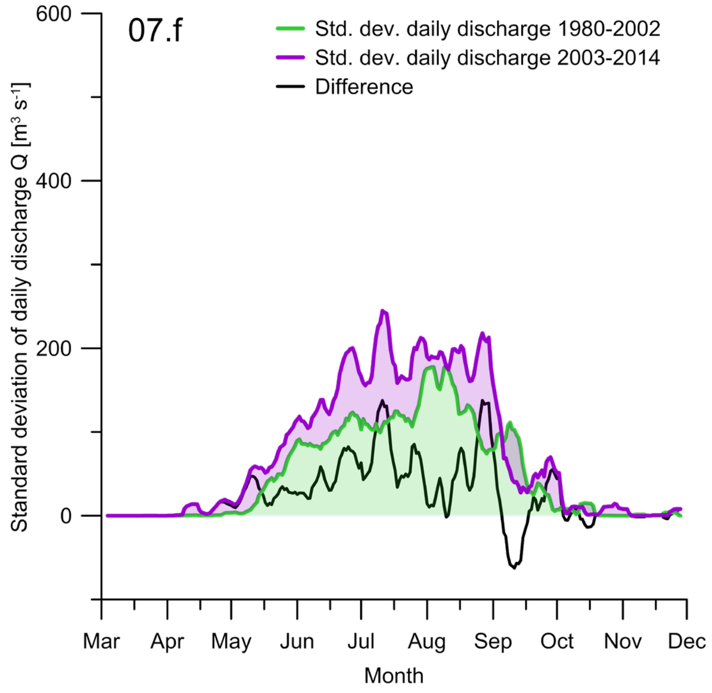

Figure 67. The standard deviation of the daily discharge (see Figure 66) on any given day during the periods 1980-2002 (green) and 2003-2014 (purple). The difference between the periods is marked by the black curve.

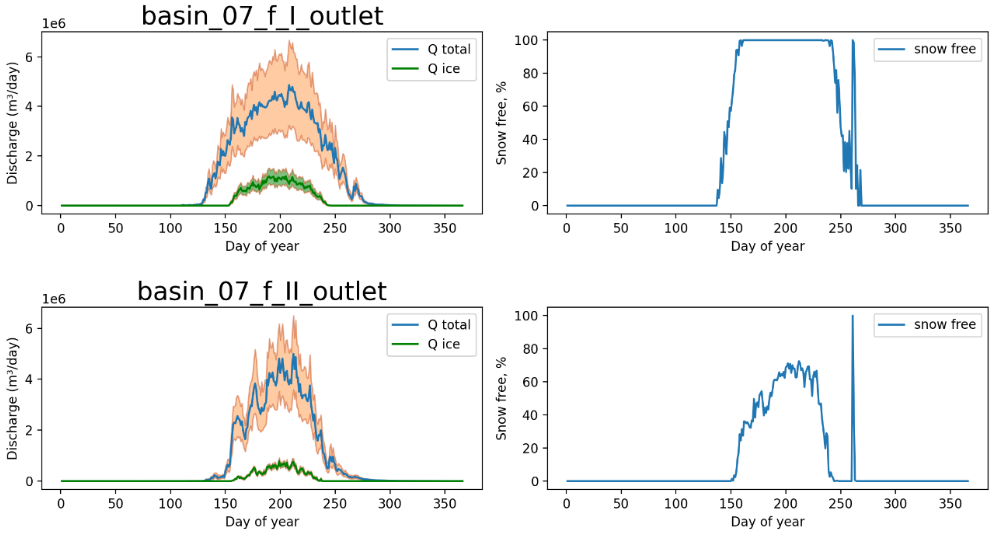

Figure 68. Left graphs: seasonal variation of the total daily discharge from the catchment, averaged over 1981-2020 (blue line “Q total”), including uncertainty interval (light brown) with the daily discharge from the glaciated part of the catchment (green curve “Q ice”) specified, also including uncertainty interval (light green). Right graphs: daily percentage of the total catchment (ice-covered and ice-free) experiencing snow-free conditions.

Hydro Power Potential 12.j

The hydro power potential 12.j Nuussuaq is based on the natural catchment of the lake centrally positioned on the Nuussuaq peninsula (see Figure 69).

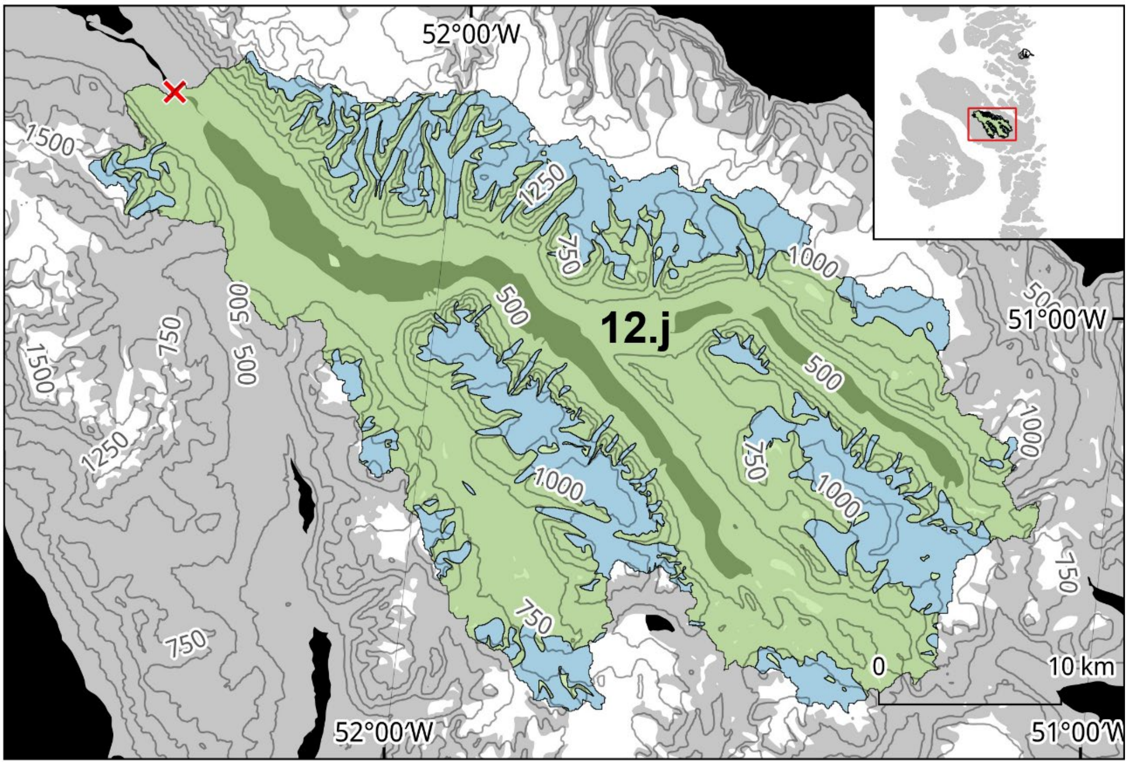

Figure 69. Map showing the catchment. Blue signifies ice cover and green is ice-free land. The red cross marks the outlet, listed in Table 1.

Monitoring of the water resource

Investigations of hydro power potential 12.j were initiated in 1981 by the Greenland Technical Organization (GTO). The monitoring program was terminated in 1984.

The few manual discharge measurements carried out at catchment 12.j form a relatively weak basis for the stage-discharge relation. Especially measurements at low discharge are lacking (see Table 26).

An overview of the data coverage of the discharge time series for the catchment is given in Figure 70.

Catchment	Manual discharge measurements	Part of total discharge volume found by extrapolation of stage-discharge relation or gap filling, %		
		Upward extrapolation	Downward extrapolation	Gap filling
12.j	5	8 %	34 %	6 %

Table 26. Basis for the stage-discharge relation for the catchment and part of total discharge volume found by extrapolation of the stage-discharge relation or gap filling.

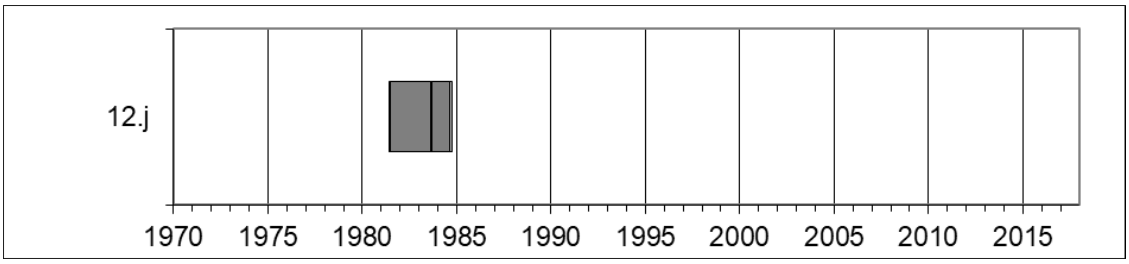

Figure 70. Data coverage of measured discharge time series for the catchments of hydro power potential 06.c. Periods with measured data are shown as dark grey bars, periods with larger, filled data gaps are shown with light grey bars (for description of gap filling method see method section).

Establishing the 1980-2014 time series

The measured discharge time series for the catchment does not cover the entire period from 1980 to 2014 (see Figure 70). Therefore, modelled runoff from HIRHAM5 is used to supplement the measured discharge time series. The measured time series for catchment 12.j has 4 years overlapping with the HIRHAM5 runoff time series. For each year the ratio between measured and modelled runoff have been calculated and the mean ratio have been used to adjust the yearly HIRHAM5 runoff values. This method is used as model and measurement does not correlate well (R^2 = 0.45). The 1980-2014 yearly discharge time series is constructed with the measured data supplemented with yearly runoff values from HIRHAM5 adjusted by the mean ratio.

Water resource

Based on the 1980-2014 discharge time series the mean yearly water resource at hydro power potential 12.j has been calculated to 0.57 km^3, see Table 27. Notably, the five highest yearly resource values occur within the period 2000-2014. The yearly water resource shows a statistically significant, positive trend (significance level $p<0.002$) in a Spearman Rho test. The trend for the discharge time series is estimated to be a 0.003 km^3/year increase in discharge (Theil & Sen slope estimator).

Catchment	**Yearly water resource, km^3**		
	Mean	**Maximum**	**Minimum**
12.j	0.57	0.69	0.44

Table 27. Water resource at hydro power potential 12.j.

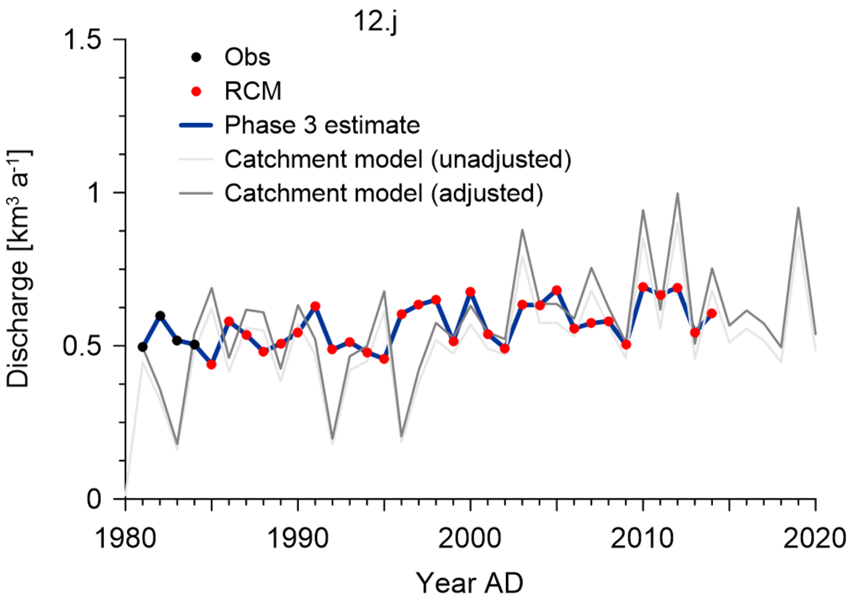

Figure 71. The annual discharge ("Phase 3 estimate") from the hydropower potential 06.d with the following labelling of data sources; "Obs": measured data, "RCM": based on regression between results from climate models and measured data from other years. Catchment model results are shown in both the original unadjusted and bias-corrected adjusted versions.

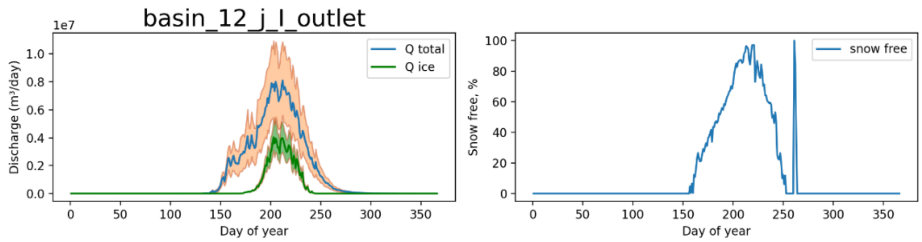

Figure 72. Left graph: seasonal variation of the total daily discharge from the catchment, averaged over 1981-2020 (blue line "Q total"), including uncertainty interval (light brown) with the daily discharge from the glaciated part of the catchment (green curve "Q ice") specified, also including uncertainty interval (light green). Right graph: daily percentage of the total catchment (ice-covered and ice-free) experiencing snow-free conditions.

Hydro Power Potential 15.a

The hydro power potential 15.a has two proposed outlines; either utilizing the catchment 15.a.I or utilizing the slightly smaller sub-catchment 15.a.II (see Figure 73).

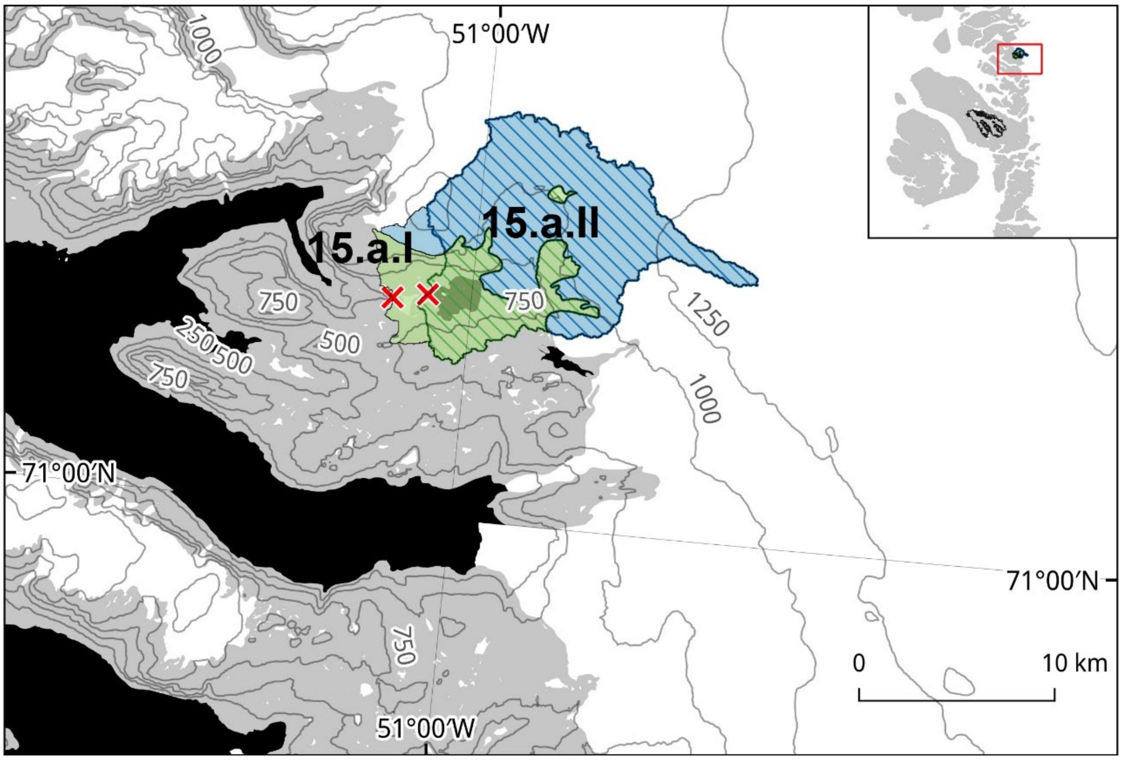

Figure 73. Map showing the catchments. Blue signifies ice cover and green is ice-free land. Red crosses mark outlets, listed in Table 1. The sub-catchment 15.a.I includes 15.a.II (hatched part).

Monitoring of the water resource

Investigations of the catchment 15.a.II were initiated in 1979 by the mining company running the nearby Maarmorilik mine. The water resource was measured during the summers of 1979 – 1988 by Arctic Consultant Group. For this report we have not had access to the detailed measurements and documentation, only the monthly discharge values.

An overview of the data coverage of the discharge time series for the catchments is given in Figure 74.

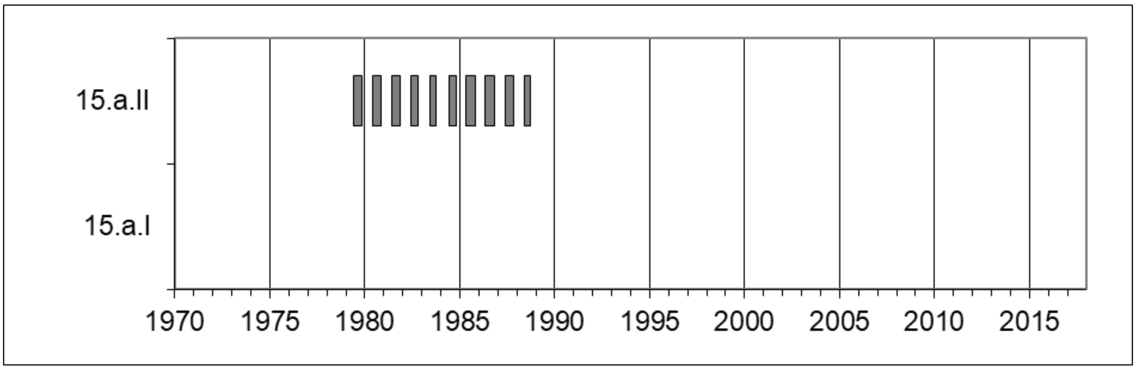

Figure 74. Data coverage of measured discharge time series for the catchments of hydro power potential 15.a.II. Periods with measured data are shown as dark grey bars.

Establishing the 1980-2014 time series

For none of the catchments the measured discharge time series covers the entire period from 1980 to 2014, Figure 74. Therefore, modelled runoff from HIRHAM5 is used to supplement the measured discharge time series.

For catchment 15.a.II the measured time series has 8 years/summers overlapping with the HIRHAM5 runoff time series and the correlation is reasonably good ($R^2 = 0.83$). The 1980-2014 yearly discharge time series is constructed with the measured data supplemented with yearly runoff values from HIRHAM5 adjusted linearly by the regression formula.

For catchment 15.a.I no measurements exist. The 1980-2014 yearly discharge time series is constructed from the catchment 15.a.II time series adjusted with the ratio between the modelled runoff from catchment 15.a.I and catchment 15.a.II.

Water resource

Based on the 1980-2014 discharge time series the mean yearly water resource at hydro power potential 15.a has been calculated. If catchment 15.a.I is utilized the mean yearly water resource is 0.13 km^3, if catchment 15.a.II is utilized the mean yearly water resource is slightly less, see Table 28.

Notably, the ten highest yearly resource values occur within the period 2003-2014. The yearly water resource shows a statistically significant, positive trend (significance level $p<0.00001$) in a Spearman Rho test. The trend for the discharge time series of catchment 15.a.I is estimated to be a 0.004 km^3/year increase in discharge (Theil & Sen slope estimator).

Catchment	Yearly water resource, km^3		
	Mean	Maximum	Minimum
15.a.I	0.13	0.32	0.02
15.a.II	0.11	0.29	0.02

Table 28. Water resource at hydro power potential 15.a. Note that catchment 15.a.II is a sub-catchment of catchment 15.a.I.

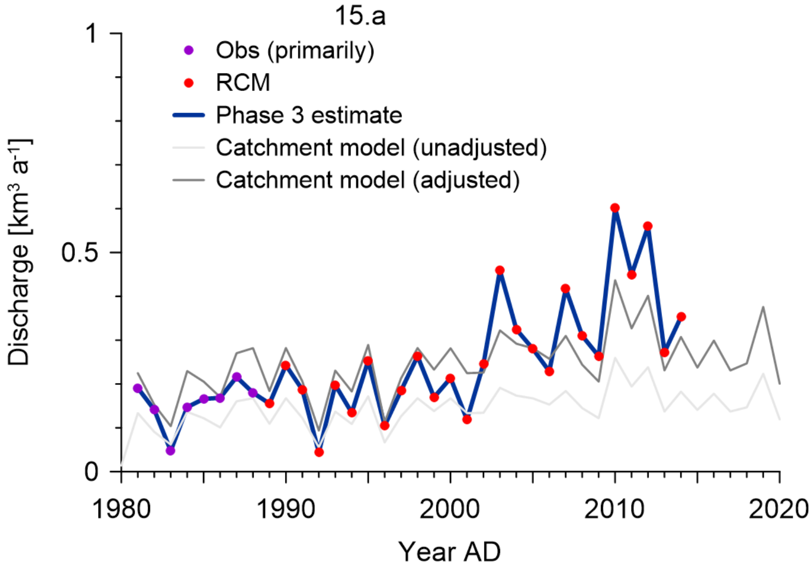

Figure 75. The annual discharge ("Phase 3 estimate") from the hydropower potential 15.a with the following labelling of data sources; "Obs (primarily)": mainly based on measured data, "RCM": based on regression between results from climate models and measured data from other years. Catchment model results are shown in both the original unadjusted and bias-corrected adjusted versions.

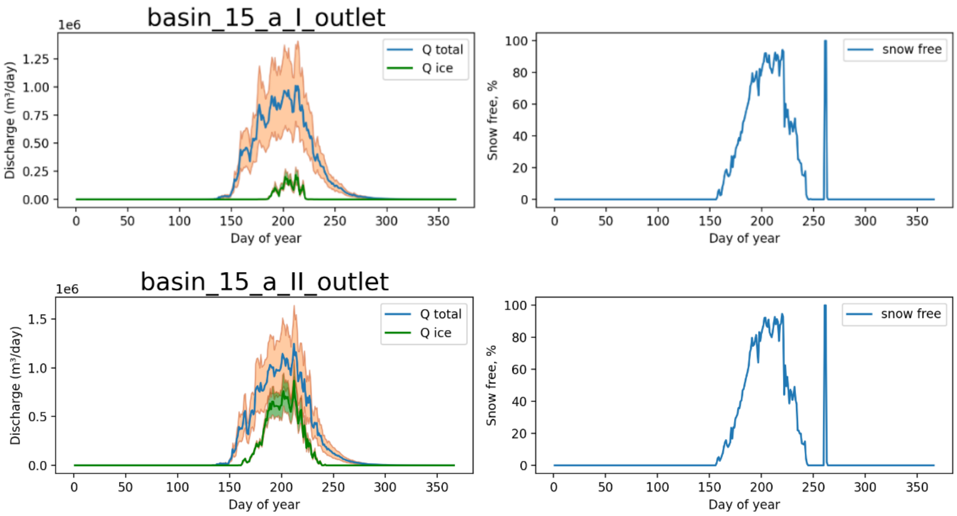

Figure 76. Left graphs: seasonal variation of the total daily discharge from the catchment, averaged over 1981-2020 (blue line “Q total”), including uncertainty interval (light brown) with the daily discharge from the glaciated part of the catchment (green curve “Q ice”) specified, also including uncertainty interval (light green). Right graphs: daily percentage of the total catchment (ice-covered and ice-free) experiencing snow-free conditions.

Conclusion

Accessible water resources in Southwest Greenland have seen a remarkable change over the last decade, as documented in this report and in Ahlstrøm & Petersen and others (2017). Analysing the reasons behind this change, Ahlstrøm & Petersen and others (2017) found that the origins of the air masses arriving over the catchment in the summertime seems to be shifting southwards, consequently carrying more heat and moisture. This leads to intensified summertime melting on the ice sheet surface, with a significant influence on the large hydropower potentials where the water resource primarily depends on the amount of meltwater runoff.

The changes in the general atmospheric circulation, leading to an intensified meridional transport of heat and moisture is believed to be due to global warming. On catchment scale, the result of this is a significantly larger mean annual discharge and a slightly longer melt season, but also a significantly higher variability in the discharge. All these parameters should be considered in future considerations of the exploitation of the water resource for hydropower. Although a connection to global climate change has been pointed out, it should be kept in mind that a part of these changes may be due to natural variability, e.g. in recurring modes of the ocean circulation. Thus, an investigation into the future development of the water resource must include model results based on the most likely climate scenarios, incorporating knowledge of both natural and anthropogenic climate change.

In this evaluation we assessed the available water resource for the 16 hydropower potentials in Greenland deemed most interesting for industrial use. Focus was on producing reliable values for the period 1980-2014 as reported in Table 29. Four of the catchments had never been gauged, requiring the use of a catchment scale model driven with input from a regional climate model. While results from these four catchments are less certain, they still indicate the likely range of the water resource available. Additionally, the catchment model was run for the other 12 catchments, partly to evaluate reliability of the modelled output, and partly to obtain an idea of the general evolution of the available water resource from 2014 up to 2020. While the extended time series have not been tabulated, inspection of the graphs for each catchment indicates a period from 2014-2020 with less extreme discharge compared to especially 2010 and 2012. Yet, knowledge from the monitoring programme for the Greenland ice sheet (PROMICE) indicates that melt has been extreme also in the period 2014-2020, but less so in Southwest Greenland where the majority of the hydropotentials are situated. This implies that the higher interannual variability observed from 2003-2014 is likely to continue, and that higher melt rates are anticipated for the ice sheet and glaciated parts of the catchments. Thus, catchments with a high proportion of runoff originating from ice sheet or glacier meltwater are likely to experience an increase in the available water resource.

Hydropower potential ID	Mean yearly discharge (km^3) Catchments					Total
	I	II	III	IV	V	
03.h	0.19	0.02	0.01	0.01	0.01	**0.25**
03.j	*0.61*	*1.70*				***1.70***
05.h	*0.28*	*0.01*	*0.01*			***0.30***
05.j	*0.21*					***0.21***
05.k	*2.91*					***2.91***
06.b	1.12					**1.12**
06.c	0.49	0.02				**0.51**
06.d	0.21	0.26				**0.46**
06.e	1.98	1.64	0.14			**1.98**
06.h	6.92					**6.92**
06.g	0.10	0.89	0.05	0.04		**1.08**
07.d	1.00	0.17				**1.17**
07.e	2.78					**2.78**
07.f	0.26	1.09				**1.36**
12.j	0.57					**0.57**
15.a	0.13	0.11				**0.13**

Table 29. Overview of the water resources from the 16 hydropower potentials assessed for the period 1980-2014. Ungauged catchments marked in *italics*.

Showcasing four large hydropower potentials of industrial interest in Southwest Greenland, 06.g, 07.d, 07.e and 07.f, we see the same overall development towards more discharge and higher variability over the last decade up to 2014, as illustrated in Figure 77. However, this change is more pronounced for the two most northerly hydropower potentials (07.e and 07.f) which are situated on the lee side of a topographical barrier, leading to less sensitivity to precipitation and more sensitivity to increased amounts of meltwater from the Greenland ice sheet (see Table 30 and Table 31). The evaluation covers the development over the period 1980-2014, but data from the potential 07.e for 1975-1979 published in Ahlstrøm & Petersen and others (2017) does not change the conclusion. Table 30 and Table 31 describe the absolute and the relative rise in the water resource from two earlier periods, respectively, namely 1980-2002 (Table 30) and 1980-1991 (Table 31) and up to the period 2003-2014. The latter period was chosen because it has been identified as a possible new climatic state in Ahlstrøm & Petersen and others (2017). The period 1980-2002 just represents all the years prior to the shift in 2003 where regional climate model results are available, whereas the period 1980-1991 has been included to provide a comparison on catchment scale with the initial evaluation of the development of the water resources from all Southwest Greenland.

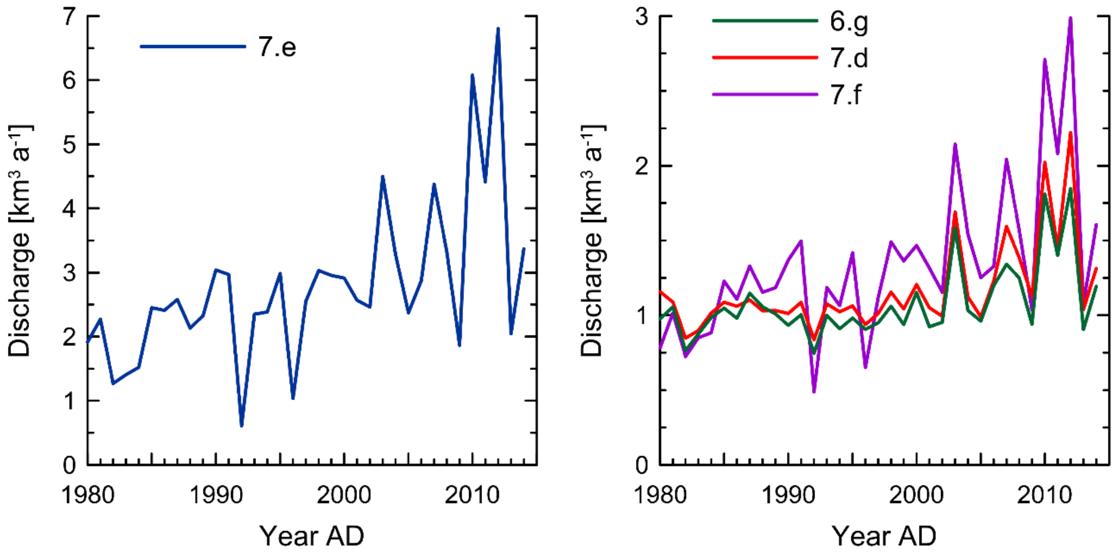

Figure 77. The annual discharge for four selected potentials for the period 1980-2014 as estimated in this report. Note that the two graphs have different scales. The change in discharge after 2002 is quantified in Table 30.

Catchment	Discharge km^3/yr 1980-2002	Discharge km^3/yr 2003-2014	Increase in %
06.g	0.97	1.29	33
07.d	1.03	1.43	38
07.e	2.27	3.77	66
07.f	1.12	1.78	59

Table 30. Change in the discharge for the four selected hydropower potentials from the period 1980-2002 to the period 2003-2014.

Catchment	Discharge km3/yr 1980-1991	Discharge km3/yr 2003-2014	Increase in %
06.g	0.99	1.29	31
07.d	1.03	1.43	38
07.e	2.19	3.77	72
07.f	1.09	1.78	63

Table 31. Change in the discharge for the four selected hydropower potentials from the period 1980-1991 to the period 2003-2014.

A change in the water resource is not equivalent to a corresponding change in the possible energy production from the hydropower potential. The change in energy production is influenced by the relation between the annual discharge and the potential size of the storage, causing a non-linear relation through the resulting adjustment factor. Other technical assumptions include expected efficiency, fall height, pipes and type of turbines, and operating time per year. Generally, an increase in the water resource would yield a lower degree of regulation and thus a lower adjustment factor, implying a less efficient utilization of the given water resource. It is thus possible, that the relative increase in the water resource documented in this report could result in a lower relative increase in the theoretically possible energy production.

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