DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2019/37

Revised assessment of potential locations for export of meltwater from the glaciers in Greenland

Kristian K. Kjeldsen, Andreas P. Ahlstrøm, Christian N. Albers, Signe H. Larsen, Anders R. Johnsen, Signe B. Andersen, Camilla S. Andresen, Michele Citterio, Robert S. Fausto, & Anne M. Solgaard

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
DANISH MINISTRY OF CLIMATE, ENERGY AND UTILITIES

GEUS

DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2019/37

Revised assessment of potential locations for export of meltwater from the glaciers in Greenland

Kristian K. Kjeldsen, Andreas P. Ahlstrøm, Christian N. Albers, Signe H. Larsen, Anders R. Johnsen, Signe B. Andersen, Camilla S. Andresen, Michele Citterio, Robert S. Fausto, & Anne M. Solgaard

Confidential report

Copy No.

Released 01.01.2025

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
DANISH MINISTRY OF CLIMATE, ENERGY AND UTILITIES

G E U S

Contents

1. Summary

The Greenland Ice Sheet contains 2.85 million cubic kilometres of glacier ice, with ancient parts dating back more than 100,000 years. River systems of variable size transport meltwater originating from the ice sheet and from local glaciers and ice caps to fjords and ocean. Here we map potential sites in Southwest Greenland that can be exploited for extraction of meltwater, expanding on the earlier analyses from Ahlstrøm et al. (2016) and Ahlstrøm et al. (2018).

Identification of the potential sites was performed using different Geographical Information System (GIS) and remote sensing data and analysis. The final selection of potential sites is based on inspection and evaluation of all catchments larger than 20 km^2, located in Southwest Greenland, that intersect with glacial ice. Initial screening includes: 1) evaluation of extent of ice cover in the individual catchments, 2) fjord bathymetry, 3) river morphology near the river mouth including identification of large submerged deltas or river migration and erosion into extensive fluvial deposits, 4) logistical obstacles including assessment of bathymetrical shoals and shallow waters, 5) enclosed fjord systems with potential hazardous navigation, 6) proximity to large calving tidewater glaciers, and 7) occurrence of geochemical samples with values exceeding defined thresholds. This assessment yielded 58 individual sites suited for meltwater extraction.

2. Introduction

Drinking water of high quality is becoming a scarce resource worldwide. As the world population grows, demand is rising while the supply is under pressure from the impact of climate change. In Greenland, meltwater running off the Greenland Ice Sheet and local glacier and ice caps provides the solution. As the annual hydrological cycle intensifies with higher temperatures in the Arctic, the available water resource only increases. Unlike mountain glaciers which are vanishing globally, the Greenland Ice Sheet is vast, containing 2.85 million cubic kilometres of glacier ice providing a freshwater reservoir without equal in the northern hemisphere.

The Greenland Ice Sheet covers most of the land in Greenland with rivers transporting the meltwater a short distance through the mountains to the fjords through the largely uninhabited country. Due to limited sea ice, the fjords in Southwest Greenland provide direct access by ship to the meltwater river mouths.

The Government of Greenland actively supports the prospect of drinking water export from this immense resource. To attract investments from the industry, an extensive effort has been launched to map possible extraction locations, determine the quality of the meltwater and review the existing ice and water export legislation.

Mapping and water quality assessments are undertaken by the Geological Survey of Denmark and Greenland (GEUS) adhering to the highest international standards. GEUS has been contracted by the Government of Greenland to identify suitable locations for extraction of drinking water from meltwater rivers, conduct field investigations and water sampling, and subsequently, carry out water quality assessments in certified laboratories. GEUS is the National Data Centre for water quality information for all of Denmark's more than 280,000 drinking water wells and has carried out extensive geoscientific fieldwork in Greenland since 1946.

3. Selection of potential locations

Locations are defined as outlets of significant meltwater rivers to accessible fjords in the south-western part of Greenland. The initial assessment of locations is based on a three-level approach, evaluating in turn *accessibility*, *abundance*, and *water quality*, respectively, as suggested in Ahlstrøm et al. (2016) and first applied in Ahlstrøm et al. (2018). For each of these three levels, different criteria were identified and assigned a weight in the assessment with the goal to single out the most promising locations to visit in the field.

The *accessibility* criteria includes proximity to infrastructure, marine chart coverage, availability of bathymetry data, abundance of sea ice and icebergs, and river slope, respectively. The *abundance* criteria relates to water discharge, length of the melt season, existence of proglacial lakes, risk of outburst floods, upstream catchment changes, total ice cover within the catchment, and the ice cover relative to the size of the catchment, respectively. Finally, the *water quality* criteria focuses on origin of the water, age of the source ice, expected sediment concentration in the meltwater, and other issues from contact with naturally occurring minerals.

The selection of a potential location is a two-phase process. In the first part, each location was meticulously examined and rated with respect to the 18 criteria from the considerable geospatial, geological and geochemical datasets available to the Government of Greenland and GEUS. The criteria, sorted by level, and their graduation and weight are illustrated in Table 1 and represents an expansion of the original 15 criteria defined in Ahlstrøm et al. (2018). The rating of a location assigns a number, moderated by a relative weight, for each criteria. In the second phase potential locations and their catchments were assessed manually. The manual assessment prevented the inclusion of catchments that appeared promising in relation to the general criteria, but where one or more factors lead to the conclusion that it would be unviable to include the specific site in the final selection group. The final outcome of the two phases is the ranking of the locations, which in turn is used to select the most promising locations to visit in the field for water sampling and further data collection.

Figure 1 illustrates an overview of the final selected locations and their respective catchments.

Criterion		Poor 5	Mainly poor 4	Useful 3	Mainly good 2	Good 1	Weight
Accessibility	Proximity to infrastructure	Unknown/sporadic access from marine/land side and/or >100 km	Occasional access from the marine side in the operational part of the season, and/or >100 km	Access possible from marine side in the operational part of the season	<25 km with access possible from the marine side all year round	Access by road all year round	Low
	Marine chart coverage	No charts	In proximity of older charts	In proximity of recent charts	Older charts	Recent charts	Low
	Bathymetry	Known shallow waters	No nearby data - estimated risk of shallow waters	No nearby data - estimated deep waters to the coast	Assumed deep water to coast based on experience and nearby data	Deep waters directly to the coast known	High
	Sea ice	Occasional blocking sea ice and fjord ice	Occasional blocking fjord ice	Occasional blocking sea ice	Narrow fjord access, ice-free ocean	Open fjord, ice-free ocean	High
	Icebergs	In fjord with calving glacier and some icebergs in ocean	In fjord with minor calving glacier and some icebergs in ocean	In fjord with minor calving glacier and few icebergs in ocean	No calving glacier in fjord and some icebergs in ocean	No calving glacier in fjord and few icebergs in ocean	High
	River slope over the lowermost 500 m	0 – 0.005 m/m	0.005 – 0.025 m/m	0.025 – 0.050 m/m	0.050 – 0.100 m/m	> 0.100 m/m	High
Abundance	Discharge	Small catchment with no ice cover	Small catchment with partial ice cover	Large catchment with minor ice cover	Large catchment with partial ice cover	Very large catchment with partial inland ice sheet cover	Medium
	Length of melt season	Northwestern	Western	Southwestern	Southern, with small lake	Southern, with large lake	Medium
	Proglacial lake	No lake	Small lake	Several small lakes	Large lake	Several large lakes	Medium
	Outburst floods	Clear indications of outburst flood from lake	Likely outburst flood from lake	Lake with adjoining ice cover, but outburst flood less likely	Outburst flood not likely, but small lake with adjoining ice cover	No lakes with adjoining ice cover	High
	Catchment change	Small catchment with significant risk of change	Small catchment with some risk of change	Large catchment with risk of change	Large catchment with low risk of change over ice cover	Very large catchment on the inland ice (change not important)	Medium
	Total ice cover in catchment	0 – 4 km^2	4 – 8 km^2	8 – 15 km^2	15 – 30 km^2	> 30 km^2	High
	Ice cover relative to catchment size	0 – 10 %	10 – 15 %	15 – 20 %	20 – 30 %	> 30 %	High
Water quality	Origin of water	Primarily from ice-free catchment	Primarily from local ice cover (not inland ice)	Both from local glaciers and inland ice	Primarily meltwater from the inland ice	Almost exclusively meltwater from the inland ice	Low
	Age of ice source	Minor local glacier	Primarily from local ice cap	Both from local glaciers and inland ice	Younger inland ice	Older inland ice	Low
	Sediment concentration	Extremely high (>2000 mg/L)	High (1000-2000 mg/L)	Medium (300-1000 mg/L)	Low (50-300 mg/L)	Weak (<50 mg/L)	Low
	Radioactivity	High concentration	Medium-high concentration	Medium concentration	Medium-low concentration	Low concentration	High
	Inorganic compounds	High concentration	Medium-high concentration	Medium concentration	Medium-low concentration	Low concentration	High

Table 1. *The 18 criteria sorted by the three levels (accessibility, abundance and water quality) and the specific graduation into five levels, expanding on the 15 criteria listed in Ahlstrøm et al. (2018). The column to the right assigns a weight to each criterion with respect to the others.*

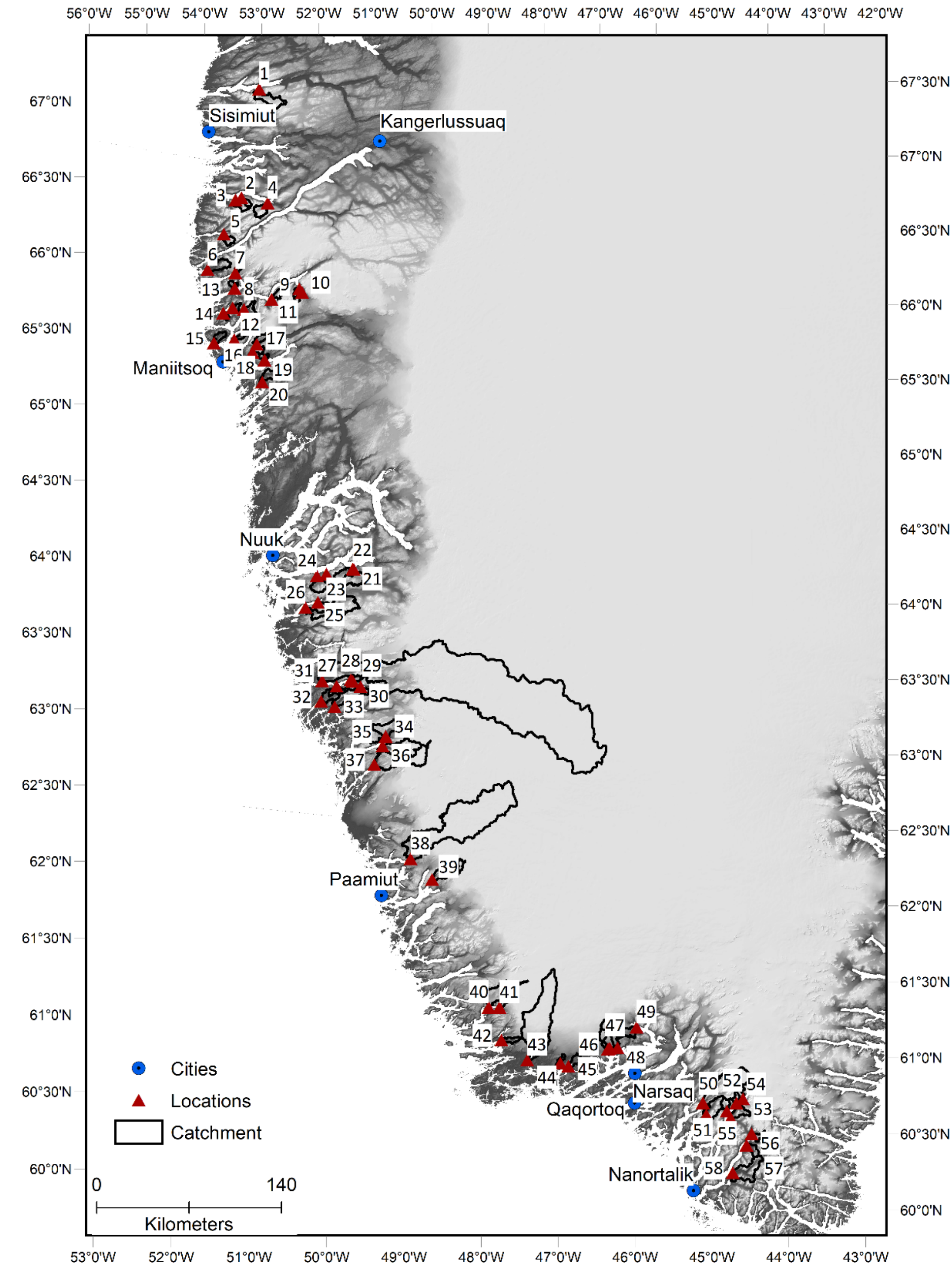

Figure 1. *Overview map showing the selected locations (red triangles) and their catchments (as a black line) and larger cities in the region of interest.*

4. Accessibility assessment

An intimate knowledge of the sailing conditions is crucial in order to determine whether a location is suitable for meltwater collection. Primary parameters to be assessed include bathymetry, nearby ports, fjord ice conditions, sea ice and iceberg occurrence, which together determine what kind of ship or vessel is appropriate for a given location. Currently, five ports in South and Southwest Greenland, i.e. in the vicinity of the selected locations, service shipping over the Atlantic Ocean: Sisimiut, Nuuk, Narsaq, Qaqortoq and Nanortalik. These ports have a maximum capacity between 550 and 3300 TEU. The most proximate port to most locations is Nuuk, which is also the largest of the ports.

4.1 Sea ice and iceberg conditions

Conditions for sea ice and icebergs vary over the extensive southwestern Greenland coastline. In South Greenland, the ice floating the fjords mainly consists of sea ice and glacier ice transported down along the East Greenland coast with the East Greenland current where it eventually flows around the southern tip of Greenland, Kap Farvel (Cape Farewell). South Greenland is generally free from sea ice from August to December, while icebergs can be expected year-round. Unlike the sea ice in South Greenland, the sea ice in Southwest Greenland is produced locally during the winter. Icebergs are present year-round, but more so to the north near Disko Bay, where calving glaciers are more proliferate. According to the Danish Meteorological Institute (DMI), it is normally possible to sail to Aasiaat and Ilulissat from around May to December. The monthly mean concentration of sea ice around Greenland for the time period 2000-2010 is shown in Figure 2, which illustrates the difference between South and Southwest Greenland and also that a significant part of the coast towards Disko Bay remains relatively ice free for significant parts of the year. Still, icebergs are present year-round. All the locations selected are situated in the part of Greenland least affected by sea ice and icebergs, and are thus optimal for transportation, and in addition favourable in relation to the length of the extraction season. The former is evaluated on the basis of the maps shown in Figure 2 and maps from DMI’s ice mapping service in the Kap Farvel region and southwestern Greenland for the period April 2010 to February 2017.

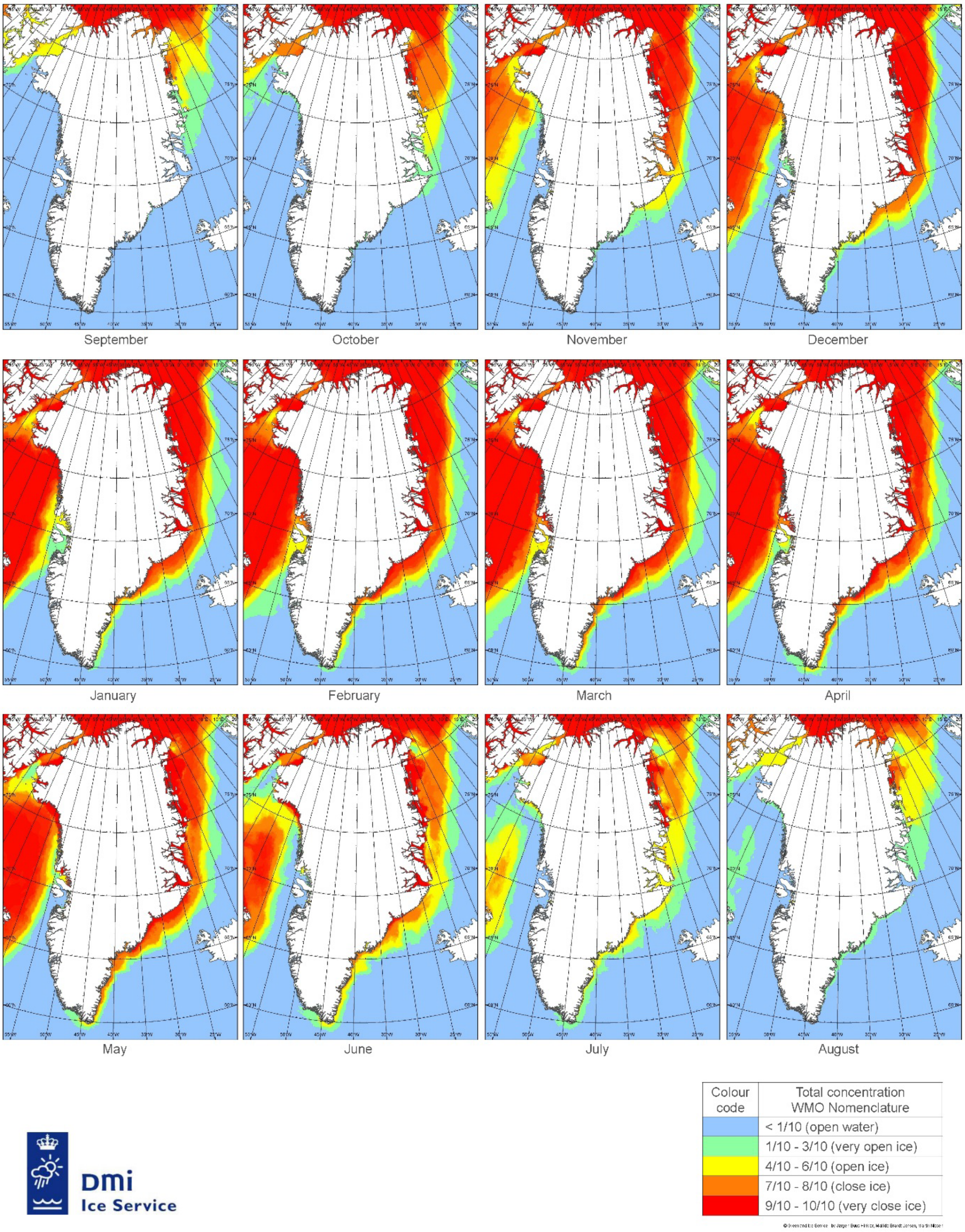

Figure 2. *Monthly mean sea ice concentration derived from Greenland overview ice charts over the period 2000-2010.*

4.2 Bathymetry

The international bathymetric compilation of data around Greenland (IBCAO, International Bathymetric Chart of the Arctic Ocean) does not cover the Greenlandic fjords adequately.

Generally, routing of larger vessels take place only through regions with bathymetric charts suitable for navigation. By special agreement with the Danish Geodata Agency we have been granted access to yet unpublished bathymetric charts for the regions where these are so far available. A more thorough survey of the fjords in Greenland is currently underway, but not yet completed.

To ensure the best possible evaluation of the access to the selected locations, we also included unpublished water depth observations collected from a range of sources by the Greenland Institute of Natural Resources (Pers. Comm. K. Brix Zinglersen). These water depth data cover a wider region than the bathymetric charts of the Danish Geodata Agency and are often the only data source in the vicinity of the selected locations. However, these data are not tied to a vertical reference surface (e.g. mean sea level, lowest astronomical tide, geoid, ellipsoid), implying that no corrections, e.g. tidal corrections, etc., have been applied, but generally just indicates the water depth below a ship at a given time. Thus, data should be used with caution and only as an indication of accessibility of a given location and not for navigational purposes.

Summarizing, the observations of water depth presented below are derived from three datasets:

1. A dataset from the Greenland Institute of Natural Resources (GINR), which consists of single beam water depth data from tour boats and trawlers recorded during navigation, not originally intended as bathymetric measurements. These are generally depicted as lines, or rather a series of point measurements. Kindly provided by Karl Brix Zinglersen (GINR).
2. A bathymetric dataset from the Danish Geodata Agency recorded with multibeam sonar. These data provide full areal coverage when available. Kindly provided by Danish Geodata Agency.
3. A dataset resembling (1) above, recorded from the boat during fieldwork.

Note that datasets (1) and (3) are not proper bathymetric datasets and have not been corrected for tidal water level differences. They are only intended to provide an indication of the likely accessibility by ship and may not be relied on for actual navigational purposes. The water depths presented in Figure 4 through Figure 9 illustrate the minimum water depth within 100 m x 100 m grid cells. For an overview of the coverage of each figure, see Figure 3, where the colour of the boxes refer to the frame of Figure 4 - Figure 9.

Moreover, to supplement the assessment of the bathymetry we incorporate available nautical maps, though recognizing that their accuracy may be questionable. Thus, most emphasis is on the bathymetrical datasets during the selection phase. The map coverage is illustrated in Figure 3.

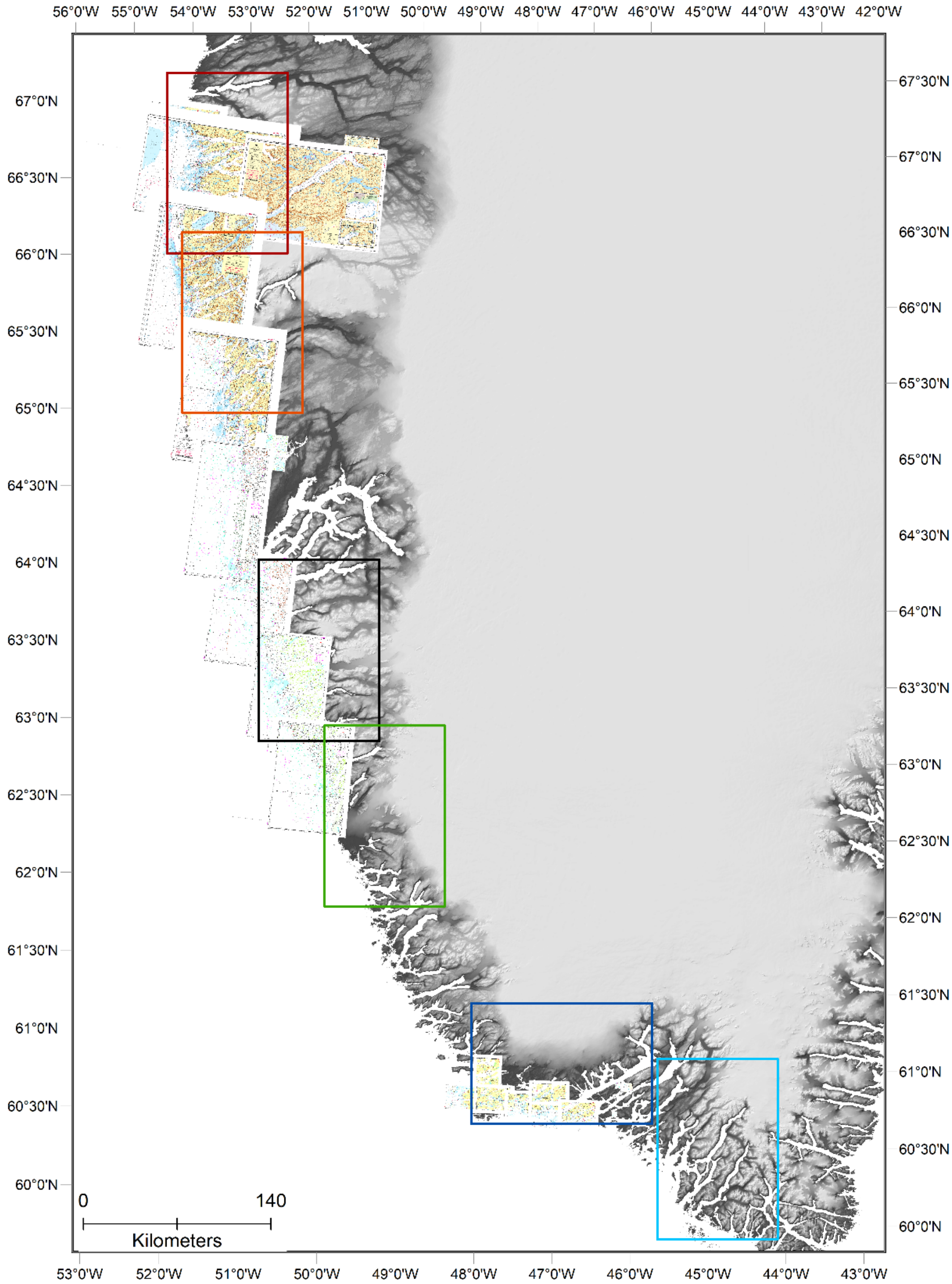

Figure 3. *Overview map showing the availability of nautical maps used during the selection process. Also illustrated is the extent of six sub-sectors presented in* Figure 4 - Figure 9*. Note that the colour of the extent on this figure relates to the frame colour on the figures.*

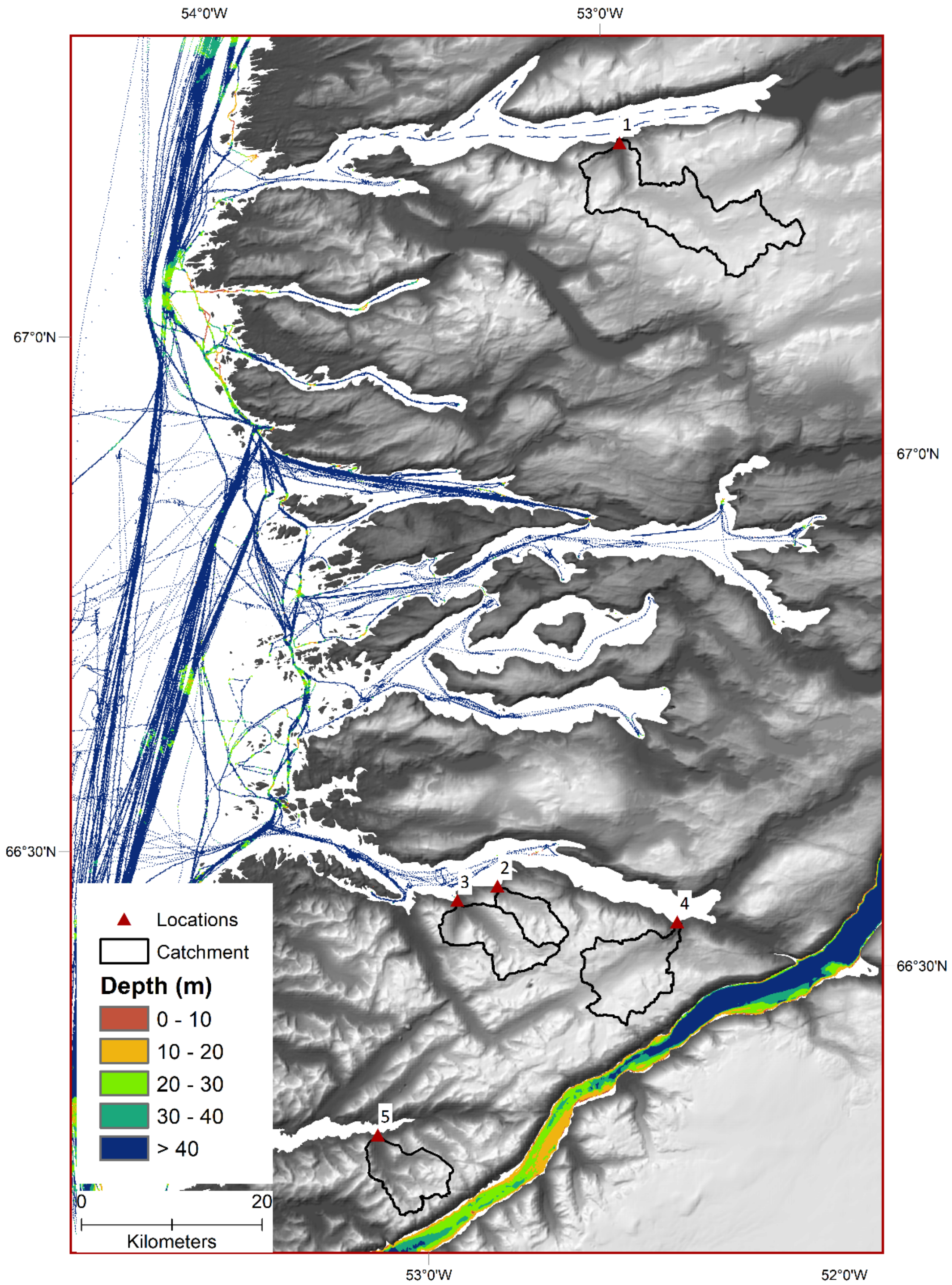

Figure 4. *Sector North-N. Map showing the locations (red triangles) and their catchments (as a black line). The colour scale indicates approx. water depth from three different sources of data described in detail the text. The catchment delineation method is presented in a subsequent section. Depth relates to the minimum water depth within 100 m x 100 m grid cells.*

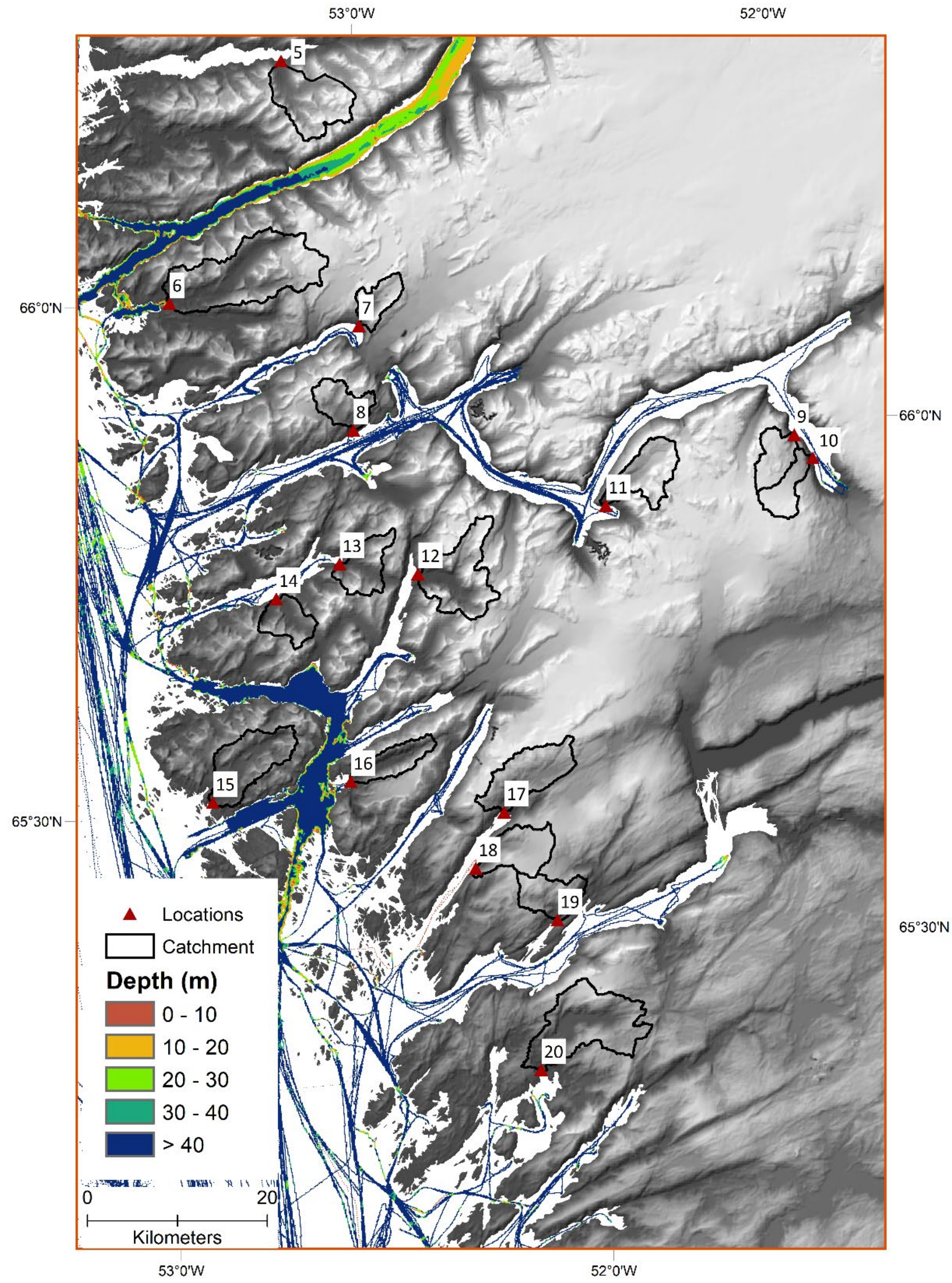

Figure 5. *Sector North-S. Map showing the locations (red triangles) and their catchments (as a black line). The colour scale indicates approx. water depth from three different sources of data described in detail the text. The catchment delineation method is presented in a subsequent section. Depth relates to the minimum water depth within 100 m x 100 m grid cells.*

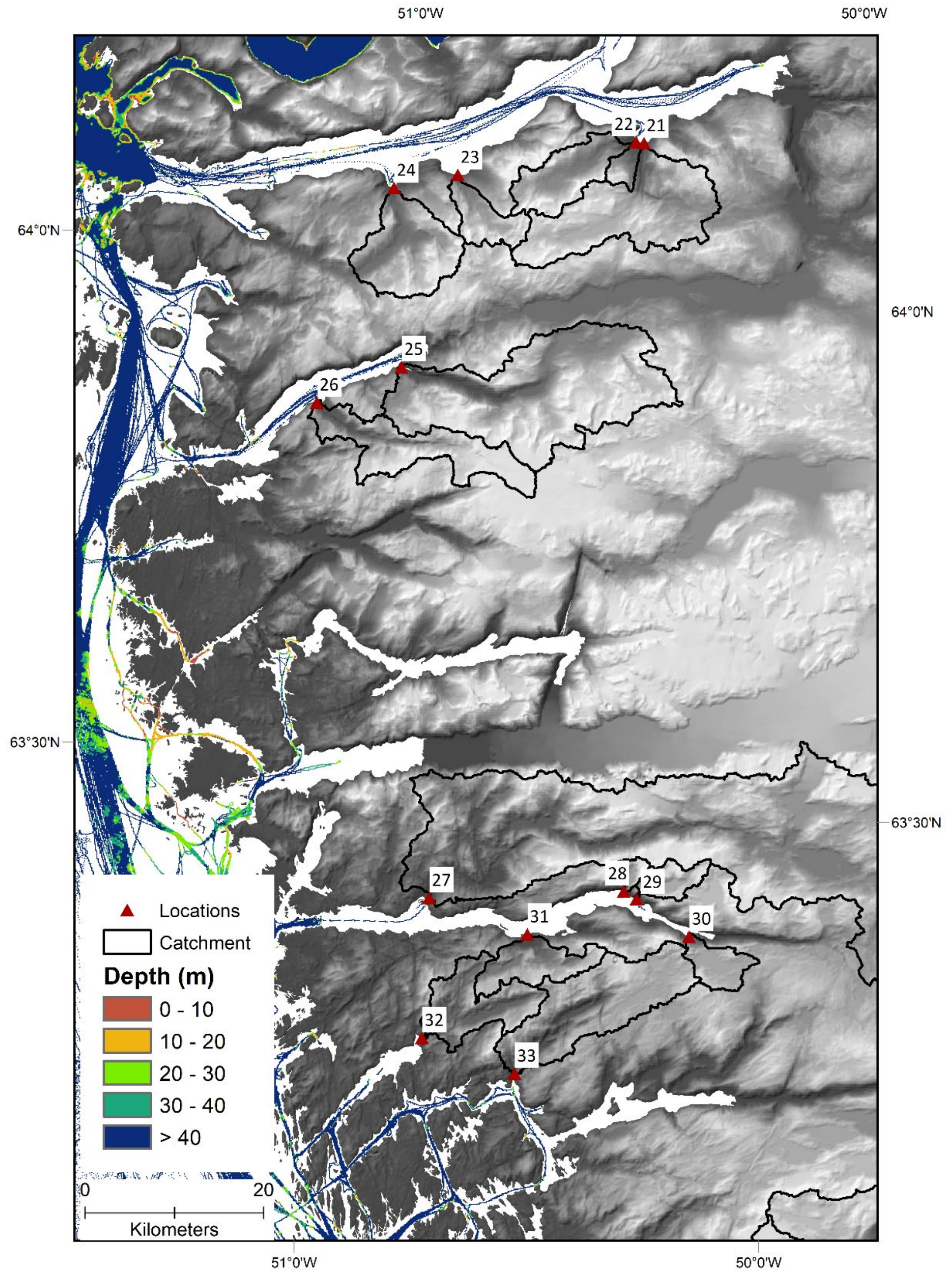

Figure 6. *Sector Mid-N. Map showing the locations (red triangles) and their catchments (as a black line). The colour scale indicates approx. water depth from three different sources of data described in detail the text. The catchment delineation method is presented in a subsequent section. Depth relates to the minimum water depth within 100 m x 100 m grid cells.*

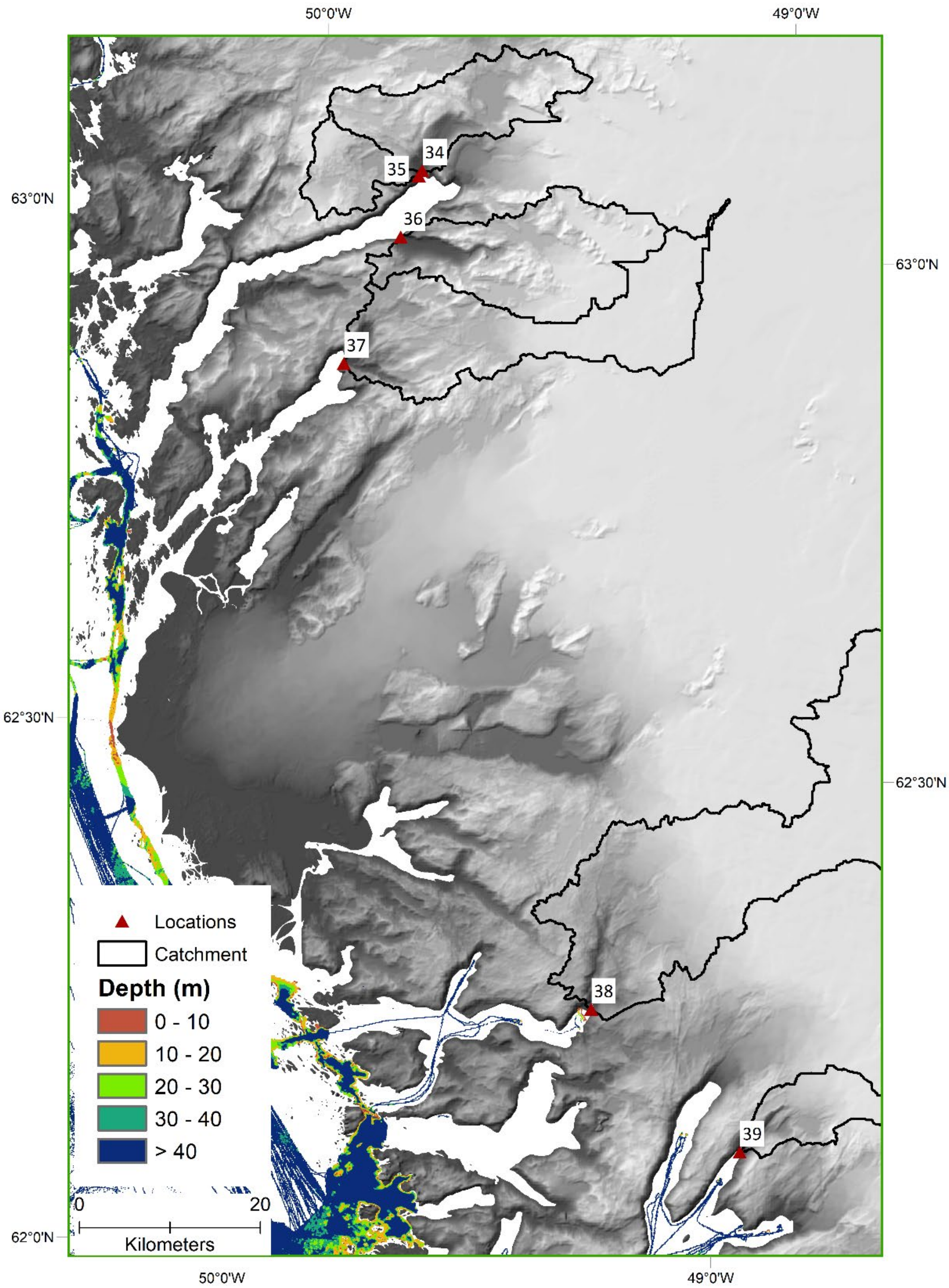

Figure 7. *Sector Mid-S. Map showing the locations (red triangles) and their catchments (as a black line). The colour scale indicates approx. water depth from three different sources of data described in detail the text. The catchment delineation method is presented in a subsequent section. Depth relates to the minimum water depth within 100 m x 100 m grid cells.*

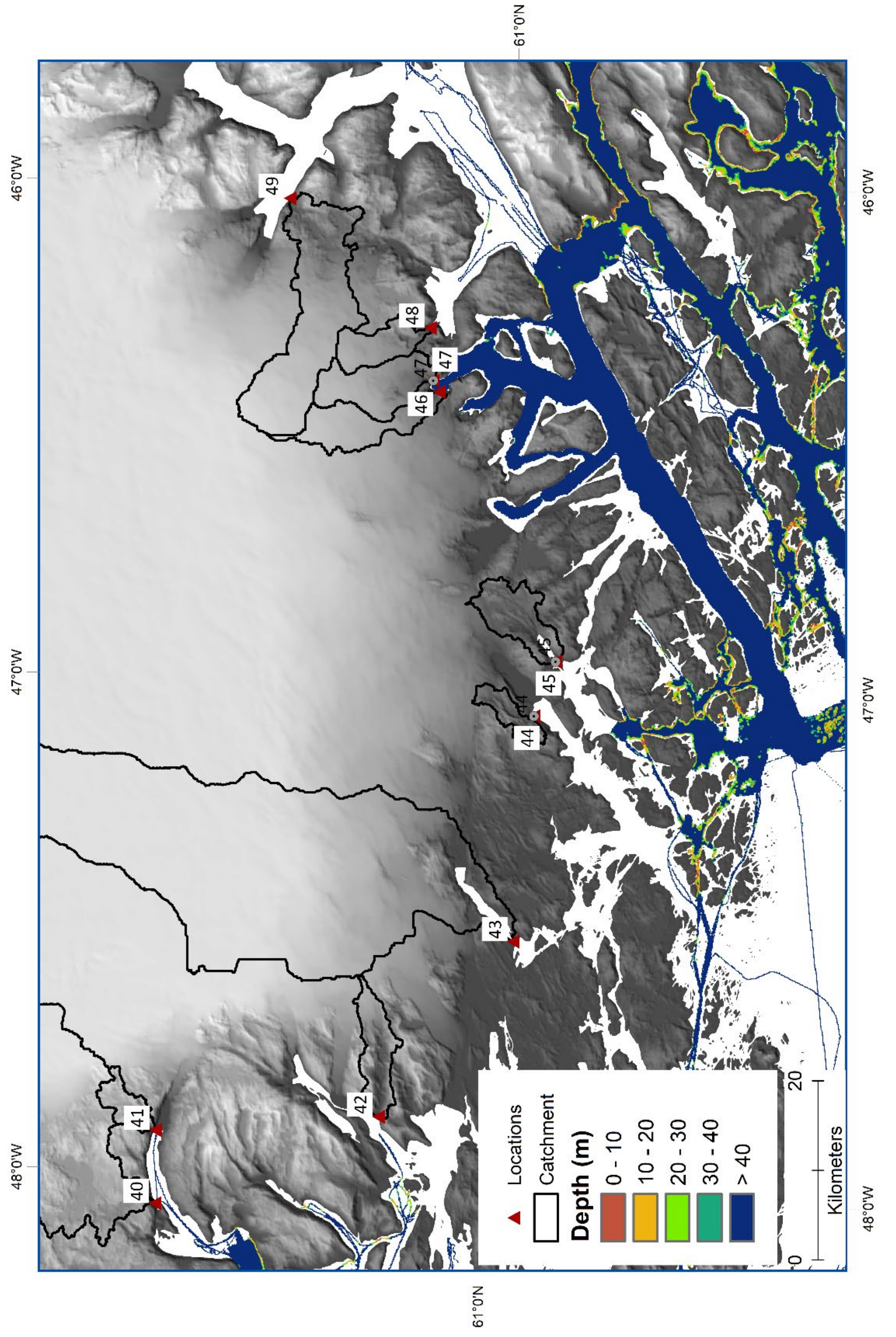

Figure 8. *Sector South-N. Map showing the locations (red triangles) and their catchments (as a black line). The colour scale indicates approx. water depth from three different sources of data described in detail the text. The catchment delineation method is presented in a subsequent section. Depth relates to the minimum water depth within 100 m x 100 m grid cells.*

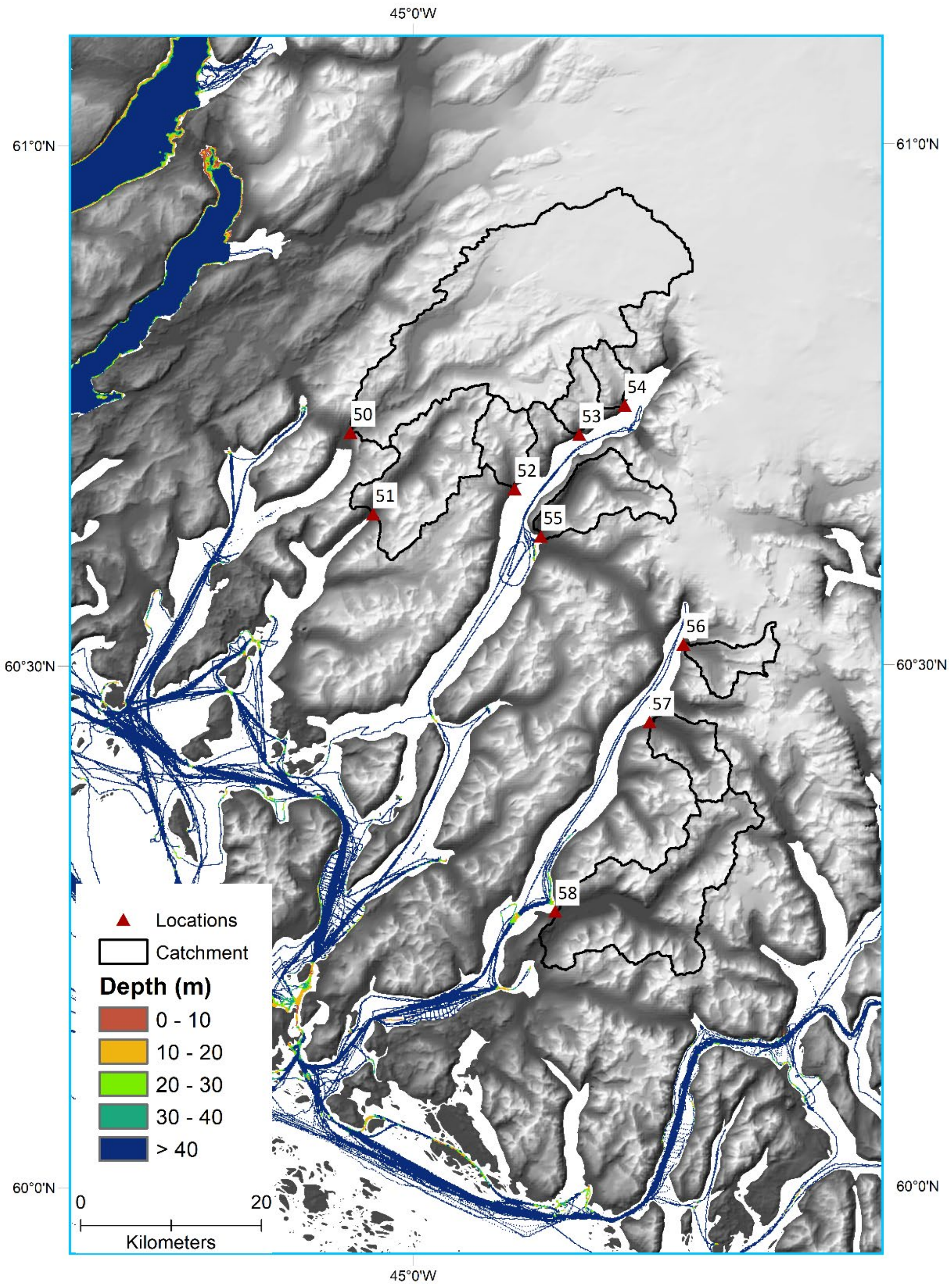

Figure 9. *Sector South-S. Map showing the locations (red triangles) and their catchments (as a black line). The colour scale indicates approx. water depth from three different sources of data described in detail the text. The catchment delineation method is presented in a subsequent section. Depth relates to the minimum water depth within 100 m x 100 m grid cells.*

4.3 River slope

Around Greenland, water flows to the ocean via different size rivers and streams influenced by the surrounding topography. This implies that water will discharge through settings ranging from steep waterfalls to low gradient, almost flat, river outlets. In the latter case, the setting may likely be influenced by tidewater induced estuarine circulation, causing surface ocean water to impact the freshwater discharge from the river. The slope is defined by the change in elevation (the vertical) over a known stretch (the horizontal), and thus has the unit of meter elevation change per meter (m/m).

The slope of the individual river outlets is computed in a two-step sequence, where we first derive the horizontal stretch of the river we want to assess, and secondly, use a digital elevation model (DEM) to provide elevation differences between the start- and end-points of the desired stretch.

The horizontal stretch is obtained from manually digitizing the lowermost 500 m from the ocean/river-interface and upstream following the river configuration. In some cases, a proglacial lake is present before reaching the 500 m cut-off, and here, we use the outflow point of the lake instead of the 500 m cut-off.

Subsequently, we extract surface elevations from the start- and end-points. The surface elevation is described using a DEM, where available data is homogenized to a common fixed grid (a raster map) and each grid cell (square) is assigned a certain elevation. Here the "Greenland Ice Mapping Project" (GIMP) DEM is used (*Howat et al.*, 2014). The DEM is comprised of different remote sensing dataset and is posted to 30 m horizontal resolution using the vertical datum WGS84.

Each outlet is given a score according to Table 2

Score	River gradient over the lowermost 500 m
1	> 0.100 m/m
2	0.050 – 0.100 m/m
3	0.025 – 0.050 m/m
4	0.005 – 0.025 m/m
5	0 – 0.005 m/m

Table 2. *Score based on average River slope over the lowermost 500 m of the river.*

In addition to the slope criteria, we also generate elevation contour lines from the GIMP-DEM to use during the manual screen-phase, as these provide valuable information about the topography of a given location.

5. Glaciological analysis

Knowledge of the glaciological conditions and how these may change over time is a pre-condition for assessing potential locations. This includes estimating the associated catchment and the ice cover within each catchment and its age, while also paying attention to potential hazards from lake outbursts.

5.1 Catchment delineation and change risk assessment

Delineating hydrological catchments in ice-covered regions is complicated by the drainage system of the ice that may occur both internal and at the base of the ice, which is further complicated by changes throughout the melting season. For this assessment, we have employed a simplified approach in which the basal drainage system of the ice is assumed to have an internal pressure balancing the pressure exerted by the overhead ice.

A catchment represents the area that contributes to river runoff. This implies that water originating from either melting of ice or falling as precipitation anywhere within the catchments will make its way to the river outlet and contribute to the runoff (Figure 10).

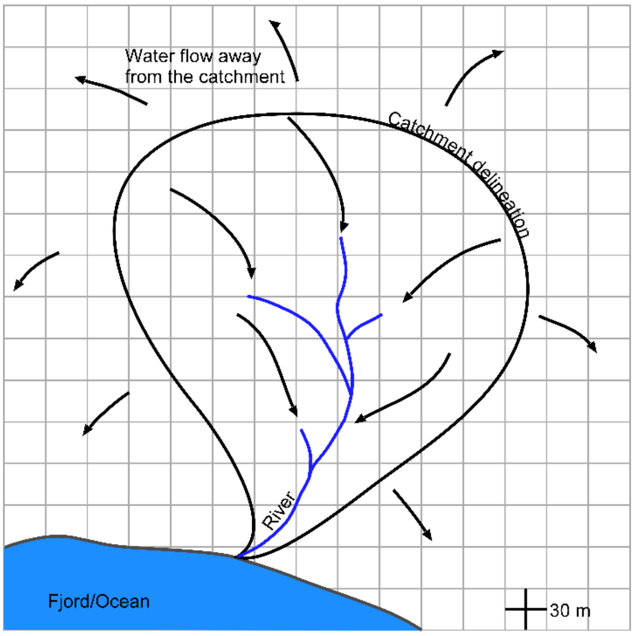

Figure 10. Illustration of catchment delineation. Water originating from either melting of ice or falling as precipitation anywhere within the catchments contribute to the river runoff and ultimately ends in the fjord.

The catchment delineation is generated from quantifying the surface gradient of the individual grid cells to determine the flow direction. Subsequently the adjoining grid cells, where water will flow from one grid cell to another is summarized, and ultimately provide the catchment delineation for each river or stream outlet.

Catchment delineation for individual streams have been generated for all of Greenland using a 30 m x 30 m version of the "Greenland Ice Mapping Project" (GIMP) DEM (*Howat et al.*, 2014). This resulted in a total of 868,947 individual catchments throughout Greenland, of which 256,461 covered southwest Greenland. An initial threshold of only assessing catchments larger than 20 km^2 yielded 509 and of those only 281 intersected with local glacier ice or the ice sheet proper. These were subsequently screened based on the criteria outlined in this report to arrive at the 58 locations and catchments presented in Figure 1.

5.2 Ice cover

While the Greenland Ice Sheet cover the vast majority of Greenland, many smaller local glaciers and ice caps combined, make up a large quantity of Greenland's areal coverage. Quantification of the areal ice cover was a factor in the ranking of the locations.

The ice cover is assessed using a vectorised version of the PROMICE (Programme for Monitoring of the Greenland Ice Sheet) ice mask, which is derived from manually digitized ice extent using the 1985 stereo-photogrammetric imagery (*Citterio and Ahlstrøm*, 2013). This was manually revised using optical Sentinel-2 satellite imagery recorded during summer 2018, obtained from http://earthexplorer.usgs.gov. Additionally, ice coverage is assessed using the Randolph Glacier Inventory version 6.0 (RGI6.0) (*Pfeffer et al.*, 2014), derived from semi-automated classification scheme of available satellite imagery around year 2000. This dataset, however, only cover local glaciers and ice caps detached from the ice sheet proper.

Combining the two datasets allow quantification of the areal coverage of the ice sheet proper as well as the extent of local glaciers and ice caps within each catchment. For catchments where both datasets are represented we only use the RGI6.0 year 2000 estimate for the local glaciers and ice caps. Figure 11 provides an example of the areal extent of the ice cover based on the different datasets within a few catchments.

It should be noted that the ice coverage has changed since the time of recording the aerial- and satellite imagery in response to a changing climate. However, most changes have occurred at the lower parts of large tidewater outlet glaciers of the ice sheet proper, areas that generally do not intersect with the catchments assessed here. Further investigation of the changes is based on a manual assessment using a 2m x 2m ortho-photo mosaic from aerial vertical stereo-photogrammetric imagery recorded in 1985 (*Korsgaard et al.*, 2016) and optical Sentinel-2 satellite imagery recorded during summer 2018, obtained from http://earthexplorer.usgs.gov.

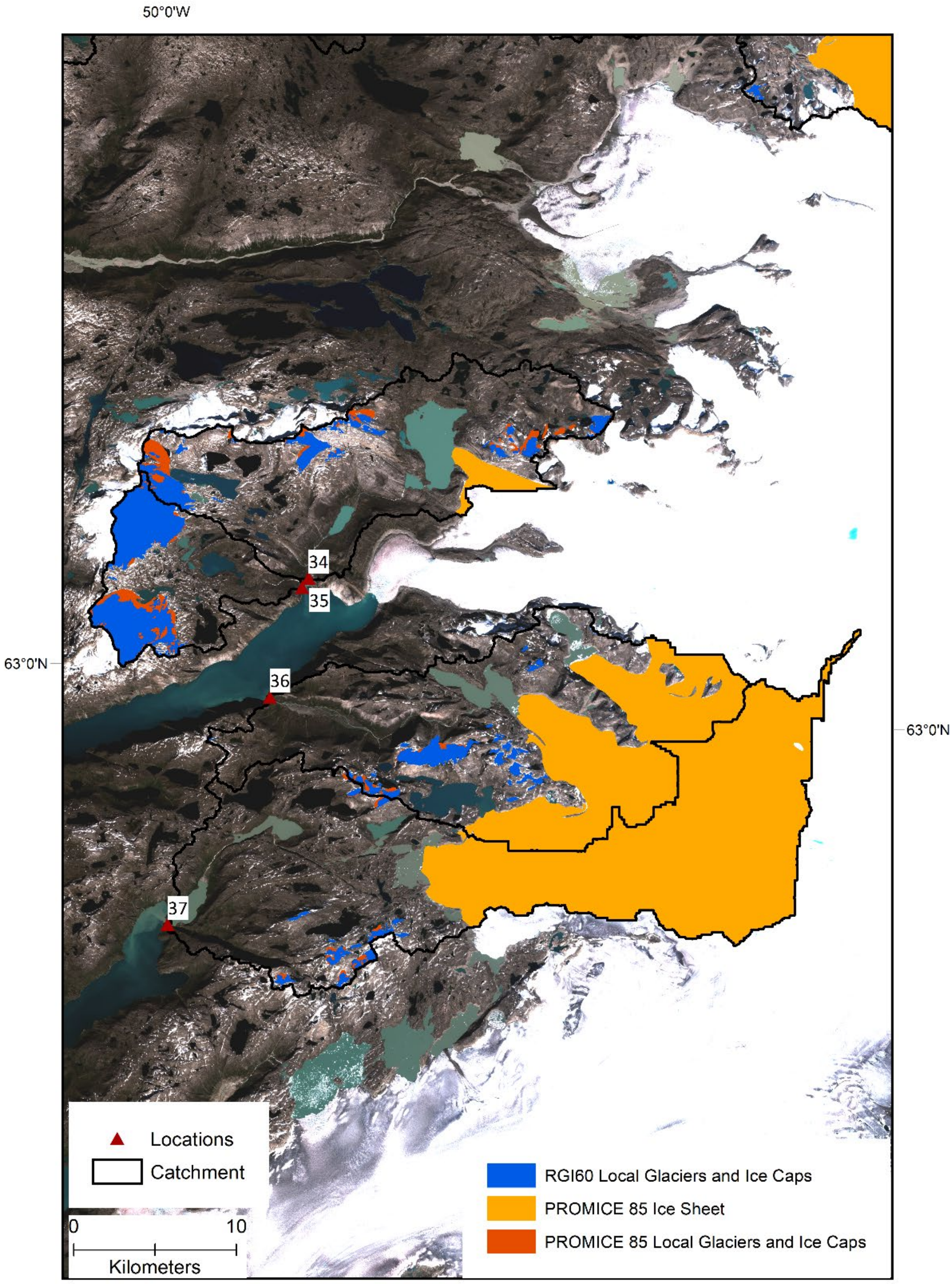

Figure 11. *Example of the ice coverage datasets. The map shows locations (red triangles) and their catchments (as a black line) and three different sources of data described in the text. The base-map is a summer 2018 optical Sentinel-2 satellite image.*

5.3 Risk assessment of glacial lake outburst floods

A common feature of catchments adjoining the Greenland Ice Sheet is glacial lake outburst floods (GLOFs), which occur when a water volume stored in an ice-dammed- or moraine-dammed lake becomes sufficient to lift the ice barrier blocking its path downstream or if the barrier is breached. Some GLOFs are known to take place from the same ice-dammed lake every few years as the lake fills up sufficiently to break through. However, the frequency of these events is changing as the ice bodies blocking the lakes are generally thinning due to a warming climate. Thus, previous knowledge may turn out to be outdated and a known GLOF-prone lake system may pose a risk to anything and anyone downstream. To accommodate this, we have assessed the risk of GLOFs at the selected locations based on the criteria listed in Table 3.

Risk level	Criteria
1	*No lakes by ice margin*
2	*Outburst flood not so likely. but minor lake at the ice margin*
3	*Lake adjoining ice margin, but outburst flood less likely*
4	*Glacial lake outburst flood is likely*
5	*Clear indications of past glacial lake outburst floods from lakes*

Table 3. *Glacial lake outburst flood (GLOF) risk level*

5.4 Estimation of the age of the meltwater source ice

A significant part of the water discharge consists of ice sheet or glacier meltwater. The age of the source ice for this meltwater can be many thousands of years and depends partly on local conditions, but is generally governed by upstream conditions. The left part of Figure 12 shows a cross section of an ice sheet, from surface to bedrock. Two trajectories illustrate possible particle paths through the ice sheet for an ice crystal, originally falling as snow, depending on where it originates on the ice surface. It illustrates that the higher up on the ice sheet the snow fell in the accumulation zone, the deeper the trajectory of the ice crystal, and subsequently, the closer to the ice margin the reappearance in the ablation zone. The accumulation zone is the only region on an ice sheet or glacier, where the mass balance is positive, i.e. more snow is deposited than what melts or blows away, whereas the opposite is true in the ablation zone, where the mass balance is negative, i.e. more mass is removed than added. This implies that layer after layer of snow is buried in the accumulation zone every year, while in the ablation zone they reappear. If there was no melting at the base of the ice sheet and the internal ice layers never folded, it would in principle be possible to make 'horizontal' ice cores along the surface of the ice margin, with the oldest ice closest to the margin as illustrated in the right side of Figure 12. The age of the ice at the margin is thus determined by the distance and pace of the ice movement towards the margin. This implies that under the right circumstances, it is possible to find extremely old ice at the ice sheet margin, as shown in e.g. Reeh et al. (2002).

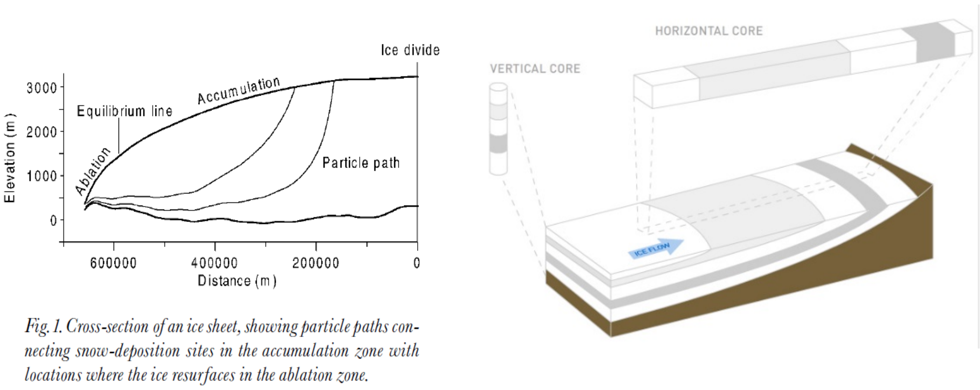

Figure 12. *Two figures, illustrating why old ice can be expected at the ice sheet margin. Left: Reeh et al. (2002). Right: figure from www.niwa.co.nz.*

5.4.1 Ice-dynamic model setup

To estimate the age of the ice at the ice sheet margin, we have employed the ice-dynamic model PISM (Parallel Ice Sheet Model), which is a three-dimensional, thermo-mechanical coupled model (Bueler and Brown, 2009; Winkelmann et al., 2011; Aschwanden et al, 2012). The model is developed at the University of Alaska and the Potsdam Institute for Climate Impact Research. PISM makes use of a simplified description of ice-dynamics, combining the so-called ’shallow-ice’ and ’shallow-shelf’ approximations, which makes it possible to study the flow of large ice masses like the Greenland Ice Sheet, over long time scales (tens of thousands of years), as those of interest here. The model has an ’age-tracking’ method, thereby keeping track of the age of the ice, a method we employ to estimate the age of the ice at the margin.

As input to the model, we have used present-day topography forced with present-day climate (surface mass balance and air temperature; Ettema *et al.* (2009). The model covers the entire Greenland Ice Sheet with a spatial resolution of 10 km. All model experiments have been conducted over a 100,000-year period of constant climate, reaching a steady state during this time. Additionally, model experiments at 20 km spatial resolution with only the ’shallow ice’ approximation have been conducted to test the robustness of the results. These sensitivity model runs show the same results as the main model experiments on the spatial scale examined here.

Surface mass balance, which can be simplified to precipitation minus runoff, of the present day is shown in Figure 13, where blue-ish colours illustrate regions with net melting (the ablation zone), while yellow/green-ish colours shows the accumulation zone, where snowfall exceeds melt. The ablation zone is generally quite narrow, but widens in some regions, like western Greenland, where it is more likely to find ancient ice at the surface due to the long distance between the ice margin and ice divide in the interior. Contrary to this, in south Greenland, it is expected that ice at the margin is typically younger and that the older ice resurfaces in a narrower region as the distance to the ice divide is short, the accumulation rate is high, and the ablation zone is narrow.

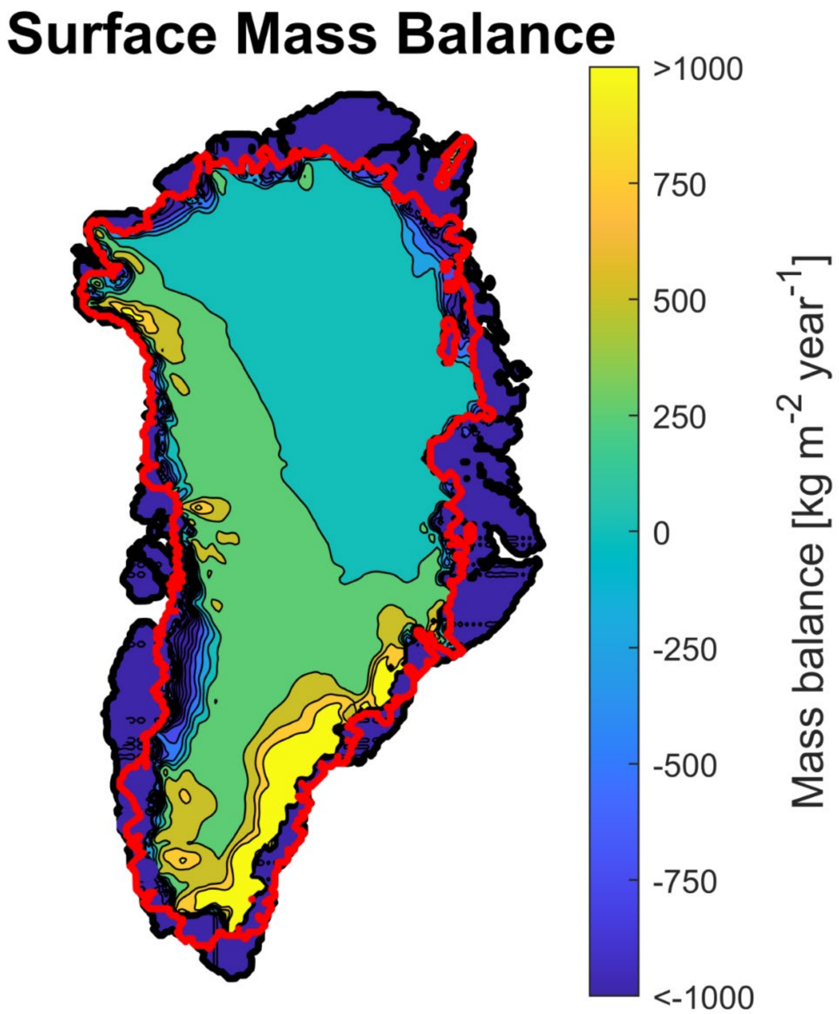

Figure 13. *Present-day surface mass balance from Ettema et al. (2009). The red line indicates the extent of the ice in the model following spin-up over 100,000 years. The black line separates land/ice from ocean. The region between the red and the black line is thus ice-free land in the model.*

5.4.2 Estimated age of the ice

During the spin-up phase, the model is set to run over 100,000 years, forced with present-day climate, for which it reaches a steady state. The resulting configuration of the modelled ice sheet is a somewhat larger extent and volume than the actual present-day Greenland Ice Sheet. This is a consequence of using a present-day climate to force the model, as the present-day ice sheet is not in balance with present-day climate, as well as the choice of the shallow-ice- and shallow-shelf approximation on 10 km spatial resolution. More detail could be resolved if running the model at higher spatial resolution, both with respect to the surface mass balance, where it may play an important role due to the narrow ablation zone, and in relation to the basal topography, where smaller outlet glaciers would become apparent, however, the age estimates will broadly remain the same.

While the model experiments have been conducted prescribing a 100,000 years of constant climate, the climate has of course not been constant over this period. During the last ice age, which terminated around 11,700 years ago, it was of course much colder than today and accumulation was around half of the present-day value. These conditions influence the flow of the ice and has an impact on the estimation of the age of the ice. For this reason, we distinguish between either ice-age ice (i.e. generally older than 11,700 years) or the younger Holocene ice (Holocene: Geological era covering 11,700 years ago to present).

The modelled age of the ice appearing on the surface is shown in Figure 14, while Figure 15 shows two examples of cross sections, where layers of various age can be traced in the ice sheet.

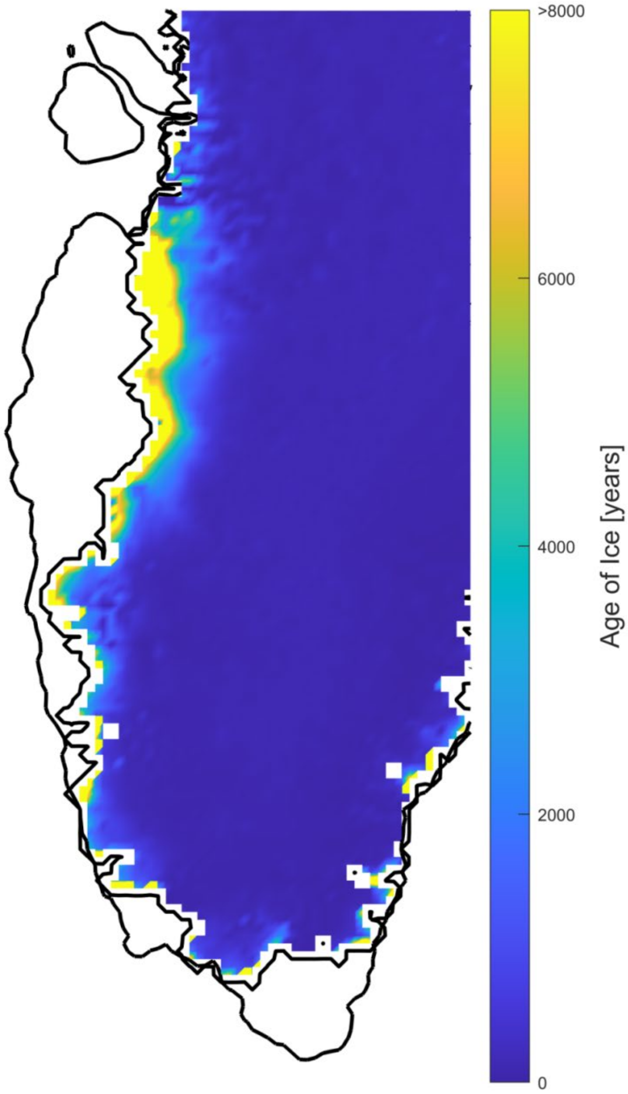

Figure 14. *Model result: age of the ice at the surface at the conclusion of the model run.*

In the region with the broad yellow ablation zone in Figure 14, the age at the surface of the ice exceeds 8,000 years. However, the narrow, yellow areas/dots in the southern region are artefacts from the ice modelling in combination with the contouring method, and thus; are a real indication of pre-Holocene ice surfacing.

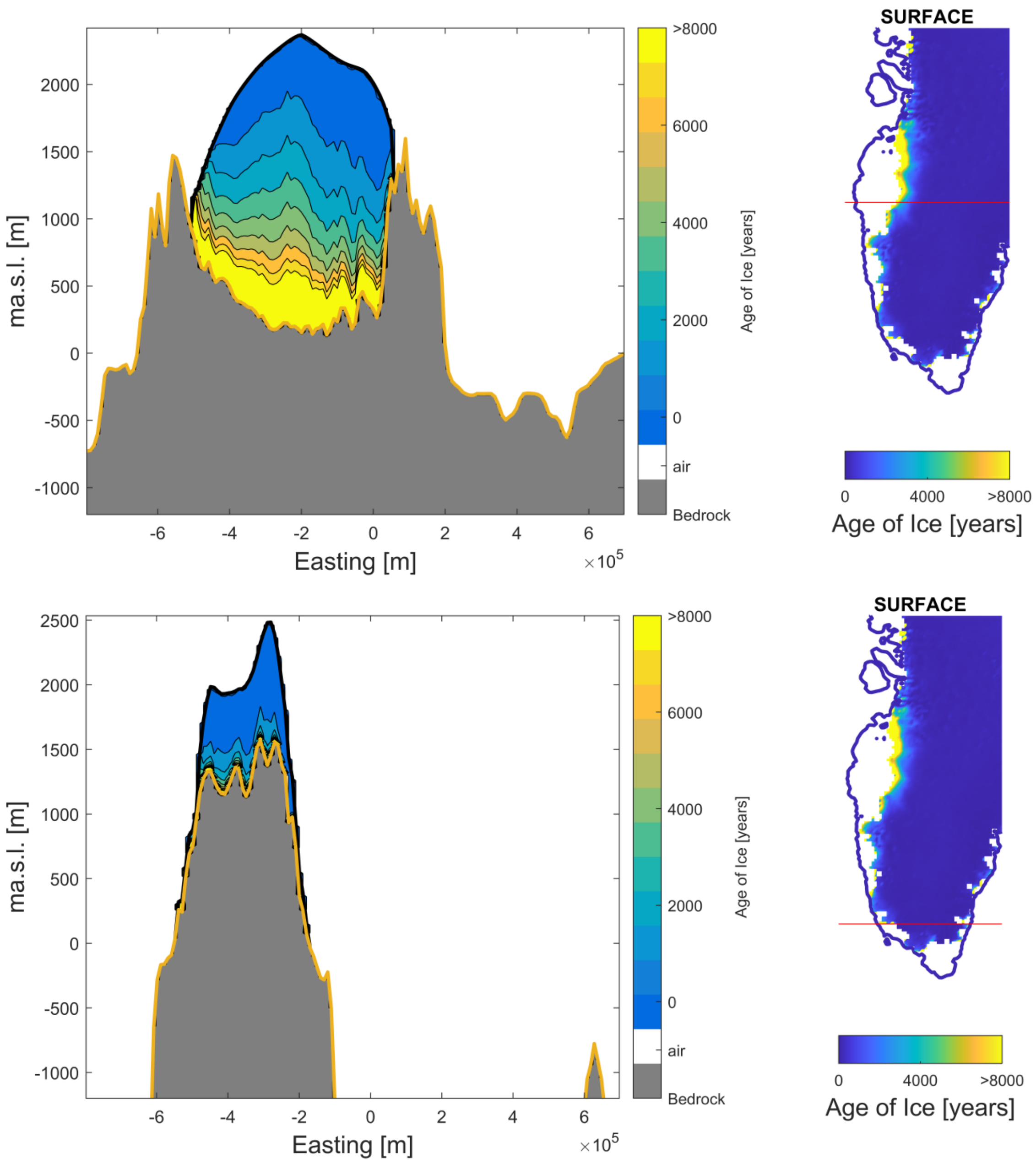

Figure 15. *Top left panel: cross section of the ice sheet in southern West Greenland showing the age of the ice at depth along the thin, red line shown in top right panel. Bottom left panel: cross section of the ice sheet in the extreme South Greenland showing the age of the ice at depth along the thin, red line shown in bottom right panel. Notice the different scale of the x- and y-axis, distorting the relationship between the width and the height of the ice sheet.*

Our results indicate that ice from the last ice age can be found at the surface of the ice margin in a region between Disko Bay and south of Kangerlussuaq in Southwest Greenland. This is supported by oxygen isotope measurements from a few sites in the region (Reeh et al., 2002). In South Greenland, the ice is mainly of Holocene age. Even though the ice extent in our simulation is larger than actual present-day extent, it is still possible to conclude that the ice is of Holocene origin. This also matches an earlier investigation by Mayer et al. (2003), who found ice of an age of 5-6,000 years at two locations in South Greenland.

For the locations that do not receive meltwater from the Greenland Ice Sheet, but rather from local glaciers and ice caps, the age of the melting ice is expected to be young and most likely not older than the Mid-Holocene, c. 5-6,000 years before present. This conclusion is based on their smaller extent and their location in a maritime climate with more precipitation.

The coarse subdivision of ice into that of *late Holocene*-, *Holocene*-, or *ice-age*- ice is a consequence of the simplified model setup. A more specific age determination of ice from a particular location can be estimated by combining high resolution modelling of the ice dynamics within the individual ice catchment with oxygen isotope measurements of samples from the ice surface.

The criteria used to assess the age of ice within each catchment is listed Table 4.

Score	Source	Age	From
1	Older inland ice	Holocene/ice-age	Model
2	Younger inland ice	Holocene	Model
3	Both from local glaciers and inland ice	Late Holocene	Estimate/Model
4	Primarily from local ice cap	Late Holocene	Estimate
5	Minor local glacier	Late Holocene	Estimate

Table 4. *The modelled or estimated age of the ice from which the meltwater originates at the selected locations. The age has been estimated from glaciological expertise and comparison to model results of the ice sheet proper.*

6. Water quality

6.1 Geochemical data

The bedrock geology of Greenland has a great influence of the chemical composition of the water flowing in streams and rivers. As water flows over and through the bedrock, it incorporates geochemical compounds of the underlying geology.

To provide an initial assessment of the geochemical composition of the water, we take advantage of GEUS' Geochemical Atlas of Southwest and South Greenland (*Steenfelt*, 1999), which contains 7,065 sediment samples from rivers. We note that there may likely be a difference between the riverine sediments sampled and the actual water composition; however, it provides a first-order assessment of the conditions.

In the screening process, we focus on five main elements, each with its own threshold value. This infers that catchments are discarded from further inclusion in the screening process where one or more of the elements are found and their values exceeds the threshold - except if values are close to threshold and the catchment otherwise seems promising. Figure 16 provides an example of the distribution of the sampled locations, and an example of a catchment preserved for further investigation, despite the threshold value for Chromium was exceeded at a sampling site within catchment 36.

We recognize that this procedure only provides a first-order assessment of the geochemical conditions and as such, water samples must be obtained in the field for further analysis.

Element	Threshold value
Uranium	> 70 ppm
Thorium	> 70 ppm
Arsenic	> 100 ppm
Chromium	> 700 ppm
Nickel	> 400 ppm

Table 5. *Threshold values for five main elements used during the screening phase.*

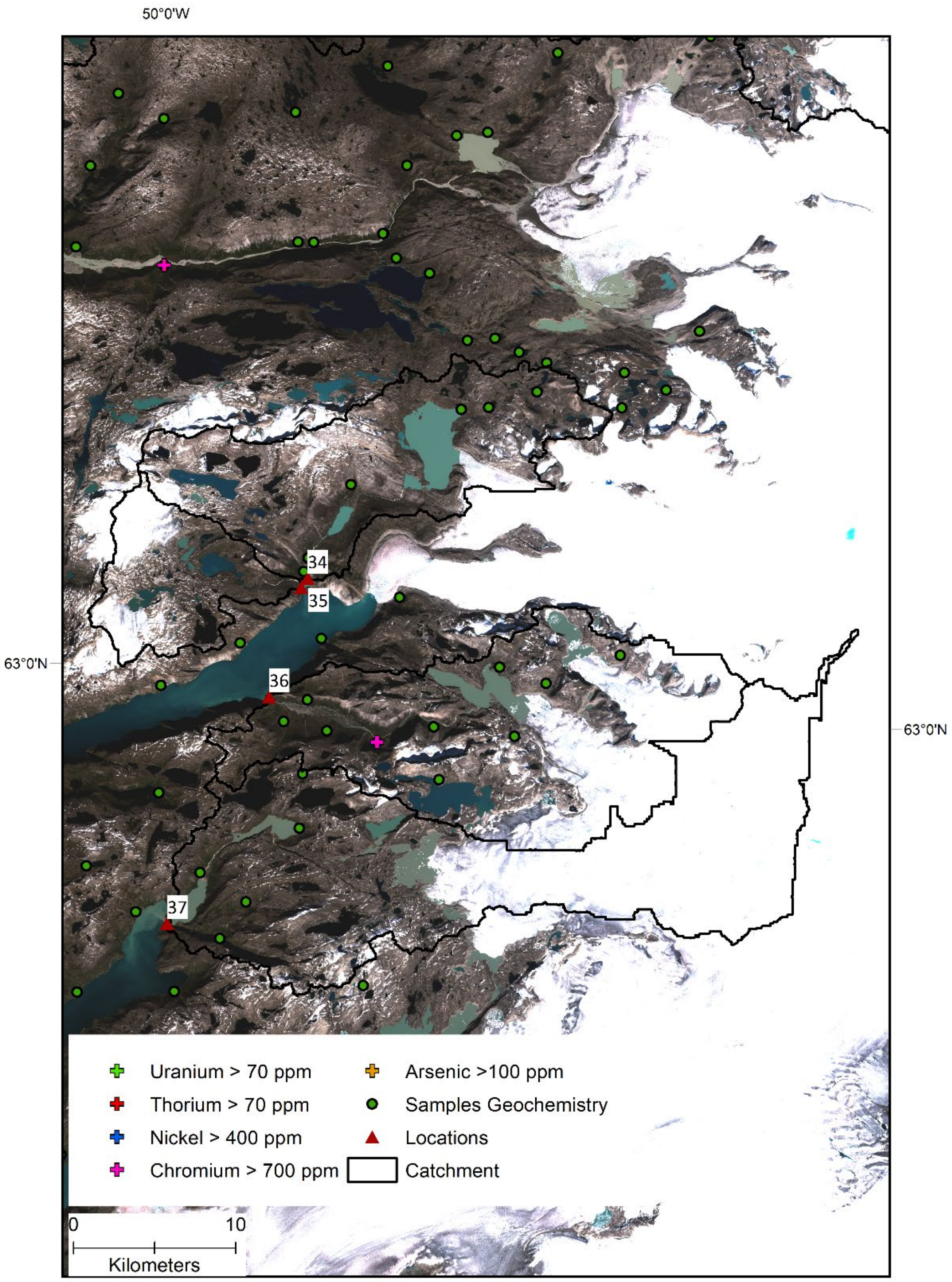

Figure 16. *Example of Geochemical sampling sites (green circles and coloured crosses) and the locations (red triangles) and their catchments (as a black line). The map shows an example of sampling sites where Chromium above the threshold value were reported, however; the site within catchment 36 was close to the threshold value, and because the catchment otherwise appeared promising, it was preserved for further investigation. The base-map is a summer 2018 optical Sentinel-2 satellite image.*

6.2 Sediment concentration

When flying over Greenland, it is impossible not to notice how the lakes and rivers vary in colour, from clear and dark to blueish, ”milky”, grey and brown. The difference in colour is due to the variation in the content of sediment (rock in particle form), which is found in different concentrations (mg/L) in the water. Rivers may differ quite substantially; in some valleys, rivers flow through green areas within a single riverbed whereas in other valleys, rivers form vast networks of braided channels making up the entire vegetation-free valley floor. When investigating the origin of the braided river systems, they most often originate from local glaciers or the inland ice. As a glacier flows over a landscape it erodes the underlying bedrock thereby producing sediment that eventually ends in the rivers. This form of erosion is one of the most powerful on the Earth. Water originating from melting local glaciers or the Greenland Ice Sheet will thus always contain a certain amount of sediment.

The largest concentrations of sediments are observed where the meltwater leaves the glacier. The concentration of sediment decreases downstream as stream-power generally decreases. Moreover, the presents of proglacial lakes between the ice and the outlet location act as natural sediment traps that filter away the coarser sediments and thus reduces the sediment concentration. Once the sediment-laden water reaches the fjord, it will appear as plumes in front of the river mouths. The resulting sediment concentration has an influence on the required filtering treatment following the extraction of water. An example of water flow through proglacial lakes and sediment plumes in the fjord is illustrated in Figure 17.

The presence of proglacial lakes in a river system also provide an additional benefit as they act as buffers of the water discharge. This leads to a more stable water flow with fewer high frequency, high amplitude excursions from the general seasonal water flow pattern; for instance in relation to melting of ice on a day-to-day basis, or in response to rainfall events, etc.

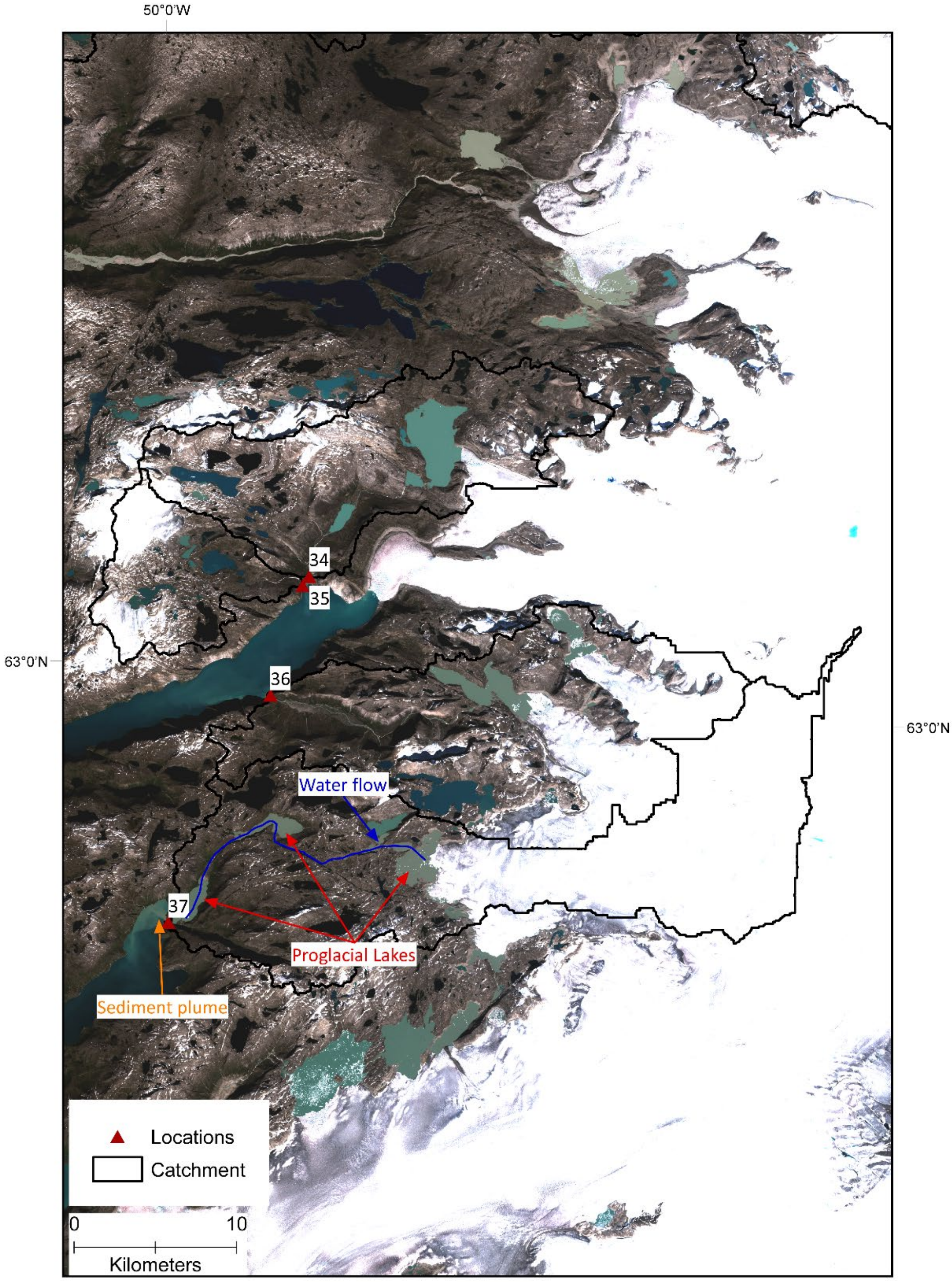

Figure 17. *Example of water flow, a sediment plume, and proglacial lakes in a catchment. As water flows through the proglacial lakes, these as act as natural sediment traps filtering away sediments. Once the water reaches the fjord the outflow of water containing the remaining sediment will appear as a plume in the surface layers of the fjord water. The map shows locations (red triangles) and their catchments (as a black line). The base-map is a summer 2018 optical Sentinel-2 satellite image.*

7. Conclusion

This report contains information on 58 selected locations that may be utilized for industrial collection of drinking water. A prerequisite in the investigation has been that the water should be at least partly derived from meltwater originating either from the Greenland Ice Sheet or from local glaciers and ice caps.

Eighteen criteria, broadly grouped into three categories related to *Accessibility, Abundance, and Water Quality,* have been incorporated as part of the selection process (Table 1). Each criteria has been assigned a weight *Low, Medium, High* to strengthen certain parameters.

As a starting point, we used a total of 256,461 hydrologic catchments covering the south-western part of Greenland generated using a digital elevation model. An initial threshold of only assessing catchments larger than 20 km^2 yielded 509 and of those only 281 intersected with local glacier ice or the ice sheet proper. These were assessed according to the criteria in this report, and subsequently, examined and screened manually to prevent inclusion of locations and their catchments that may appear promising in relation to the 18 criteria, but one or more factors would lead to the conclusion that is would be unviable to include the specific site in final selection group.

The coordinates of each of the resulting 58 locations and their respective catchment size and rank is provided in Table 6a and Table 6b, while an overview of the spatial location is provided in Figure 18.

ID	**Longitude (DMS)**	**Latitude (DMS)**	**Area (km^2)**	Rank
1	52° 54' 53.998" W	67° 16' 25.644" N	141.3	28
2	52° 57' 24.491" W	66° 31' 46.302" N	27.1	4
3	53° 3' 4.640" W	66° 30' 33.091" N	55.5	25
4	52° 30' 24.524" W	66° 31' 5.529" N	74.7	22
5	53° 9' 46.389" W	66° 16' 12.182" N	49.1	20
6	53° 20' 51.351" W	66° 1' 1.811" N	99.0	31
7	52° 52' 37.823" W	66° 1' 34.335" N	18.0	32
8	52° 51' 49.512" W	65° 55' 10.346" N	24.2	49
9	51° 48' 24.817" W	65° 58' 18.651" N	22.2	7
10	51° 45' 21.734" W	65° 57' 0.941" N	20.5	3
11	52° 14' 8.037" W	65° 52' 41.164" N	35.5	9
12	52° 39' 47.074" W	65° 47' 16.957" N	54.5	47
13	52° 51' 9.187" W	65° 47' 14.456" N	26.8	41
14	52° 59' 28.640" W	65° 44' 41.554" N	22.6	18
15	53° 4' 21.634" W	65° 32' 13.981" N	46.8	46
16	52° 45' 20.846" W	65° 34' 34.805" N	23.3	37
17	52° 23' 15.121" W	65° 33' 56.128" N	45.0	28
18	52° 26' 11.563" W	65° 30' 29.413" N	33.7	15
19	52° 13' 33.296" W	65° 28' 3.385" N	27.5	38
20	52° 13' 14.369" W	65° 19' 11.012" N	76.2	41
21	50° 28' 30.072" W	64° 8' 42.099" N	158.9	33

22	50° 29' 34.053" W	64° 8' 45.137" N	64.0	40
23	50° 53' 3.599" W	64° 5' 43.627" N	37.4	30
24	51° 1' 27.549" W	64° 4' 34.004" N	95.9	45
25	50° 58' 16.168" W	63° 54' 4.773" N	300.1	2
26	51° 8' 35.757" W	63° 51' 36.630" N	102.9	11
27	50° 46' 59.229" W	63° 23' 4.918" N	7174.0	16
28	50° 21' 32.634" W	63° 24' 41.692" N	9.4	6
29	50° 20' 4.411" W	63° 24' 15.399" N	23.3	1
30	50° 12' 35.106" W	63° 22' 31.426" N	29.3	26
31	50° 33' 43.982" W	63° 21' 34.876" N	52.0	4
32	50° 46' 10.047" W	63° 14' 53.754" N	74.8	13
33	50° 33' 34.100" W	63° 13' 20.241" N	146.7	38
34	49° 46' 31.451" W	63° 3' 25.837" N	196.1	55
35	49° 46' 55.130" W	63° 3' 6.924" N	78.3	9
36	49° 48' 41.589" W	62° 59' 32.397" N	279.5	7
37	49° 54' 26.312" W	62° 51' 52.635" N	359.6	17
38	49° 17' 0.593" W	62° 15' 42.504" N	1782.7	14
39	48° 57' 18.355" W	62° 8' 3.850" N	133.1	47
40	48° 3' 20.765" W	61° 19' 0.786" N	302.3	12
41	47° 54' 51.525" W	61° 19' 7.915" N	22.1	56
42	47° 51' 53.120" W	61° 6' 13.053" N	43.6	41
43	47° 30' 11.379" W	60° 58' 52.730" N	937.7	54
44	47° 3' 6.043" W	60° 58' 15.711" N	20.2	57
45	46° 56' 35.348" W	60° 57' 3.614" N	49.8	58
46	46° 24' 44.886" W	61° 4' 15.650" N	54.9	18
47	46° 23' 24.711" W	61° 4' 37.222" N	61.4	23
48	46° 17' 4.231" W	61° 4' 52.772" N	37.0	41
49	46° 1' 51.845" W	61° 13' 9.211" N	172.2	24
50	45° 7' 20.968" W	60° 43' 34.221" N	513.2	33
51	45° 4' 43.531" W	60° 38' 52.781" N	141.9	53
52	44° 48' 4.687" W	60° 40' 19.256" N	44.2	27
53	44° 40' 26.825" W	60° 43' 26.268" N	27.7	20
54	44° 35' 6.849" W	60° 45' 7.034" N	23.3	33
55	44° 45' 1.206" W	60° 37' 34.288" N	77.5	52
56	44° 28' 30.725" W	60° 31' 18.855" N	38.6	36
57	44° 32' 26.472" W	60° 26' 50.671" N	53.2	51
58	44° 43' 32.945" W	60° 15' 58.903" N	225.0	50

Table 6a. *The 58 locations with ID, catchment size and rank.*

ID	Longitude (DMS)	Latitude (DMS)	Area (km^2)	Rank
29	50° 20' 4.411" W	63° 24' 15.399" N	23.3	1
25	50° 58' 16.168" W	63° 54' 4.773" N	300.1	2
10	51° 45' 21.734" W	65° 57' 0.941" N	20.5	3
2	52° 57' 24.491" W	66° 31' 46.302" N	27.1	4
31	50° 33' 43.982" W	63° 21' 34.876" N	52.0	4
28	50° 21' 32.634" W	63° 24' 41.692" N	9.4	6
9	51° 48' 24.817" W	65° 58' 18.651" N	22.2	7
36	49° 48' 41.589" W	62° 59' 32.397" N	279.5	7
11	52° 14' 8.037" W	65° 52' 41.164" N	35.5	9
35	49° 46' 55.130" W	63° 3' 6.924" N	78.3	9
26	51° 8' 35.757" W	63° 51' 36.630" N	102.9	11
40	48° 3' 20.765" W	61° 19' 0.786" N	302.3	12
32	50° 46' 10.047" W	63° 14' 53.754" N	74.8	13
38	49° 17' 0.593" W	62° 15' 42.504" N	1782.7	14
18	52° 26' 11.563" W	65° 30' 29.413" N	33.7	15
27	50° 46' 59.229" W	63° 23' 4.918" N	7174.0	16
37	49° 54' 26.312" W	62° 51' 52.635" N	359.6	17
14	52° 59' 28.640" W	65° 44' 41.554" N	22.6	18
46	46° 24' 44.886" W	61° 4' 15.650" N	54.9	18
5	53° 9' 46.389" W	66° 16' 12.182" N	49.1	20
53	44° 40' 26.825" W	60° 43' 26.268" N	27.7	20
4	52° 30' 24.524" W	66° 31' 5.529" N	74.7	22
47	46° 23' 24.711" W	61° 4' 37.222" N	61.4	23
49	46° 1' 51.845" W	61° 13' 9.211" N	172.2	24
3	53° 3' 4.640" W	66° 30' 33.091" N	55.5	25
30	50° 12' 35.106" W	63° 22' 31.426" N	29.3	26
52	44° 48' 4.687" W	60° 40' 19.256" N	44.2	27
1	52° 54' 53.998" W	67° 16' 25.644" N	141.3	28
17	52° 23' 15.121" W	65° 33' 56.128" N	45.0	28
23	50° 53' 3.599" W	64° 5' 43.627" N	37.4	30
6	53° 20' 51.351" W	66° 1' 1.811" N	99.0	31
7	52° 52' 37.823" W	66° 1' 34.335" N	18.0	32
21	50° 28' 30.072" W	64° 8' 42.099" N	158.9	33
50	45° 7' 20.968" W	60° 43' 34.221" N	513.2	33
54	44° 35' 6.849" W	60° 45' 7.034" N	23.3	33
56	44° 28' 30.725" W	60° 31' 18.855" N	38.6	36
16	52° 45' 20.846" W	65° 34' 34.805" N	23.3	37
19	52° 13' 33.296" W	65° 28' 3.385" N	27.5	38
33	50° 33' 34.100" W	63° 13' 20.241" N	146.7	38
22	50° 29' 34.053" W	64° 8' 45.137" N	64.0	40
13	52° 51' 9.187" W	65° 47' 14.456" N	26.8	41
20	52° 13' 14.369" W	65° 19' 11.012" N	76.2	41
42	47° 51' 53.120" W	61° 6' 13.053" N	43.6	41
48	46° 17' 4.231" W	61° 4' 52.772" N	37.0	41

24	51° 1' 27.549" W	64° 4' 34.004" N	95.9	45
15	53° 4' 21.634" W	65° 32' 13.981" N	46.8	46
12	52° 39' 47.074" W	65° 47' 16.957" N	54.5	47
39	48° 57' 18.355" W	62° 8' 3.850" N	133.1	47
8	52° 51' 49.512" W	65° 55' 10.346" N	24.2	49
58	44° 43' 32.945" W	60° 15' 58.903" N	225.0	50
57	44° 32' 26.472" W	60° 26' 50.671" N	53.2	51
55	44° 45' 1.206" W	60° 37' 34.288" N	77.5	52
51	45° 4' 43.531" W	60° 38' 52.781" N	141.9	53
43	47° 30' 11.379" W	60° 58' 52.730" N	937.7	54
34	49° 46' 31.451" W	63° 3' 25.837" N	196.1	55
41	47° 54' 51.525" W	61° 19' 7.915" N	22.1	56
44	47° 3' 6.043" W	60° 58' 15.711" N	20.2	57
45	46° 56' 35.348" W	60° 57' 3.614" N	49.8	58

Table 7b. *The same 58 locations as Table 6a, but listed according to rank.*

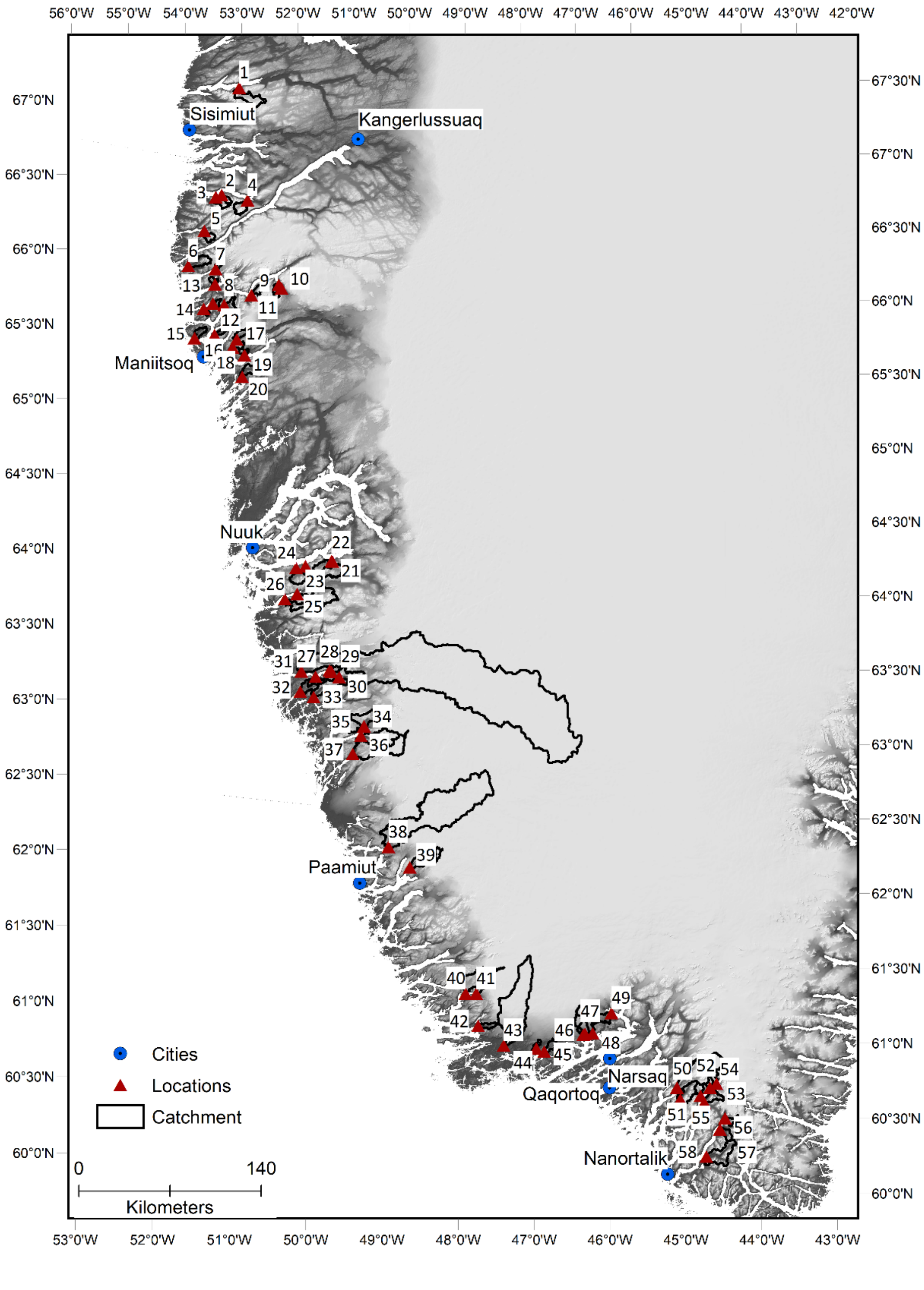

Figure 18. *Overview map showing the selected locations location (black triangles) and their catchments (as a black line). Numbers refer to the ID in Table 6 and 6b.*

8. References

Ahlstrøm, A.P., C.N. Albers, S.B. Andersen, C.S. Andresen, D. van As, M. Citterio, R.S. Fausto, K. Hansen, B. Hasholt, A.R. Johnsen, K.K. Kjeldsen, A.M. Solgaard (2018): Greenland Ice Cap Water, Technical Report on five potential locations for meltwater export, Geological Survey of Denmark and Greenland Report 2018/29.

Ahlstrøm, A.P., C.N. Albers, S.B. Andersen, C.S. Andresen, D. van As, M. Citterio, P. Gravesen, A.R. Johnsen (2016): Kriterier for udpegning af lokaliteter til eksport af smeltevand fra gletsjere i Grønland, Geological Survey of Denmark and Greenland Report 2016/32.

Aschwanden, A., E. Bueler, C. Khroulev and H. Blatter (2012): An enthalpy formulation for glaciers and ice sheets, Journal of Glaciology 58(209), 441-457.

Bueler, E, and J. Brown (2009): Shallow shelf approximation as a "sliding law" in a thermodynamically-coupled ice sheet model, Journal of Geophysical Research - Earth Surface, 114, F03008, doi:10.1029/2008JF001179.

Citterio, M., and A. Ahlstrøm (2013): *Brief communication:* The aerophotogrammetric map of Greenland ice masses, The Cryosphere, *7*(2), 445–449, doi:10.5194/tc-7-445-2013.

Ettema, J., M.R. van den Broeke, E. van Meigaard, W.J. van de Berg, J.L. Bamber, J.E. Box and R.C. Bales (2009): Higher surface mass balance of the Greenland ice sheet revealed by high-resolution climate modeling, Geophys. Res. Lett., 36, L12501, doi:10.1029/2009GL038110.

Howat, I. M., A. Negrete, and B. E. Smith (2014): The Greenland Ice Mapping Project (GIMP) land classification and surface elevation data sets, The Cryosphere, 8, 1509–1518, doi:10.5194/tc-8-1509-2014.

Korsgaard, N. J., C. Nuth, S. A. Khan, K. K. Kjeldsen, A. A. Bjørk, A. Schomacker, and K. H. Kjær (2016): Digital elevation model and orthophotographs of Greenland based on aerial photographs from 1978-1987, Scientific Data, 3, doi:10.1038/sdata.2016.32.

Mayer, C.J., C.E. Bøggild, O.B. Olesen and S Podlech (2003): Ice studies in relation to ice/water export, data collection, modelling and evaluation approach, Geological Survey of Denmark and Greenland Report 2003/6.

Pfeffer, W. T., Arendt, A. A., Bliss, A., Bolch, T., Cogley, J. G., Gardner, A. S., et al. (2014). The Randolph Glacier Inventory: a globally complete inventory of glaciers. *Journal of Glaciology*, *60*(221), 537–552. https://doi.org/10.3189/2014JoG13J176

Reeh, N., H. Oerter and H.H. Thomsen (2002): Comparison between Greenland ice-margin and ice-core oxygen-18 records. Annals of Glaciology, 35, 136–144.

Steenfelt, A. (1999): *Compilation of data sets for a geochemical atlas of West and South Greenland based on stream sediment surveys 1977 to 1997*, Geological Survey of Denmark and Greenland Report 1999/41.

Winkelmann, R., Martin, M. A., Haseloff, M., Albrecht, T., Bueler, E.,Khroulev, C. and Levermann, A. (2011): The Potsdam Parallel Ice Sheet Model (PISM-PIK) Part 1: Model description, The Cryosphere, 5, 715–726.