DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2003/62

Glaciological observations at the Qorlortorsuaq glacial lake, S-Greenland

Potential hazard and water ressource assessment

Christoph Mayer

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1. Summary

At Qorlortorssup tasia in S-Greenland, the site of a projected hydropower station, a sudden rise in water level was connected with the breach of a glacier dammed lake in the upstream basin. In order to assess potential hazards, but also a possible future water contribution due to the new situation, the glacial lake and its surroundings have been visited and a number of measurements have been carried out. The subsequent analysis resulted in a number of conclusions.

The lake very likely was generated in the first decades of the last century due to the recession of the ice cap in this area. Due to the high glacial dam in the West, the lake drained over a shallow rock barrier towards Sermeq kangigdleq. Since that time the damming glacier was separated from major mass input which, because the equilibrium line altitude in this area is higher than the glacier surface, lead to a continuous shrinking. The flood was initiated after the glacier surface was low enough to allow drainage of the water over the glacier towards Qorlortorssup tasia basin. The overflow lead to the creation of a gully through the glacier which finally resulted in the drainage of approx. 55Mio m^3 of water over a period of 8-10 days. Due to the large retention potential of the Qorlortorssup tasia basin and the temporal retardation of the flood, there was no serious threat for the farm situated downstream.

In the future only minor floods, due to partial closure of the gully by ice movement or snow drift, can be expected. As the recession of the glacier will continue under the current climate conditions, the potential floods will become even smaller. The new drainage pattern into Qorlortorssup tasia basin, however, will be a permanent situation. The amount of this new water contribution can only be very roughly estimated, until more information is collected.

2. Introduction

The locality of Qorlortorsuaq is the projected site for a hydropower plant, which is aimed to supply the town of Qaqortoq and Narsaq with energy, within a few years time. Water supply for this power plant comes from an almost glacier-free drainage basin upstream of Amitsuarssuk fjord, a north-eastern tributary of Lichtenau fjord. In the drainage basin there exist several lakes. One of them (Qorlortorssup tasia) draining over a large casacade (Qorlortorsuaq, "Store Vandfall"), the projected power plant site, will be used as the water reservoir.

The north-eastern border of the drainage area constituted of a local glacier (1AE0001), which dammed a roughly 2.24 km^2 lake (1985), nourished mainly by glacial melt water from the adjacent ice cap (Fig. 1). This glacial dammed lake used to discharge over a small rock ridge at its northern margin into the adjacent Sermeq kangigdleq (1AF0802). During a visit of GEUS glaciologists in 1992 it was recognised that the threshold of the local glacier, preventing the lake to empty into the Qorlortorssup tasia basin, was about 20m above the lake level (Ole B. Olesen, GEUS rapport 02.03.1999). According to these investigations the glacial dam has receeded about 800-1000m from 1942 until 1985.

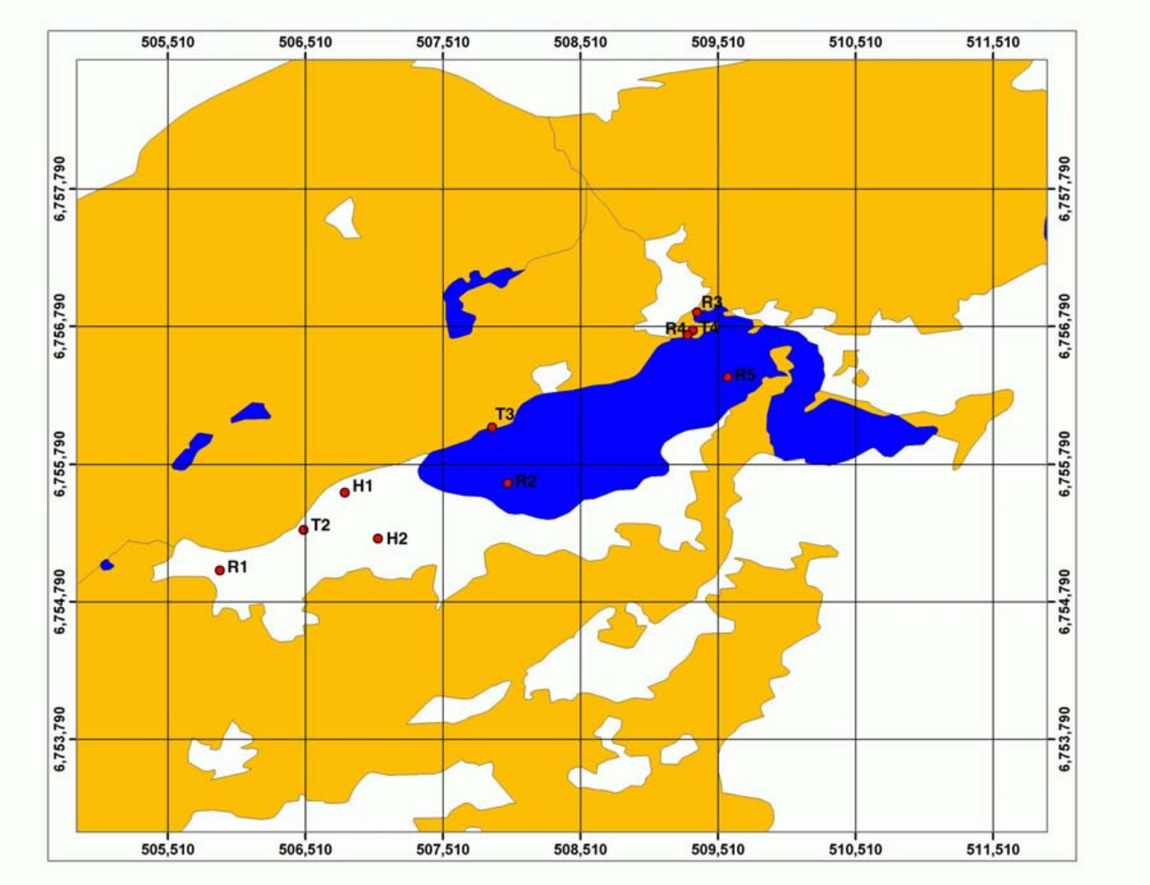

Fig. 1: Qorlortorsuaq ice dammed lake before the outbreak, according to the electronically available GEUS/KMS map (UTM N23, WGS84). The general map based on geographical information from 1953, analysed and compiled in 1:250000 map sheets. The source of the displayed lake boundary is from 1985. Measurement positions from the recent visit are indicated. The G/250 vector map basis is copyright by KMS, 1998. Colour code: yellow: land, white: ice, blue: lakes

During week 27 a strong increase of water transport was observed at Store Vandfall, resulting in a partial flooding of nearby sheep farm fields. A first helicopter reconnaisance on 2nd of July revealed that the glacial dam was penetrated and the lake water now flowing into the Qorlortorssup tasia basin. As a result the lake level of Qorlortorssup tasia was rising by more than half a meter, increasing the outflow over the cascade dramatically. In order to evaluate the potential dangers and also the further consequences of this breach in the ice dam, a site visit for a glaciological assessment was organised by Greenland Resources on short notice.

3. Field visit, measurements and additional information

A first overview of the situation was given during a short visit by helicopter on the 9th of July, followed by more thorough investigations on the following day. Compared to photographs from the 2nd of July, the trench through the glacier had deepened considerably and the outflow of water seemed to slowly approach balance with the inflow to the lake. This also is in agreement with observations from the visit on the second day, where no indications were observed for a considerable further lowering of the lake level. The old drainage site and its surroundings were found high above the new lake level. The water level at Qorlortorssup tasia, however, was still declining at this time.

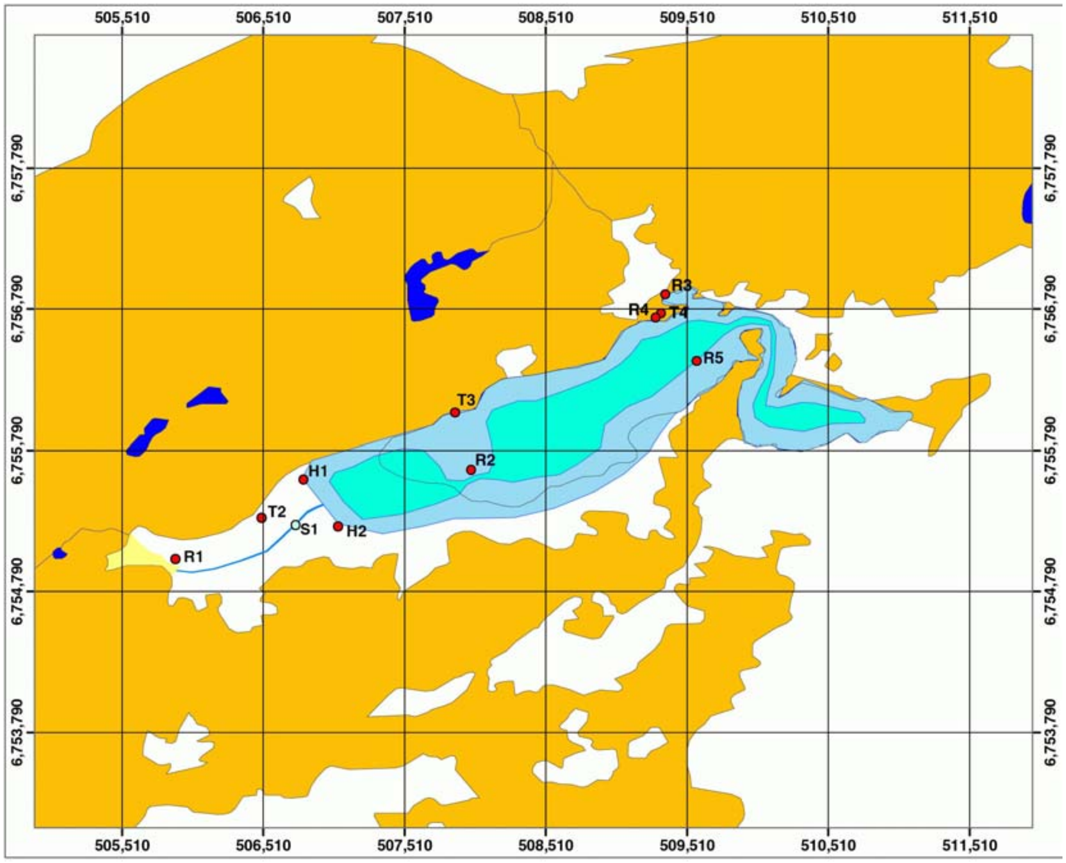

Fig. 2: New situation at the Qorlortorsuaq ice lake: The maximum extent of the lake before the outbreak is given in light blue. The greenish colour describes the approximate conditions during the visit at the lake. The glacier area which is marked with light yellow close to R1 has collapsed during the flood. In addition to the terrestrial measurement positions also the site of the gully depth measurement is given (S1). The basis of the map is the same as for Fig. 1.

2.1 Measurements

On the basis of this first reconnaissance, several measurements have been planned for the 2nd visit, the day after. Most importantly the reason for the breach and associated potential dangers should be assessed. In addition to a general survey of the situation, measurements of several positions of the new glacier geometry and lake geometry have been carried out using a combination of GPS and terrestrial survey methods. In expectation of a future aerial photogrammetric survey, several of the used GPS locations have been marked with red and white colour. Identification of this locations on the aerial photographs will allow a better geocoding of the images. These control points have been established on a nunatak close to the exit of the new water drainage from the glacier (R1), a prominent rock on a former peninsula close to the old drain and on a moraine ridge now dividing the lake in two parts (for locations see Figs. 1 and 2). This marked positions have been connected by a terrestrial survey, including also the now highest point of the northern glacier part, two positions at the old lake shore, one position at the new lake shore and the deepest location of the former drain. An overview of all the measurements at the glacier is given in the Appendix. The depth of the new gully, which now conducts the lake water toward Qorlortorssup tasia, was measured from the hovering helicopter (location S1 in Fig. 2) with a rope and an attached stone down to the water level. Ground based measurements close to the gully edge are too dangerous, which was testified by the collapse of part of the southern gully wall between the two visits.

2.2 Accuracy

The location accuracy of the GPS measurements lies within 5-10 m and fits very well with the related features in the map (G/250 vector copyright: KMS, 1998). The distances of the triangulation should be better than a few centimeters, whereas the vertical measurements are afflicted with refraction uncertainties. A comparison of the independent measurements of the old lake shore at two different positions (T3, R4), relative to a fixed point (R2) showed a difference of only 25 cm over a distance of 1600 m. Therefore, the accuracy of the vertical measurements can be estimated to a maximum of 25-30 cm. The gully depth measurement is affected from the uncertain height of the helicopter over the ice surface. The given value of 48.5 m, however, should be accurate within 2m. The uncertainty of the new lake surface areas and associated volumes due to errors in extrapolation is estimated to be 20%.

2.3 Supplemental information

In addition to the measurements at the lake, a number of pictures have been taken from the shore and from the helicopter. These pictures have been compared with aerial photographs from 1942, the available electronic map, which is based (in this area) on information from 1985 and a Landsat-5 scene from 1993.

4. Actual situation and accompanied changes

The visit at the ice-lake happened a bit more than a week after the onset of the flooding. At that time the outflow from the lake into the Qorlortorssup tasia basin was still higher than the normal discharge, which could be expected from the upstream glacial basin. The outflow of the water now occurs through a gully in the damming glacier which is about 1200 m long, 10-15 m wide and at maximum almost 50 m deep.

3.1 Historical information

According to the analysis of available images and maps, the lake evolved from about 1.7 km^2 in 1942 to 2.25 km^2 in 1985. During the same time the glacial front retreated a mean distance of 1000 m, which was followed by a further retreat of 600 m in the last 18 years. The final maximum extent of the lake was then 2.9 km^2, which left a glacier length of 1100 m to prevent the lake from draining into the Qorlortorssup tasia basin.

During the visit in 1992 the ice wall above the lake was still 20 m higher than the lake level. The new measurements have shown that the glacier surface melted down to the lake surface level in the last 11 years, which represents a netto mass balance of –1.8 m per year. The highest point of the northern margin of the glacier is only 2.4 m above the lowest point of the former outlet, or 1.8 m above the lake level before the flood. Measurements closer to the gully and thus the center of the glacier have not been possible due to security reasons, but it is obvious from a visible survey that the glacier surface is at least 2 m lower in the central part than at its northern margin.

Fig. 3: Aerial view of the lake after the outbreak. The moraine ridge in the image centre now divides the lake in two parts, with a difference in water surface level of about 12 m. On the left of the image, snow and ice which covered this part of the lake earlier is now draped over the andscape. On the southern waterside (here the upper right shore) the old lake level is visible as the boundary line between ice and bare rock

3.2 Recent conditions

At the time of the visit, the former lake basin basically was divided into two lakes (Figs. 2 and 3). The level of the larger, main lake is now 27 m below the old lake level. The uppermost part of the old lake, close to the ice margin of the ice cap, is divided into several smaller ponds, which are situated a few metres higher than the main lake (Fig. 4). The front of the ice cap in this area is about 1.2 km wide.

Fig. 4: Upper part of the former lake which now consists of a number of small ponds. The ice front adjacent to the ponds represents the main input region from the upstream ice cap.

From the analysis of pictures taken during the visit it can be concluded that the smaller ones of the new lakes, bordering the glacier dam, is roughly 12 m below the main lake. The difference in lake levels can clearly be recognised along the small stream in Fig. 3. The height difference between this lake and the deepest part of the glacier gully therefore is about 10m. As can bee seen from Fig. 5, there is a small cascade at the entrance of the gully, where the water plunges down over a still glaciated bed. If there is no bedrock or morainic threshold below the ice, the lake level of the smaller lake potentially could reduce another ten metres, due to further basal erosion/melting of the ice bed.

Fig. 5: The uppermost part of the gully, with the small cascade at its beginning. The lake bottom in this area still consists of glacier ice. In the left part of the image the change in surface conditions between last years lake extent and the recently flooded glacier surface is easily distinguishable.

The water depth of the first 100-200 m of the lake at the glacier margin seemd to be only a few metres (smooth white area in Fig. 5). This indicates that the melting of the glacier through lake water was only very gradual.

The deepest part of the gully is only a few metres higher than the water level at the glacier outlet. Also, the river in the ice gully runs already over bedrock for more than half of the gully length, as could be observed from the helicopter. A further decline in the lake level of more than the 10 m mentioned above, therefore, cannot be expected.

The remaining size of total lake surface at the time of the visit reduced to 1.18 km^2 (a reduction of almost 60% in respect to the maximum extent), where the smaller, lower lake accounts for 0.25 km^2. The total amount of water discharged within these 8-10 days since the onset of the flood was estimated to be about 55Mio m^3. In case of a further erosion of the gully entrance, accompanied by a potential reduction of the lower lake level of 10m, another 2Mio m^3 would be discharged during the recent days. After that the minimum extent of the lakes will be reached and the outflow will be reduced to a normal level. Even for the maximum of the given value (10 m additional lowering), this state will be reached within the next one or two weeks. Much smaller amounts of excess water can still be expected from the melting of ice blocks breaking off the gully walls also in the future.

5. Evaluation of the breakout event

After revising all the available material about the Qorlortorsuaq glacial lake, the following scenario very likely has happened:

4.1 Lake evolution

Observed trim lines in the area show that during the last maximum ice extent, towards the end of the 19th century, the entire lake basin was filled with a glacier, which was up to 100 m higher than the modern gacier surface (Fig. 6). At that time this glacier drained into the Qorlortorssup tasia basin, as well as into the adjacent Sermeq kangigdleq. During the onset of the general retreat of ice masses in S-Greenland at the beginning of the last century, drainage through the wide gap in the mountain range into Sermeq kangigdleq led to a shut down of the Qorlortorsuaq tributary and a subsequent surface lowering in the recent lake area. As soon as the ice flow over the rock threshold into Sermeq kangigdleq, due to further melting and retreat, was considerably reduced, the lake generation began. This happened most probably during the first two decades of the last century. In 1942, the lake already was about 60% of its latest maximum size.

Fig. 6: Gully through the damming local glacier. The nunatak to the lower left was used as reference point. The flooded area and the creation of erosion channels is detecable to the right of the gully. At the mountain side at the left, the trim line of the last maximum glaciation (end of 19th century) can be recognized.

As the local glacier, which dammed the lake, had no input from the ice cap anymore, it started to melt down inevitably, because the equilibrium line altitude in this area is about 200 m higher than the modern glacier surface. During winter there is still some extra mass input through avalanches from the mountain ridge to the South, but this is obviously not enough to keep the glacier in balance. As stated earlier, in 1992 the glacier surface was only 20 m above the lake level, which was defined by the outlet towards Sermeq kangigdleq. During the last eleven years this threshold vanished due to melting.

4.2 Flood generation

Very probably during the last days of June this year, the water started to drain over the glacier towards Qorlortorssup tasia. This first happened on a rather broad strech of the glacier (approx. 100 m) as can be seen in Fig. 6. The water flow subsequently concentrated to a few erosion channels, which finally were united into one stream. It is believed that this process of stream concentration, where only minor amounts af water were involved, took only a few days, as the surface of the glacier consisted of soft firn. As soon as there was a considerable flow of water reached, the channel started to erode from the lowest point, where the stream flow was fastest. The concentration of water flow into one channel eventually reached the lake shore and further erosion/melting of the channel accelerated the process of a retrograde creation of the gully. At the time of the visit the gully streched over the entire length of the glacier (Fig. 6) and the water at the lake margin plunged down into the gully already at the lake margin. From there it continued through the glacier with no large gradient of the stream bed. As the gully is only 10-15 m wide and it was created gradually, the drainage of the lake was temporally distributed over at least 10 to 14 days.

6. Conclusions on potential hazards and future development

As already stated in the last paragraph, the eventual breakout of the lake into the Qorlortorssup tasia basin was, under the given climatic conditions, inevitable. This was also metioned in the report of O. B. Olesen from 2nd March, 1999.

5.1 Actual hazard situation

Due to the still considerable length of the glacier (approx. 1100 m), a catastrophic breakout by a total breach of the damming ice wall or an isostatic uplift of the ice mass was prevented. Instead, the retrograde erosion of the drainage gully assured an increasing, but continuous discharge of lake water. The retention potential of the Qorlortorssup tasia basin, which measures 23 km from the glacier to the lake was large enough to further alleviate the flood. This circumstances finally resulted in an increased water level of almost 1m in Qorlortorssup tasia for a period of several days. There have been only minor damages observed at a protection wall of the already existing small hydropower station. The neighbouring farm itself was at no time seriously threatended by the flood.

5.2 Potential future conditions

At the time being, the water discharge from the glacier lake should already have been returned to normal values. With the current state of knowledge, this also will remain so until the end of the summer. Even if there are intermediate blockages through ice coming off the gully wall, this will only result in very minor fluctations of the water discharge. During the coming winter the water discharge will eventually stop due to the cold temperatures and thus no melt water production. At that time there will be no erosional force (water flow) remain in the gully, preventing it from closure. Ice is a viscoplastic material, which deforms readily under pressure. A simple evaluation of the geometry of the gully, prevailing ice conditions (close to the melting point) and the realistic assumption of simple shear ($\dot{\varepsilon}_x = \dot{\varepsilon}_y = 0$) show that the shear strain rate in the gully is high enough to close the lowermost 15 m of the gully in the deepest stretch. The shear strain rate is connected to the shear stress through the Arrhenius type flow law for ice:

$$\dot{\varepsilon}_{xz} = A\tau^{n}_{xz},$$

where A=6.8x10^{-15} s^{-1} (kPa)$^{-3}$ at T= 0 °C and n = 3. This, however, means that only the lower, smaller lake would be affected by the closure. A subsequent maxium water level during the next melt period would still be 9 m below the level of the main lake. Assuming the same erosion/melting mechanics as have been observed this year, the resulting maximum excess of 2-3Mio km^3 water, retained by the closed gully, would be released over a period of several days next summer. This would only result in a minor increase of water discharge over the Store Vandfall at that time. Melt generated floods from the glacial lake should then continuously decrease in the following years, under the prevailing climatic conditions. The glacier itself will then eventually dissapear, or being reduced to a perennial snowfield below the southern mountain ridge within the next 25-30 years.

Still, due to uncertainties in observations, a risk of minor hazards down at Qorlortorssup tasia cannot be entirely excluded. One unknown process is snow drift during the winter, which could close the gully to a rather high level. It is believed that, after the start of the melt season, water would rather fast penetrate through the snow pack in the gully and melt its way down to the ice level. But this cannot be guaranteed.

The lower end of the glacier itself and the edges of the gully will remain a dangerous area, especially during late spring. Constructive protection of future installations at Store Vandfall against the mentioned smaller floods are highly recommended.

Fig. 7: Oblique aerial photograph from July 1942. The lake can be seen in the left middle part of the image. At that time it was clearly smaller than in 1985. A considerable part of the ice cap seen on the picture could potentially drain into the ice lake basin.

Before the breach of the glacier, the contribution of this area to the Qorlortorssup tasia basin consisted only of rather small amounts of meltwater from the local glacier (a few 10^5 m^3/year). Now, the entire drainage basin on the ice cap, upstream of the glacial lake, drains into the Qorlortorssup tasia basin. Earlier estimates resulted in an annual contribution of roughly 14Mio m^3. If the ice cap would be in steady state (which it is very probably not), and the estimation of the drainage basin in the Glacier inventory of West Greenland is correct (which is also questionable), then the contribution would be even a factor three higher. The oblique aerial photograph from 1942 (Fig. 7) shows that possibly a substantial area of the ice cap drains through the now 1200 m wide ice margin into the ice lake area. How large the contribution is and, for hydropower considerations equally important, how long this will be maintained, cannot be answered with the current state of knowledge.

7. Further recommendations

The observed flood from the ice lake during July this year was decidedly larger as what can be expected during the coming years. Therefore, the hazard situation in the Qorlortorssup tasia area is rather small. Constructive protection, as mentioned above, however is highly recommended for future installations close to the river. A monitoring station, measuring the lake level in the lower glacial lake, could be very valuable, in order to prevent surprises.

Besides that, the positive effect of an extra water supply for a potential hydropower plant should not be underestimated. This contribution could amount to 30-50% of the existing discharge. Also, the buffering effect of glacial melt water during summer months could have positive implications on the concept of the hydropower plant. At the moment, however, it is not clear how much water and for how long it will drain into this basin. The surface of the ice cap in this area is rather flat and no distinct water shed can be readily observed, between the glacial lake basin and Sioragdlip Sermia to the South. In order to solve this problem a detailed digital terrain model (DTM) of at least the lower ice cap area is required. With such a DTM in hand, a first estimate of the actual discharge can be made and eventually be compared to discharge measurements at the terminus of the damming glacier.

In order to evaluate the long term water contribution from the ice cap to the glacial lake basin, a more intensive glaciological investigation is required. The state of balance of this part of the ice cap needs to be established, melting areas, the equilibrium line altitude and the ice flow identified. Such a project would require the installation of two climate stations and a small stake network for a period of minimum three years. Some additional investigations, like velocity measurements with GPS, radar measurements of the ice thickness, snow pits and the analysis of recent satellite images would be required.

The glaciology team at GEUS readily would design and conduct such an investigation, if such a decision should be made. A first and very rough estimate of costs for a three year period, including field trips and material would be 500000.- DKK. A detailed project proposal could be delivered in short time, if such a project is envisaged by the respective authorities.

Appendix:

Table of all measurements and derived values during the field visit at the Qorlortorsuaq glacial lake.

1. GPS Positions:

Source	name	Marking	lon-dec	lat-dec	UTM-x (zone 23, WGS84)	UTM-y
WP2	Qaqortoq	no	-46.02995	60.71572	443798.74	6731564.23
WP3	R1	yes	-44.89132	60.93022	505890.94	6755019.86
WP4	T2	no	-44.88008	60.93285	506499.66	6755313.86
WP5	T3	no	-44.85477	60.93948	507869.82	6756055.11
WP6	T4	yes	-44.82782	60.94577	509328.36	6756759.24
WP7	R3	yes	-44.82725	60.94697	509358.89	6756892.28
Heli1	H1	no	-44.87458	60.93528	506797.24	6755585.08
Heli2	H2	no	-44.87012	60.93227	507039.62	6755250.29
Heli3	R2	yes	-44.85268	60.93587	507983.98	6755653.27

Position descriptions:

Qaqortoq: center of heli pad

T1: At the eastern margin of the nunatak on the snow

T2: Highest point of the glacier, at its northern margin, close to a "valley" between glacier and adjacent hill (probably 30m deep)

T3: On the northern shore of the old lake level, marked by the first cracks in the remaining lake-ice/snow cover, NW end of the moraine dividing the basin now in two lakes

T4: Highest point of a peninsula in the former lake, close to the original drain

R1: Top of nunatak in the western end (northern part) of the glacier, altimeter 950m a.s.l.

R2: prominent rock on the center of the moraine ridge diving the remaining lake in two parts

R3: Lowermost (central) point of the original lake drain

R4: Old lake level S of T4, on the remaining snow surface

R5: New lake level at a peninsula opposite of (South) T4

H1: NW edge of the recent glacier extent, former triple point glacier, lake, shore

H2: SE edge of the recent glacier extent, former triple point glacier, lake, shore

Measurement of the gorge depth at its, estimated, deepest point:

S1	50.7 m, from helicopter window, skids about half a meter above the ice
	48.5 m,corrected

2. Surface survey:

Theodolite measurements (total station)

2.1 Tripod heights (m):

T1	1.23
T2	1.50
T3	1.34
T4	1.45

2.2 Observations:

From	To	Hz (Grd)	V (Grd)	delta x (m)	delta h (m)	delta h corrected (m)
T1	R1				2.570	3.800
T2	R1	42.686	103.706	669.737	-38.474	-36.974
T2	R2	255.400	100.316	1529.110	-7.370	-5.870
T3	R2	204.968	100.836	406.334	-5.327	-3.987
T4	R3	4.600	104.870	138.999	-10.655	-9.205
T4	R4	247.020	112.492	49.317	-9.803	-8.353
T4	R5	163.936	105.540	423.576	-36.946	-35.496
T4	R2	246.394	100.524	1735.891	-14.042	-12.592

2.3 Calculated elevations, relative to the old lake drain R3:

T4	9.205	
R5	-26.291	new lake level
R4	0.852	old lake level
R2	-3.387	central transverse moraine
T3	0.600	old lake level
T2	2.483	highest point on glacier
R1	-34.491	
T1	-38.291	

2.4 Calculated UTM positions:

R4	509289.98	6756728.27
R5	509580.90	6756419.18