REPORT

Tsunami hazard analysis in Greenland

RUNUP MODELLING OF POTENTIAL TSUNAMIS FROM KIGARSIMA

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Client contact person:	Jens Jørgen Møller
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Project manager:	Finn Løvholt
Prepared by:	Finn Løvholt and Sylfest Glimsdal
Reviewed by:	Sylfest Glimsdal and Carl B. Harbitz

NORWEGIAN GEOTECHNICAL INSTITUTE
NGI.NO

Main office
PO Box 3930 Ullevaal St.
NO-0806 Oslo
Norway

Trondheim office
PO Box 5687 Torgarden
NO-7485 Trondheim
Norway

T 22 02 30 00
NGI@ngi.no

BIC NO. DNBANOKK
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ORGANISATION NO.
958 254 318MVA

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Executive Summary

GEUS has recently discovered a potentially unstable rock slope named Kigarsima located in the Uummannaq fjord system with relatively large downslope motions. The average motion of the entire Kigarsima slope is about 1 m per year. The volume of Kigarsima is roughly estimated to 20-30 Mm^3, which is slightly smaller than the 2017 Karratfjord landslide, still large enough to pose a significant threat related to tsunami impact towards the Uummannaq fjord settlements. Hence, it is important to understand the tsunamigenic potential of a possible rock slope failure and subsequent avalanche, and to quantify the possible consequential inundation heights in potentially affected villages along the Uummannaq fjord system.

NGI has therefore been contracted by GEUS to investigate the tsunami threat posed by these unstable rock slopes in case of a catastrophic failure. In this report, potential rock avalanche tsunami hazard is quantified at the sevn coastal villages Qaarsut, Niaqornat, Uummannaq, Saattut, Ukkusissat, Ikerasak, and Illorsuit. For each of these sites, the hazard is quantified through inundation maps. The probability of occurrence for the various scenarios are not assessed in this report.

Two scenarios for the Kigarsima landslide tsunami were modelled. These two scenarios (named Upper and Lower scenario) give for each location an estimated range of the run-up heights that may potentially be caused by the rock avalanche in the case of a future catastrophic failure, see Table below. The run-up heights in the Table are both without (Lower and Upper scenario) and with (Upper scenario) an added maximum tide level of 1.3 m.

Scenario	Qaarsut	Ukkusissat	Uummannaq	Saattut	Niaqornat	Ikerasak	Illorsuit
Lower scenario [m]	2-6	2-3	1-3	1-2	< 1.5	< 0.5	1.0-1.5
Upper scenario [m]	4-9	3-5	1-5	2-5	1-3	< 1	2-3
Upper scenario – high tide[m]	5-10	4-7	2-5	2-5	3-5	< 2	3-4
Arrival times [minutes]	13	5	15	14	15	22	14

The analysis shows that the tsunami impact can be significant for most of the villages, with the upper scenario estimates of the maximum tsunami run-up heights (with added high tide) ranging up to 10 m in Qaarsut, and 5-7 m in Uummannaq, Saattut, Ukkusissat, and Niaqornat, and up to 4 m in Illorsuit. For Ikerasak we find run-up estimates to be less than 2 m with very little inundation.

The highest inundation estimates for Qaarsut for the situation of added high tide shows that several buildings can be inundated here. A relatively large fraction of buildings is also inundated in Illorsuit. With added high tide, a limited number of buildings are also inundated by the tsunami in Uummannaq and Ukkusissat, while fewer buildings can be potential impacted by the tsunami without added tide. For Niaqornat, the effect of high tide is very important because this site is relatively flat and low lying, and hence about 2/3 of the houses can be inundated in the scenario with added tide, compared to no houses in the situation without added tide. For Ikerasak the modelling shows that no buildings are located within the modelled inundation zone.

As the modelling predicts several meter high tsunamis for most locations, it is stressed that the tsunami may still pose a significant threat to life and property also where buildings are not directly impacted.

Contents

Review and reference page

1 Introduction and background

GEUS has recently discovered a potentially unstable rock slope with relatively large downslope motions named Kigarsima located in the Uummannaq fjord system. The average motion of the entire Kigarsima slope is about 1 m per year. The volume of Kigarsima is roughly estimated to 20-30 Mm^3, which is slightly smaller than the 2017 Karratfjord landslide, still large enough to pose a significant threat related to tsunami impact towards the Uummannaq fjord settlements. Hence, it is important to understand the tsunamigenic potential of a possible rock avalanche, and to quantify the possible inundation heights in potentially affected villages along the Uummannaq fjord system.

NGI has therefore been contracted by GEUS to investigate the tsunami threat posed by these unstable rock slopes in case of a catastrophic failure. In this report, the potential rock avalanche induced tsunami hazard is quantified at seven coastal villages namely Qaarsut, Niaqornat, Uummannaq, Saattut, Ukkusissat, Ikerasak, and Illorsuit, through various inundation maps. Unless otherwise noted, the simulations are without added tide level. For the scenario that gives the highest run-up, we have estimated the run-up heights and inundated areas also with an added high tide of 1.3 m. The probability of occurrence for the various scenarios are not assessed in this report.

The work is performed by means of numerical modelling of the landslide dynamics, tsunami generation, propagation, and run-up. This modelling work has been conducted by NGI, in close collaboration with GEUS. GEUS has also provided NGI the necessary detailed topo-bathymetric data to carry out the analysis, as well as background data on past events. NGI has based the tsunami simulations employed for the hazard analysis here on hindcasts of several historical events in western Greenland. This includes previous simulations of the 2017 Karrat fjord tsunami (NGI, 2021) as well as simulations of the 1996 and 2000 Paatuut tsunamis (NGI, 2022, in final prep). For the hazard analysis carried out for the potential Kigarsima rock avalanche, we simulate tsunami generation for two different scenarios represented by two different landslide volumes with different sets of other rock avalanche parameters, respectively. These scenarios provide the basis for roughly estimating the tsunami run-up uncertainty range.

The report is organised as follows: Section 2 describes the study area and gives a brief overview of the main modelling assumptions in addition to a description of the rock avalanche scenarios. In Section 0 the results are presented, both as listed range of run-up heights for the rock avalanche scenarios, as well as hazard zones for selected parts of all locations. Concluding remarks are given in Section 4.

2 Study area, model setup, and scenarios

An overview of the Uummannaq fjord system study area is depicted in Figure 1, showing also the bathymetric water depth, the approximate area of landslide release, and the seven different locations for inundation modelling, namely:

- Qaarsut
- Niaqornat
- Uummannaq
- Saattut
- Ukkusissat
- Ikerasak
- Illorsuit

The modelling procedure presented in this report combines four modelling steps, from landslide dynamics, tsunami generation, propagation, to inundation. Individual inundation models are performed for all these six locations, applying high-resolution datasets near the settlement area to resolve the detailed inundation pattern to an adequate detail.

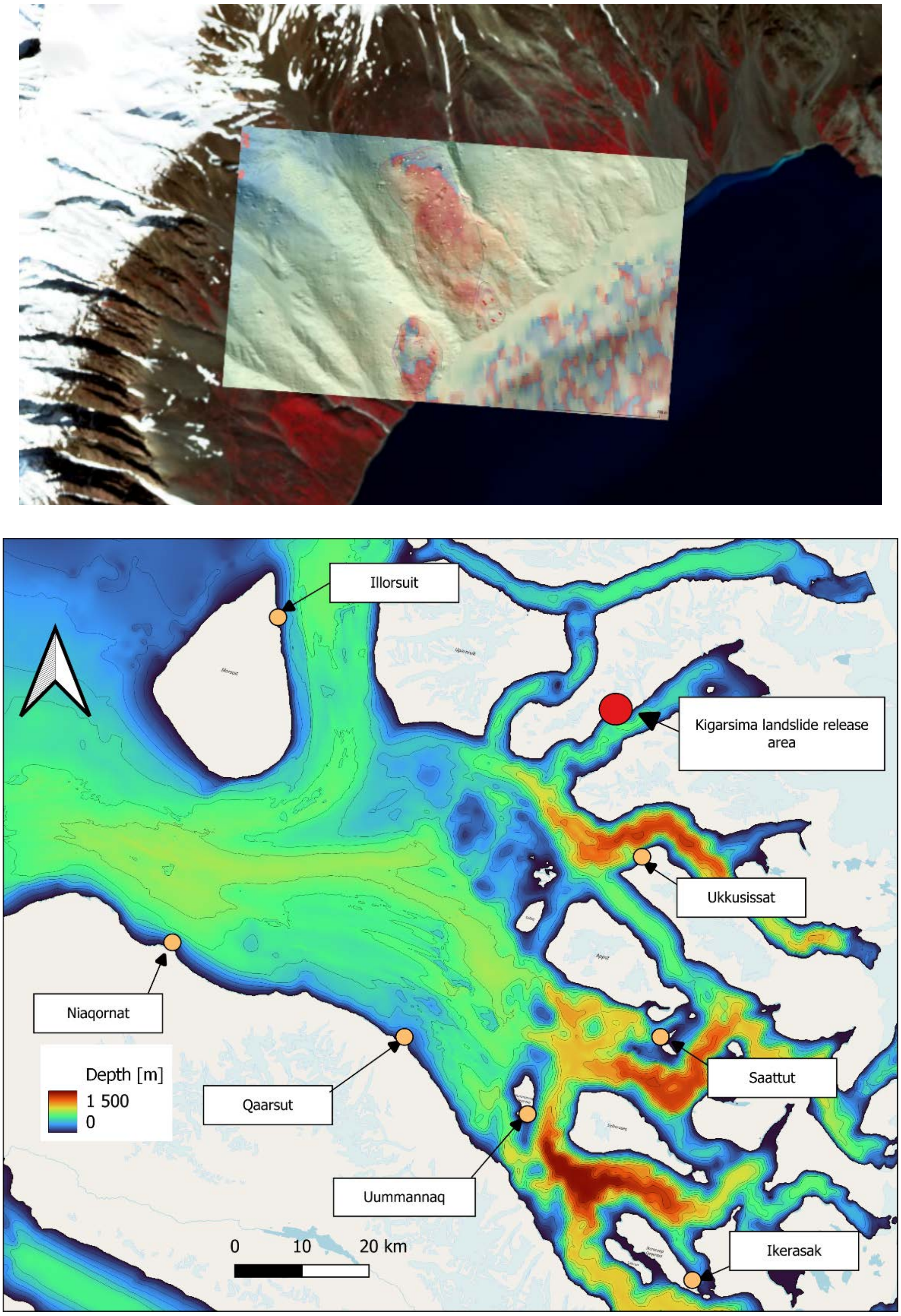

Figure 1: Overview of locations for hazard evaluation and the rock avalanche release area. The upper panel shows a close-up of the unstable Kigarsima slope system, with slope motions given by different colours based on Sentinel 2 measurements. The lower panel shows the location of the Kigarsima slope in the Uummannaq fjord system. The Kigarsima rock avalanche area is indicated with a red bullet. The depth contours are drawn every 100 m.

Details of the applied model setup and the combinations of models are given in NGI (2021), and NGI (2022, in final prep). Validation of the procedure and further justification for selecting the landslide parameters are elaborated in NGI (2021) and NGI (2022, in final prep). The latter reference will also provide more details related to the modelling, while the present report focusses on presenting the key findings related to the tsunami hazard posed by the potential Kigarsima rock avalanche.

The tsunami analysis is carried out for the potential Kigarsima rock avalanche with two different potential landslide scenarios that represent potential catastrophic failures of the identified unstable rock slopes. They are named the Upper and Lower scenarios for quantifying the tsunami inundation (a summary of the scenario landslide parameters is given in Table 1).

- Lower scenario: A modelled rock avalanche volume of 20 Mm^3 with moderately high landslide friction. The scenario landslide volume 20 Mm^3 is the lowest in the range of the estimated landslide volume. Friction is relatively high, with a friction angle of 10° and a quadratic friction coefficient ξ = 2000 m/s^2. The higher friction reduces the landslide velocity and consequently the tsunamigenic strength of the landslide, and also the landslide run-out distance.
- Upper scenario: A landslide volume of 30 Mm^3 with a bulking factor of 1.25 (added rock avalanche volume factor) and low landslide friction. The scenario landslide volume of 30 Mm^3 represents the highest range of the estimated volume from the field, while the added volume takes into account the effect of additional fluid mixing as well as the impact of the rock avalanche. In total, this gives a modelled landslide volume of 37.5 Mm^3. The friction is relatively low, with a friction angle of 5° and a quadratic friction coefficient ξ = 5000 m/s^2. The lower friction increases the landslide velocity and consequently the tsunamigenic strength of the landslide, and also the landslide run-out distance.

These scenarios also roughly represent end members in the range of observed rock avalanche drop height to run-out distance ratio H/L from past landslides in Greenland. To this end, it is noted that the Upper scenario provides a relatively long run-out distance reaching almost to the opposite side of the fjord. The reason for this is the low friction parameters in the model. As will be discussed in NGI (2022, in final prep), we see that scenario models with a slightly elongated simulated run-out distances often tend match the tsunami inundation better than models that provide a perfect match or underestimate the run-out distance. Consequently, the Upper scenario was given a relatively low friction angle of 5° in order to match past tsunami run-up heights (NGI, 2021 and NGI 2022, in final prep).

Table 1: Rock avalanche scenario parameters, runout distances, and output H/L (drop height to run-out distance) ratio.

Scenario	Volume [10^6 m^3]	Bulking factor	Friction angle [°]	Friction coefficient	Run-out distance [m]	H/L
Lower	20.0	1.0	10	2000	3900	0.31
Upper	30.0	1.25	5	5000	5600	0.21

3 Results

The results from the analyses are summarised in Table 2, which gives both the range in run-up heights for the Upper and Lower scenarios as well as the arrival time of the first wave. It should however be noted that the highest run-up for all scenarios and locations are linked to the trailing wave system, i.e. the larger waves arrive later than the first wave arrival. The related inundation maps for each of the six villages are shown in Figure 2 - Figure 7. A map showing the arrival times for the whole fjord system is found in Figure 10.

Table 2: Range of run-up heights in meters for the Lower and Upper scenarios. The corresponding arrival times are given in minutes. Unless otherwise noted, the results are without high tide.

Scenario	Qaarsut	Ukkusissat	Uummannaq	Saattut	Niaqornat	Ikerasak	Illorsuit
Lower scenario [m]	2-6	2-3	1-3	1-2	< 1.5	< 0.5	1.0-1.5
Upper scenario [m]	4-9	3-5	1-5	2-5	1-3	< 1	2-3
Upper scenario – high tide[m]	5-10	4-7	2-5	2-5	3-5	< 2	3-4
Figure	Figure 2	Figure 3	Figure 4	Figure 5	Figure 6	Figure 7	Figure 8
Arrival times [minutes]	13	5	15	14	15	22	14

The analysis shows that the tsunami impact can be significant for most of the villages, with the upper scenario estimates of the maximum tsunami run-up heights (with added high tide) ranging up to 10 m in Qaarsut, and 5-7 m in Uummannaq, Saattut, Ukkusissat, and Niaqornat, and up to 4 m in Illorsuit. For Ikerasak we find run-up estimates to be less than 2 m with very little inundation. In Qaarsut the horizontal inundation distance can be up to 200 m, and in Niaqornat several hundred meters for the Upper scenario with added high tide. Yet, except for these low-lying flat areas, the inundation distance for all locations is typically limited to a few 10's of meters away from the shoreline.

The tsunami travel time is between 13 and 15 minutes for Qaarsut, Uummannaq, Saattut, Illorsuit, and Niaqornat. For Ukkusissat and Ikerasak the tsunami travel time is 5 and 22 minutes, respectively.

For the analysis without tide the maximum run-up height at Qaarsut can reach up to 9 m, while for the locations Ukkusissat, Uummannaq, and Saattut, the maximum tsunami inundation heights can reach up to 5 m. For Niaqornat and Illorsuit the maximum tsunami run-up height does not exceed 3 m. For Ikerasak the waves are considerably smaller than for the other locations, and the areas inundated are minor, with all run-up heights less than 1 m.

The highest inundation estimates for Qaarsut for both the situations with and without added high tide shows that several buildings can be inundated here. A relatively large fraction of buildings is also inundated in Illorsuit. With added high tide, a limited number of buildings are also inundated by the tsunami in Uummannaq, Saattut, and Ukkusissat. For these three locations, fewer buildings can be potential impacted by the tsunami without added tide. For Niaqornat, the effect of high tide is very important because this site is relatively flat and low lying, and hence about 2/3 of the houses can be inundated in the scenario with added tide, compared to no houses in the situation without added tide. For Ikerasak the modelling shows that no buildings are located within the modelled inundation zone.

As the modelling predicts several meter high tsunamis for most locations, it is stressed that the tsunami may still pose a significant threat to life and property also where buildings are not directly impacted.

It is noted that there is significant uncertainty related to the simulations, and that the lower estimate scenario gives run-up heights less than 3 m for all villages apart from Qaarsut (up to 6 m run-up height). This uncertainty stems partly from the uncertainty in the landslide dynamics and bathymetry. The difference between the estimates in the Upper and Lower scenarios reflects this uncertainty. The uncertainty becomes most apparent for the cases with significant run-up heights and is hence most visible for gentle terrain in Qaarsut.

Figure 2: Upper and Lower scenario inundation zones for Qaarsut.

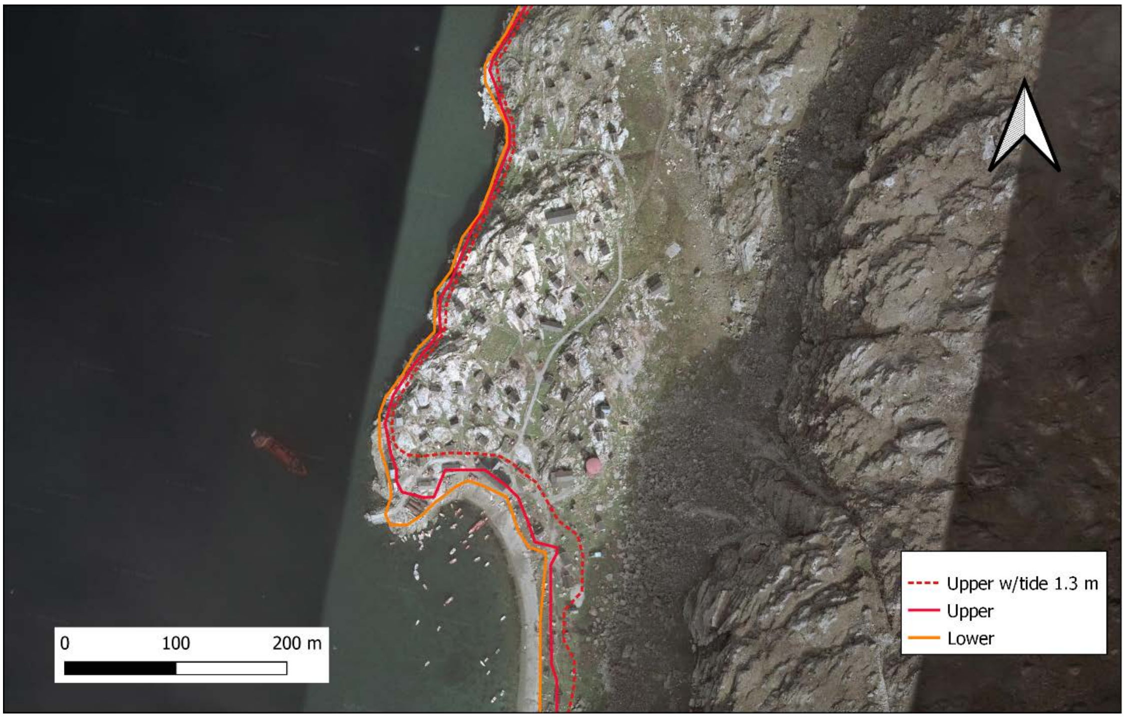

Figure 3: Upper and Lower scenario inundation zones for Ukkusissat.

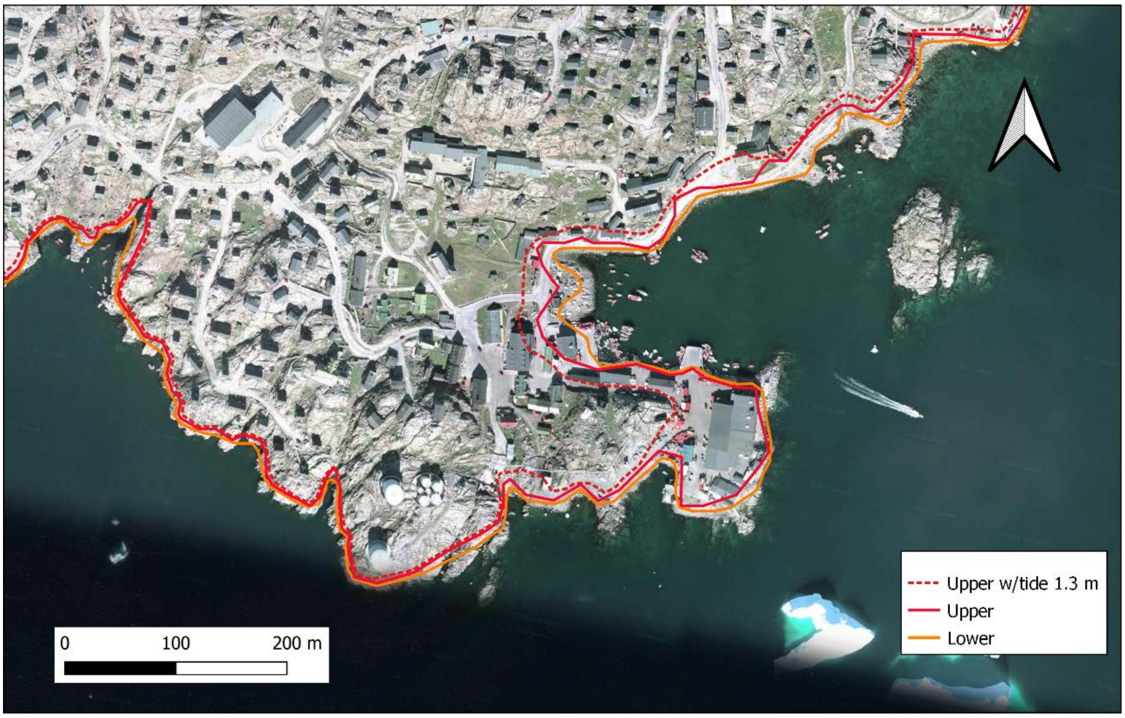

Figure 4: Upper and Lower scenario inundation zones for Uummannaq.

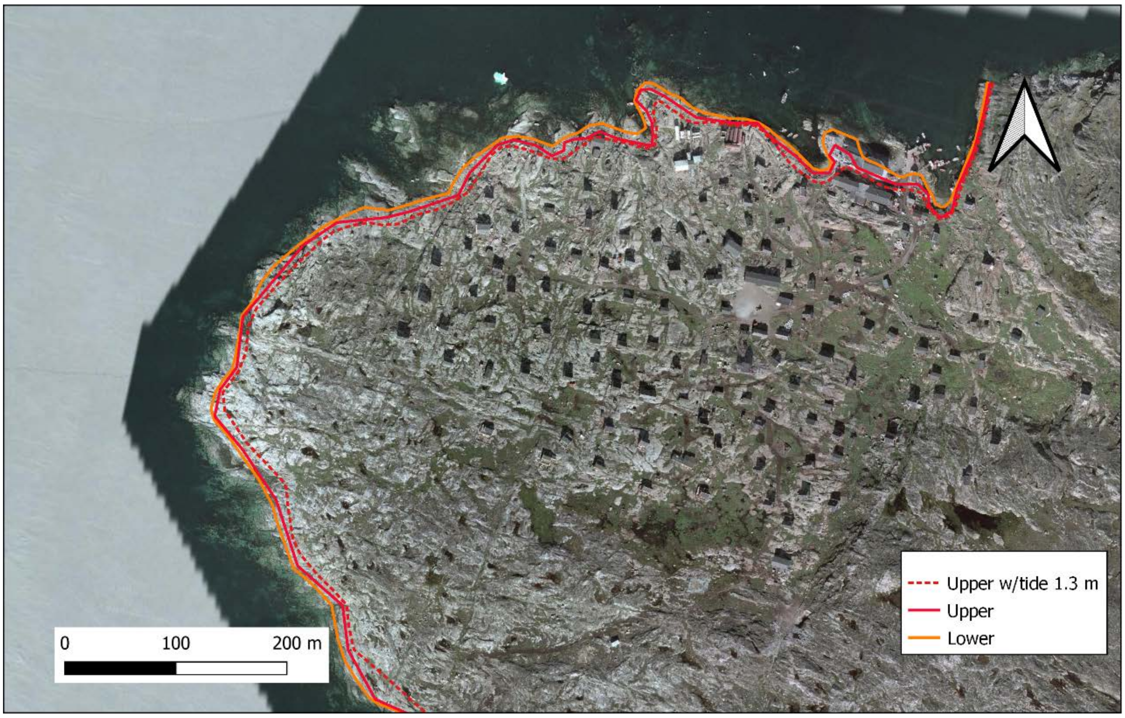

Figure 5: Upper and Lower scenario inundation zones for Saattut.

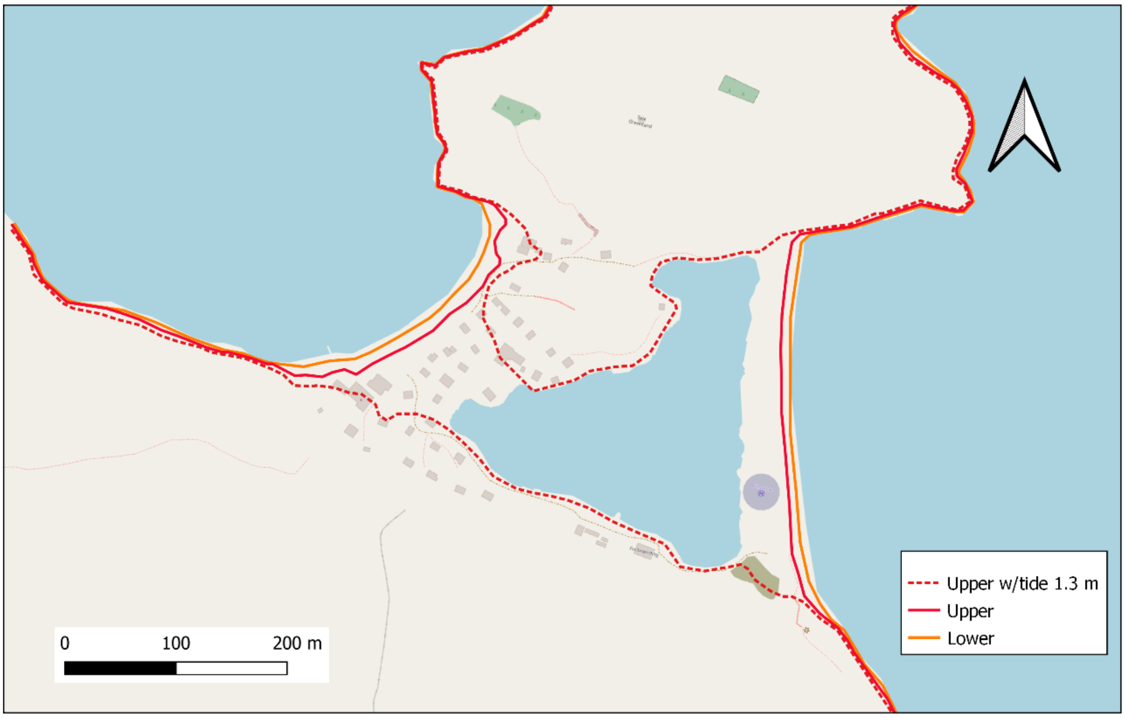

Figure 6: Upper and Lower scenario inundation zones for Niaqornat.

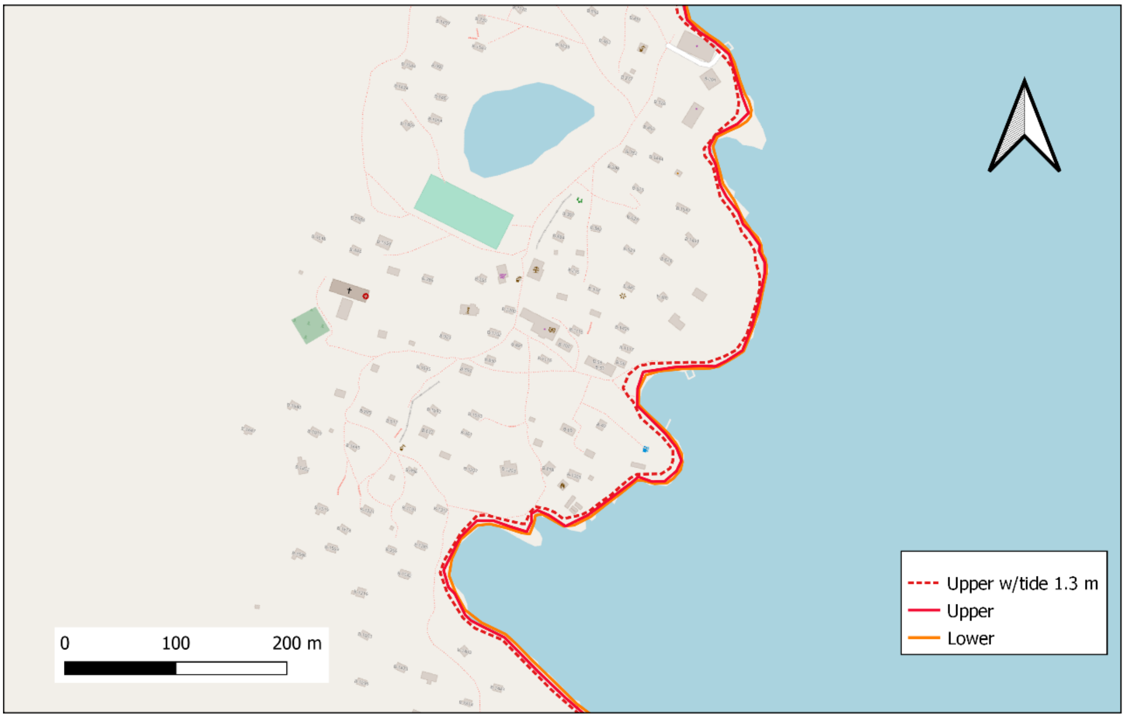

Figure 7: Upper and Lower scenario inundation zones for Ikerasak.

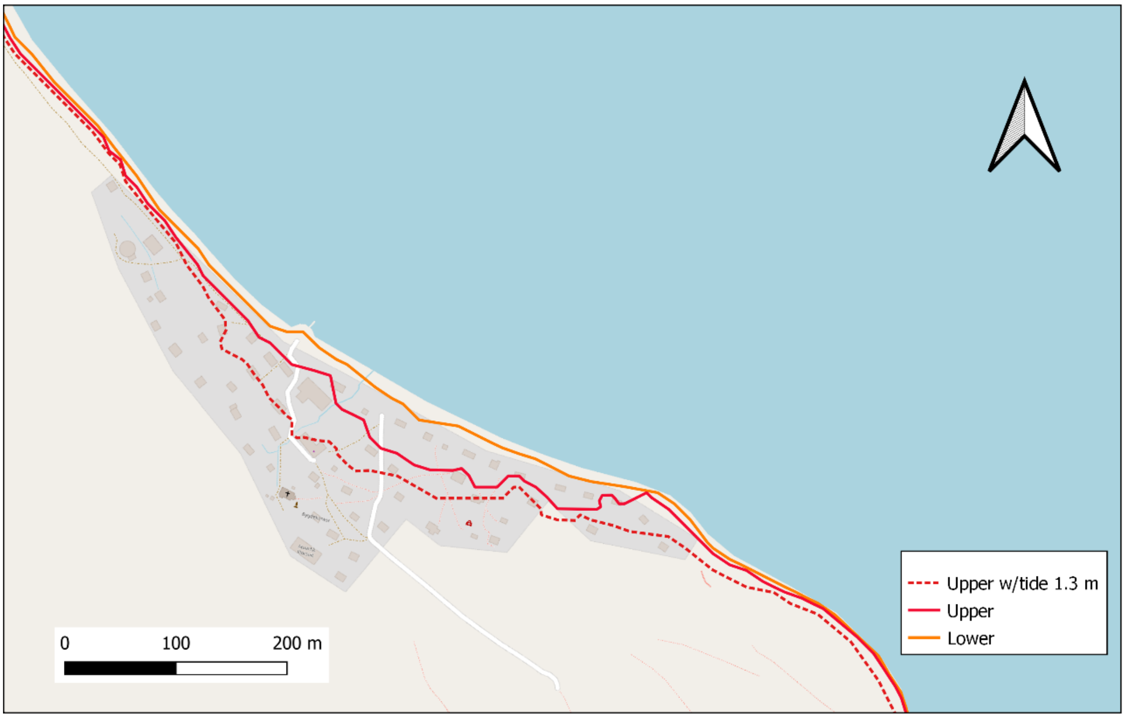

Figure 8: Upper and Lower scenario inundation zones for Illorsuit.

It is noted that the modelled landslide run-out distances for the upper and lower scenario ranges from the median to the maximum range of the observed H/L (drop-height to run-out ratio) ranges from past landslides in Greenland. The upper estimate scenario represents the more mobile (with higher velocity) landslide scenario that is also more tsunamigenic, while the lower estimate scenario is less mobile (and with lower velocities) and consequently less tsunamigenic. The modelled final run-out distance for the two scenarios is shown in Figure 9. As noted above, the run-out distance of the upper scenario likely exaggerates the rock avalanche run-out distance.

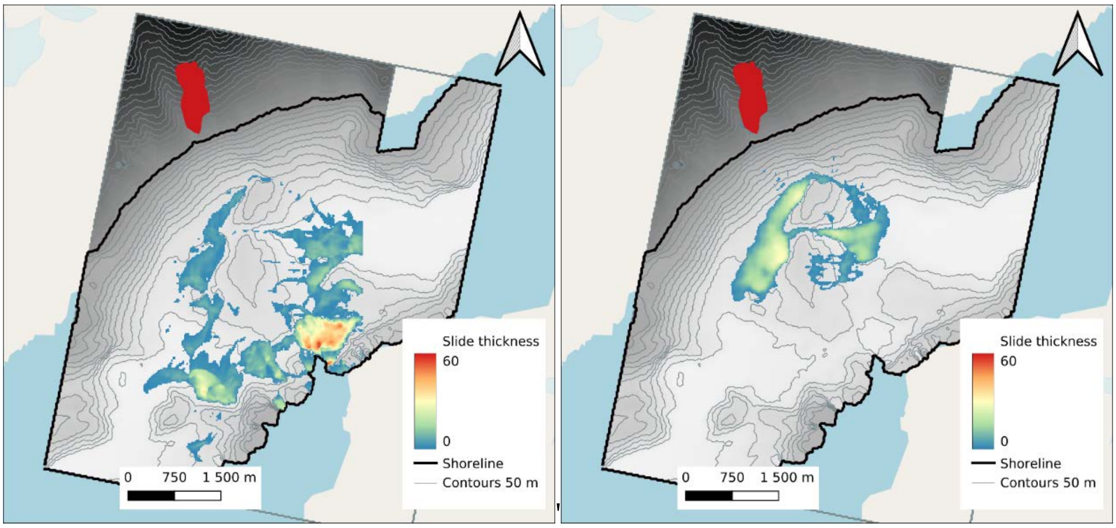

Figure 9: Modelled landslide run-out distance for the lower (right) and upper (left) estimate scenarios. The modelled final landslide deposits in the model is coloured. The depth contours are drawn every 50 m. The initial landslide volume is marked in red.

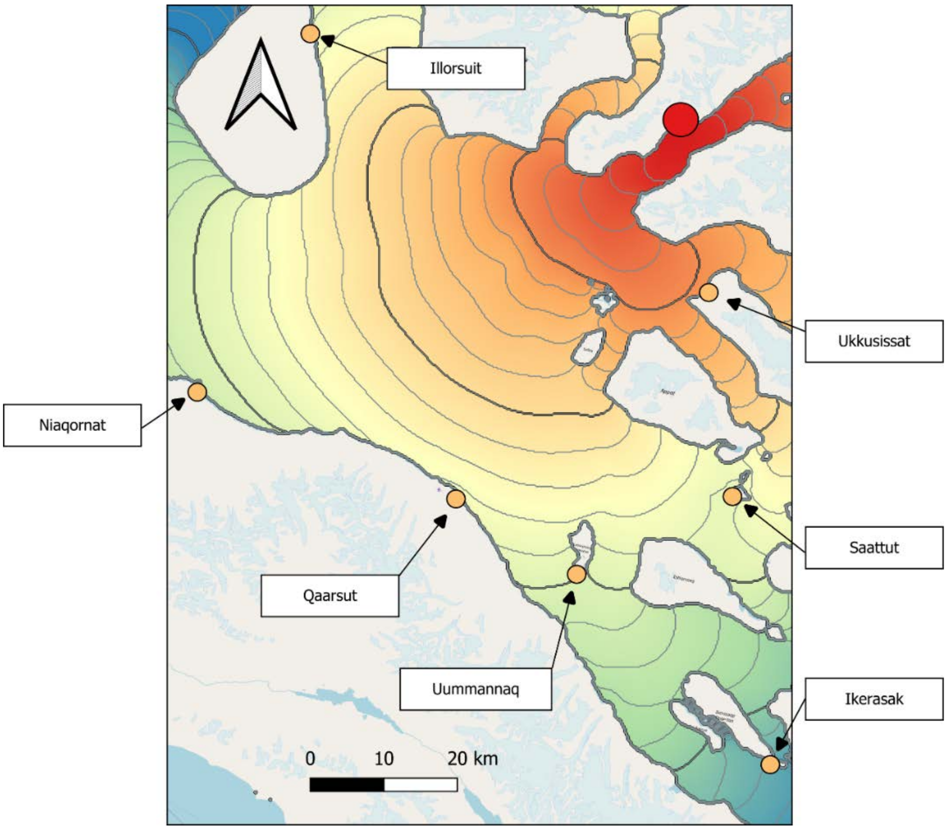

Figure 10: Arrival times for the leading tsunami generated by the potential landslide Kigarsima given in minutes for the Uummannaq fjord system. Contour lines are drawn every minute, with a thicker line every 5 min.

4 Concluding remarks

Based on a request from GEUS, NGI has performed numerical simulations of tsunamis generated by a potential rock avalanche from the Kigarsima rock slope for six locations in the Uummannaq fjord system, i.e. Qaarsut, Niaqornat, Uummannaq, Saattut, Ukkusissat, Ikerasak, and Illorsuit. Two different scenarios are investigated, an Upper scenario resulting in the highest waves, and a Lower scenario resulting in the smaller waves.

The analysis shows that the tsunami impact can be significant for most of the villages, with the upper scenario estimates of the tsunami run-up heights (including 1.3 m high tide) reaching up to 10 m in Qaarsut, and 5-7 m in Uummannaq, Saattut, Ukkusissat, and Niaqornat, and up to 4 m in Illorsuit. For Ikerasak we find the run-up height estimates to be less than 2 m with very little inundation.

The highest inundation estimates for Qaarsut for both the situations with and without added high tide shows that several buildings can be inundated here. A relatively large fraction of buildings is also inundated in Illorsuit. With added high tide, a limited number of buildings are also inundated by the tsunami in Uummannaq, Saattut, and Ukkusissat. For these three locations, fewer buildings can be potential impacted by the tsunami without added tide. For Niaqornat, the effect of high tide is very important because this site is relatively flat and low lying, and hence about 2/3 of the houses can be inundated in the scenario with added tide, compared to no houses in the situation without added high tide. For Ikerasak the modelling shows that no buildings are located within the modelled inundation zone.

The arrival time of the leading waves is between 13 and 15 minutes for all sites, except the closest site Ukkusissat and the most distant one Ikerasak with arrival times of 5 and 22 minutes, respectively. It should however be noted that the largest tsunami run-up height appears later than the first arrival in the simulations. This was also the case for the 2017 Karrat fjord tsunami, where later wave arrivals caused the largest run-up heights.

There is significant uncertainty related to the simulations, and that the lower estimate scenario gives run-up heights less than 3 m for all villages apart from Qaarsut (up to 6 m run-up height).

5 References

NGI (2021) Tsunami hazard screening for the Uummannaq fjord system – Greenland. Hazard scenario simulations and 2017 event hindcast. NGI-report 20200823-01-R.

NGI (2022, in final prep) Tsunami hazard analysis in Greenland – Vaigat region. NGI-report 20210737-02-R.

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OSLO
TRONDHEIM
HOUSTON
PERTH

NORWEGIAN GEOTECHNICAL INSTITUTE
NGI.NO

Main office
PO Box 3930 Ullevaal St.
NO-0806 Oslo
Norway

Trondheim office
PO Box 5687 Torgarden
NO-7485 Trondheim
Norway

T (+47)22 02 30 00
NGI@ngi.no

BIC NO. DNBANOKK
IBAN NO26 5096 0501 281
ORGANISATION NO.
958 254 318MVA

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