Author's Response to the second round of reviews

Response to the Editor:

Dear Professor Gonzalez,

We would like to thank you for giving us a chance to respond to the second round of reviews. We were surprised by the discrepancy of opinions between reviewers. Reviewer 1 (world-leading expert in Arcitc coastal change and geohazard – Professor Donald Forbes) presented very positive feedback and emphasized the importance of our study. This is the first survey of the tsunami damages in the Arctic where the wave impacted inhabited settlement. On the other hand we did not fulfilled the expectations of the Reviewer 2.

In order to improve the manuscript and dispel Reviewer 2 and Editor doubts we have implemented all changes suggested by Professor Forbes and we followed the key suggestion of Dr Shugar – extracting more information from ArcticDEM resources.

As you will notice, we have processed two scenes from ArcticDEM in ArcGIS and calculated terrain changes between pre- and post-wave landscapes. The GIS algebra confirmed our field observations and proved that the erosion was concentrated on the 'saddle area' between beach and harbour.

We hope the revised manuscript will better suit the NHESS but are happy to consider further revisions, and we thank you for your continued interest in our research.

Sincerely,

Matt Strzelecki and Marek Jaskolski

Reviewer 1 – Professor Don Forbes

The new title is appropriate. The revised paper includes topographic data but does not fully exploit these. Recognizing the limitations of the DEM resolution and vertical datum wrt WL at the time of the event, the approximate runup elevation limit should be reported in text, conclusions, and abstract. New figure is good. Thanks for including. I attach a file with suggestions for more idiomatic wording.

Ad. Dear Professor Forbes, we are very grateful for you review and all the suggestions you have given us to improve the manuscript. We have corrected the manuscript, introduced all suggested changes. In addition, after suggestion from Reviewer 2, we have added new Figure 6 – where we present our results of GIS analyses. We have compared ArcticDEM scenes before and after the event, and found that the remote sensing data support our field observations. The major zones of tsunami erosion were beach and cliffed coast on the opposite sites of the saddle.

Reviewer 2– Professor Dan Shugar

Paper No.: NHESS 2019-376.R1
Author(s): Strzelcki and Kaskolski
Title: Arctic tsunamis threaten coastal landscapes and communities – survey of Karrat Isford 2017 tsunami effects in Nuugaatsiaq, western Greenland.Thank you to the authors for revising their paper. It is improved, but I remain underwhelmed. The authors state that the lack of detail in their observation is at least partly related to having only spent 2.5 days on site. But this, in my opinion, does not negate the fact that the observations are pretty sparse. I cannot recommend publication in its current state.

Although I have not downloaded the data to examine in detail, it appears that there are two dozen ArcticDEM strips covering the study area, including several immediately post-tsunami. Have the authors tried downloading these in order to do a quantitative assessment of erosion and deposition? In the previous version, this was suggested (by both reviewers) and while the authors use ArcticDEM to produce a contour map, they don't really take full advantage of the data. I am disappointed to see it not acted upon.

Dear Professor Shugar,

we are sorry to disappoint you with not including the results of GIS analyses in the revised version of the manuscript. It was not intentional, as we were confident that we presented significant amount of new data and knowledge in our work. As you have noticed we explored the ArcticDEM resources and used the best resolution scene to construct our topography map presented in Fig. 3. Your second round review motivated us to use the results of DTM subtraction between models from scenes before and after the tsunami. In the corrected

manuscript we present the new figure (Fig. 6) where the results of DTM algebra are shown. In short, GIS analyses confirm our field evidence that the major erosion occurred in local beach (site 4 in Fig. 1) and along the edge of the cliffed coast in the local harbour.
Please check lines 70-75 and lines 580 – 589.

We hope that with this additional data our paper will be accepted.
For the future, we will appreciate if you could use correct spelling of our names.

SPECIFIC COMMENTS

L502 – If you are going to state that arctic tsunamis have been increasing in frequency, you need to back that statement up with data or at least citations.
Ad. Thank you for your advise, we have added the citations to support our statement – Line 34

L512 – Including (Taan Fjord, 2015) parenthetically makes it look like a paper by someone called Taan Fjord. This also appears on line 772.
Ad. Thank you for advise. We have changed it into:
' …recorded in 2015 in Taan Fjord, Alaska…' **- Line 39**

L515 – You state that climate change played a role in the Paatuut landslide and tsunami but fail to demonstrate this. Dahl-Jensen et al (2004) do not invoke climate change, permafrost thaw, or glacial retreat in their analysis, nor do Buchwal et al (2015), both of which you cite in support of your statement.

Ad. Thank you for your comment. We have been involved in mapping Paatuut landslide and post-tsunami coastal change surveys. Our study with Agata Buchwał (Buchwał et al. 2015) provide a clear evidence that climatic change was the main trigger of Paatuut landslide. The summer season preceding the event was one of the warmest and wettest in the century, what resulted in a significant permafrost thawing and in addition, saturated thick active layer with rainfall water - Line 45

L527 – You state that "We followed the post-tsunami traces mapping described in the seminal paper of Szczuciński (2012) on post-depositional changes of onshore tsunami deposits", but key to Szczuciński's efforts were careful and detailed field observations. Such observations are lacking in the current manuscript.
Ad. We have consulted our fieldwork and results presented in the paper with Professor Szczucinski, who is our main mentor in Arctic tsunami research projects. In the corrected version of the manuscript we present all collected data on sediment size and thickness.

L545 – The new paragraphs about the physiography of the study area are a welcome addition but the English needs some editing. Some of the descriptions (in Vegetation section) are Results.
Ad. Thank you for kind words and suggestion. We have moved the results fragments to section 4.2.1 – Lines 194 – 199.

L615 – While the information about the settlement history is interesting, I'm not sure most of it is relevant here.
Ad. Both paragraphs were required by the Reviewer 1 and their content fulfilled his requests.

L639 – Why is 'Event' uppercase? There are numerous other places where spelling and grammar need to be addressed. I do not point any further issues here.
Ad. Thank you for spotting this. The manuscript was corrected by native-speaker and additional grammar improvements were made by Reviewer 1 (Professor Don Forbes).

L786 – I am no expert in social science, but if the authors are reporting interviews with residents, surely they need approval from their ethics board.
We have deleted the information about personal communication for our local friends.

L870 – Replace 'man-made' infrastructure with 'built' infrastructure.
Ad. Thanks for suggestion. Done. Line 303

L877 – The Taan Fiord landslide was not an Arctic event.
Ad. Thanks for suggestion. We have rewritten the sentence, stating that it was a cold region setting.

L882 – As most readers are likely unfamiliar with the coast of West Greenland, provide an approximate distance between Sigguup Nunaa and Qeqertarsuaq.
Ad. Thanks for suggestion. We have added information about the distance (ca. 230 km). Line 315

L895 – I'm not sure whether a bulleted Conclusion section is allowed by the journal.
Ad. Thanks for your question. We have double check list of most downloaded papers published in NHESS and formatted our conclusions to fit the style of previously published papers in the journal.

L898 – You state a 'majority' of buildings were destroyed, but then provide the number of 48%. This is not a majority, though it is a lot.
Ad. Thanks for suggestion. Done. Line 335.

L913 – While warming may increase the numbers and severity of landslides going forward, it is not an obvious contributing factor in the current example. Either prove that it was, or remove this statement.
Ad. Thanks for suggestion. We have deleted this statement from our conclusions.

L947 – The statement that data can be made available implies there are observations that were made that are not reported in full. What additional data exist? Since my main criticism is a lack of data/robust observations, these would be most welcome.
Ad. We have presented all quantitative data collected in the field in the paper. We are opened to share our photographical documentation of the site

L965 – You include Bloom et al in the references but it is not cited in the paper.
Ad. We have double checked this and the paper was in the reference list. Please check the revised manuscript file.

L1007 – You cite Haeussler et al in the references but it is not cited in the paper.
Ad. We have double checked this, and the paper was in the reference list. Please check the revised manuscript file.

Fig 6 – The legend should be within panel (a) since it is not relevant to the lower panels. The right-hand panels are also not lettered.
Ad. Thank you for suggestion, we have moved legend to (a). The lower panels (c) and (b) are now divided by a white dashed line to show the site before and after the tsunami impact.

Fig XX – there is a figure that is unlabeled (the old caption for Fig 4 seems deleted but no new fig caption is added). It is unclear where the yellow buildings were moved *from*. Is this figure deleted? I am confused.

Ad. Yes this figure was deleted. We would be grateful if you could refer to the revised manuscript file (document starting on page We worry that you have checked the tracked-changes version of the manuscript where some of the important modification could be lost due to the number of changes and improvements.

MANUSCRIPT WITH TRACKED CHANGES

Arctic tsunamis threaten coastal landscapes and communities - survey of Karrat Isfjord 2017 tsunami effects in Nuugaatsiaq, western Greenland

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Abstract

On the 17th of June 2017, a massive landslide which mobilized ~~ca.~~ 35–58 million m^3 of material entered the Karrat Isfjord in western Greenland. It triggered a tsunami wave with a runup height exceeding 90 m close to the landslide, ca. 50 m on the opposite shore of the fjord. The tsunami travelled ca. 32 km along~~across~~ the fjord and reached the settlement of Nuugaatsiaq with ca. 1-1.5 m high waves which flooded the terrain up to 8 m above sea-level. ~~, which~~ Tsunami waves were powerful enough to destroy the community infrastructure, impact fragile coastal tundra landscape, ~~–~~and unfortunately, injure several inhabitants and cause 4 deaths. Our field survey carried out 25 months after the event results in documentation of the previously unreported scale of damages in the settlement (ca. 48% of infrastructure objects including houses and administration buildings were destroyed by tsunami). We have observed a recognizable difference in the concentration of tsunami deposit accumulations between areas of the settlement overwashed by by the wave and areas of runup and return flow.~~wave and areas where tsunami flooded terrain and return to the fjord.~~ The key tsunami effects preserved in the coastal landscape were eroded coastal bluffs, gullied and dissected edges of cliffed coast in ~~local~~ the harbour and ~~compressed~~ tundra vegetation compressed by boulders or icebergs rafted onshore ~~land~~ during the event.

1 Introduction

Although known to the research community for at least 60 years, the occurrence, scale and impacts of tsunamis in cold regions (Arctic and subarctic) still shock the wider public. Their increasing frequency in this rapidly warming region already poses a serious threat to a fragile polar coastal environment and infrastructural needs of human communities (Miller 1960; Dahl-Jensen et al. 2004; Buchwal et al. 2015; Higman 2018).

The unstable nature of cold region landscapes in terms of permafrost-thawing or glacier retreat-or earthquake- induced landslides provide potential tsunami sources. The effects of waves are particularly destructive in fjords and narrow straits, where a constraining topography can amplify the wave heights. For instance, the landslide which entered Lituya Bay in Alaska in 1958 triggered a~~the~~ giant tsunami wave with runup height of over 500 m (Miller, 1960). Another wave (runup over 190 m) recorded in 2015 in Taan Fjord, ~~coastal~~ Alaska, ~~(Taan Fjord, 2015)~~ was caused by a~~the~~ landslide from local slopes destabilized by the retreat of Tyndall Glacier (Dufresne et al., 2018; Higman et al., 2018; Haeussler et al. 2018, Bloom et al. 2020). In the last hundred years tsunamis were recorded also in Norwegian fjords e.g. the Tafjord 1934 event (e.g. Harbitz et al., 2014).

In Greenland, due to the recent climate change (i.e. shrinking of glaciers and permafrost thawing) many mountain slopes were destabilized and released numerous tsunamigenic landslides. For example, in November 2000 a landslide from Paatuut mountain triggered a tsunami (runup ca. 50 m) which destroyed Qullissat town (Disko Island, western Greenland) and destabilized shores along Vaigat Strait even up to 150 km from the landslide site (Dahl-Jensen et al., 2004; Buchwał et al., 2015). The same region was also hit by a tsunami after the Niiortuut landslide in 1952, as mentioned in the recent inventory of Greenland landslides carried out by Svennevig (2019).

Here we report on the largest documented tsunami wave in Greenland to date (runup height ca. 90 m), which resulted from a massive landslide to Karrat Isfjord and destroyed the settlement of Nuugaatsiaq on the 17th of June 2017 (Figure 1). Based on a field survey carried out two years after the event, our study provides insights into the lasting tsunami-induced geo-ecological changes in coastal landscape and in addition presents an inventory of tsunami damages to settlement infrastructure.

2 Materials and Methods

This study is based on field observations carried out in July 2019. We followed the post-tsunami traces mapping protocol described in the seminal paper of Szczuciński (2012) on post-depositional changes of onshore tsunami deposits. It is important to note that the visit occurred 25 months after the event, which means that at least two spring melt-out seasons happened between the event and the mapping. It is likely that some of the tsunami traces (particularly fine deposits, tsunami salt precipitation ~~covers~~ and iceberg erosional and depositional marks) were partly erased from the landscape. The largest boulders and litter lines were marked with a handheld GPS. We took a careful survey of the vegetation cover change, as suggested by Buchwał et al. (2015) in their study of 2000 Paatuut tsunami impact on an Arctic shrub ecosystem. We photographed each settlement building or facility (e.g. cemetery, playground, harbour, heliport) and noted any visible infrastructure and landscape degradation. We observed some signs of human action on the site, focused on removing most of the toxic substances left in the settlement, that is petrol. In order to properly understand the scale of post-tsunami changes we compared a series of aerial images (available at NunaGIS portal: www.nunagis.gl), field photos, online ~~movies~~ video taken in the settlement before and after the wave, and settlement spatial planning maps and risk assessment documents published by the local government. Apart from land-based photos, we collected a number of aerial images using a DJI Mavic Pro drone. As our UAV was not allowed to enter the no-fly zone above the settlement centre, we took oblique images from the recommended distance. We have also explored ArcticDEM (Porter et al., 2018) resources and compared ~~elevation~~terrain changes between pre- and post- tsunami digital terrain models (DTM) to determine the scale of coastal landscape modification entailed by tsunami impact. In ESRI ArcGIS software 2 m DTM constructed from satellite images captured on the 11th of September 2016 was subtracted from DTM captured on the 19th of June 2017 to calculate elevation difference between models and check if sites where tsunami erosion and deposition detected during fieldwork were traceable in digital terrain models (Fig. 6). Information about landslide genesis and some of the tsunami

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wave characteristics was~~ere~~ extracted from remote-sensing analyses produced by USGS (Bessette-Kirton et al., 2017) and the collection of geophysical reports published soon after the event (Clinton et al., 2017; Chao et al., 2018; Gauthier et al., 2018; Butler, 2019; Poli, 2017; Paris et al., 2019).

3 Research area

3.1.1 Geographical setting

The surrounding landscape is mountainous (mountain ranges with numerous summits and plateaus reaching 2000 m a.s.l) and is characterized by some~~one~~ of the highest relief in western Greenland (Roberts et al. 2013). The major role in shaping the present-day geomorphology was played by retreat of~~ing~~ Uummannaq ice stream system (UISS) which left the diverse set of glacial landsystems in fjords, mountains and valleys of the region. The landscape was dissected by selective linear glacial erosion with lowlands dominated by glacial scour and mountain ranges occupied by cirque, plateaus, and valley-type glaciers (Lane et al. 2016). Lane et al (2016) classified banks of Karrat fjord and southern coasts of Qeqertarsuaq island, where studied settlement is located, to areal scour terrestrial landsystem exposed after the retreat of two northern branches of UISS (Umiamako Isbrae and Rink Isbrae). Ice streams significantly modelled the topography of local fjords. Dowdeswell et al. (2016) described submarine landscape (Rink Fjord and Karrat Isfjord) as a ~~-~~system with relatively smooth seafloor, broken by bedrock ridges and pinnacles that divide the fjord into several deep basins. Bathymetry maps derived from multibeam echo soundings data acquired in 2007-2014 and compiled by Rignot et al. (2016) revealed that the entrance to Karrat Isfjord is 600 m deep, 5 km wide, with a sill at 400 m depth about 160 km from Rink Isbrae The deepest basin of the fjord (1100 m) is located ca. 25 km to the east of Nuugaatsiaq. Fjord near the settlement is shallow with seafloor depths 0-240 m.

The coastal landscape of Nuugaatsiaq ~~coastal landscape~~ is predominantly rocky with an undulating and ragged coastline dissected by narrow coves and headlands (Fig.2a, Fig. 3). Rocky coves along the southern coast of Nuugaatsiaq are filled with narrow beaches underlaid by rocky bedrock (Fig. 2a). Beach deposits are thin (< 1m) and composed of mixed coarse sand and gravel deposits as well as boulders deposited by icebergs or left along the shores by retreating ice streams. The largest cape in the area, located to the SW of the settlement centre is characterized by bare rocky surface with well-preserved signs of glacial scour e.g. striations and polished bedrock (Fig.2b). ~~-~~Close to the shoreline most of smooth rocky hollows were filled with accumulations of boulders (ca. 0.2-0.5 m in diameter). The Nuugaatsiaq harbour (site 7 in Fig. 1c) is backed by the cliffed coast (between 2-4 m high) formed in bedrock ~~(ca. 0-2 m .a.s.l.)~~ and overlain~~d~~ by ~~1.5 – 3 m~~ layer of soils/glacial deposits and covered with ~~dense~~ well-vegetated tundra (Fig. 2c). At the base of the cliff narrow (1-3 m wide) mixed sand-gravelly beaches are present.

3.1.2 Geology

The dominant rocks in the region are Archean gneisses mixed with supracrustal rocks of the Palaeoproterozoic Karrat Group (Sørensen and Guarnieri, 2018). The slopes of Ummiammakku mountain where the tsunamigenic landslide occurred are composed of gneisses (Archean) overlain by quartzites (Palaeoproterozoic) and schist of the so-called Karrat Group (Mott et al., 2013).

3.1.3 Permafrost

The study area was historically included in the continuous permafrost zone (Christiansen and Humlum, 2000). The m~~M~~ost recent northern hemisphere permafrost map based on the modelling of temperature at the top of the permafrost (2000-2016) at the 1 km^2 scale presented by Obu et al. (2019) place it close to the boundary zone between continuous and discontinuous permafrost zone. To our knowledge no direct ground temperature measurements have been conducted in the close surroundings.

Commented [A1]: Response to prof. Frobes question What does the linear scour mean?:
As the term '**selective linear**' suggests, there are preferential lines along which **glacial erosion** has been concentrated

3.1.4 Vegetation

This area is a part of the mid-arctic oceanic vegetation zone (Bay 1997). The vegetation comprises a shrub-grassland system, with commonly found circumpolar species including *Carex ursina*, *Cassiope* heath, *Salix glauca*, *Festuca groenlandica, Puccinellia groenlandica*. Coastal grasslands are dominated by dense Honckenyo-Elymetum mollis associations (Lepping & Daniëls 2007). ~~Inspection of satellite images and photographs taken in Nuugaatsiaq before the event suggest that grassy-tundra covers dominated the top of coastal bluffs and the stripe of coastal lowlands between the predominantly rocky shore and main coastal road passing the settlement from west to east. During our fieldwork we noticed very dense and relatively high (0.4 – 0.6 m) grassy meadows covering coastal lowlands, and recolonizing abandoned playgrounds, roads, backyards. The observed post-event vegetation cover in study area was significantly denser and higher than in other settlements visited in the region in the same season.~~

3.2 Settlement history & economy

Nuugaatsiaq is a settlement in the district of Uummannaq in the Avannaata Kommunia. Nuugaatsiaq is located in the south of the Qeqertarsuaq Island (Fig.1), dominated by Snehætten (Nuugaatsiap Qaqqaa) mountain range The island is separated from Karrat Island located between Karrat Fjord and Karrat Isfjord by the Torsuuk strait. The closest settlement is Illorsuit and lies about 35 km south-west.

Nuugaatsiaq was probably settled shortly after 1918. In 1923 it was proposed in Grønlands Landsråd to divide the municipality of Illorsuit. For this purpose, a new Udsted had to be built. Udsted (roughly translatable as outlying settlement): Udsteder were smaller trading settlements, which were administered by an Udsteds administrator. Most of the Udsteders later became villages. In 1925 Nuugaatsiaq was granted Udsteds status and in the same year a dwelling was built for the Udsteds administrator. In 1926 the village received a school chapel. In 1930 Nuugaatsiaq already had 119 inhabitants. In the same year a shop with a warehouse was built and in 1936 a packing house (Madsen 2009). In 1960 the population reached its maximum with 159 people. In 2017 the settlement had 102 inhabitants (bank.stat.gl).

Nuugaatsiaq has been living mainly from halibut fishing, while some time ago there was still seal hunting and catfish fishing. A small trading branch of Royal Greenland with a maximum of ten employees stored the fish. Other jobs were in administration, at Pilersuisoq, in tourism and at Atuarfik Saamu School, which taught twelve students in grades one to nine and also offered a library and youth leisure activities. There was also a day care centre, the post office, an infirmary, and a village hall. The m~~M~~ajority of the buildings were located on undulating coastal lowland ~~between~~ from 1 to 4 m a.s.l. (Fig.3a)

There is a small quay on the headland that gives the village its name. Most of the boats were usually launched directly at the water's edge in the small harbour on the west side. In the north is the heliport Nuugaatsiaq. In winter, the traffic was by snowmobile and dog-sledge.

Nukissiorfiit (state utility company) supplied the village with electricity via the power station in the east and with fresh water from reservoir supplied by local streams.~~via a tank.~~ Garbage was burned or dumped into the sea. TELE Greenland provided the telecommunications.

Commented [A2]: Prof. Forbes question: how was this supplied?

The events of June 17th 2017 resulted in the evacuation of the settlement and abandonment of community ~~which last till~~continuing to the present. Currently former inhabitants of Nuugaatsiag were relocated to Uummannaq and Qaarsut settlement placed over 100 km south of Nuugaatsiaq (Fig.1).

4 Results and discussion

4.1 Landslide and tsunami characteristics

According to the analysis of seismic precursors of the e~~E~~vent carried out by Butler (2019), the tsunami was a direct result of the landslide triggered by the following sequence of processes. An earthquake ruptured the fault surface and released the hanging wall ca. 1000 m above the sea, and a head scarp was created. Rockfall wasand transformed into a rock avalanche which entered the fjord, causing the wave. Gauthier et al. (2018) calculations suggest that the Karrat fjord landslide was much larger (~35-58 x10ˆ6 m^3) than the famous tsunamigenic rockslide into Lituya Bay, Alaska in 1958 (~30x10ˆ6 m^3). Interestingly, on the map of the Nuussuaq Basin showing landslide prone areas published by Pedersen et al. (2002), the Karrat Fjord region is not marked as a potential risk area.

A field survey carried out by a group of researchers led by Professor Fritz from the Georgia Institute of Technology (Schiermeier, 2017; https://ce.gatech.edu/news/after-recon-trip-researchers-say-greenland-tsunami-june-reached-300-feet-high) found evidence that the wave runup height was ca. 90 m at the landslide site, and up to 50 m on the opposite side of the Karrat Fjord. Numerical modelling of the landslide and wave performed by Paris et al. (2019) indicates that the Nuugaatsiaq located ca. 32 km from the landslide was hit by three 1 – 1.5 m high waves, inundating the settlement over a period of ca. 3 minutes. The wave inundated terrain up to 8 m a.s.l. (Fig. 3 a)

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4.2 Landscape degradation

4.2.1 Soil and tundra cover

Inspection of satellite images and photographs taken in Nuugaatsiaq before the event suggest that grassy-tundra covers dominated the top of coastal bluffs and the strip of coastal lowlands between the predominantly rocky shore and main coastal road passing the settlement from west to east. During our fieldwork we noticed very dense and relatively high (0.4 – 0.6 m) grassy meadows covering coastal lowlands, and recolonizing abandoned playgrounds, roads, backyards (Fig. 2a). The observed post-event vegetation cover in study area was significantly denser and higher than in other settlements visited in the region in the same season. The striking feature of the Nuugaatsiaq post-tsunami landscape is a dense and high (0.4-0.6 m) grass that covers a significant part of the settlement (Fig. 2a). Two years after the event most of the blocks of eroded soil, rafts of tundra, boulders, or litter that were found were almost entirely hidden in a high grass cover (Fig. 4a). The wave has torn blocks of tundra (shrubs, mosses, grass) off the coastal slope and deposited them on land (Fig. 4 b, c). We have noticed thatnoted a significant removal of tundra cover, soil erosion, and associated formation of rills or small gullies (0.2-0.6 m deep) concentrated on surfaces exposed after the washing away of buildings. Tundra and soil were also eroded along the cliffed coast of the harbour (Fig. 4 d, e). At a few places along the main road and in the surroundings vicinity of the playground the vegetation cover (grasses) was covered by a thin layer of tsunami deposits (3 – 7 cm) composed mainly of marine gravels mixed with coarser sands. Salty patches with dead-vegetation were observed mainly across the saddle between southern coast and local western harbour (site 6 in Fig. 1c). After analyzing the video coverage of the event and post-event images (please checksee list of online resources in references), we assume that some parts of the grass cover were compressed by the fragments of icebergs or ice-floes washed on shore by tsunami. In sites where ice-bergs or ice-floes were deposited and melted away grasses were weighted down and melt-out sediments (gravel, sand, mud) was observed between grass blades. Such spots were surrounded by lush grassy tundra. Tundra was compressed also by tsunami-derived boulders both eroded from beaches and melted out of icebergs (Fig. 3bb).

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4.2.2 Coastal erosion

The tsunami We recognized two main effects on coastal geomorphology induced by tsunami impact. The tsunami erosion was concentrated on the low bluffs of tundra along the coast between narrow beaches (section of the coast between sites 1-4-5 in Fig. 1c, Fig 2a). Eroded blocks of tundra cover were deposited on land (Fig. 4b). The returning wave caused additional erosion of bluffs edges and dissected them by a series of rills/gullies (Fig. 4d). The direction of the wave flow recorded in the orientation of deposited litter, buildings, marine deposits, boulders, and tundra blocks suggest that the wave overwashed the section of settlement through a saddle (site 6 in Fig. 1c) between the middle beach (site 4 in Fig.

1c) and local harbour (site 7 in Fig. 1c), and modified the relief of cliffs in the harbour. The edges of the sedimentary cliffs were gullied, and the steep cliff slopes were spread with eroded blocks of tundra and litter (Fig. 4e). Two years after the event, normal coastal processes (wave and tidal action) ~~did not manage to~~had not yet ~~-~~removed or redistributed the eroded blocks of tundra and litter from the slopes and bases of the cliffs (Fig.2c).

4.2.3 Tsunami deposits and boulders

During the field survey the tsunami deposits were found in two areas located in the direct proximity to small beaches in the central part of the settlement (between sites 4 and 5 in Fig. 1c). Sand and gravel washed from narrow and thin beaches was deposited along the main road (ca. 30 - 50 m from the shore), where the thickness of deposits exceeds 8-10 cm (Fig. 5 a,b). Thin layers of tsunami deposits (3 – 5 cm), most probably reworked by snow-melt flow (Fig. 5 e, f) were found in the saddle (playground area) between site 4 and 7 (see Fig. 1c). The general scarcity of tsunami deposits can be explained by the geomorphology of the local coastal zone, dominated by sediment-free rocky capes and coves with narrow (7-20 m wide), gravel-dominated beaches (Fig 2a). Apart from gravel deposits washed from local beaches, waves transported boulders which were found in the inundated terrain in 2 main types: groups of smaller boulders (a-axis ca. 0.2-0.4 m) deposited on marine gravels along the local road, and ~~separated~~ individual larger boulders (a-axis over 1.0 m), washed up to 100 - 120 m inland between beach and local harbour (Fig. 5 b,f). In a few places we found pad~~t~~s of marine gravels and boulders deposited up to 100 m from the shore and surrounded by dense grass cover (Fig. 5 c,d). Based on the inspection of videos taken during the event we correlated their location with the deposition of icebergs. In comparison with other Greenlandic coastal sites ~~zone~~ transformed by a tsunami i.e. Paatuut 2000 tsunami (Buchwał et al., 2015) the thickness, extent, and diversity of tsunami deposits found in Nuugaatsiaq was much smaller. ~~, what we associated with~~We attributed this to the ~~-~~ sediment-poor beach source and predominantly rocky coastal relief with sediment-free and glacially scoured surfaces. We detected a~~the~~ recognizable difference in tsunami landscape modification between the areas of wave overflow covering most of the saddle in central part of settlement (site 6, Fig. 1c) and area of wave uprush and drainage covering eastern part of the settlement (terrain between sites 1 and 2, Fig. 1c). In the first zone, the tsunami waves eroded material (sand, gravel, boulders) from the largest beach in the settlement and fragments of sedimentary and tundra bluffs covering rocky coastal slopes (site 4– Fig. 1c) and transported this mixed load of deposits through the settlement to the harbour (site 7, Fig. 1c). This explains the larger number of sites and zones with accumulations of tsunami deposits, signs of tsunami erosion and infrastructure destruction concentrated in this zone. In the second area, tsunami waves approached the rocky coastal zone, almost sediment free, and inundated the grassy lowland carrying mainly community litter and only small amount of sediments, which was difficult to detect in the ~~trace in~~ lush~~y~~ tundra vegetation inspected 2 years after the event.

It is important to note that the only two sites where terrain changes detected in the field were also traceable in GIS analyses were beach and cliffed coast (Fig. 6 ~~c~~) located on the opposite sites of the morphological saddle in the middle of the settlement (sites 4 and 7 in Fig. 1). Other elevation changes detected between two ArcticDEM scenes were attributed to relocation of buildings as coastal landforms erosion and subsequent tsunami sediments deposition were too small to be tracked in 2 m resolution terrain models (Fig. 6).

4.3 Settlement degradation

4.3.1 Infrastructure damage

Before the tsunami event the Nuugaatsiaq community infrastructure was composed of 94 buildings (houses, services and administration buildings, dog kennels, technical facilities etc.). The wave destroyed 45 buildings (48% of the original infrastructure) ~~within:~~viz. 22 buildings were fully swept away from land, 23 buildings were partly ~~broken~~ damaged, and 11 ~~of them~~ were moved between 2 m to over 100 m from original location (~~Fig. 6~~Fig. 7). Most of the buildings were constructed on a wooden frame, covered with wooden boards and settled on pier foundations. Only a few of the settlement buildings were built on a metal frame coated with corrugated metal sheet settled on a concrete frame foundation. The first type of building (with pier foundations) was~~ere~~ not strong enough to resist the wave impact and these structures were pushed by the tsunami or in some cases washed away to the fjord (~~Fig. 7~~Fig. 8 a,c).

In those buildings which were not moved but still affected by the wave, we observed some damage of their wooden ~~lining~~cladding, as well as a deposition of marine sediments and litter in the ground floor area. The typical damages observed in buildings which were pushed by the tsunami but remained on land were: *broken windows and doors, devastated interior*. In contrast to buildings with pier foundations, much smaller damages were observed in buildings with concrete frame foundations. These, due to a more stable anchoring in the ground, gave a much higher resistance to the wave impact. The most common damages included broken walls, bowed and twisted metal construction frames (~~Fig. 7~~Fig. 8 b, d). It should be considered extremely fortunate that the fuel tanks situated at the power plant (which were one of the first parts of infrastructure hit by tsunami) were not destroyed and no leakage of petrol was reported (~~Fig. 7~~Fig. 8b).

4.3.2 Assessment of social, economic and environmental impacts of tsunami in Nuugaatsiaq.

The Karrat fjord tsunami, which hit Nuugaatsiaq settlement in 2017, was the first event which had such a devastating effect on an inhabited Arctic settlement, both in terms of landscape modification and infrastructure damage. Previous waves known from the ~~Arctic~~ cold and glaciated regions such ~~as~~as Alaskan Lituya (1958) and ~~,~~ Taan (2015) flooded unpopulated and remote areas. In Greenland the Paatuut tsunami (2000) damaged the infrastructure of Qullissat, however in this case, due to the earlier closure of ~~unprofitable~~ the coal mine (1972) the settlement was already abandoned years before the event. Therefore, this was~~is~~ the first time an assessment of the social and economic effects of a tsunami in this region was possible. ~~to undertake~~ (Table 1).

The financial data from the Government of Greenland (Naalakkersuisut) documents (Forslag til TILLÆGSBEVILLINGSLOV for 2017, from 2018/8), shows the costs associated with the relocation of tsunami victims of 14 877 000.00 DKK (ca. 2 248 085.00 USD [15.05.2020]) which can be treated as a rough estimate of an economic cost of the event. The document also declares a one-off payment to tsunami victims amounting to DKK 50,000 (~~-~~7548.00 USD [15.05.2020]~~-~~). In our opinion the total economic cost was significantly higher as the total market value of 45 destroyed settlement infrastructure objects (incl. buildings) was not included in the reports. Nevertheless, the settlement remains abandoned to this day and the threat of another tsunami wave remains active (Fritz et al. 2018; Paris et al. 2019). Apart from the tragedy of 4 fatalities, 9 wounded inhabitants and countless dog deaths, the catastrophe still has its social repercussions. Thirty-nine people were evacuated and separated into the settlements of Uummannaq and Qaarsut. The Displaced have lost their life's work, their hunting area, sentimental value, and social bo~~u~~nds. In their new places more expensive rent, isolation and adaptation difficulties often awaits them. ~~(*personal communication* of local respondent).~~

From the perspective of environmental protection and coastal management, the remaining material and waste in the settlement area still constitute a serious hazard. Despite the considerable effort from the local government to secure the site through reinforcement of damaged constructions, pumping fuel out of the tanks, the removal of batteries and engines from machines and vehicles, we mapped significant amounts of waste (~~Fig. 7~~Fig. 8 e-g). We found broken pieces of electronic equipment, ammunition, rotting food supplies, bags with faecal matter, sledge dog carcasses, and other municipal waste which had not been disposed from the settlement before and after the event (~~Fig. 7~~Fig. 8). In Nuugaatsiaq plastic litter is widespread not only along narrow beaches (already mixed with beach sediments), but also spread long main road of the settlement and around overwashed saddle between southern coast and harbour, and subject to further transport by strong winds (~~Fig. 7~~Fig. 8). Plastic waste is a serious problem of Arctic coastal environments and Nuugaatsiaq case is unfortunately another contributor to this type of environmental pollution (e.g. Cózar et al. 2017; Bergmann et al. 2017; Jaskólski et al. 2018). After the evacuation of Nuugaatsiaq the disposal of waste and better securing of damaged infrastructure at the site is hindered by the existing high risk of another tsunamigenic landslide in Karrat Fjord (Paris et al. 2019).

4.4 Arctic coastal communities threatened by tsunamis – rising risk and rising awareness

One of the most evident effects of Arctic climate warming is the increased ~~operation~~ activity of geohazard processes along the circum-~~A~~arctic coasts (e.g. Fritz et al., 2017). The majority of these processes pose a significant threat to Arctic coastal communities and ~~man-made~~built infrastructure (e.g. Forbes et al., 2011; Hatcher and Forbes 2015; Radosavljevic et al., 2016; Jaskólski et al., 2018). Most of the recent Arctic coastal change studies concentrated on accelerated coastal erosion rates in locations spread across the Arctic region and associated them with diminishing sea-ice extent, longer exposure to storm wave impacts, and thawing coastal permafrost (e.g. Farquharson et al., 2018; Irrgang et al., 2018;; Isaev et al., 2019). Also, in glaciated parts of the Arctic, such as Greenland or Svalbard, coastal research focused on the response of coastal zone to increased delivery of glacial sediments (e.g. Bendixen et al., 2017; Strzelecki et al., 2018) or rocky coast interaction with coastal permafrost (e.g. Strzelecki et al. 2017; Lim et al. 2020). At the same time little attention was paid to ~~Arctic~~ cold region tsunami hazards whose effects are devastating to both human and natural coastal environments. The recent examples of ~~Arctic~~ tsunamis in Alaska (Taan 2015) and Greenland (Paatuut 2000, Karrat 2017) demonstrate how severe impacts on coastal environments and communities can be. It is important to note that with continued warming (favouring permafrost thaw, glacier retreat, or extreme meteorological phenomena), such tsunamigenic landslides are likely to be far more frequent (Gosse et al., 2019).

To put it into a Greenlandic perspective, the recent mapping of potential tsunamigenic landslides performed by Svennevig (2019) indicated 564 landslides just between Sigguup Nunaa and Qeqertarsuaq in West Greenland (ca. 230 km in a straight line). Benjamin et al., (2018) mapped 20 rock avalanches just along one short section (ca. 25 km) of southern coast of Nuussuaq Peninsula in a direct proximity of Vaigat Strait (similar avalanche triggered Paatuut tsunami in 2000). Svennevig et al. (2019) demonstrated that the area around the Karrat Fjord landslide has continued to be active and another tsunamigenic landslide is highly probable.

Although beyond the scope of this study, here it is important to mention another type of extreme phenomenon~~a~~ impacting Greenlandic coastal zone - waves triggered by iceberg-roll events that are powerful enough to erode local beaches and wash away coastal infrastructure (Long et al., 2018). Calving of Greenlandic glaciers also produces extreme waves that are able to erode glacial landforms and lead to substantial degradation of coastal landscape (e.g. Lüthi and Vieli, 2016). It is important to note that with continued temperature warming in the Arctic, such landslides, glacier calving~~s~~ and iceberg rollover events ~~s~~ are projected to be far more common and have ~~. ~~profound effects on the functioning of coastal communities and landscapes.

5 Conclusions

In the present study an attempt has been made to evaluate the impact of 17th June 2017 tsunami wave on Nuugaatsiaq settlement infrastructure and coastal landscape using combination of field-based geomorphological mapping, spatial planning and GIS analyses. Based on the present investigation, the following conclusions have been reached.

~~1. Based on the observations we have drawn the following conclusions:~~

1. The Karrat Fjord event is the first known example of Arctic tsunami which directly impacted an Arctic inhabited settlement and forced its evacuation.~~;~~

~~2.1. Tsunami inundated terrain up to 8 m a.s.l.~~

~~3.~~2. The scale of tsunami damages, including destruction of ~~several~~a ~~majority of buildings (~~48% of settlement community infrastructure ~~)~~ and a high risk of another event, prevents the community from~~to~~ returning to the settlement.~~;~~

~~4.~~3. Apart f~~o~~rom housing facilities, 3 waves destroyed most public service buildings e.g. school, power plant, shopping centre, administration centre, seafood processing plant.~~;~~

~~5.~~ Among the waste accumulations left in the area ~~are:~~are electronic equipment, rotting food supplies, faecal matter, sledge-dog carcass, as well as ammunition and a lot of municipal waste, including a large quantity plastic. Most of the waste is completely unprotected and exposed to weather conditions and wildlife.~~;~~

4. Although the t~~T~~sunami inundated terrain up to 8 m a.s.l. t

~~6.~~5. ~~T~~he geomorphological effects of the tsunami were less pronounced than in previously described examples of ~~Arctic~~ cold region tsunami impacts (Lituya 1958, Paatuut 2000, Taan 2015) which can be explained by the local coastal morphology and geology (rock dominated coasts with small and sediment-poor beaches) and relatively low wave~~s~~ heights (1-1.5 m).~~;~~

~~7.~~ Mapped tsunami deposits included gravel-dominated beach sediments, boulders and ice-rafted material derived from icebergs ~~material which melt out from fragments of ice-bergs~~ stranded on land.~~;~~

6.

~~8.~~7. Two years after the event the effects of tsunami erosion was still detectable on the surface of local roads and edges of sedimentary cliffs along the ~~local~~ harbour.~~;~~

- ~~In the warming Arctic region, the landslide-triggered tsunamis become one of the most important geo-hazards with profound effects on the functioning of coastal communities and landscapes.~~

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Online resources:

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Video Nuugaatsiaq tsunami 1: https://wwwyoutubecom/watch?v=LzSUDBbSsPI , last access: 08 November 2019.

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Figures and Tables

Observed tsunami impacts in Nuugaatsiaq		
Environmental	**Social**	**Economic**
• Landscape degradation (tundra and soil erosion, salt residues, coastal erosion) • hazardous materials left on site and exposed to harsh climate • waste accumulations • rotting food supplies easily accessible to wildlife	• separation of the community, relocation of people to Uummannaq and Qaarsut • loss of a logistic point for expeditions (hunting, fishing) for other settlements • loss of settlement continuity • loss of sentimental value • relocated people forced to pay more expensive rent in new substitute premises • isolation and adaptation difficulties in a new place • 39 people evacuated https://knr.gl/da/nyheder/39-evakueret-fra-nuugaatsiaq • 4 fatalities, 9 injured https://knr.gl/da/nyheder/fjeldskred-i-karrat-isfjorden-skyld-i-flodb%C3%B8lge • death of sledge dogs (during the inventory found 4 carcasses)	• costs of relocation, reparations and accommodation recognized in the budget for 2018 in the municipality of Naalakkersuisut DKK 14,877,000 (Forslag til TILLÆGSBEVILLINGSLOV for 2017, from 2018/8) • the need to allocate substitute accommodation and a one-off compensation payment of DKK 50,000 • impoverishment and loss of property (new premises are not given) • at least 27 sites with destroyed community infrastructure

Future risk reduction actions in Arctic coastal communities	
Earth science and remote sensing research community: • mapping and detection of landslides and slopes recently ~~slopes~~ exposed from glacier ice or with significant degradation of permafrost • mapping/re-mapping seabed topography of deglaciated fjords and embayments • monitoring of present-day slope processes (slope stability) • investigations of paleo-records of waves • design of databases with seismic, remote sensing, geophysical and sedimentological information of past and recent tsunamigenic landslides and associated waves	Local authorities: • funding tsunami alert network • preparation of evacuation plans/delimitation of safe zones • consideration of tsunami and landslide hazard in spatial plans/documents • establishment of insurance procedures and securing financial reserves to cover post-event costs of relocation ~~and reinstalment~~ of communities in new locations

Table 1. Summary of tsunami effects on coastal landscape and Nuugaatsiaq community and recommended hazard risk reduction actions.

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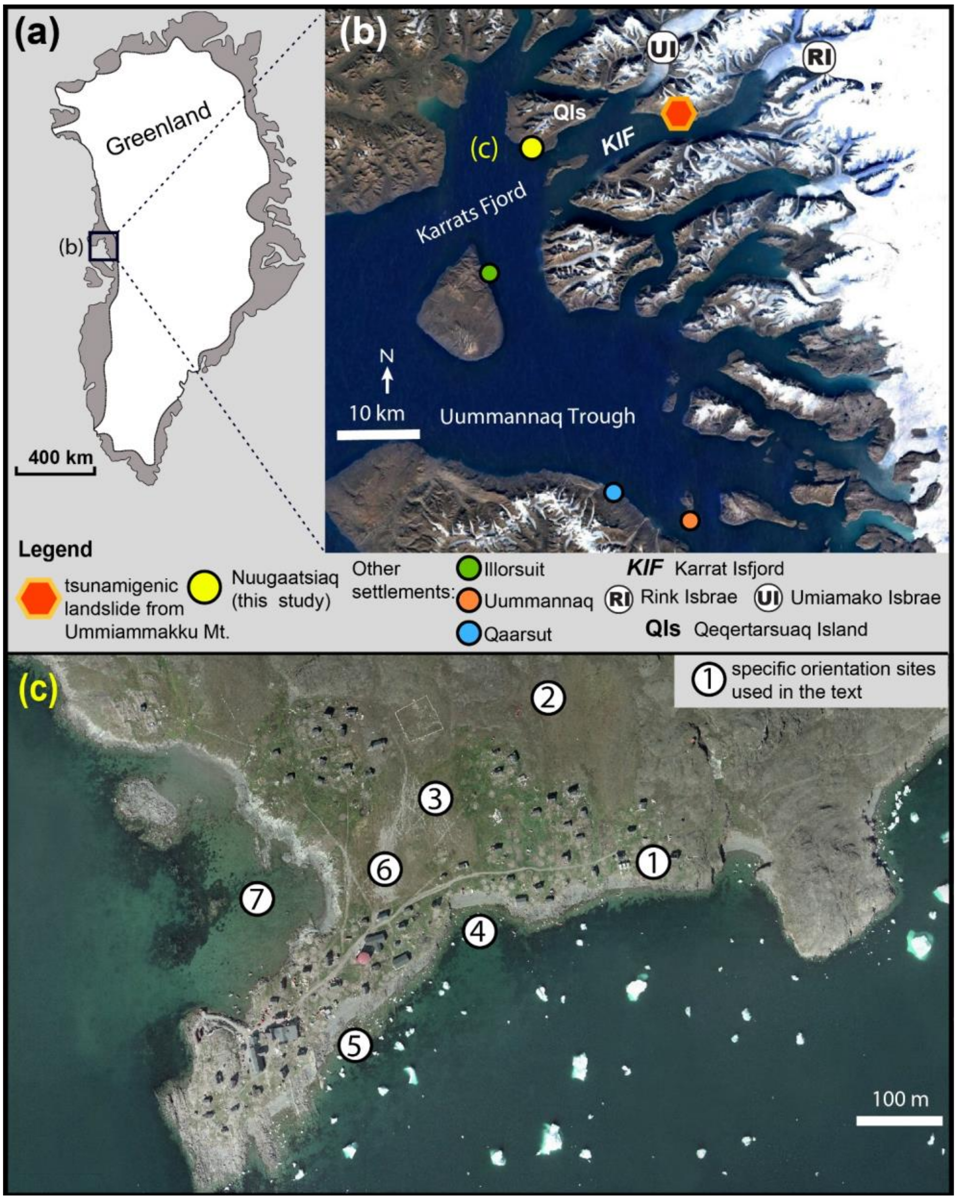

Figure 1. Location of study area. a) General position of Karrat Fjord in western Greenland (Source: Google Earth); b) Karrat Fjord area, where tsunamigenic landslide occurred on 17 June 2017 and inundated settlement of Nuugaatsiaq; c) Aerial image of Nuugaatsiaq before the event (nunuagis.gl), Number in circles mark orientation sites used in the text 1 – area with first line of buildings destructed by tsunami, 2 – heliport above the tsunami inundation limit, 3 – playground area, partly flooded by tsunami, 4 – first beach eroded by tsunami; 5 – second beach eroded by tsunami; 6 – saddle between beach(4) and harbour; 7 – local harbour.

Figure 2. Coastal landscapes in NuggatsiaqNuugaatsiaq. (a) Densely vegetated (grasses and shrubs) coastal lowland with ragged shoreline dissected by rocky capes and coves with narrow beaches; (b) Main headland with exposed glacially scoured bare rock surfaces, note accumulations of boulders in rocky hollows; (c) Cliffed coast in Nuugaatsiaq harbour. Tops of the cliff were eroded and gullied by tsunami.

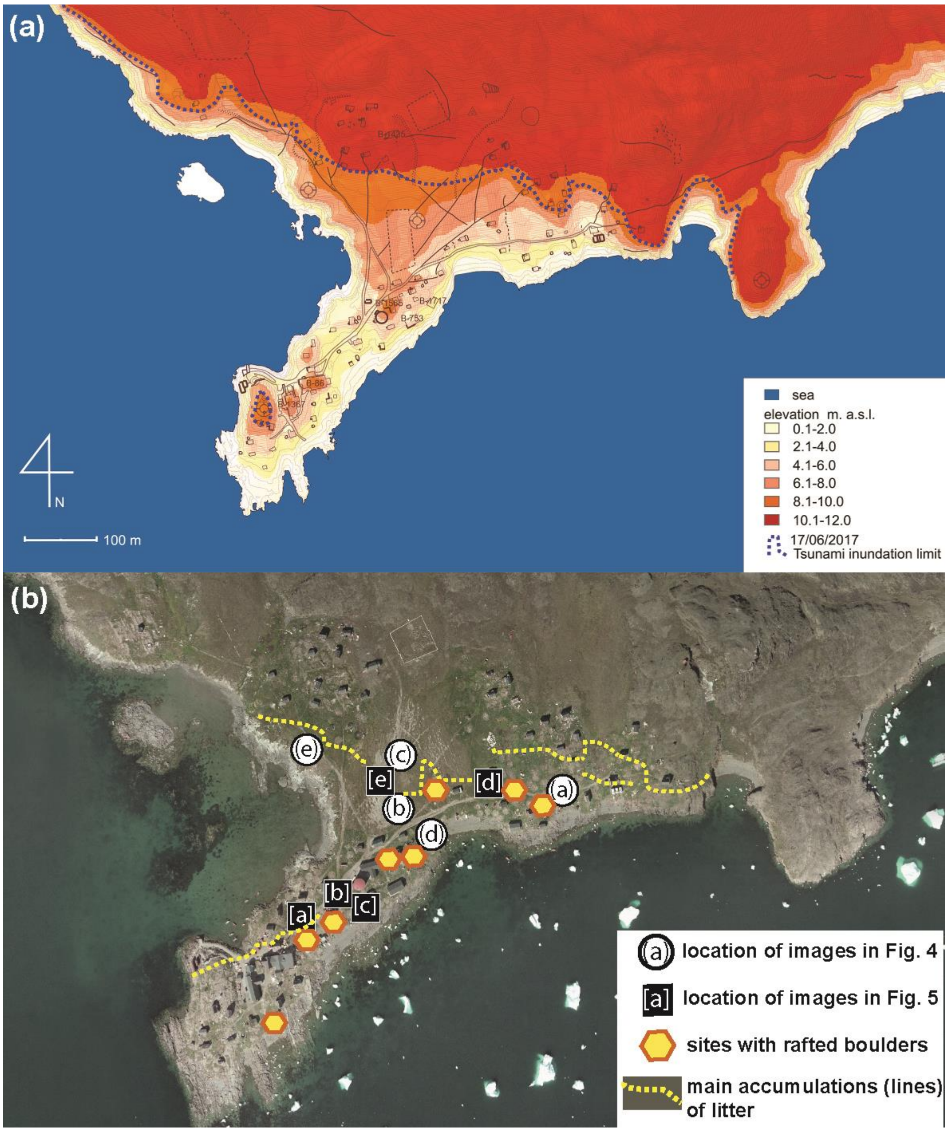

Figure 3. (a) Digital elevation model (2-m DEM, https://www.pgc.umn.edu/data/arcticdem/) of Nuugaatsiaq with marked tsunami inundation limit (wave flooded the terrain up to 8 m a.s.l). (b) Overview map of the settlement with marked location of images from Fig. 4 and 5. Lines of litter visible in the landscape 2 years after the event and sites were large boulders rafted by tsunami were marked too. Background: technical map of settlement from nunagis.gl

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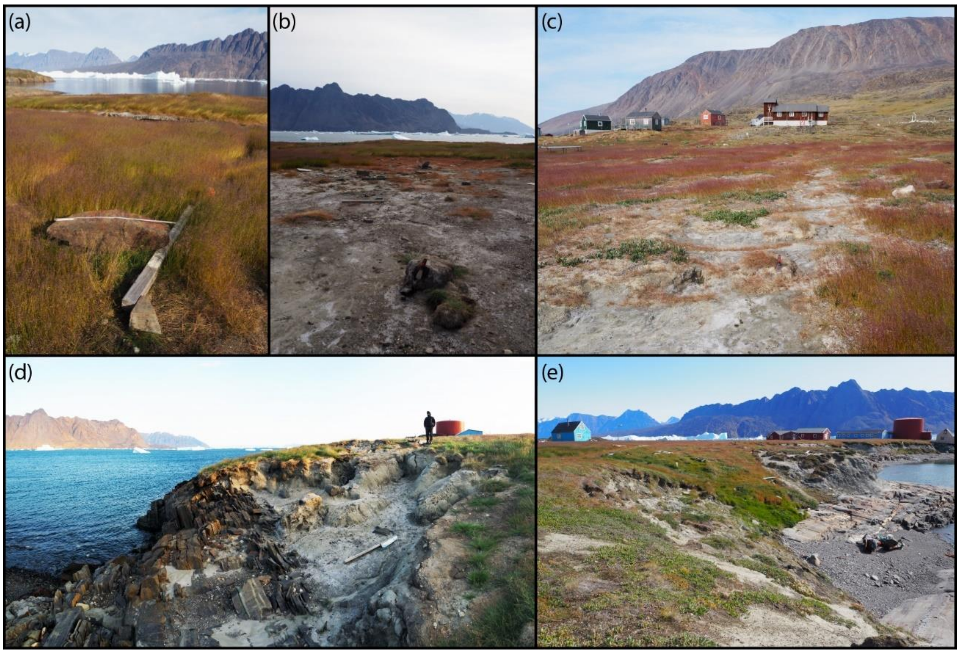

Figure 4. Examples of tsunami effects on tundra and soil covers in Nuugaatsiaq two years after the event. (a) High grass covers eroded tundra blocks, boulders and litter deposited by tsunami; (b) eroded tundra block/raft deposited on the coastal lowland inundated by tsunami with thin layer of redistributed marine sediments and salt covers; (c) deposited tundra and soil blocks and gullied ground surface by wave which backwash to the fjord; (d) eroded edges of low bluffs above the small beach (site 4 in Fig. 1c); (e) cliffed coast heavily dissected by tsunami which overwashed the saddle (site 6 in Fig. 1c) between beach (site 4 in Fig. 1c) and drained to local harbour (site 7 in Fig. 1c).

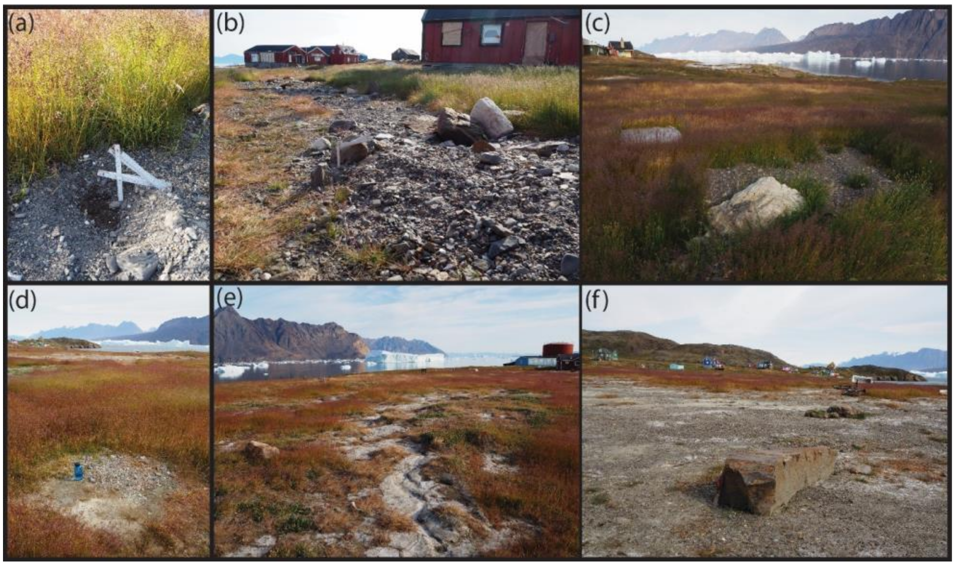

Figure 5. Examples of tsunami deposits preserved in Nuugaatsiaq two years after the event. (a) Ca. 4-6 cm thick cover of marine gravels covering grass vegetation; (b) Up to 10 cm thick layer of tsunami deposits eroded from local beach and deposited on road and grass vegetation; (c) Melt-out material from iceberg (gravels and mud) and ca. 100 cm long boulder thrown onshore by tsunami; (d) Deposits melted-out from iceberg washed on shore by waves; (e) rills eroded in soil and tsunami deposits by returning wave; (f) Over 100 cm long boulder moved by wave on the thin layer of gravels and eroded soil deposits. Note salty surfaces and eroded tundra rafts in the background.

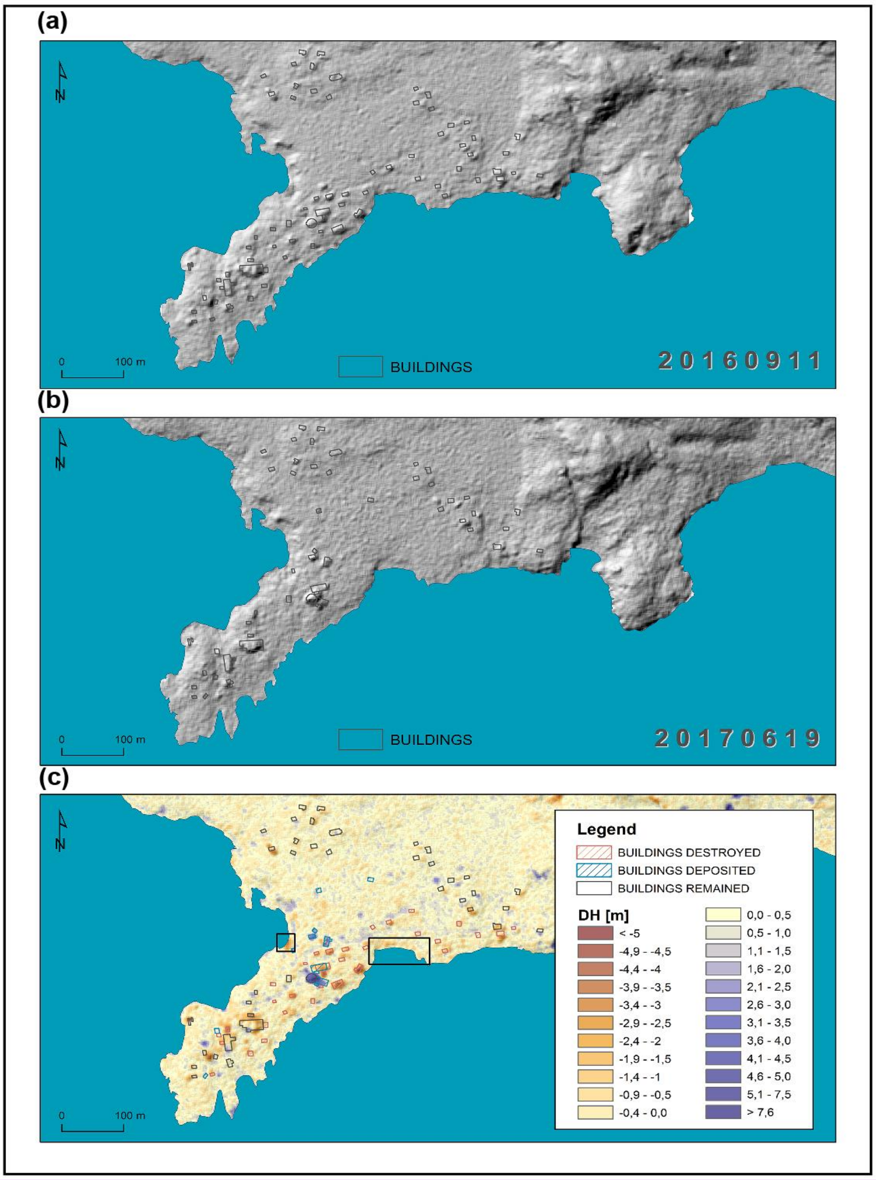

Figure 6. Post-tsunami terrain change in the Nuugaatsiaq area. (a) DTM of study site on the 11th September 2016 – pre-tsunami conditions; (b) DTM of study site on the 19th September 2017 – post-tsunami conditions.; (c) Terrain change calculated from two digital terrain model (DTM) data. The colour scale illustrates values of terrain change (DH), where warm colours stand for an elevation decrease due to erosion, and cold colours represent an elevation increase led by the effects of deposition. Please notice that major changes in the terrain are associated with construction, destruction or relocation of buildings. The resolution of model (2 m) precluded detection of small-scale landscape modifications observed during the fieldwork. Two sites were both field observations and remote sensing analyses detected significant change (erosion) was beach (site 4 in Fig. 1) and cliff edge in the harbour (site 7 in Fig.1) on the opposite sites of the saddle (marked by red rectangles).

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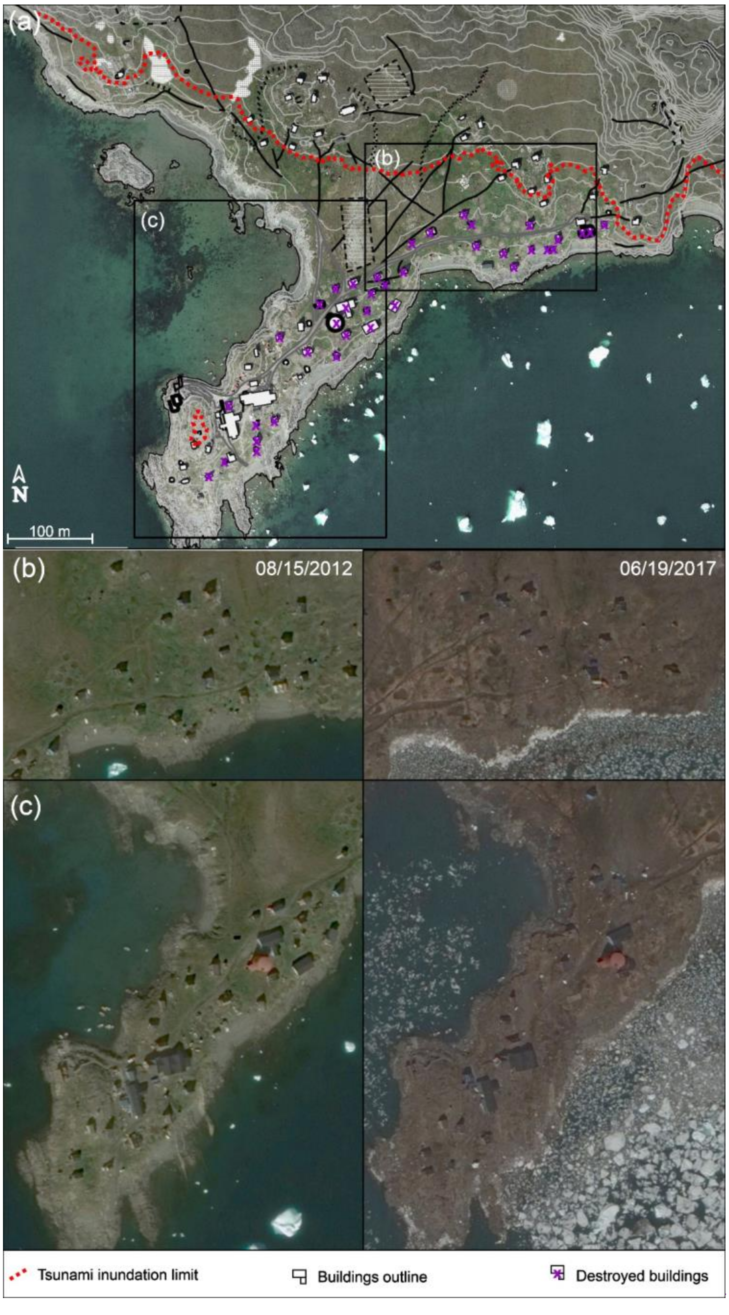

(a)
(b)
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100 m
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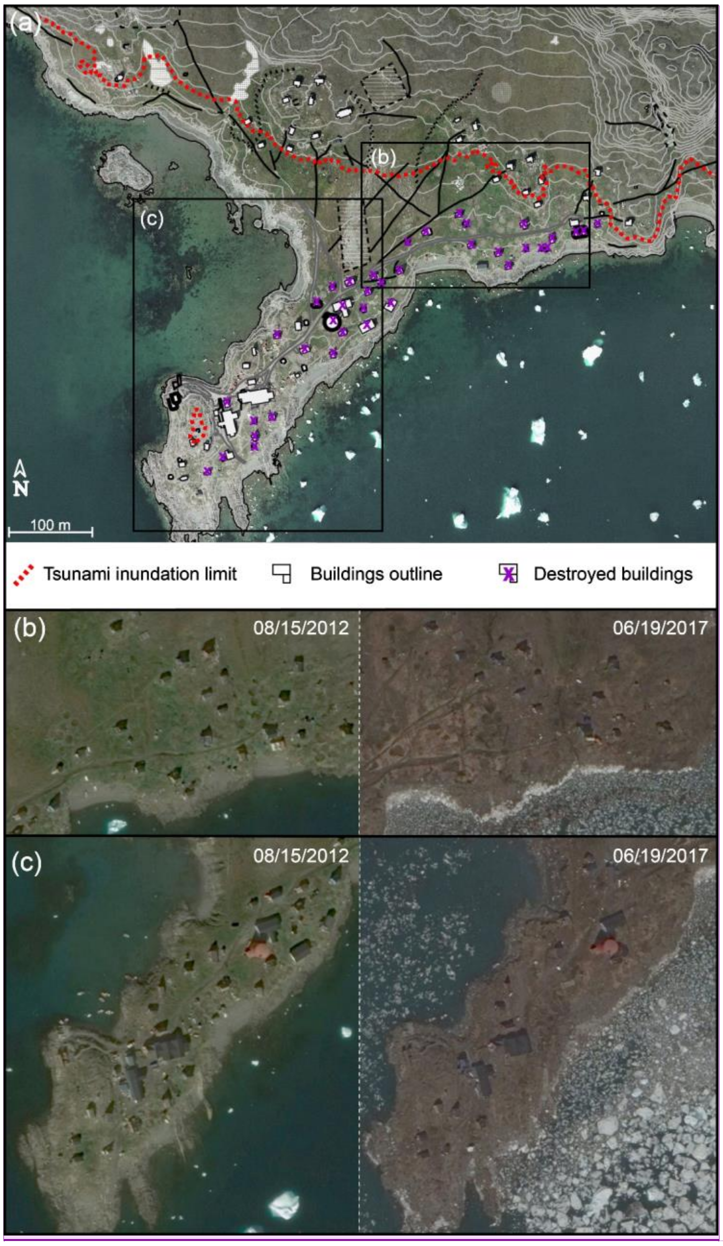
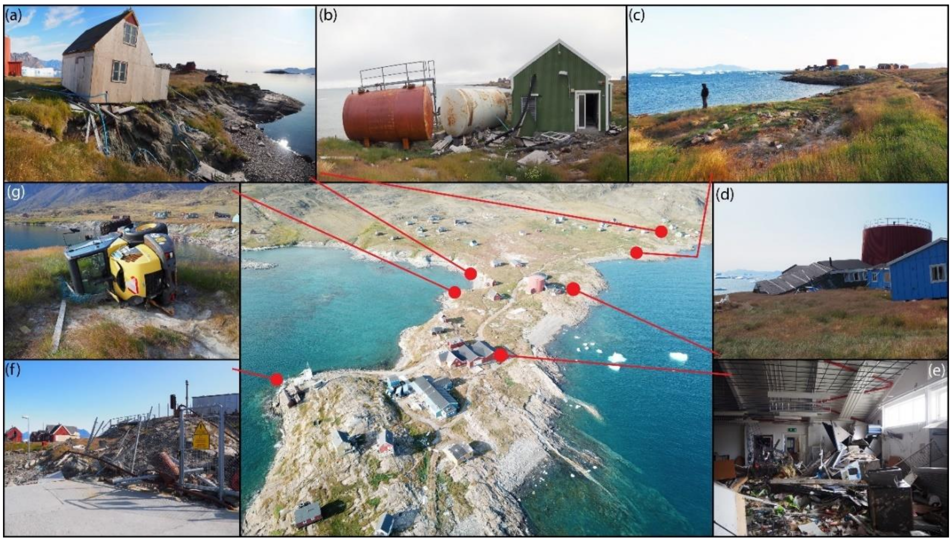
(c)
Tsunami inundation limit
Buildings outline
Destroyed buildings



~~Figure 6~~Figure 7. Scale of destruction in settlement infrastructure. (a) General overview of area inundated by tsunami with location of damaged buildings. The inventory of tsunami-induced changes of settlement infrastructure are based on interception of aerial images, local spatial plans and field surveying. Background ortophoto and topographic map~~& technicalmap~~: nunagis.gl.; (b) Satellite image of settlement before the tsunami impact (15th August 2012) and; (c) Satellite image of settlement after the tsunami impact illustrate the scale of destruction and dislocation of buildings (19th June 2017) Background Google Earth Image © 2020 Maxar Technologies.

Commented [A4]: Figure corrected as suggested by Reviewer 2



~~Figure 7~~**Figure 8.** Examples of infrastructure damages caused by 2017 tsunami in Nuugaatsiaq. (a) Wooden house removed by wave from point foundation transported several dozen of meters; (b) Fuel tanks washed away from concrete frames and pushed towards power plant. Note large accumulation of litter and tsunami deposits around and inside the buildings; (c) site of former building position, which was destroyed and swept away by tsunami. Note broken wooden point foundations, media connections and erosional gullies; (d) Smashed and collapsed wooden school building moved towards major water tank; (e) Interior of local shopping centre passed by tsunami. Note large amounts of litter and rotting food supplies and twisted and bowed metal frame construction; (f) Partly-torn metal fence around fuel storage site which acted as a trap for litter transported by tsunami; (g) example of heavy machine knocked over by waves.

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Arctic tsunamis threaten coastal landscapes and communities - survey of Karrat Isfjord 2017 tsunami effects in Nuugaatsiaq, western Greenland

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Abstract

On the 17th of June 2017, a massive landslide which mobilized 35–58 million m^3 of material entered the Karrat Isfjord in western Greenland. It triggered a tsunami wave with a runup height exceeding 90 m close to the landslide, ca. 50 m on the opposite shore of the fjord. The tsunami travelled ca. 32 km along the fjord and reached the settlement of Nuugaatsiaq with ca. 1-1.5 m high waves which flooded the terrain up to 8 m above sea-level. Tsunami waves were powerful enough to destroy the community infrastructure, impact fragile coastal tundra landscape, and unfortunately, injure several inhabitants and cause 4 deaths. Our field survey carried out 25 months after the event results in documentation of the previously unreported scale of damages in the settlement (ca. 48% of infrastructure objects including houses and administration buildings were destroyed by tsunami). We have observed a recognizable difference in the concentration of tsunami deposit accumulations between areas of the settlement overwashed by by the wave and areas of runup and return flow. The key tsunami effects preserved in the coastal landscape were eroded coastal bluffs, gullied and dissected edges of cliffed coast in the harbour and tundra vegetation compressed by boulders or icebergs rafted onshore during the event.

1 Introduction

Although known to the research community for at least 60 years, the occurrence, scale and impacts of tsunamis in cold regions (Arctic and subarctic) still shock the wider public. Their increasing frequency in this rapidly warming region already poses a serious threat to a fragile polar coastal environment and infrastructural needs of human communities (Miller 1960; Dahl-Jensen et al. 2004; Buchwal et al. 2015; Higman 2018).

The unstable nature of cold region landscapes in terms of permafrost-thawing or glacier retreat-or earthquake- induced landslides provide potential tsunami sources. The effects of waves are particularly destructive in fjords and narrow straits, where a constraining topography can amplify the wave heights. For instance, the landslide which entered Lituya Bay in Alaska in 1958 triggered a giant tsunami wave with runup height of over 500 m (Miller, 1960). Another wave (runup over 190 m) recorded in 2015 in Taan Fjord, Alaska, was caused by a landslide from local slopes destabilized by the retreat of Tyndall Glacier (Dufresne et al., 2018; Higman et al., 2018; Haeussler et al. 2018, Bloom et al. 2020). In the last hundred years tsunamis were recorded also in Norwegian fjords e.g. the Tafjord 1934 event (e.g. Harbitz et al., 2014).
In Greenland, due to the recent climate change (i.e. shrinking of glaciers and permafrost thawing) many mountain slopes were destabilized and released numerous tsunamigenic landslides. For example, in November 2000 a landslide from Paatuut mountain triggered a tsunami (runup ca. 50 m) which destroyed Qullissat town (Disko Island, western Greenland) and destabilized shores along Vaigat Strait even up to 150 km from the landslide site (Dahl-Jensen et al., 2004; Buchwał et al., 2015). The same region was also hit by a tsunami after the Niiortuut landslide in 1952, as mentioned in the recent inventory of Greenland landslides carried out by Svennevig (2019).
Here we report on the largest documented tsunami wave in Greenland to date (runup height ca. 90 m), which resulted from a massive landslide to Karrat Isfjord and destroyed the settlement of Nuugaatsiaq on the 17th of June 2017 (Figure 1). Based on a field survey carried out two years after the event, our study provides insights into the lasting tsunami-induced geo-ecological changes in coastal landscape and in addition presents an inventory of tsunami damages to settlement infrastructure.

2 Materials and Methods

This study is based on field observations carried out in July 2019. We followed the post-tsunami traces mapping protocol described in the seminal paper of Szczuciński (2012) on post-depositional changes of onshore tsunami deposits. It is important to note that the visit occurred 25 months after the event, which means that at least two spring melt-out seasons happened between the event and the mapping. It is likely that some of the tsunami traces (particularly fine deposits, tsunami salt precipitation and iceberg erosional and depositional marks) were partly erased from the landscape. The largest boulders and litter lines were marked with a handheld GPS. We took a careful survey of the vegetation cover change, as suggested by Buchwał et al. (2015) in their study of 2000 Paatuut tsunami impact on an Arctic shrub ecosystem. We photographed each settlement building or facility (e.g. cemetery, playground, harbour, heliport) and noted any visible infrastructure and landscape degradation. We observed some signs of human action on the site, focused on removing most of the toxic substances left in the settlement, that is petrol. In order to properly understand the scale of post-tsunami changes we compared a series of aerial images (available at NunaGIS portal: www.nunagis.gl), field photos, online video taken in the settlement before and after the wave, and settlement spatial planning maps and risk assessment documents published by the local government. Apart from land-based photos, we collected a number of aerial images using a DJI Mavic Pro drone. As our UAV was not allowed to enter the no-fly zone above the settlement centre, we took oblique images from the recommended distance. We have also explored ArcticDEM (Porter et al., 2018) resources and compared terrain changes between pre- and post- tsunami digital terrain models (DTM) to determine the scale of coastal landscape modification entailed by tsunami impact. In ESRI ArcGIS software 2 m DTM constructed from satellite images captured on the 11th of September 2016 was subtracted from DTM captured on the 19th of June 2017 to calculate elevation difference between models and check if sites where tsunami erosion and deposition detected during fieldwork were traceable in digital terrain models (Fig. 6).Information about landslide genesis and some of the tsunami wave characteristics was extracted from remote-sensing analyses produced by USGS (Bessette-Kirton et al., 2017) and the collection of geophysical reports published soon after the event (Clinton et al., 2017; Chao et al., 2018; Gauthier et al., 2018; Butler, 2019; Poli, 2017; Paris et al., 2019).

3 Research area

3.1.1 Geographical setting

The surrounding landscape is mountainous (mountain ranges with numerous summits and plateaus reaching 2000 m a.s.l) and is characterized by some of the highest relief in western Greenland (Roberts et al. 2013). The major role in shaping the present-day geomorphology was played by retreat of Uummannaq ice stream system (UISS) which left the diverse set of glacial landsystems in fjords, mountains and valleys of the region. The landscape was dissected by selective linear glacial erosion with lowlands dominated by glacial scour and mountain ranges occupied by cirque, plateaus, and valley-type glaciers (Lane et al. 2016). Lane et al (2016) classified banks of Karrat fjord and southern coasts of Qeqertarsuaq island, where studied settlement is located, to areal scour terrestrial landsystem exposed after the retreat of two northern branches of UISS (Umiamako Isbrae and Rink Isbrae). Ice streams significantly modelled the topography of local fjords. Dowdeswell et al. (2016) described submarine landscape (Rink Fjord and Karrat Isfjord) as a system with relatively smooth seafloor, broken by bedrock ridges and pinnacles that divide the fjord into several deep basins. Bathymetry maps derived from multibeam echo soundings data acquired in 2007-2014 and compiled by Rignot et al. (2016) revealed that the entrance to Karrat Isfjord is 600 m deep, 5 km wide, with a sill at 400 m depth about 160 km from Rink Isbrae The deepest basin of the fjord (1100 m) is located ca. 25 km to the east of Nuugaatsiaq. Fjord near the settlement is shallow with seafloor depths 0-240 m.

The coastal landscape of Nuugaatsiaq is predominantly rocky with an undulating and ragged coastline dissected by narrow coves and headlands (Fig.2a, Fig. 3). Rocky coves along the southern coast of Nuugaatsiaq are filled with narrow beaches underlaid by rocky bedrock (Fig. 2a). Beach deposits are thin (< 1m) and composed of mixed coarse sand and gravel deposits as well as boulders deposited by icebergs or left along the shores by retreating ice streams. The largest cape in the area, located to the SW of the settlement centre is characterized by bare rocky surface with well-preserved signs of glacial scour e.g. striations and polished bedrock (Fig.2b). Close to the shoreline most of smooth rocky hollows were filled with accumulations of boulders (ca. 0.2-0.5 m in diameter). The Nuugaatsiaq harbour (site 7 in Fig. 1c) is backed by the cliffed coast (between 2-4 m high) formed in bedrock and overlain by layer of soils/glacial deposits and covered with well-vegetated tundra (Fig. 2c). At the base of the cliff narrow (1-3 m wide) mixed sand-gravelly beaches are present.

3.1.2 Geology

The dominant rocks in the region are Archean gneisses mixed with supracrustal rocks of the Palaeoproterozoic Karrat Group (Sørensen and Guarnieri, 2018). The slopes of Ummiammakku mountain where the tsunamigenic landslide occurred are composed of gneisses (Archean) overlain by quartzites (Palaeoproterozoic) and schist of the so-called Karrat Group (Mott et al., 2013).

3.1.3 Permafrost

The study area was historically included in the continuous permafrost zone (Christiansen and Humlum, 2000). The most recent northern hemisphere permafrost map based on the modelling of temperature at the top of the permafrost (2000-2016) at the 1 km^2 scale presented by Obu et al. (2019) place it close to the boundary zone between continuous and discontinuous permafrost zone. To our knowledge no direct ground temperature measurements have been conducted in the close surroundings.

3.1.4 Vegetation

This area is a part of the mid-arctic oceanic vegetation zone (Bay 1997). The vegetation comprises a shrub-grassland system, with commonly found circumpolar species including *Carex ursina*, *Cassiope* heath, *Salix glauca*, *Festuca* *groenlandica, Puccinellia groenlandica*. Coastal grasslands are dominated by dense Honckenyo-Elymetum mollis associations (Lepping & Daniëls 2007).

3.2 Settlement history & economy

Nuugaatsiaq is a settlement in the district of Uummannaq in the Avannaata Kommunia. Nuugaatsiaq is located in the south of the Qeqertarsuaq Island (Fig.1), dominated by Snehætten (Nuugaatsiap Qaqqaa) mountain range The island is separated from Karrat Island located between Karrat Fjord and Karrat Isfjord by the Torsuuk strait. The closest settlement is Illorsuit and lies about 35 km south-west.

Nuugaatsiaq was probably settled shortly after 1918. In 1923 it was proposed in Grønlands Landsråd to divide the municipality of Illorsuit. For this purpose, a new Udsted had to be built. Udsted (roughly translatable as outlying settlement): Udsteder were smaller trading settlements, which were administered by an Udsteds administrator. Most of the Udsteders later became villages. In 1925 Nuugaatsiaq was granted Udsteds status and in the same year a dwelling was built for the Udsteds administrator. In 1926 the village received a school chapel. In 1930 Nuugaatsiaq already had 119 inhabitants. In the same year a shop with a warehouse was built and in 1936 a packing house (Madsen 2009). In 1960 the population reached its maximum with 159 people. In 2017 the settlement had 102 inhabitants (bank.stat.gl).

Nuugaatsiaq has been living mainly from halibut fishing, while some time ago there was still seal hunting and catfish fishing. A small trading branch of Royal Greenland with a maximum of ten employees stored the fish. Other jobs were in administration, at Pilersuisoq, in tourism and at Atuarfik Saamu School, which taught twelve students in grades one to nine and also offered a library and youth leisure activities. There was also a day care centre, the post office, an infirmary, and a village hall. The majority of the buildings were located on undulating coastal lowland from 1 to 4 m a.s.l. (Fig.3a) There is a small quay on the headland that gives the village its name. Most of the boats were usually launched directly at the water's edge in the small harbour on the west side. In the north is the heliport Nuugaatsiaq. In winter, the traffic was by snowmobile and dog-sledge.

Nukissiorfiit (state utility company) supplied the village with electricity via the power station in the east and with fresh water from reservoir supplied by local streams. Garbage was burned or dumped into the sea. TELE Greenland provided the telecommunications.

The events of June 17th 2017 resulted in the evacuation of the settlement and abandonment of community continuing to the present. Currently former inhabitants of Nuugaatsiag were relocated to Uummannaq and Qaarsut settlement placed over 100 km south of Nuugaatsiaq (Fig.1).

4 Results and discussion

4.1 Landslide and tsunami characteristics

According to the analysis of seismic precursors of the event carried out by Butler (2019), the tsunami was a direct result of the landslide triggered by the following sequence of processes. An earthquake ruptured the fault surface and released the hanging wall ca. 1000 m above the sea, and a head scarp was created. Rockfall was transformed into a rock avalanche which entered the fjord, causing the wave. Gauthier et al. (2018) calculations suggest that the Karrat fjord landslide was much larger (~35-58 x10ˆ6 m^3) than the famous tsunamigenic rockslide into Lituya Bay, Alaska in 1958 (~30x10ˆ6 m^3). Interestingly, on the map of the Nuussuaq Basin showing landslide prone areas published by Pedersen et al. (2002), the Karrat Fjord region is not marked as a potential risk area.

A field survey carried out by a group of researchers led by Professor Fritz from the Georgia Institute of Technology (Schiermeier, 2017; https://ce.gatech.edu/news/after-recon-trip-researchers-say-greenland-tsunami-june-reached-300-feet-high) found evidence that the wave runup height was ca. 90 m at the landslide site, and up to 50 m on the opposite side of the Karrat Fjord. Numerical modelling of the landslide and wave performed by Paris et al. (2019) indicates that

Nuugaatsiaq located ca. 32 km from the landslide was hit by three 1 – 1.5 m high waves, inundating the settlement over a period of ca. 3 minutes. The wave inundated terrain up to 8 m a.s.l. (Fig. 3 a)

4.2 Landscape degradation

4.2.1 Soil and tundra cover

Inspection of satellite images and photographs taken in Nuugaatsiaq before the event suggest that grassy-tundra covers dominated the top of coastal bluffs and the strip of coastal lowlands between the predominantly rocky shore and main coastal road passing the settlement from west to east. During our fieldwork we noticed very dense and relatively high (0.4 – 0.6 m) grassy meadows covering coastal lowlands, and recolonizing abandoned playgrounds, roads, backyards (Fig. 2a). The observed post-event vegetation cover in study area was significantly denser and higher than in other settlements visited in the region in the same season. Two years after the event most of the blocks of eroded soil, rafts of tundra, boulders, or litter that were found were almost entirely hidden in a high grass cover (Fig. 4a). The wave has torn blocks of tundra (shrubs, mosses, grass) off the coastal slope and deposited them on land (Fig. 4 b, c). We noted a significant removal of tundra cover, soil erosion, and associated formation of rills or small gullies (0.2-0.6 m deep) concentrated on surfaces exposed after the washing away of buildings. Tundra and soil were also eroded along the cliffed coast of the harbour (Fig. 4 d, e). At a few places along the main road and in the vicinity of the playground the vegetation cover (grasses) was covered by a thin layer of tsunami deposits (3 – 7 cm) composed mainly of marine gravels mixed with coarser sands. Salty patches with dead-vegetation were observed mainly across the saddle between southern coast and western harbour (site 6 in Fig. 1c). After analyzing the video coverage of the event and post-event images (see list of online resources in references), we assume that some parts of the grass cover were compressed by the fragments of icebergs or ice-floes washed on shore by tsunami. In sites where ice-bergs or ice-floes were deposited and melted away grasses were weighted down and melt-out sediments (gravel, sand, mud) was observed between grass blades. Such spots were surrounded by lush grassy tundra. Tundra was compressed also by tsunami-derived boulders both eroded from beaches and melted out of icebergs (Fig. 3b).

4.2.2 Coastal erosion

We recognized two main effects on coastal geomorphology induced by tsunami impact. The tsunami erosion was concentrated on the low bluffs of tundra along the coast between narrow beaches (section of the coast between sites 1-4-5 in Fig. 1c, Fig 2a). Eroded blocks of tundra cover were deposited on land (Fig. 4b). The returning wave caused additional erosion of bluffs edges and dissected them by a series of rills/gullies (Fig. 4d). The direction of the wave flow recorded in the orientation of deposited litter, buildings, marine deposits, boulders, and tundra blocks suggest that the wave overwashed the section of settlement through a saddle (site 6 in Fig. 1c) between the middle beach (site 4 in Fig. 1c) and local harbour (site 7 in Fig. 1c), and modified the relief of cliffs in the harbour. The edges of the sedimentary cliffs were gullied, and the steep cliff slopes were spread with eroded blocks of tundra and litter (Fig. 4e). Two years after the event, normal coastal processes (wave and tidal action) had not yet removed or redistributed the eroded blocks of tundra and litter from the slopes and bases of the cliffs (Fig.2c).

4.2.3 Tsunami deposits and boulders

During the field survey the tsunami deposits were found in two areas located in the direct proximity to small beaches in the central part of the settlement (between sites 4 and 5 in Fig. 1c). Sand and gravel washed from narrow and thin beaches was deposited along the main road (ca. 30 - 50 m from the shore), where the thickness of deposits exceeds 8-10 cm (Fig. 5 a,b). Thin layers of tsunami deposits (3 – 5 cm), most probably reworked by snow-melt flow (Fig. 5 e, f) were found in the saddle (playground area) between site 4 and 7 (see Fig. 1c). The general scarcity of tsunami deposits can be explained by the geomorphology of the local coastal zone, dominated by sediment-free rocky capes and coves with narrow (7-20 m wide), gravel-dominated beaches (Fig 2a). Apart from gravel deposits washed from local beaches, waves transported boulders which were found in the inundated terrain in 2 main types: groups of smaller boulders (a-axis ca. 0.2-0.4 m) deposited on marine gravels along the local road, and individual larger boulders (a-axis over 1.0 m), washed up to 100 - 120 m inland between beach and local harbour (Fig. 5 b,f). In a few places we found pads of marine gravels and boulders deposited up to 100 m from the shore and surrounded by dense grass cover (Fig. 5 c,d). Based on the inspection of videos taken during the event we correlated their location with the deposition of icebergs. In comparison with other Greenlandic coastal sites transformed by a tsunami i.e. Paatuut 2000 tsunami (Buchwał et al., 2015) the thickness, extent, and diversity of tsunami deposits found in Nuugaatsiaq was much smaller. We attributed this to the sediment-poor beach source and predominantly rocky coastal relief with sediment-free and glacially scoured surfaces. We detected a recognizable difference in tsunami landscape modification between the areas of wave overflow covering most of the saddle in central part of settlement (site 6, Fig. 1c) and area of wave uprush and drainage covering eastern part of the settlement (terrain between sites 1 and 2, Fig. 1c). In the first zone, the tsunami waves eroded material (sand, gravel, boulders) from the largest beach in the settlement and fragments of sedimentary and tundra bluffs covering rocky coastal slopes (site 4– Fig. 1c) and transported this mixed load of deposits through the settlement to the harbour (site 7, Fig. 1c). This explains the larger number of sites and zones with accumulations of tsunami deposits, signs of tsunami erosion and infrastructure destruction concentrated in this zone. In the second area, tsunami waves approached the rocky coastal zone, almost sediment free, and inundated the grassy lowland carrying mainly community litter and only small amount of sediments, which was difficult to detect in the lush tundra vegetation inspected 2 years after the event.

It is important to note that the only two sites where terrain changes detected in the field were also traceable in GIS analyses were beach and cliffed coast (Fig. 6) located on the opposite sites of the morphological saddle in the middle of the settlement (sites 4 and 7 in Fig. 1). Other elevation changes detected between two ArcticDEM scenes were attributed to relocation of buildings as coastal landforms erosion and subsequent tsunami sediments deposition were too small to be tracked in 2 m resolution terrain models (Fig. 6).

4.3 Settlement degradation

4.3.1 Infrastructure damage

Before the tsunami event the Nuugaatsiaq community infrastructure was composed of 94 buildings (houses, services and administration buildings, dog kennels, technical facilities etc.). The wave destroyed 45 buildings (48% of the original infrastructure) viz. 22 buildings were fully swept away from land, 23 buildings were partly damaged, and 11 were moved between 2 m to over 100 m from original location (Fig. 7). Most of the buildings were constructed on a wooden frame, covered with wooden boards and settled on pier foundations. Only a few of the settlement buildings were build on a metal frame coated with corrugated metal sheet settled on a concrete frame foundation. The first type of building (with pier foundations) was not strong enough to resist the wave impact and these structures were pushed by the tsunami or in some cases washed away to the fjord (Fig. 8 a,c).

In those buildings which were not moved but still affected by the wave, we observed some damage of their wooden cladding, as well as a deposition of marine sediments and litter in the ground floor area. The typical damages observed in buildings which were pushed by the tsunami but remained on land were: *broken windows and doors, devastated interior*. In contrast to buildings with pier foundations, much smaller damages were observed in buildings with concrete frame foundations. These, due to a more stable anchoring in the ground, gave a much higher resistance to the wave impact. The most common damages included broken walls, bowed and twisted metal construction frames (Fig. 8 b, d). It should be considered extremely fortunate that the fuel tanks situated at the power plant (which were one of the first parts of infrastructure hit by tsunami) were not destroyed and no leakage of petrol was reported (Fig. 8b).

4.3.2 Assessment of social, economic and environmental impacts of tsunami in Nuugaatsiaq.

The Karrat fjord tsunami, which hit Nuugaatsiaq settlement in 2017, was the first event which had such a devastating effect on an inhabited Arctic settlement, both in terms of landscape modification and infrastructure damage. Previous waves known from the cold and glaciated regions such as Alaskan Lituya (1958) and Taan (2015) flooded unpopulated and remote areas. In Greenland the Paatuut tsunami (2000) damaged the infrastructure of Qullissat, however in this case, due to the earlier closure of the coal mine (1972) the settlement was already abandoned years before the event. Therefore, this was the first time an assessment of the social and economic effects of a tsunami in this region was possible. (Table 1).

The financial data from the Government of Greenland (Naalakkersuisut) documents (Forslag til TILLÆGSBEVILLINGSLOV for 2017, from 2018/8), shows the costs associated with the relocation of tsunami victims of 14 877 000.00 DKK (ca. 2 248 085.00 USD [15.05.2020]) which can be treated as a rough estimate of an economic cost of the event. The document also declares a one-off payment to tsunami victims amounting to DKK 50,000 (7548.00 USD [15.05.2020]). In our opinion the total economic cost was significantly higher as the total market value of 45 destroyed settlement infrastructure objects (incl. buildings) was not included in the reports. Nevertheless, the settlement remains abandoned to this day and the threat of another tsunami wave remains active (Fritz et al. 2018; Paris et al. 2019). Apart from the tragedy of 4 fatalities, 9 wounded inhabitants and countless dog deaths, the catastrophe still has its social repercussions. Thirty-nine people were evacuated and separated into the settlements of Uummannaq and Qaarsut. The Displaced have lost their life's work, their hunting area, sentimental value, and social bonds. In their new places more expensive rent, isolation and adaptation difficulties often awaits them.

From the perspective of environmental protection and coastal management, the remaining material and waste in the settlement area still constitute a serious hazard. Despite the considerable effort from the local government to secure the site through reinforcement of damaged constructions, pumping fuel out of the tanks, the removal of batteries and engines from machines and vehicles, we mapped significant amounts of waste (Fig. 8 e-g). We found broken pieces of electronic equipment, ammunition, rotting food supplies, bags with faecal matter, sledge dog carcasses, and other municipal waste which had not been disposed from the settlement before and after the event (Fig. 8). In Nuugaatsiaq plastic litter is widespread not only along narrow beaches (already mixed with beach sediments), but also spread long main road of the settlement and around overwashed saddle between southern coast and harbour, and subject to further transport by strong winds (Fig. 8). Plastic waste is a serious problem of Arctic coastal environments and Nuugaatsiaq case is unfortunately another contributor to this type of environmental pollution (e.g. Cózar et al. 2017; Bergmann et al. 2017; Jaskólski et al. 2018). After the evacuation of Nuugaatsiaq the disposal of waste and better securing of damaged infrastructure at the site is hindered by the existing high risk of another tsunamigenic landslide in Karrat Fjord (Paris et al. 2019).

4.4 Arctic coastal communities threatened by tsunamis – rising risk and rising awareness

One of the most evident effects of Arctic climate warming is the increased activity of geohazard processes along the circum-Arctic coasts (e.g. Fritz et al., 2017). The majority of these processes pose a significant threat to Arctic coastal communities and built infrastructure (e.g. Forbes et al., 2011; Hatcher and Forbes 2015; Radosavljevic et al., 2016; Jaskólski et al., 2018). Most of the recent Arctic coastal change studies concentrated on accelerated coastal erosion rates in locations spread across the Arctic region and associated them with diminishing sea-ice extent, longer exposure to storm wave impacts, and thawing coastal permafrost (e.g. Farquharson et al., 2018; Irrgang et al., 2018;; Isaev et al., 2019). Also, in glaciated parts of the Arctic, such as Greenland or Svalbard, coastal research focused on the response of coastal zone to increased delivery of glacial sediments (e.g. Bendixen et al., 2017; Strzelecki et al., 2018) or rocky coast interaction with coastal permafrost (e.g. Strzelecki et al. 2017; Lim et al. 2020). At the same time little attention was paid to cold region tsunami hazards whose effects are devastating to both human and natural coastal environments. The recent examples of tsunamis in Alaska (Taan 2015) and Greenland (Paatuut 2000, Karrat 2017) demonstrate how severe impacts on coastal environments and communities can be. It is important to note that with continued warming (favouring permafrost thaw, glacier retreat, or extreme meteorological phenomena), such tsunamigenic landslides are likely to be far more frequent (Gosse et al., 2019).

To put it into a Greenlandic perspective, the recent mapping of potential tsunamigenic landslides performed by Svennevig (2019) indicated 564 landslides just between Sigguup Nunaa and Qeqertarsuaq in West Greenland (ca. 230 km in a straight line). Benjamin et al., (2018) mapped 20 rock avalanches just along one short section (ca. 25 km) of southern coast of Nuussuaq Peninsula in a direct proximity of Vaigat Strait (similar avalanche triggered Paatuut tsunami in 2000). Svennevig et al. (2019) demonstrated that the area around the Karrat Fjord landslide has continued to be active and another tsunamigenic landslide is highly probable.

Although beyond the scope of this study, here it is important to mention another type of extreme phenomenon impacting Greenlandic coastal zone - waves triggered by iceberg-roll events that are powerful enough to erode local beaches and wash away coastal infrastructure (Long et al., 2018). Calving of Greenlandic glaciers also produces extreme waves that are able to erode glacial landforms and lead to substantial degradation of coastal landscape (e.g. Lüthi and Vieli, 2016). It is important to note that with continued temperature warming in the Arctic, such landslides, glacier calving and iceberg rollover events are projected to be far more common and have profound effects on the functioning of coastal communities and landscapes.

5 Conclusions

In the present study an attempt has been made to evaluate the impact of 17th June 2017 tsunami wave on Nuugaatsiaq settlement infrastructure and coastal landscape using combination of field-based geomorphological mapping, spatial planning and GIS analyses. Based on the present investigation, the following conclusions have been reached.

1. The Karrat Fjord event is the first known example of Arctic tsunami which directly impacted an Arctic inhabited settlement and forced its evacuation.
2. The scale of tsunami damages, including destruction of 48% of settlement community infrastructure and a high risk of another event, prevents the community from returning to the settlement.
3. Apart from housing facilities, 3 waves destroyed most public service buildings e.g. school, power plant, shopping centre, administration centre, seafood processing plant.
4. Among the waste accumulations left in the area are electronic equipment, rotting food supplies, faecal matter, sledge-dog carcass, as well as ammunition and a lot of municipal waste, including a large quantity plastic. Most of the waste is completely unprotected and exposed to weather conditions and wildlife.
5. Although the tsunami inundated terrain up to 8 m a.s.l. the geomorphological effects of the tsunami were less pronounced than in previously described examples of cold region tsunami impacts (Lituya 1958, Paatuut 2000, Taan 2015) which can be explained by the local coastal morphology and geology (rock dominated coasts with small and sediment-poor beaches) and relatively low wave heights (1-1.5 m).
6. Mapped tsunami deposits included gravel-dominated beach sediments, boulders and ice-rafted material derived from icebergs stranded on land.
7. Two years after the event the effects of tsunami erosion was still detectable on the surface of local roads and edges of sedimentary cliffs along the harbour.

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Figures and Tables

<table>
<tr><th colspan="6">Observed tsunami impacts in Nuugaatsiaq</th></tr>
<tr><th colspan="2">Environmental</th><th colspan="2">Social</th><th colspan="2">Economic</th></tr>
<tr>
<td colspan="2">• Landscape degradation (tundra and soil erosion, salt residues, coastal erosion)

• hazardous materials left on site and exposed to harsh climate

• waste accumulations

• rotting food supplies easily accessible to wildlife</td>
<td colspan="2">• separation of the community, relocation of people to Uummannaq and Qaarsut

• loss of a logistic point for expeditions (hunting, fishing) for other settlements

• loss of settlement continuity

• loss of sentimental value

• relocated people forced to pay more expensive rent in new substitute premises

• isolation and adaptation difficulties in a new place

• 39 people evacuated https://knr.gl/da/nyheder/39-evakueret-fra-nuugaatsiaq

• 4 fatalities, 9 injured https://knr.gl/da/nyheder/fjeldskred-i-karrat-isfjorden-skyld-i-flodb%C3%B8lge

• death of sledge dogs (during the inventory found 4 carcasses)</td>
<td colspan="2">• costs of relocation, reparations and accommodation recognized in the budget for 2018 in the municipality of Naalakkersuisut DKK 14,877,000 (Forslag til TILLÆGSBEVILLINGSLOV for 2017, from 2018/8)

• the need to allocate substitute accommodation and a one-off compensation payment of DKK 50,000

• impoverishment and loss of property (new premises are not given)

• at least 27 sites with destroyed community infrastructure</td>
</tr>
<tr><th colspan="6">Future risk reduction actions in Arctic coastal communities</th></tr>
<tr>
<td colspan="3">Earth science and remote sensing research community:
• mapping and detection of landslides and slopes recently exposed from glacier ice or with significant degradation of permafrost
• mapping/re-mapping seabed topography of deglaciated fjords and embayments
• monitoring of present-day slope processes (slope stability)
• investigations of paleo-records of waves
• design of databases with seismic, remote sensing, geophysical and sedimentological information of past and recent tsunamigenic landslides and associated waves</td>
<td colspan="3">Local authorities:
• funding tsunami alert network
• preparation of evacuation plans/delimitation of safe zones
• consideration of tsunami and landslide hazard in spatial plans/documents
• establishment of insurance procedures and securing financial reserves to cover post-event costs of relocation of communities in new locations</td>
</tr>
</table>

Table 1. Summary of tsunami effects on coastal landscape and Nuugaatsiaq community and recommended hazard risk reduction actions.

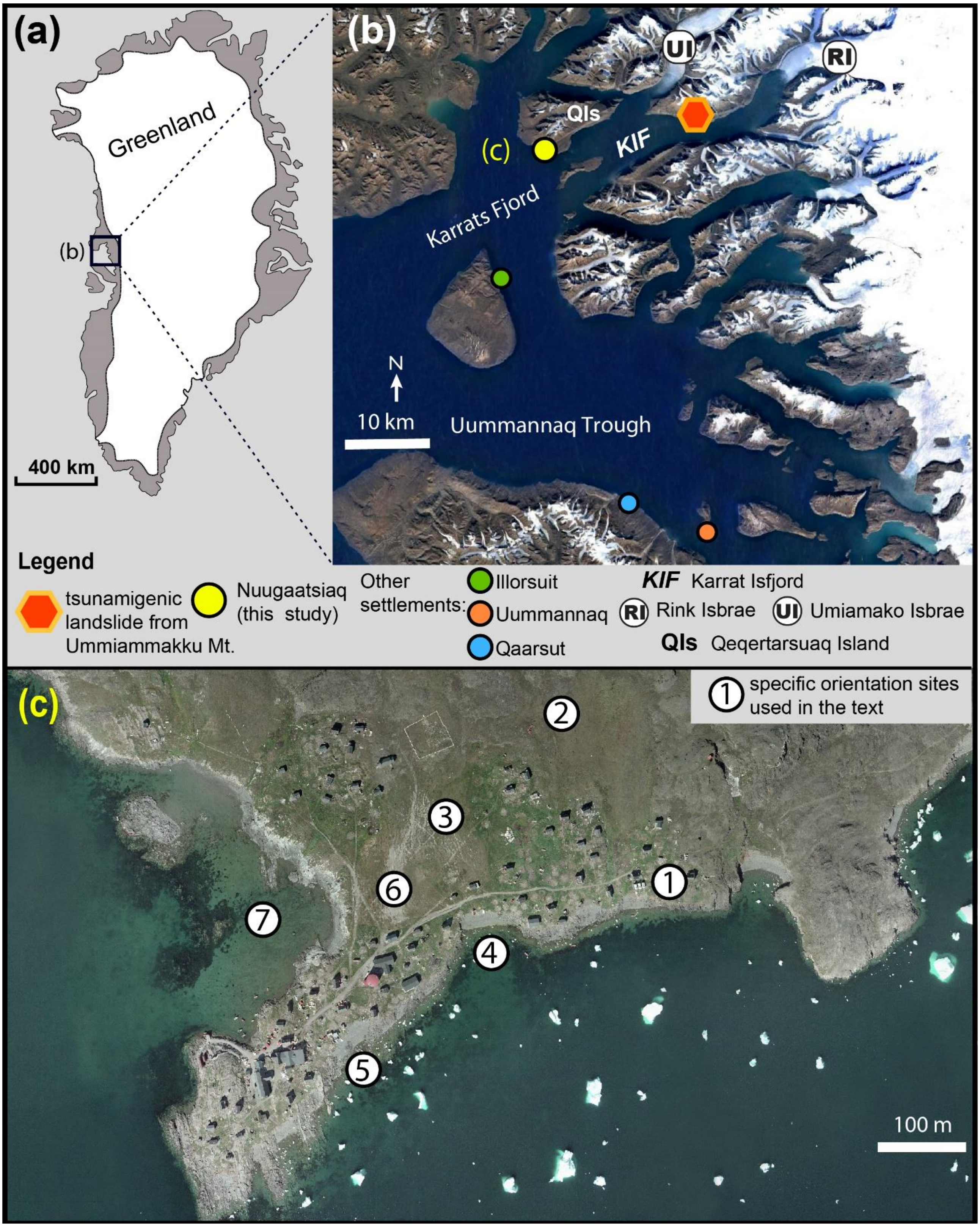

Figure 1. Location of study area. a) General position of Karrat Fjord in western Greenland (Source: Google Earth); b) Karrat Fjord area, where tsunamigenic landslide occurred on 17 June 2017 and inundated settlement of Nuugaatsiaq; c) Aerial image of Nuugaatsiaq before the event (nunuagis.gl), Number in circles mark orientation sites used in the text 1 – area with first line of buildings destructed by tsunami, 2 – heliport above the tsunami inundation limit, 3 – playground area, partly flooded by tsunami, 4 – first beach eroded by tsunami; 5 – second beach eroded by tsunami; 6 – saddle between beach(4) and harbour; 7 – local harbour.

Figure 2. Coastal landscapes in Nuugaatsiaq. (a) Densely vegetated (grasses and shrubs) coastal lowland with ragged shoreline dissected by rocky capes and coves with narrow beaches; (b) Main headland with exposed glacially scoured bare rock surfaces, note accumulations of boulders in rocky hollows; (c) Cliffed coast in Nuugaatsiaq harbour. Tops of the cliff were eroded and gullied by tsunami.

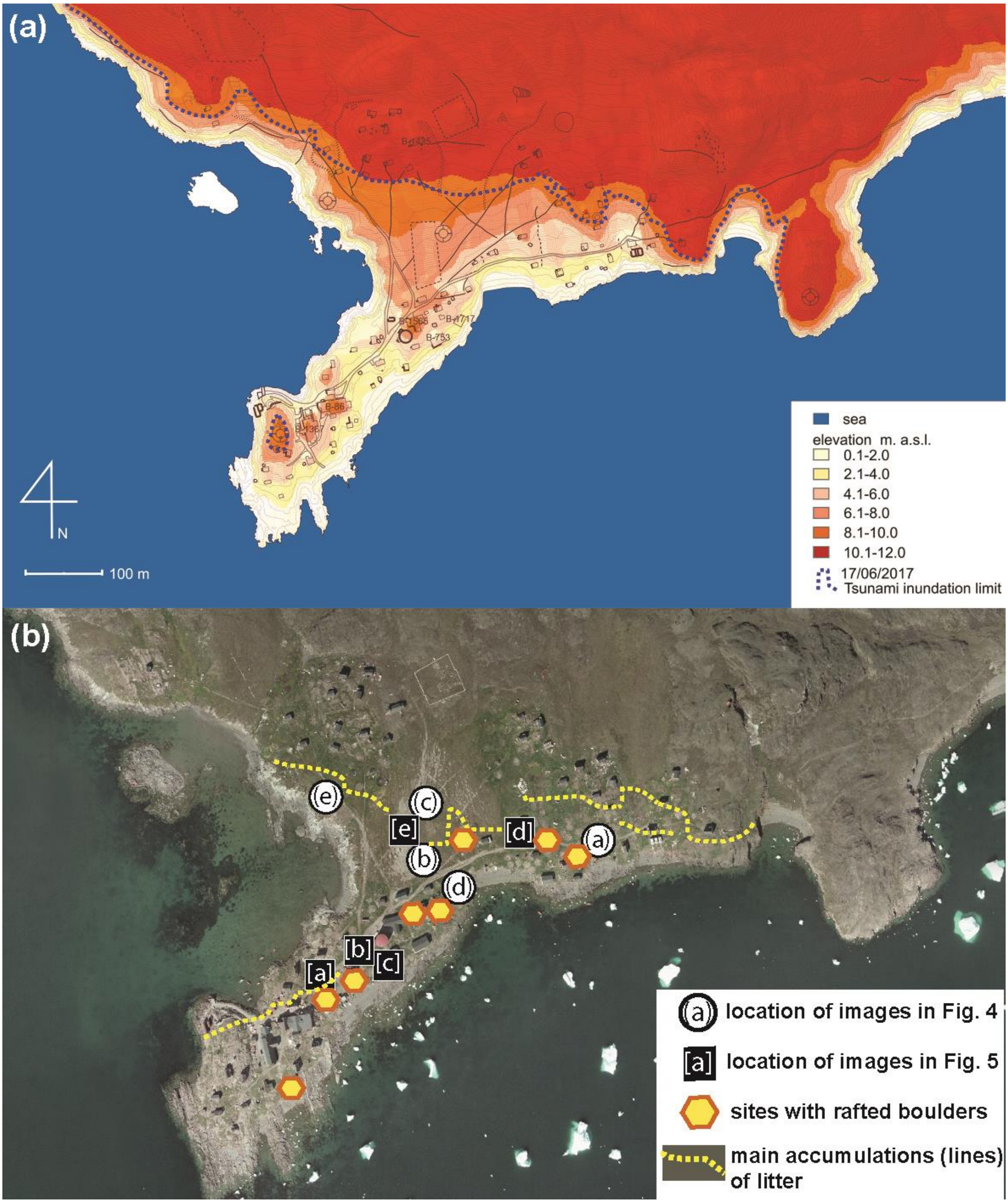

Figure 3. (a) Digital elevation model (2-m DEM, https://www.pgc.umn.edu/data/arcticdem/) of Nuugaatsiaq with marked tsunami inundation limit (wave flooded the terrain up to 8 m a.s.l). (b) Overview map of the settlement with marked location of images from Fig. 4 and 5. Lines of litter visible in the landscape 2 years after the event and sites were large boulders rafted by tsunami were marked too. Background: technical map of settlement from nunagis.gl

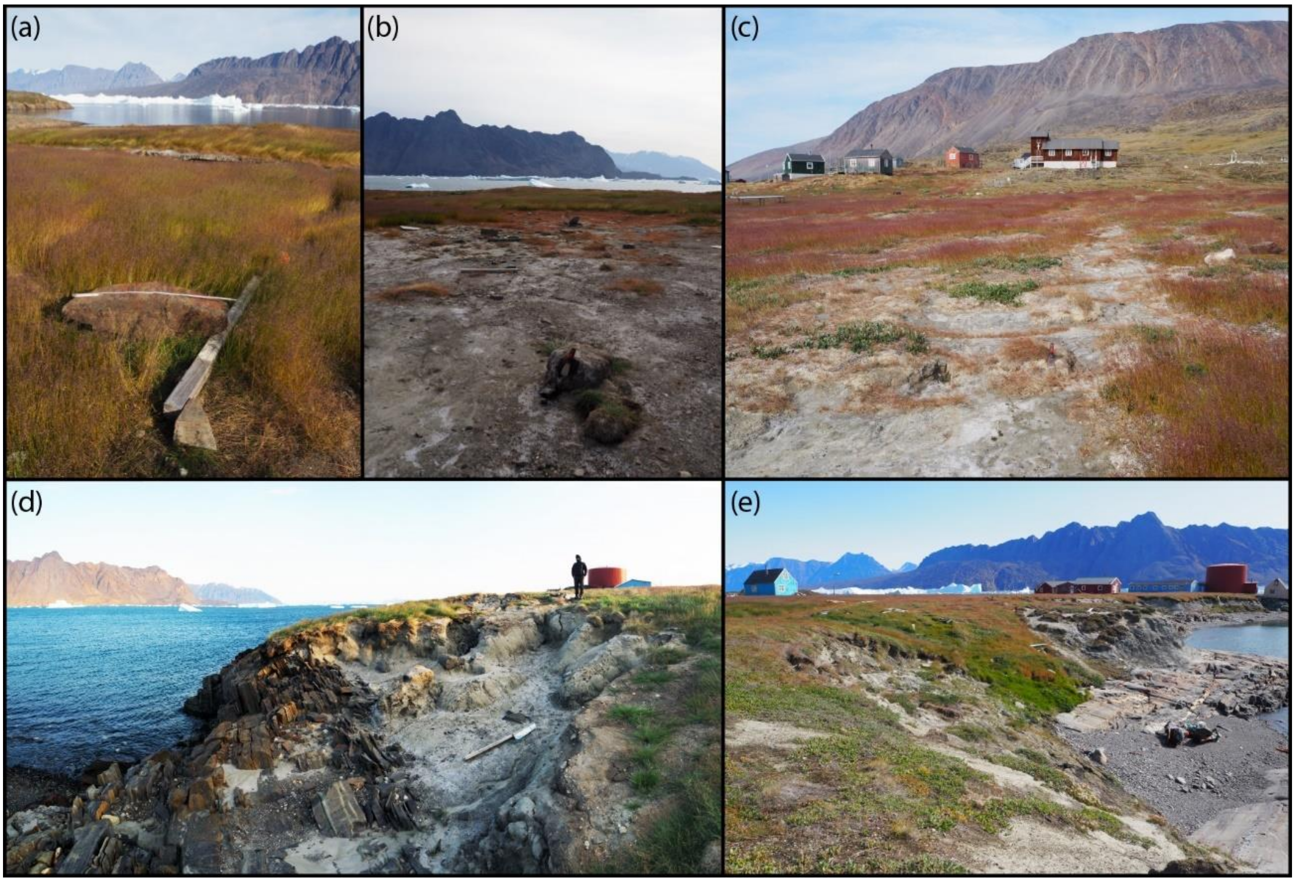

Figure 4. Examples of tsunami effects on tundra and soil covers in Nuugaatsiaq two years after the event. (a) High grass covers eroded tundra blocks, boulders and litter deposited by tsunami; (b) eroded tundra block/raft deposited on the coastal lowland inundated by tsunami with thin layer of redistributed marine sediments and salt covers; (c) deposited tundra and soil blocks and gullied ground surface by wave which backwash to the fjord; (d) eroded edges of low bluffs above the small beach (site 4 in Fig. 1c); (e) cliffed coast heavily dissected by tsunami which overwashed the saddle (site 6 in Fig. 1c) between beach (site 4 in Fig. 1c) and drained to local harbour (site 7 in Fig. 1c).

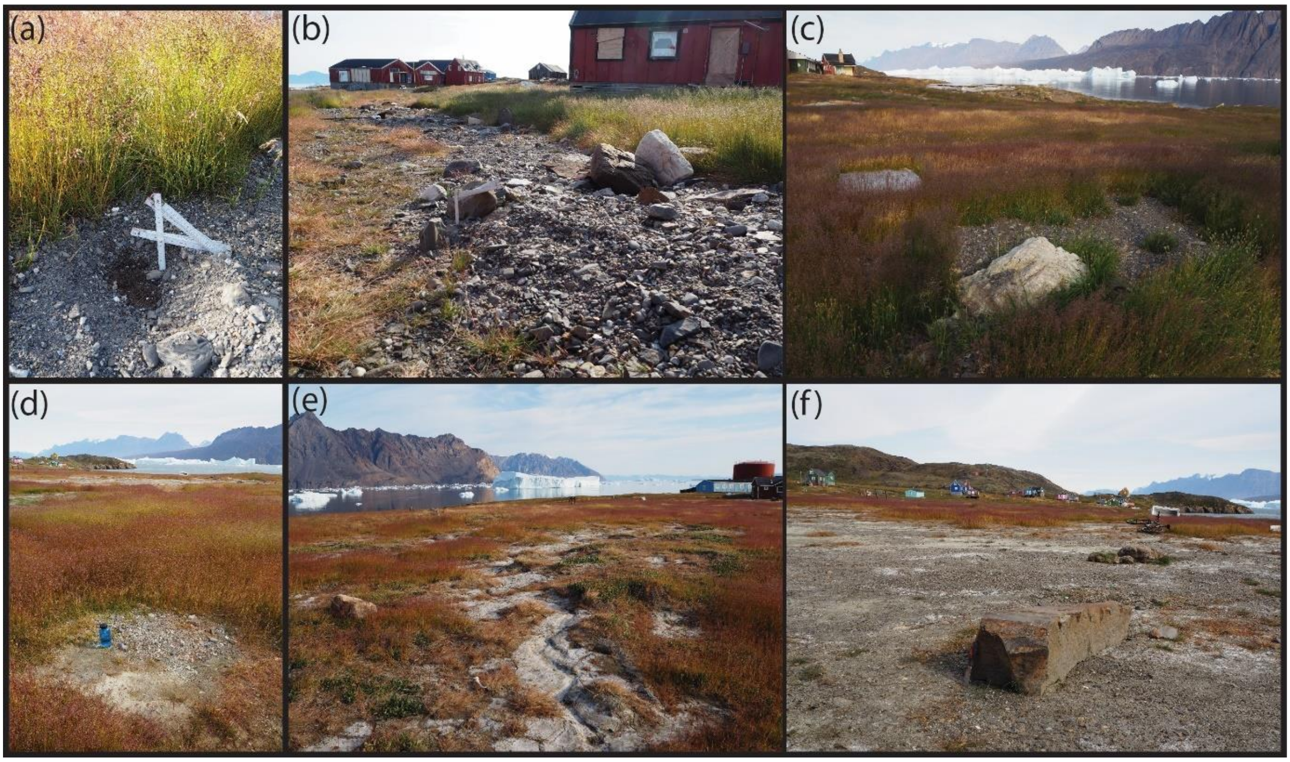

Figure 5. Examples of tsunami deposits preserved in Nuugaatsiaq two years after the event. (a) Ca. 4-6 cm thick cover of marine gravels covering grass vegetation; (b) Up to 10 cm thick layer of tsunami deposits eroded from local beach and deposited on road and grass vegetation; (c) Melt-out material from iceberg (gravels and mud) and ca. 100 cm long boulder thrown onshore by tsunami; (d) Deposits melted-out from iceberg washed on shore by waves; (e) rills eroded in soil and tsunami deposits by returning wave; (f) Over 100 cm long boulder moved by wave on the thin layer of gravels and eroded soil deposits. Note salty surfaces and eroded tundra rafts in the background.

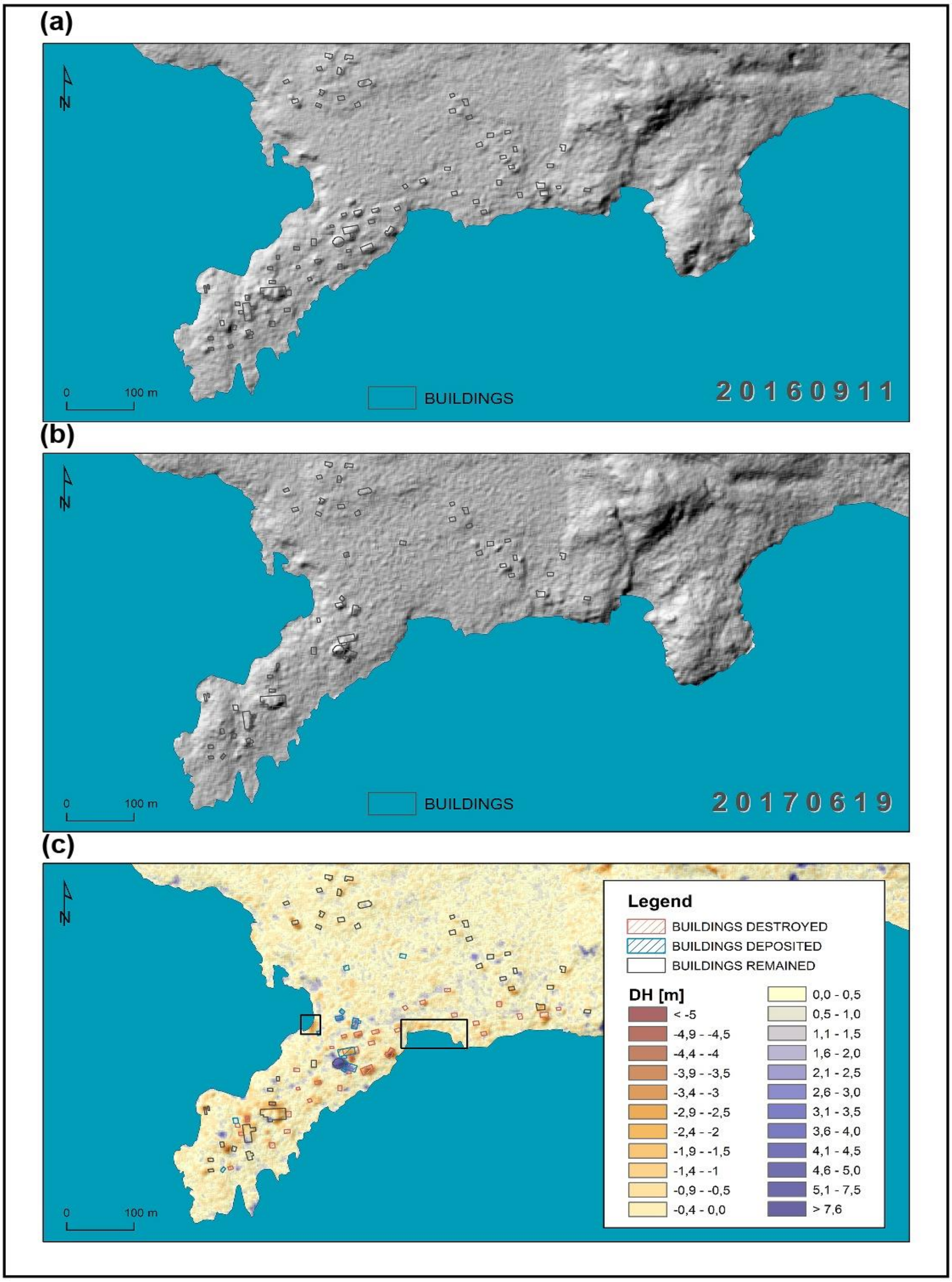

Figure 6. Post-tsunami terrain change in the Nuugaatsiaq area. (a) DTM of study site on the 11th September 2016 – pre-tsunami conditions; (b) DTM of study site on the 19th September 2017 – post-tsunami conditions.; (c) Terrain change calculated from two digital terrain model (DTM) data. The colour scale illustrates values of terrain change (DH), where warm colours stand for an elevation decrease due to erosion, and cold colours represent an elevation increase led by the effects of deposition. Please notice that major changes in the terrain are associated with construction, destruction or relocation of buildings. The resolution of model (2 m) precluded detection of small-scale landscape modifications observed during the fieldwork. Two sites were both field observations and remote sensing analyses detected significant change (erosion) was beach (site 4 in Fig. 1) and cliff edge in the harbour (site 7 in Fig.1) on the opposite sites of the saddle (marked by red rectangles).

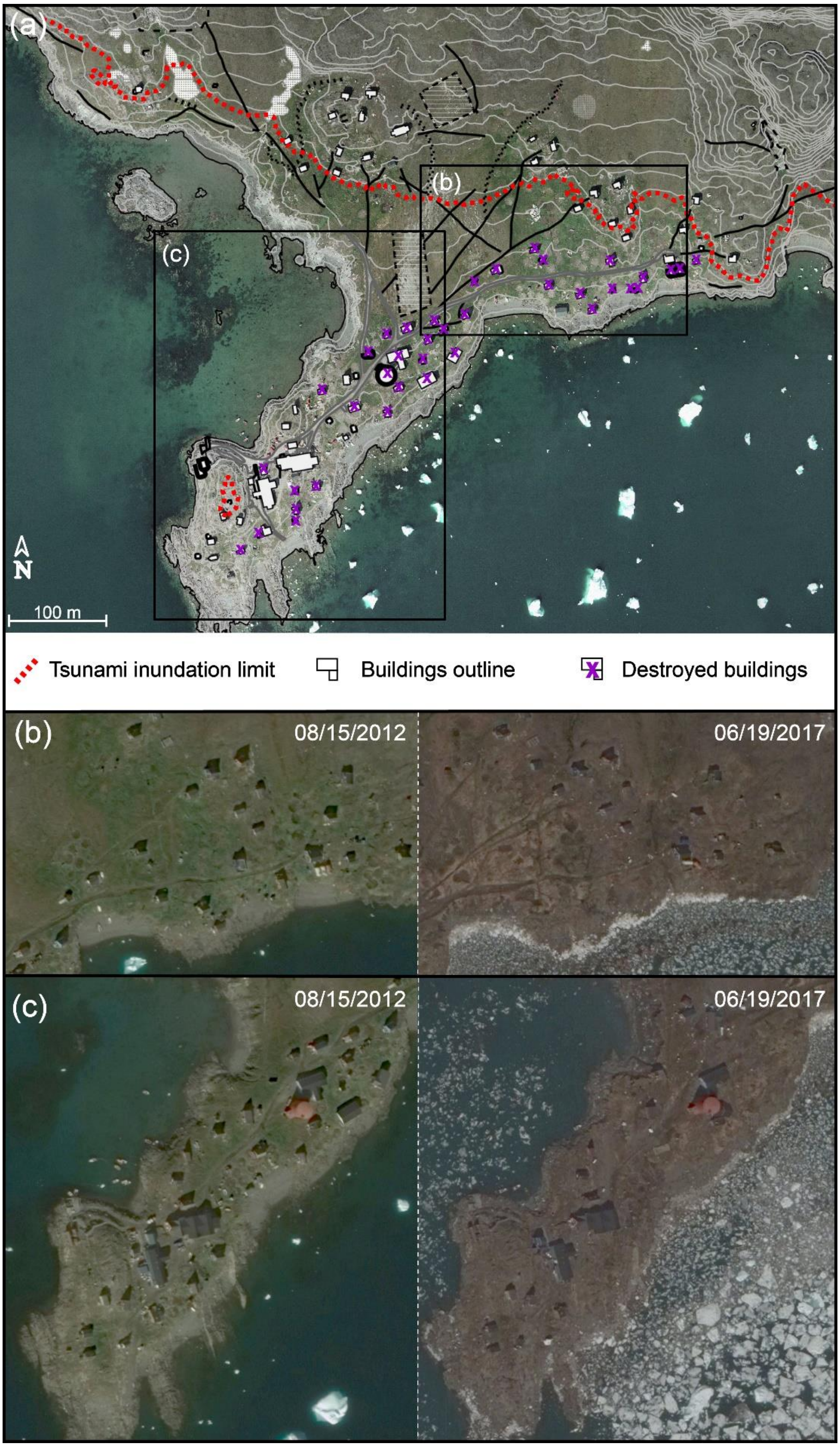

Figure 7. Scale of destruction in settlement infrastructure. (a) General overview of area inundated by tsunami with location of damaged buildings. The inventory of tsunami-induced changes of settlement infrastructure are based on interception of aerial images, local spatial plans and field surveying. Background ortophoto and topographic map: nunagis.gl.; (b) Satellite image of settlement before the tsunami impact (15th August 2012) and; (c) Satellite image of settlement after the tsunami impact illustrate the scale of destruction and dislocation of buildings (19th June 2017) Background Google Earth Image © 2020 Maxar Technologies.

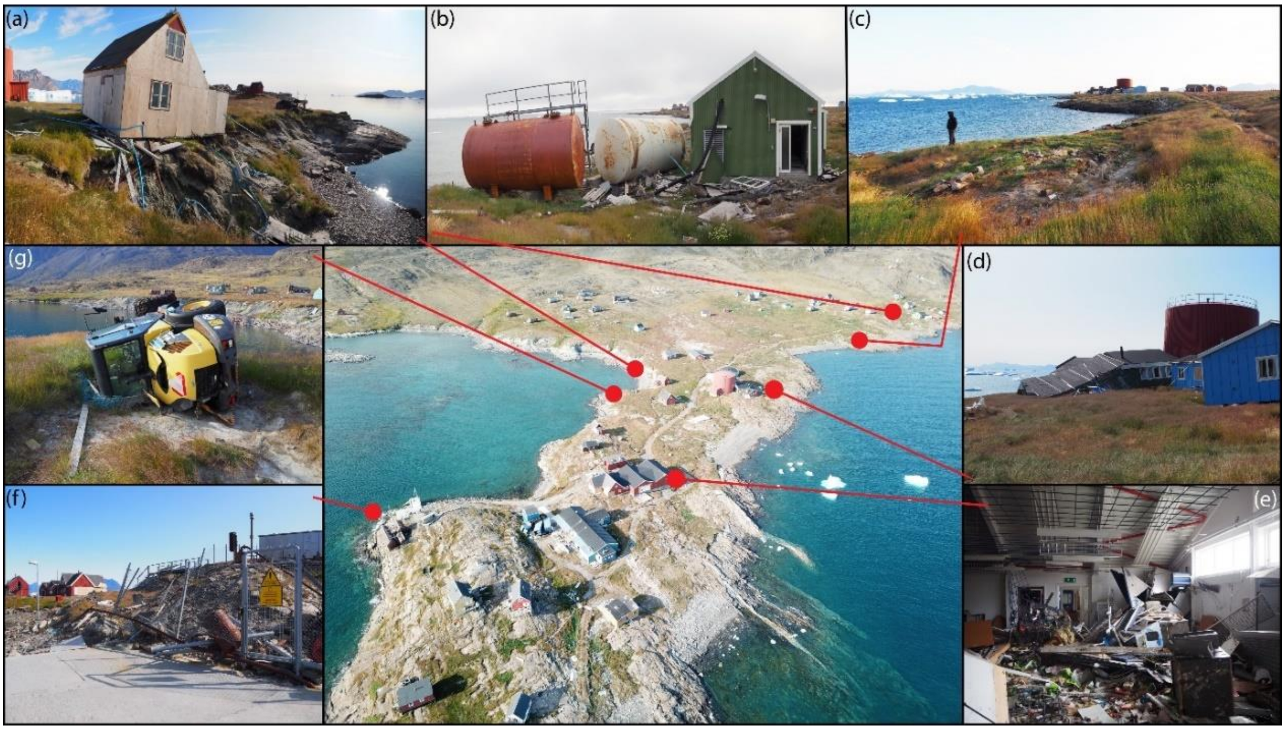

Figure 8. Examples of infrastructure damages caused by 2017 tsunami in Nuugaatsiaq. (a) Wooden house removed by wave from point foundation transported several dozen of meters; (b) Fuel tanks washed away from concrete frames and pushed towards power plant. Note large accumulation of litter and tsunami deposits around and inside the buildings; (c) site of former building position, which was destroyed and swept away by tsunami. Note broken wooden point foundations, media connections and erosional gullies; (d) Smashed and collapsed wooden school building moved towards major water tank; (e) Interior of local shopping centre passed by tsunami. Note large amounts of litter and rotting food supplies and twisted and bowed metal frame construction; (f) Partly-torn metal fence around fuel storage site which acted as a trap for litter transported by tsunami; (g) example of heavy machine knocked over by waves.