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Mapping Exposure to Flooding in Three Coastal Communities on the North Slope of Alaska Using Airborne LiDAR

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ABSTRACT
The intensification of coastal storms, combined with declining sea ice cover, sea level rise, and changes to permafrost conditions, will likely increase the incidence and impact of storm surge flooding in Arctic coastal environments. In coastal communities accurate information on the exposure of infrastructure can make an important contribution to adaptation planning. In this study, we use high resolution elevation data from airborne LiDAR to generate storm flooding scenarios for three coastal communities (Utqiaġvik, Wainwright, and Kaktovik) in northern Alaska. To estimate the potential for damage to infrastructure caused by flooding for each community, we generated data on replacement costs and used it to estimate the financial impact of 24 storm flooding scenarios of varying intensities. This analysis shows that all three communities are exposed to storm surges, but highlights the fact that infrastructure in Utqiaġvik (the administrative center of the North Slope Borough) is significantly more exposed than buildings in Wainwright and Kaktovik. Our findings show that flooding scenarios can complement information gained from past events and help to inform local-decision making.

KEYWORDS
Arctic; climate change; coastal communities; coastal exposure; infrastructure damage; vulnerability

Introduction

Global climate change is anticipated to have particularly severe impacts on coastal communities (Wong et al. 2014). Between 1901 and 2010, global sea levels rose at a mean rate of 1.7 mm/year, but between 1993 and 2010 sea levels rose 3.2 mm/year, suggesting the rate of sea level rise has increased in recent decades (Church et al. 2013). A range of modeling approaches indicate that sea level will increase an additional 0.26 to 1.10 m by the end of the century (Jevrejeva, Moore, and Grinsted 2012; Rahmstorf, Perrette, and Vermeer 2012; Church et al. 2013; Slangen et al. 2014). Sea level rise combined with more frequent and potentially stronger coastal storms is anticipated to increase the risk of coastal communities around the World (Church et al. 2013). With 23% of the

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global population living within 100 km of the ocean (Small and Nicholls 2003), research focused on the impacts of these changes is critical, particularly in the northern high latitudes where additional changes in the marine system associated with declining sea ice extents and duration are also occurring (Jones et al. 2008; Lantz, Kokelj, and Fraser 2015; Fang et al. 2018).

Sea level rise (SLR) and increased storm surges will impact coastal communities in a variety of ways. Hinkel et al. (2013) estimated that by 2100, 117–262 million people will be impacted by coastal flooding. This represents a 28-65 fold increase over the estimated four million people impacted by coastal flooding in 2000 (Hinkel et al. 2013). Nicholls et al. (2011) estimate that land loss caused by erosion and submergence associated with SLR will displace 72–187 million people by 2100. Neumann et al. (2015) estimate that the combined effects of storm surges and SLR will cause US$990 billion in property damage in the continental United States by 2100. At the global scale, costs of sea level rise in 2100 are predicted to rise to between US$1.4 and 27 trillion per year (Jevrejeva et al. 2018). Other economic impacts include decreases in ecological productivity, damages to infrastructure, and significant losses in coastal industries such as tourism (Wong et al. 2014; Neumann et al. 2015). SLR will also contribute to the degradation of coastal wetlands, which provide important ecosystem services like flood protection and carbon storage (Nichols et al. 2004; Wong et al. 2014). Costs associated with ecological changes caused by SLR in coastal wetlands are likely to be between $20–80 billion in 2100 (Diaz 2016). The landward expansion of brackish and saline water bodies could also contribute to an increased incidence of vector-borne diseases, including malaria (Ramasamy and Surendran 2011). In the Arctic, altered coastal flooding regimes will likely impact northern communities, ice-rich permafrost terrain, important wildlife habitat, and oil and gas infrastructure (Brunner et al. 2004; Kokelj et al. 2012; Tape et al. 2013; Raynolds et al. 2014).

In coastal regions of Alaska, intense ocean storms are common (Terenzi, Jorgenson, and Ely 2014) and have caused surges ranging between $1.5-3.7$ m along the Beaufort Sea and Chukchi Sea coasts (Hume and Schalk 1967; Reimnitz and Maurer 1979). Storm surges are amongst the most destructive environmental disturbances affecting Arctic coastal communities. Several recent storms on the Alaskan North Slope are estimated to have caused between 7 and 19 million USD in damage (Hume and Schalk 1967; Brunner et al. 2004). In this region, the combined effects of SLR, more frequent storm surges, increased wave activity resulting from reduced sea ice extent (Manson and Solomon 2007; Francis, Panteleev, and Atkinson 2011; Overeem et al. 2011; Barnhart et al. 2016), and permafrost thaw and surface subsidence (Raynolds et al. 2014; Streletskiy et al. 2017; Frost et al. 2018) make Arctic coastal communities particularly exposed to flooding. Accelerating coastal erosion (Mars and Houseknecht 2007; Lantuit and Pollard 2008; Jones et al. 2009; Jones et al. 2018) will exacerbate the situation in many communities and has already led to the loss of historical and cultural sites (Sturtevant et al. 2004; Jones et al. 2008; Irrgang et al. 2018). Of 213 Native villages in Alaska, 184 (~86%) have already been impacted by river or coastal flooding and erosion (Government Accountability Office 2009). As of 2009, 31 of these communities were facing immediate threats from flooding and erosion, while 12 were planning or considering relocation (Government Accountability Office 2009; Bronen 2015). The

Prudhoe Bay oilfield, which contains 16% of proven oil and gas reserves in the US (Raynolds et al. 2014) is also exposed to storm surge activity. Storm surge impacts on abandoned infrastructure and contaminated sites are also likely to increase the cumulative impacts of disturbance across the North Slope (National Research Council 2003; Melvin et al. 2017).

To confront the risks associated with SLR and storm surges, Arctic coastal communities require detailed information on the extent of potential flooding. In many temperate regions, SLR exposure maps derived from airborne Light Detection and Ranging (LiDAR) elevation data have been successfully used for identifying assets that are at risk and prioritizing adaptation measures (Webster et al. 2004; Zhang et al. 2011; Cooper, Chen, et al. 2013; Cooper, Fletcher, et al. 2013; Krolik-Root, Stansbury, and Burnside 2015). In the Arctic, this approach has seldom been applied (Radosavljevic et al. 2016). In this study, we use airborne LiDAR data to create a series of flood exposure maps for three communities on the North Slope of Alaska. By combining these maps with GIS data on local infrastructure we developed a series of scenarios that estimate the potential damage to infrastructure associated with flooding. Our findings are potentially relevant to Arctic coastal communities around the circumpolar north that will likely be exposed to more frequent and impactful storms in the future.

Methods

Study area

This study focused on three communities on the North Slope of Alaska: Utqiaġvik (previously Barrow), Wainwright, and Kaktovik that were covered by airborne LiDAR data (Figure 1). All three communities are located at low elevations (<10 m) and are directly exposed to either the Chukchi (Wainwright and Utqiaġvik) or Beaufort Sea (Utqiaġvik and Kaktovik). Utqiaġvik is the largest community and the administrative hub of the North Slope Borough. With a population of 4378 (U.S. Census Bureau 2018), Utqiaġvik hosts a range of major infrastructure in the region (a hospital, K-12 schools and a community college, a large hotel, an airport with a hardened runway, a range of federal research facilities, government buildings, etc.). In this study, we have included both the village of Utqiaġvik as well as the dwellings within the former Naval Arctic Research Laboratory (NARL). This area now hosts community housing, Alaska's only tribal college (Iḷisaġvik College), the Department of Wildlife Management, the Barrow Global Change Research Facility, the Department of Energy's Atmospheric Radiation Monitoring facility, and several heavy equipment garages and workshops. While Kaktovik (population =262) and Wainwright (population = 550) have smaller populations (U.S. Census Bureau 2018), they also have important residential infrastructure, schools, power plants, and water facilities. The majority of residents in all three communities are Iñupiat, and subsistence harvesting of marine mammals, caribou and avifauna is vital to local food economies and food security (Kruse 1991; Caulfield 2002). Harvesting marine resources including whales, fish, seals, and walruses is an especially vital part of local economies, cultural traditions, and health and well being (Caulfield 2002; Druckenmiller et al. 2013). All three communities cannot be accessed by all-season roads and rely on air and sea transportation to link with the rest of Alaska, the

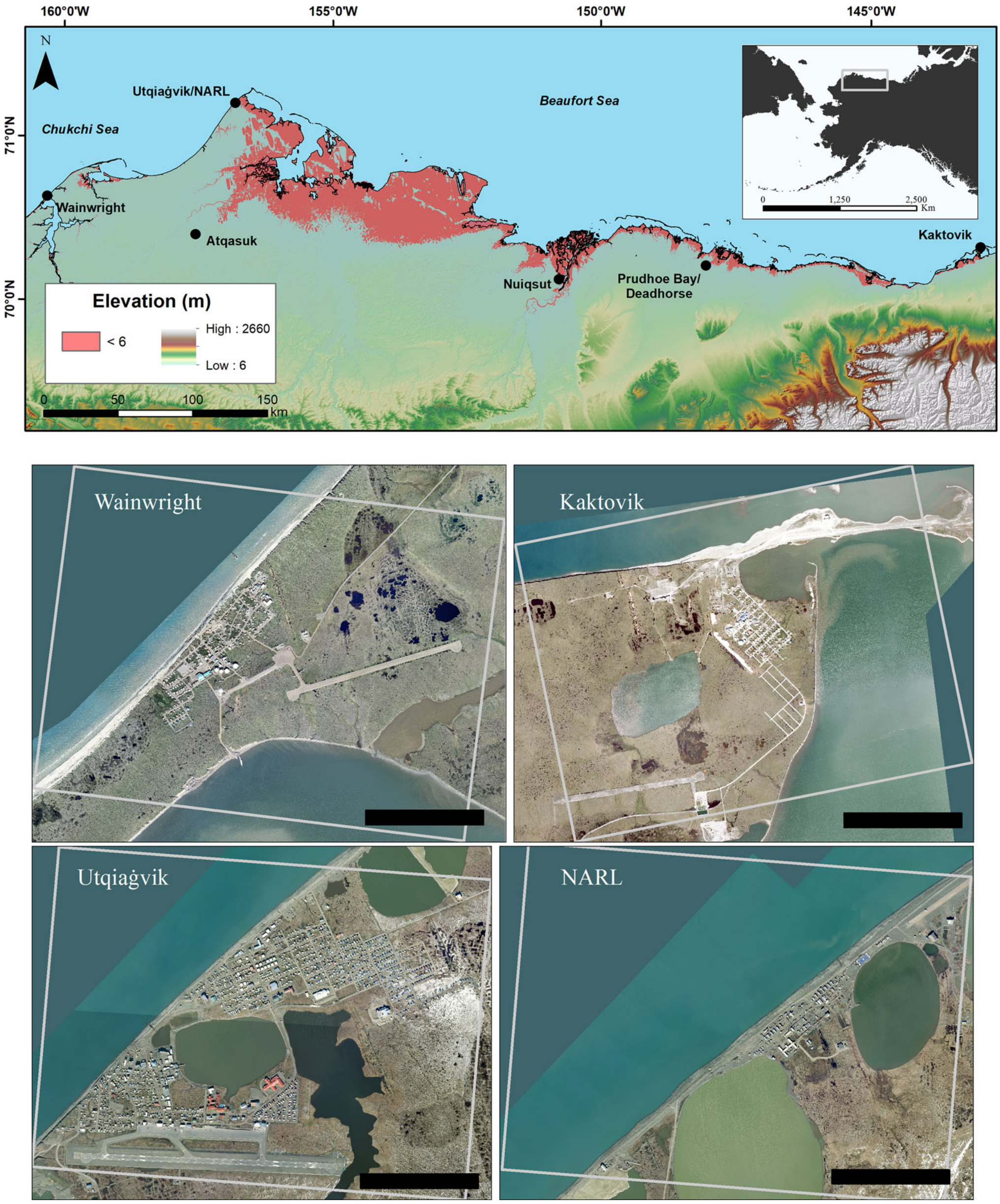

Figure 1. Maps showing the communities included in this study: Wainwright, Utqiaġvik and Kaktovik. NARL is part of Utqiaġvik (situated to the north-east). The orthophotos in the bottom panel show the areas of each community shown in Figures 2–6. The scale bars on each image represent a distance of 1 km. The elevation data in the upper map is a compilation of 5 m spatial resolution Interferometric Synthetic Aperture Radar (IFSAR) digital terrain model data acquired between 2012 and 2018 by Intermap Technologies Inc. and provided by the Alaska Division of Geological & Geophysical Surveys (https://elevation.alaska.gov/). Data are provided in orthometric heights (NAVD88/Geoid09) and reported to have a vertical RMSE < 1.0 m. Source: Authors.

continental US, and the world. A winter ice road often extends from the Prudhoe Bay oilfields to Utqiaġvik and less often to Wainwright, allowing rugged winter access for local residents and industry.

LiDAR data

The LiDAR data used in this study were obtained from the USGS as unclassified point clouds in LAS format. These data have a NAD 83 horizontal datum and elevation referenced to the GRS 1980 Ellipsoid. Surveys were flown by Aero-Metric Inc. during the snow free periods (July-September) of 2009, 2010 and 2011. Survey aircraft flew at an altitude of approximately 1800 m, at 150 kts, and imaged the surface using an Optech ALTM Gemini (03SEN145 and 07SEN201) sensor. The nominal pulse spacing and point spacing specified by the vendor are 1.2 m and 0.7 m, respectively. With a vertical accuracy of ±13.5 cm, this is the highest resolution elevation data available for this region.

LiDAR processing

Unclassified LiDAR point clouds were processed into bare earth digital terrain models (DTMs) with a horizontal resolution of 1 meter using the Toolbox for LiDAR Data Filtering and Forest Studies (Tiffs) software (Chen 2007). To ensure that processing removed all buildings from each community, bare earth models were visually inspected using ArcScene (10.3). Individual tiles surrounding each community were mosaicked into images that covered the study areas shown in Figure 1.

Accuracy and local tidal datum

To assess potential bias (i.e., systematic error) associated with the vertical datum, we compared the LiDAR returns with data from existing tidal benchmarks in each community (NOAA 2019). These benchmarks have a vertical accuracy of ±2 cm and are expressed in meters above mean local sea level (MSL). These data were then used to compute the mean difference between the LiDAR data and tidal benchmarks at each site (NOAA 2019, Table 1). Paired t-tests comparing the benchmark and LiDAR heights in each community revealed significant offsets ($p < 0.001$), that ranged from 1.91 and 2.78 m relative to mean local sea level in each community (Table 1). To correct for this bias, we used the raster calculator in ArcGIS (v10.3) to add this value to the LiDAR

Table 1. The mean difference between elevations derived from the processed LiDAR and the heights recorded at NOAA Tidal Benchmarks (m above MSL) and the 95% confidence interval of mean.

Community	NOAA station	# of Tidal benchmarks (TBM)	Mean elevation difference (TBM − LiDAR)	Bias (m)	RMS	Linear error
Wainwright	9494168	6	1.91 ± 0.23	−0.093	0.071	0.139
Utqiaġvik	9494935	7	2.10 ± 0.14	0.009	0.207	0.405
Kaktovik	9499176	8	2.78 ± 0.12	No Data	No Data	No Data
			Average:	−0.042	0.1547	0.303

Note. Linear error was calculated using National Geodetic Network benchmarks.

mosaic for each community. This resulted in a raster surface that approximated the height of each surface above mean local sea level (MSL) measured by the tide gauges in each community.

To further independently estimate the magnitude of the error associated with the LiDAR data, we compared the ellipsoid heights from processed DTMs with National Geodetic Survey (NGS) benchmarks in the study area, which had vertical control in Wainwright ($n = 3$) and Utqiaġvik ($n = 3$). These data were used to compute the bias and the vertical root mean square error of the LiDAR elevation data across the entire study area (Gesch 2009, Table 1). The bias in Wainwright and Utqiaġvik was −0.093 m and 0.009 m, respectively, and a paired t- t-test showed that the heights from the LiDAR and the NGS Benchmarks were not significantly different ($t = 0.58$, $p = 0.58$). The RMS based on the benchmarks at Wainwright and Utqiaġvik were 0.071 m and 0.207 m and the global RMS of 0.155 m was similar to the estimated vertical accuracy specified by the vendor of 0.135 m. Calculating the linear error at the 95% confidence level using our estimate of RSME indicates that the true elevation is within ±0.303 m of the LiDAR data.

To account for the potential effect of random error, we subtracted the linear error for the entire study area from the raster mosaic for each community. This approach assumes the worst case scenario, where the true elevation surface is 0.303 m below the LiDAR elevation, and was used to ensure that we did not underestimate the extent of flooding in our scenarios. To transform raster surfaces to heights above the mean daily high tide (MHW), which are typically used as the standard in sea level rise exposure assessments, we used the raster calculator to subtract the difference between MSL and MHW in each community (Utqiaġvik = 0.072 m, Kaktovik = 0.066 m, Wainwright = 0.070 m). These rasters were used to conduct the flooding scenarios described in the next section.

Flooding scenarios

To simulate the flooding associated with storm surges, we created 24 raster surfaces for each community that represented floods between 0.25 and 6 meters (i.e., 0.25 m increments). These scenarios represent the Total Water Level (TWL) above MHW and include: the astronomical tide, storm surge, wave run-up and non-tidal residuals (Pugh and Woodworth 2014). Throughout the text these are referred to as flooding scenarios. The normal tide range across the North Slope is small, with mean tide levels of ∼0.15 m at Barrow, and ∼0.14 m at Kaktovik (NOAA 2019). Our most extreme scenarios (5-6 m) exceed the historic wind-driven flood record of 3.7 m (Hume and Schalk 1967) by 1.3-2.3 m, and were included to account for the combined effects of projected increases in sea-level of between 0.43-0.84 m by 2100 (Oppenheimer et al. 2019), increased coastal erosion and terrain subsidence (Jones et al. 2009; Streletskiy et al. 2017) and elevated storm intensity (Manson and Solomon 2007; Oppenheimer et al. 2019).

In our scenarios we assumed that flooding would inundate all pixels contiguous with the ocean that were at or below the simulated flood height. Flood estimates were created using the raster calculator to subtract increments of 0.25 meters from the raster of

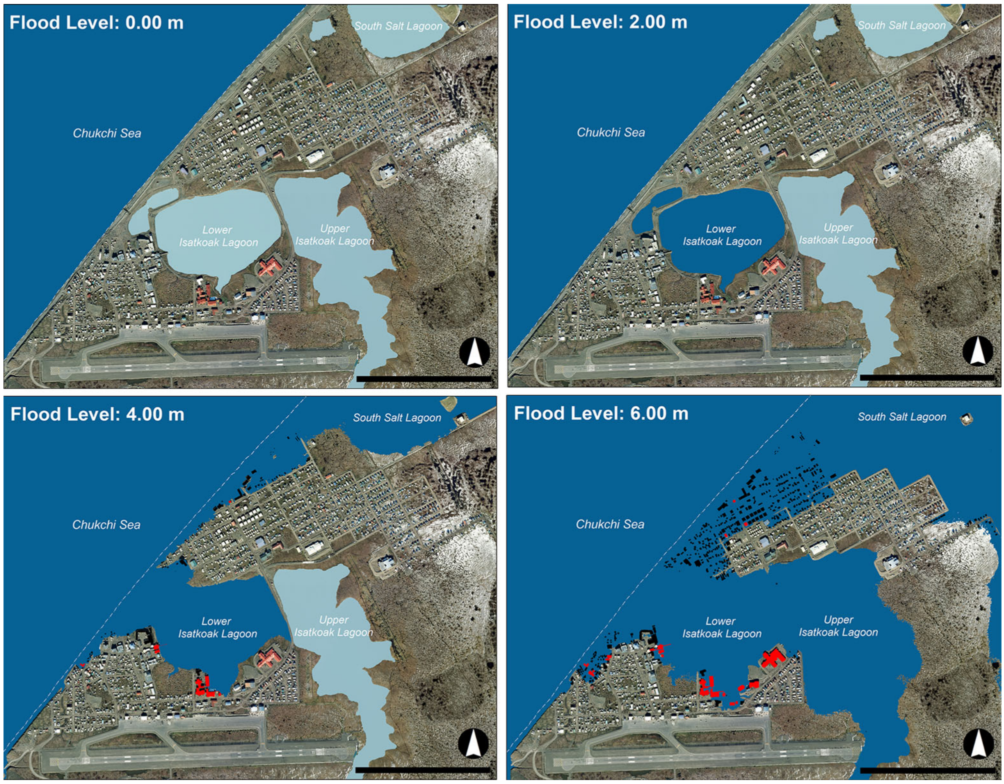

Figure 2. Flood scenarios for Utqiaġvik in the Barrow and Browerville areas. The panel shows estimated flooding at 2-meter increments. Impacted buildings are highlighted in black (residential and non-critical infrastructure) and red (critical infrastructure, such as schools and emergency service buildings). Freshwater bodies are indicated in light blue. The dashed white line marks the coastline and the scale bar represents a distance of 1 km on each map. Source: Authors.

MHW. The resulting surfaces were converted to polygons and manually edited to ensure that all inundated areas were connected to the ocean. Pixel connectivity was determined using an 8 neighbor method.

Exposure assessments

To evaluate the impacts of flooding on infrastructure, we overlaid flooding scenarios with GIS data of infrastructure in each community. Infrastructure data for each community were obtained from the State of Alaska (Department of Commerce, Community & Economic Development) as CAD data and converted to polygon files. To compare the impacts among communities, we calculated the total number of buildings that fell inside the flooded area, and their total replacement cost in each of the 24 flooding scenarios. Most infrastructure in Utqiaġvik, Wainwright, and Kaktovik are under 185 m^2, less than 6 m tall, and have not been modified to resist flooding. As such, we treated all buildings as equally susceptible to flood damage and considered them impacted if the flood surface entered the polygon delimiting a given structure.

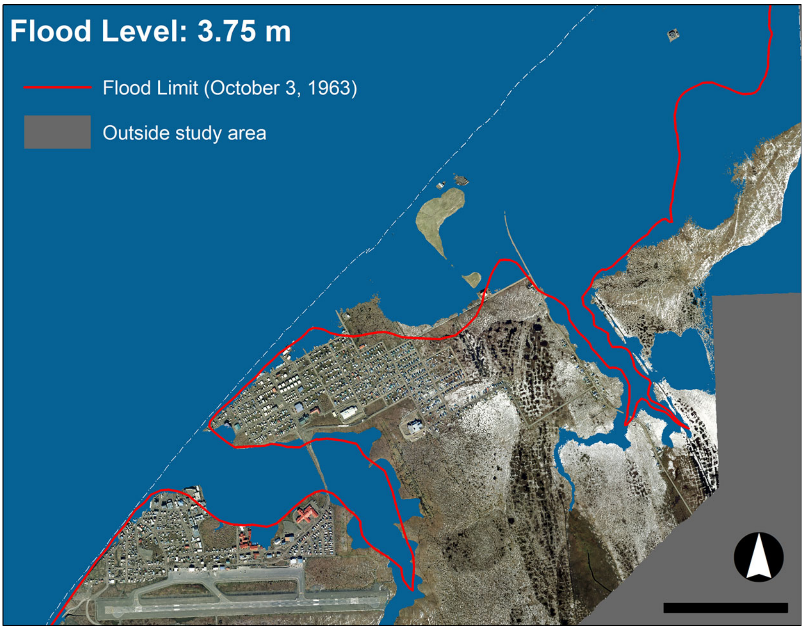

Figure 3. Storm surge scenarios for the central part of Utqiaġvik (Barrow and Browerville) showing estimated level of inundation associated with a 3.75 storm surge. The solid red line shows the maximum extent of the 1963 flood estimated by Hume and Schalk (1967) and the white dashed line marks the coastline. Source: Authors.

Replacement costs were estimated for all impacted buildings and were based on area and building type following Moselle (2015). For building types that required an estimate of the length to width ratio we used orthophotographs to estimate an average length-width ratio for all buildings in this class. Replacement costs for hotels, inns, community centers, and recreation centers were estimated using analogous buildings (Table 2). To account for the additional costs of construction in northern regions, we used an area modification factor of +22% recommended by Moselle (2015) for Alaska. This modification factor likely underestimates the cost of construction on the North Slope where materials must be barged to each community. For building types not listed in Moselle (2015) (e.g., hospitals, police stations, courthouses, etc.), we used replacement costs listed in Larsen et al. (2008). To account for the fact that these communities have different areas and populations, we also calculated the number of buildings impacted and their replacement costs relative to the total number of buildings and their replacement value. We also calculated the total length of roads flooded in each scenario and estimated their replacement cost following Larsen et al. (2008). The scenarios described here are limited in scope to the financial damage to aboveground infrastructure caused by flooding, and do not address the impacts of flooding on personal property other than housing, underground infrastructure, health and well-being, or sociocultural processes (Rygel et al. 2006; Lane et al. 2013).

Results

Our flooding scenarios show that Utqiaġvik, Wainwright, and Kaktovik are all susceptible to flooding, but that exposure varies considerably among communities

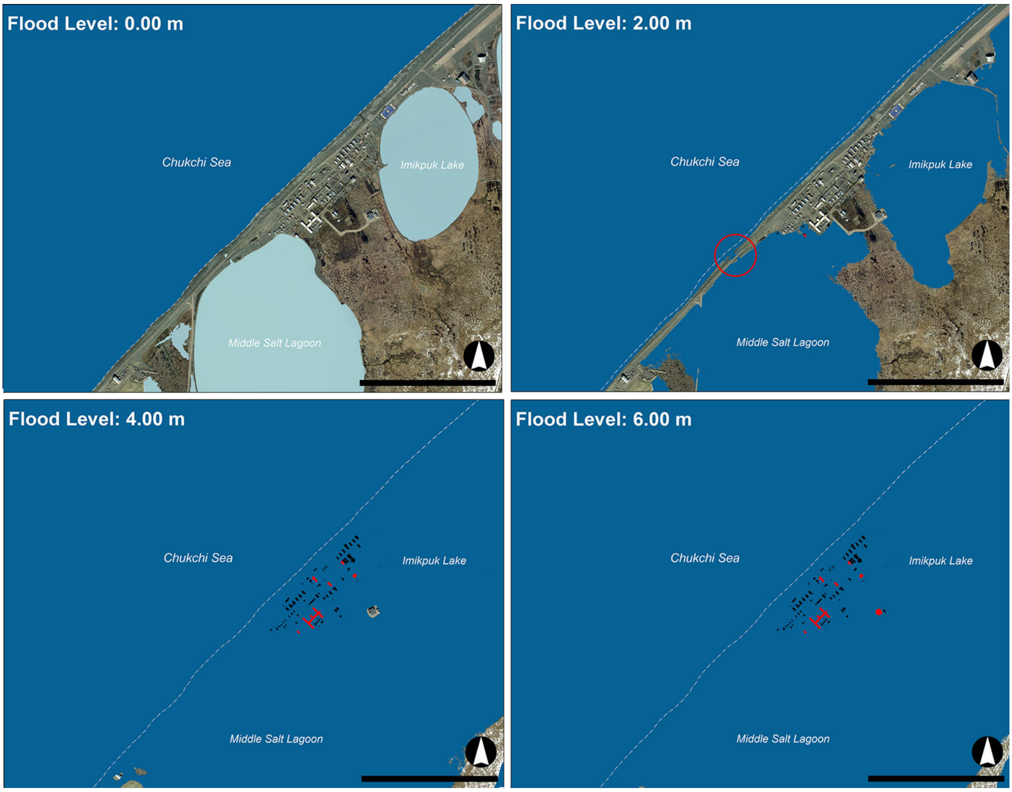

Figure 4. Flooding scenarios in NARL (north-east of Utqiaġvik). The panel shows estimated inundation at 2-meter increments. Impacted buildings are highlighted in black (residential and non-critical infrastructure) and red (critical infrastructure, such as schools and emergency service buildings). Freshwater bodies are indicated in light blue. The red circle on the 2.0 m scenario indicates the main inundation path into NARL through Middle Salt Lagoon. The white dashed line marks the coastline and the scale bar represents a distance of 1 km on each map. Source: Authors.

(Figures 2–6). Scenarios in Utqiaġvik produced the most extensive and potentially damaging flooding. Figures 2–4 illustrate potential flooding in two areas of this community: 1) central Utqiaġvik (including Barrow and Browerville) and 2) NARL (the area surrounding the former Naval Arctic Research Lab). At a flood level of 3 meters, nearly 100 buildings were impacted in Utqiaġvik, and our estimates suggest that a flood of this magnitude would cause at least 29 million dollars in damage (Figures 2, 3, 7 and 8). The number of buildings impacted showed a linear increase when flood height was increased above 3 meters, and in the 6-meter simulation, 608 of the 1547 buildings (39%) in Utqiaġvik were impacted (Figure 7). The estimated replacement cost of buildings flooded by a 6-meter flood was in excess of 215 million dollars, or approximately 44% of the total estimated infrastructure value (Figure 7). On a per capita basis this is approximately $49,175/person. In Utqiaġvik, buildings impacted by flooding included both residential homes and critical public infrastructure such as water and sewage treatment facilities; primary and secondary schools; and emergency service buildings (fire; police; and search and rescue). Although some areas remained unaffected by direct flooding, our scenarios also suggest that flooding in the southern part of town would

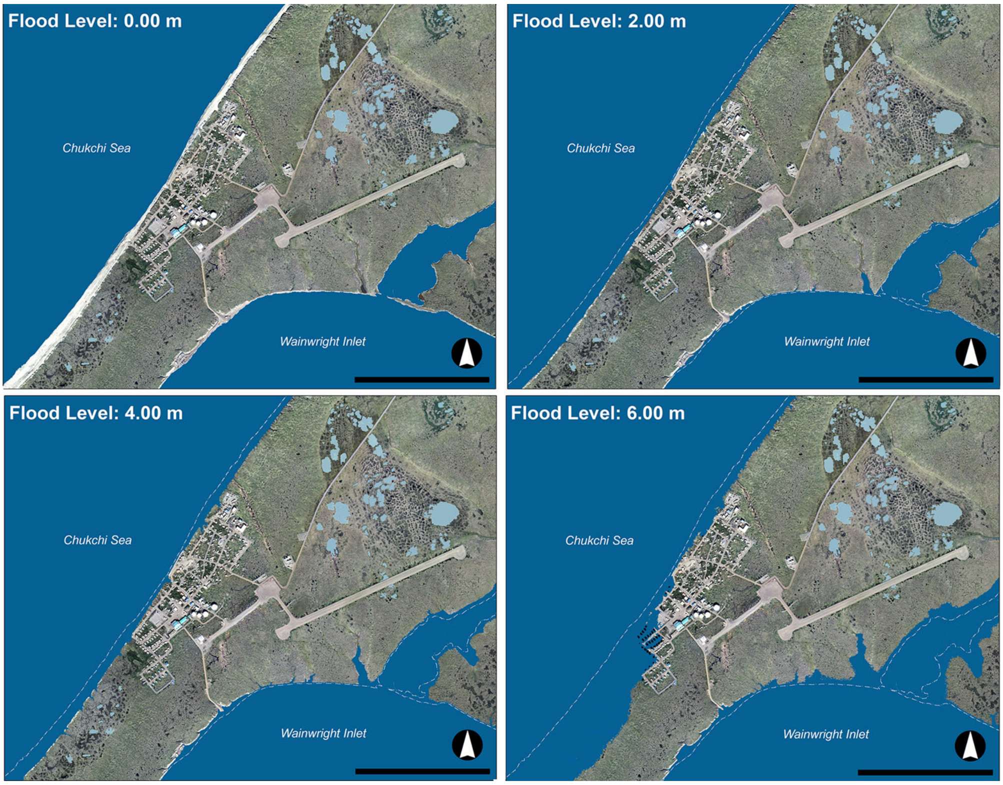

Figure 5. Storm surge scenarios for Wainwright showing estimated inundation at 2-meter increments. Residential and non-critical infrastructure impacted by flooding are shown in black. Freshwater bodies are indicated in light blue. The white dashed line marks the coastline and the scale bar represents a distance of 1 km on each map. Source: Authors.

likely separate Utqiaġvik (Barrow-side from Browerville-side) and the critical infrastructure contained in each area (Figures 2 and 3). Flood scenarios in Utqiaġvik showed that flooding was the most severe at the former NARL facilities and Iḷisaġvik College in the northern part of the community, where a 4-meter flood would impact all buildings in this area (Figure 4).

Flood scenarios in Wainwright and Kaktovik produced less extensive flooding and damage than in Utqiaġvik. In Wainwright, the 4-meter scenario flooded the beach fronting the community, but infrastructure was only impacted when flood levels exceeded 4.5 meters (Figures 5 and 7). In the 6-meter flood scenario, 36 buildings (17% of the total) were inundated. The replacement cost of this infrastructure was close to 6 million dollars, or $10,844 per resident. This represents approximately 11% of the total value of the infrastructure in Wainwright (Figure 7). In Kaktovik, floods greater than 1.5 meters flooded large areas of the spit northeast of the community. However, with the exception of the old runway located on the spit, infrastructure was not impacted until floods exceeded 2 meters (Figures 6 and 7). In this community, a 4-meter flood impacted 15 buildings, with an estimated value of 0.75 million dollars. On a per capita basis this is approximately $17,808/person. In the 6-meter flood scenario, 36 buildings in Kaktovik (~18% of the total) were affected by flooding, with an estimated damage of

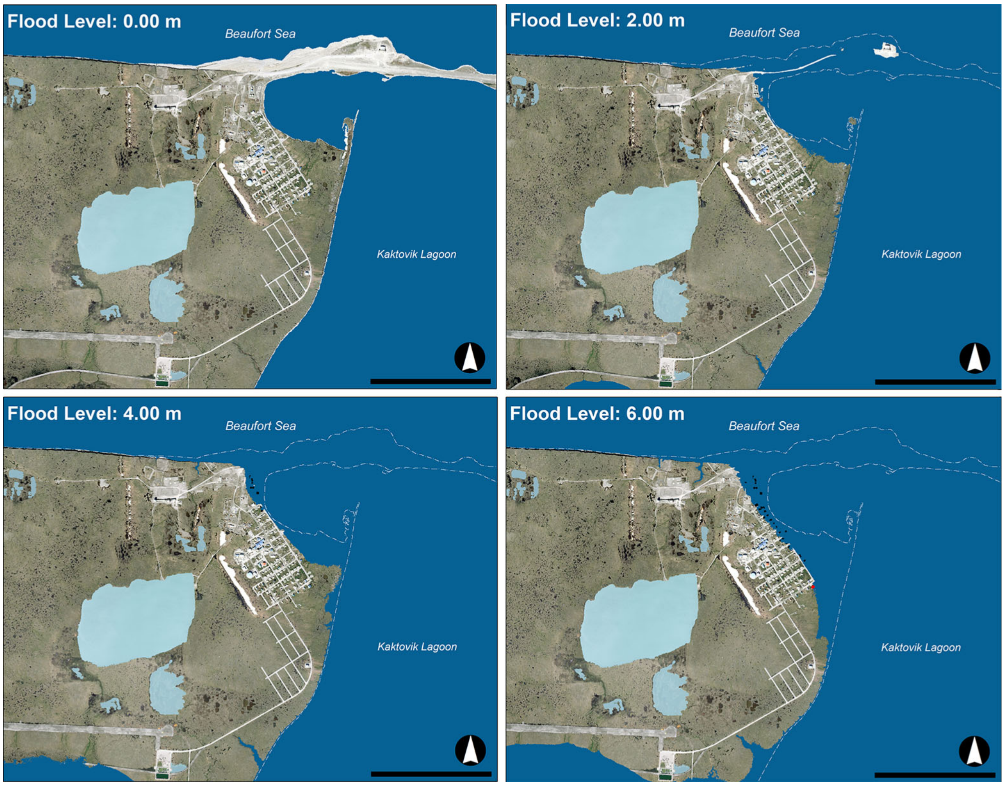

Figure 6. Storm surge scenarios for Kaktovik showing estimated inundation at 2-meter increments. Impacted buildings, which are mainly residential, are highlighted in black (residential and non-critical infrastructure) and red (critical infrastructure, such as schools and emergency service buildings). Freshwater bodies are indicated in light blue. The white dashed line marks the coastline and the scale bar represents a distance of 1 km on each map. Source: Authors.

4.7 million dollars, or approximately 9% of the total value of all infrastructure (Figure 7).

Comparing the damage in each community relative to the total number of buildings or their total value shows that the proportional damage was twice as high in Utqiaġvik compared with Kaktovik and Wainwright (Figures 7). In Wainwright and Kaktovik, the absolute and relative damage associated with the highest flood level were similar (Figure 7). However, our analysis also shows that Kaktovik is significantly more exposed than Wainwright at lower flood levels (Figure 7).

The severity of the impact to the road network in our flood scenarios also varied among communities. The larger road network in Utqiaġvik was more extensively impacted than in both Wainwright and Kaktovik (Figure 8). In Utqiaġvik, the 4-meter scenario flooded 8.7 miles of road worth an estimated value of 8.7 million dollars. This is similar to the estimated 10 million dollars in damage caused by a storm surge in 2017 (Oliver 2017). In the 6-meter flood scenario, the length and value of the road network impacted increased to 15.4 miles and 15.4 million dollars, respectively. In the most severe flood scenario, 28% of Utqiaġvik's road network was impacted (Figure 8).

Table 2. Types of infrastructure in each community and estimates used to calculate replacement cost.

Infrastructure category	Cost (US$) per unit	Unit	Source
Auto service buildings	80.34 – 111.02	Square Foot	Moselle 2015
Banks/saving offices	238.72	Square Foot	Moselle 2015
Coffee shops	234.62	Square Foot	Moselle 2015
Community centers/small learning institutions[a]	183.55 – 229.56	Square Foot	Moselle 2015
Court facilities	16000000.00[b]	Building	Larsen et al. 2008
Defence facilities	305000.00[b]	Building	Larsen et al. 2008
Ecclesiastic buildings	166.30 – 212.56	Square Foot	Moselle 2015
Fuel tanks, water storage tanks, etc.	32000.00[b]	Building	Larsen et al. 2008
Factories	72.02 – 105.02	Square Foot	Moselle 2015
Fire stations	151.12 – 169.34	Square Foot	Moselle 2015
Gas stations	202.58	Square Foot	Moselle 2015
Government buildings	200.81 – 260.09	Square Foot	Moselle 2015
Hotels/Inns[c]	96.39 – 112.87	Square Foot	Moselle 2015
Libraries	173.53	Square Foot	Moselle 2015
Law enforcement (police stations)	4000000.00[b]	Building	Larsen et al. 2008
Machinery/equipment sheds	18.82 – 25.00	Square Foot	Moselle 2015
Medical/dental buildings	183.32 – 202.61	Square Foot	Moselle 2015
Military buildings ("Satellite Communications Center")	479.33	Square Foot	Moselle 2015
Office buildings	127.73 – 160.52	Square Foot	Moselle 2015
Emergency services/search and rescue	467000.00[b]	Building	Larsen et al. 2008
Public hospitals	44700000.00[b]	Building	Larsen et al. 2008
Recreation centres[d]	197.34 – 226.31	Square Foot	Moselle 2015
Residential buildings	94.06 – 142.96	Square Foot	Moselle 2015
Restaurants	185.44 – 232.82	Square Foot	Moselle 2015
Schools	158.80 – 218.99	Square Foot	Moselle 2015
Small sheds	18.47 – 30.50	Square Foot	Moselle 2015
Steel buildings (Hangars)	21.47 – 23.84	Square Foot	Moselle 2015
Stores	85.86 – 91.37	Square Foot	Moselle 2015
Supermarkets	103.52 – 121.60	Square Foot	Moselle 2015
Theatres	135.10	Square Foot	Moselle 2015
Warehouses	76.63 – 106.40	Square Foot	Moselle 2015
Roads (unpaved)	$1000000[b]	Mile	Larsen et al. 2008

Note. Cost estimates are listed as ranges because each category typically included buildings with different areas. Building costs estimated using Moselle (2015) include the Alaska area modification factor (+22%).
[a]Estimated using the cost for libraries
[b]Estimated cost in 2006 US dollars.
[c]Estimated using the cost for residential buildings with 8 corners and multiple floors.
[d]Estimated using the cost for schools

The road networks in Kaktovik and Wainwright were less exposed to flooding than in Utqiaġvik (Figure 8). In Wainwright, a flood of 4 meters impacted 0.02 miles of road and a flood of 6 meters flooded 0.28 miles of road with an estimated replacement cost of 280,357 dollars. In Kaktovik, a flood of 4 meters impacted 1.59 miles of road, and the 2.50 miles of road flooded in the 6-meter flood scenario had an estimated replacement cost of 2.5 million dollars. Kaktovik's road network was also impacted to a greater degree at lower flood levels than Wainwright's. In Kaktovik, a 3-meter flood inundated 6.8% of the road network, whereas in Wainwright, this level of flooding impacted less than 0.2% of the road systems. In the most severe flood scenario, 19.8% of Kaktovik's road network was impacted, compared to 2.72% in Wainwright (Figure 8).

The close correspondence between our 3.75 meter scenario (Figure 4) and the flood map produced by delineating the storm debris line (3.7 m) following a 1963 storm at Utqiaġvik (Hume and Schalk 1967) confirms that our scenarios are likely reasonable estimates of flooding potential (Figure 4). However, there are several factors likely to

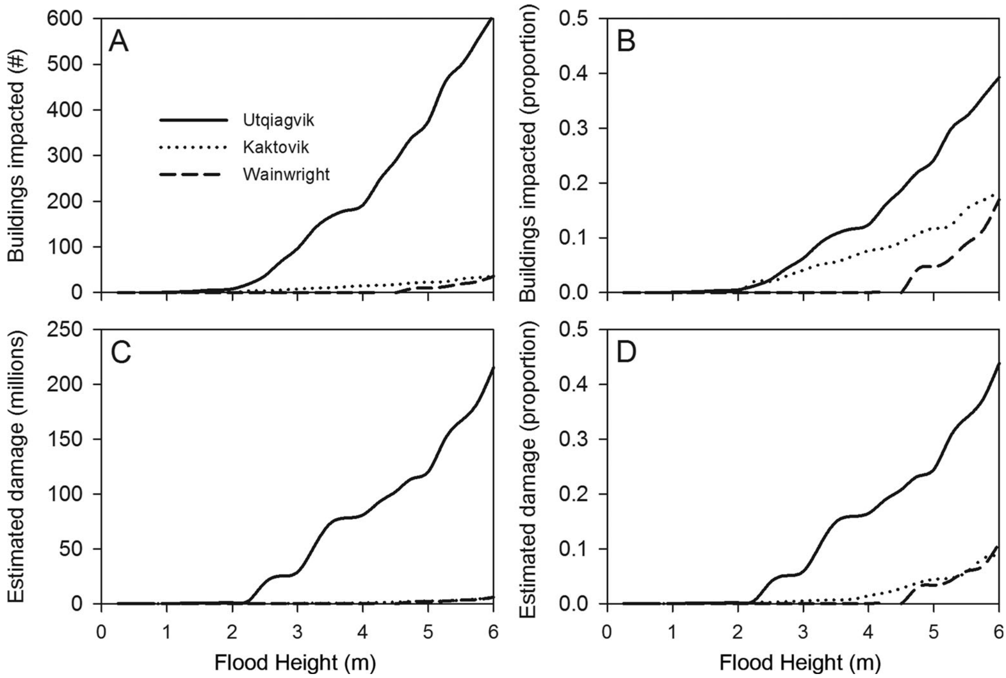

Figure 7. Estimated impacts of flooding scenarios on building infrastructure in Utqiaġvik, Wainwright and Kaktovik. (A) Estimated number of buildings impacted, (B) the proportion of the total number of buildings impacted, (C) the total replacement cost (US Dollars), (D) and replacement cost as a proportion of the total infrastructure in each community. Source: Authors.

influence flooding that were not considered in our relatively simple models. The movement of water through culverts and behind coastal berms in combination with intense wave action are both likely to cause flooding outside of the areas delineated by our conservative scenarios (Webster et al. 2004; Cooper, Chen, et al. 2013; Passeri et al. 2015). Our scenarios also did not consider the duration of flooding and the potential impact this would have on infrastructure damage (Smith 1994; Thieken et al. 2005). Random error in the LiDAR returns and errors associated with our corrections to the vertical datum may have also affected the accuracy of our scenarios. However, it is likely that the impact of these factors is small compared to the magnitude of flooding modeled in our scenarios.

Discussion

Our analysis highlights the exposure of communities on the Alaska North Slope to storm surge flooding and is consistent with historical records of previous storms in this region (Hume and Schalk 1967; Brunner et al. 2004; Lynch et al. 2004). A lack of long-term data on water levels across all three communities creates significant uncertainty regarding the likelihood of future flooding (Lynch et al. 2004), but several studies suggest that flooding between 3 and 4 meters has a high probability of recurrence on centennial scales (Reimnitz and Maurer 1979; Brunner et al. 2004). There has been a

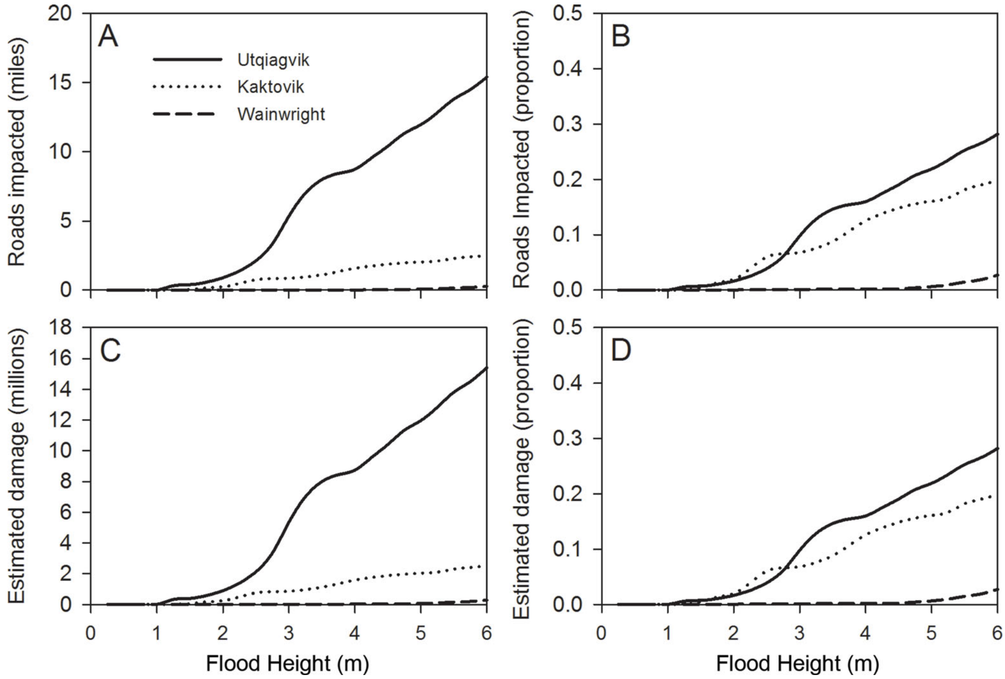

Figure 8. Estimated impacts of flooding scenarios on road infrastructure in Utqiaġvik, Wainwright and Kaktovik. (A) Estimated length of road impacted, (B) the proportion of total road network impacted, (C) the total replacement cost (US Dollars), and (D) replacement cost as a proportion of the total value of the road network in each community. Source: Authors.

significant increase in the number of extratropical cyclones at high latitudes (McCabe, Clark, and Serreze 2001; Sepp and Jaagus 2011) and the intensity of summer storms has increased in the Beaufort-Chukchi Seas (Lynch et al. 2004; Vermaire et al. 2013; Lantz, Kokelj, and Fraser 2015). It is also anticipated that ongoing increases in sea level and declining sea ice cover (Serreze and Stroeve 2015) will increase the frequency and intensity of storms in the Arctic. Taken together, this suggests that the frequency of damaging storm surges will increase across the North Slope region and highlights the importance of assessing existing exposure to flooding, particularly given plans for future development in the region.

Significant spatial variation in exposure to flooding within and among the three communities investigated highlights the utility of flooding scenarios to identify exposed infrastructure and inform local and regional decision making. The mapping approach we used in this project allowed us to generate information about exposure across a range of flooding intensities in the absence of detailed information on water levels. Our scenarios clearly show that Utqiaġvik is significantly more exposed than both Kaktovik and Wainwright at floods between 3 and 4 meters because it is located at a lower elevation than Kaktovik and Wainwright. In Utqiaġvik, a 1963 flood had a height of approximately 3.7 meters and caused an estimated $19 million (in 2000 dollars) in damage (Brunner et al. 2004, Figure 9). Our scenarios suggest that if a storm of a similar magnitude occurred today it would cause in excess of $87 million in damage to surficial infrastructure. This estimate is highly conservative because our scenarios do not include the

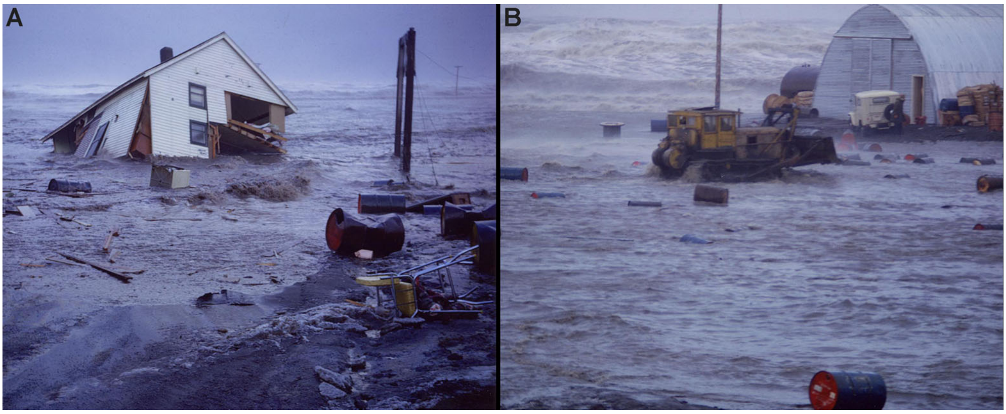

Figure 9. Storm surge flooding in Utqiaġvik in 1963. Images provided by William F. Manley.

costs associated with damage to underground water and sewer infrastructure. In 2004, the value of this infrastructure was estimated at approximately $500 million (Lynch et al. 2004). Utqiaġvik is the administrative center of the North Slope Borough and between 1963 and 2016 its population grew from 1350 to 4378 (Brunner et al. 2004; U.S. Census Bureau 2018). As part of this growth, considerable development has occurred in low-lying areas with high exposure to potential flooding (Brunner et al. 2004; Brunner and Lynch 2010). Overall, 109 commercial buildings, 13 public buildings and 58 residential buildings stand within the area that would be impacted by a 3.75-meter flood. Critical infrastructure that would be impacted includes primary and secondary schools; water and sewage treatment facilities; and emergency service buildings (fire; police; and search and rescue). Our scenarios also suggest that the Esatkuat (Isatquaq) Lagoon, the primary source of drinking water in Utqiaġvik, could be contaminated with salt water at flood levels between 3 and 4 meters. Our scenarios also show that floods greater than 2.25 meters could subject the area surrounding Iḷisaġvik College to flood waters contaminated by the nearby sewage lagoon. At floods greater than 4 meters extensive areas of Utqiaġvik would be contaminated by the sewage lagoon, and it is likely that flooding would cause significant damage to the underground infrastructure used to transport water and sewage. If this limited the supply of natural gas for heat, or caused sewage leaks into the freshwater supply, the resultant humanitarian crisis would be significant.

The size and remote location of communities on the North Slope, coupled with concurrent changes in the regional environment, likely make these communities highly vulnerable to the impacts of storm surges. The distance of these communities from material supply chains has potential to significantly increase the time required to rebuild or repair infrastructure damaged by flooding. Damage to roads is particularly concerning because high quality gravel is generally in short supply (ASCG Incorporated 2005). The concentration of critical services in Utqiaġvik means that if infrastructure is unavailable for extended periods, individuals in communities across the North Slope would be required to travel by air to Fairbanks (810 km) or beyond to access these services. Environmental changes across the Arctic are also increasing the exposure of coastal communities to flooding. On the North Slope, increasing coastal erosion (Sturtevant et al. 2004; Gibbs and Richmond 2015) and terrain subsidence between 4 mm to 10 mm per year (Streletskiy et al. 2017) are making coastal areas more exposed to storm surges.

In recent years, several local initiatives have been undertaken to reduce community vulnerability to coastal erosion and storm surges (Brunner and Lynch 2010). In Utqiaġvik, some of these include berm construction, active beach nourishment (from offshore dredging), and shoreline protection using a variety of materials (Lynch and Brunner 2007; US Army Corps of Engineers 2007). In Utqiaġvik, a group of researchers and decision makers are currently using a web-based decision support tool to evaluate and plan for the impacts of coastal erosion. The Barrow Area Information Database currently includes information on erosion, infrastructure, community assets, named places, and research sites (BAID 2018), but could potentially be expanded to include the flooding scenarios described here. A new research network focused on Permafrost Coastal Systems (PerCS-Net) is also working to provide information to researchers, managers, indigenous stakeholders, and the general public. Collaborative scenario planning (Lovecraft et al. 2017) and community-based mapping of coastal exposure (Brady 2018) have also been used to facilitate local adaptation to environmental change. Between 2014 and 2015, the North Slope Borough published comprehensive planning assessments to guide the growth and development of each village in this region, with an emphasis on past and potential future hazards associated with erosion and flooding (North Slope Borough 2004a, 2004b, 2015). Evidence that Iñupiat communities have persisted through significant changes in regional sea-level over the last several millennia (Hume 1965) also indicate that sociocultural processes (Ford and Smit 2004; Pearce et al. 2009) provide communities on North Slope with a significant capacity to adapt to ongoing changes (Lynch and Brunner 2007; Berner et al. 2016; Robards et al. 2018).

Despite the exposure of this region to storm surges, little information is currently available to residents and local or state-level decision makers. The lack of information for communities across the North Slope Borough differs markedly from the detailed information that is available in other jurisdictions. In the continental United States, the Federal Emergency Management Agency (FEMA) maintains a diverse array of maps and visualization tools that include data on flood hazard zones and flood insurance maps (FEMA 2017). The National Oceanographic and Atmospheric Administration (NOAA) also maintains an online visualization tool on flood hazard, high tide flooding, storm surge, and sea level rise for the continental US, but not Alaska (NOAA 2018). The lack of planning resources to guide mitigation and response strategies across the North Slope highlights the need for improved baseline data in these communities. Tide gauges in Kaktovik and Wainwright ceased operation in 2008, and the gauge in Utqiaġvik closed in 2010. At present only Prudhoe Bay has infrastructure to monitor water levels (NOAA 2018). Long-term data on water levels across the North Slope region is a prerequisite to predicting the expected return interval for of large magnitude storms (Lynch et al. 2004) and is essential to informed planning and decision making in this region.

Flooding scenarios provide valuable information on the exposure of community infrastructure in Utqiaġvik, Wainwright, and Kaktovik, but ultimately the knowledge and experience of local stakeholders are required to contextualize this information (Lynch et al. 2004; Dolan and Walker 2006; Marfai, Sekaranom, and Ward 2015; Gustafson et al. 2018). The economic value of the infrastructure in each community only provides limited information on the potential impacts of flooding (Rygel et al. 2006; Lane et al. 2013). Future work should draw on local knowledge to explore the socioeconomic factors that influence individual and community vulnerability (Dolan and Walker 2006; O'Brien and Wolf 2010; Marfai, Sekaranom, and Ward 2015). Future studies could use the flooding scenarios presented here as a starting point for focus groups and interviews conducted in each community. Previous analysis suggests that access to housing, subsistence foods, transportation, healthcare, and the degree of interagency coordination are likely to be significant factors (North Slope Borough 2005). Across the North Slope Borough, subsistence harvesting makes a major contribution to local diet (Shepro, Maas, and Callaway 2015) and cultural well-being (Loring and Gerlach 2009; MacDonald et al. 2015; Newell, Dion, and Doubleday 2020), and the impacts of flooding on locally available and harvested foods should also be assessed (Kokelj et al. 2012).

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