Measuring historical flooding and erosion in Goodnews Bay using datasets commonly available to Alaska communities

By

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ABSTRACT

Coastal hazards are of increasing concern to many of Alaska's rural communities, yet quantitative assessments remain absent over much of the coast. To demonstrate how to fill this critical information gap, an erosion and flood analysis was conducted for Goodnews Bay using an assortment of datasets that are commonly available to Alaska coastal communities. Measurements made from orthorectified aerial imagery from 1957 to 2016 show the shoreline eroded 0 to 15.6 m at a rate that posed no immediate risk to current infrastructure. Storm surge flood risk was assessed using a combination of written accounts, photographs of storm impacts, GNSS measurements, hindcast weather models, and a digital surface model. Eight past storms caused minor to major flooding. Wave impact hour calculations showed that the record storm in 2011 doubled the typical annual wave impact hours. Areas at risk of erosion and flooding in Goodnews Bay were identified using publicly available datasets common to Alaska coastal communities; this work demonstrates that the data and tools exist to perform quantitative analyses of coastal hazards across Alaska.

KEYWORDS: DSAS, shoreline change, wave impact hours, hazard mitigation plan.

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Coastal erosion rates in the Arctic and sub-Arctic are already some of the fastest in the world, and recently regions of the Alaska coast have exhibited even greater rates of erosion than any other location (Lantuit *et al.* 2013; Barnhart *et al.* 2014; Gibbs and Richmond 2015). Coastal erosion in Alaska is accelerated by permafrost thaw, shorter sea ice seasons and the subsequent increased frequency of marine wave energy reaching the coast during open water, warmer waters, and rising relative sea levels (Jones *et al.* 2009; USACE 2009; Chapin *et al.* 2014; Walsh and Chapman 2015; Farquharson *et al.* 2018). In an Alaska-wide baseline erosion study conducted by the U.S. Army Corps of Engineers (USACE; 2009), the most reported cause of coastal erosion in Alaska communities was storm surge. The frequency of relatively intense storm surge reaching the coastline during ice-free times is anticipated to increase due to Arctic warming and sea ice decline (Vermaire *et al.* 2013; Cohen *et al.* 2014; Huang *et al.* 2017).

In the statewide assessment by USACE (2009), 81% of "Priority Action" designees (indicating an imminent hazard to community viability) were on the west coast, as well as 40% of "Monitor Conditions" designees (meaning significant erosion may become a hazard) (USACE 2009). Socioeconomic drivers and governmental policies have led to the construction of permanent towns in hazard-prone areas, insufficient mitigation strategies, and institutional constraints regarding disaster aid and relocation (Bronen and Chapin 2013). Protection in place against frequent storm surge flooding and erosion has not proven a feasible long-term solution for some communities, and several have considered relocation (US GAO 2009; DCRA 2019a). As these communities seek opportunities to mitigate hazards, relocate infrastructure, and receive disaster aid, several have experienced funding problems because "… it is difficult to assess the severity of [erosion and flooding] because quantifiable data are not available for remote locations" (US GAO 2003).

OBJECTIVES

As Alaska communities decide how best to mitigate coastal hazards, there is a growing need for measurements of erosion and flood events, rather than just written descriptions (e.g. Mason *et al.* 2012). Datasets that can be used to produce a coastal hazard analysis exist for almost all west coast communities. These include historical and modern aerial imagery, digital elevation or surface models, and recorded accounts of erosion and flood events. The main objective of this paper is to demonstrate how to use these common datasets to identify and quantify past, current, and potential future coastal hazards. For this study a coastal hazard analysis was performed for the community of Goodnews Bay, and the resulting datasets were designed to aid the community in hazard planning to avoid significant damage from erosion and flooding. The first component of the study identified changes to beach resources and loss of developable land by measuring bluff erosion over the timespan of available datasets, 69 years. The second component used written accounts and photographs of significant storm-surge flooding in tandem with water level estimates and topographic datasets to map flood-prone areas. This two-prong analysis identified areas at-risk of erosion and flooding, and the resulting maps and data products were designed to help the community make decisions

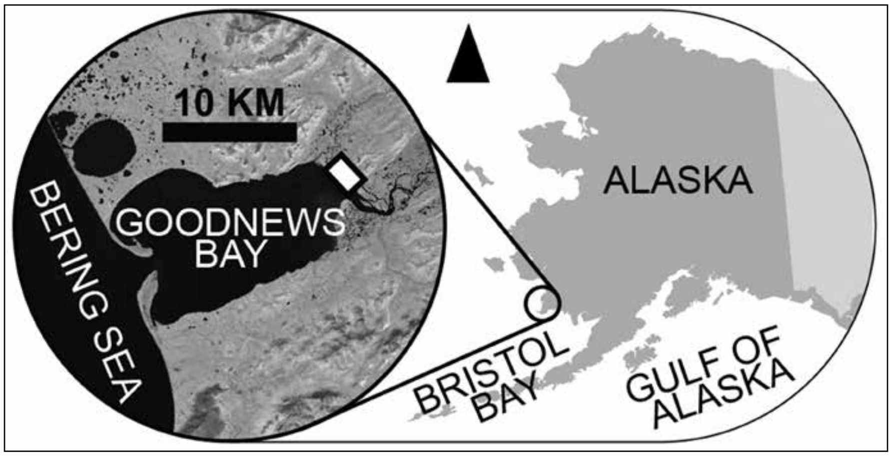

Figure 1 (above). Map shows location and Landsat image of Goodnews Bay in southwest Alaska. The community of Goodnews Bay (white rectangle) sits at the base of Rocky Mountain at the east end of the bay, where the Goodnews River terminates.

about future infrastructure and mitigation. Not all coastal communities are impacted by both flooding and erosion, but decision-makers can use mapped risk zones of both to make informed decision and prioritize mitigation strategies (US GAO 2009; USACE 2009).

STUDY SITE

The Alaska Native community of Goodnews Bay is located at the head of Goodnews Bay, a broad inlet along the eastern Bering Sea coastline in southwest Alaska (Figure 1). The community has a long history of flooding due to storm surge, and in the 1920s had to relocate from the surrounding lowlands to the hillside (Himes-Cornell *et al.* 2013; Table 1). Storm surge and wind-driven waves at high tide are the primary cause of flooding, and have repeatedly inundated the airport runway and eroded the bluff fronting the community (Table 1). The coastal bluffs are composed primarily of unconsolidated quaternary alluvial deposits (Buzard 2017). The community mitigates erosion of the bluff fronting the community with a revetment of 10-50 cm diameter rock. Homes and the power generation facility are located near the armored bluff edge, and records indicated that homes have been damaged by storm surge flooding, but not erosion (Table 1). As is typical with numerous other communities in the region, critical infrastructure such as the airport and sewage lagoon are located in low-lying areas near the coast.

The bay is a back-barrier, micro-tidal shallow lagoon with mixed semi-diurnal tides. Local relative sea-level change is poorly quantified because no direct long-

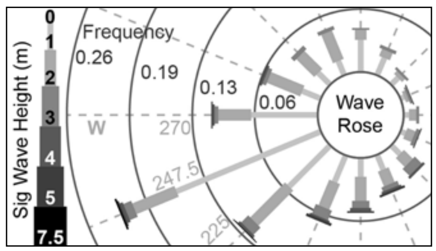

Figure 2 (below). This wave rose shows the frequency of wave energy passing near the entrance of Goodnews Bay at specified azimuths. Longer stems from the center (labeled "Wave Rose") indicate higher frequency of waves coming from that azimuth, and darker and wider stems represent greater wave energy (measured as significant wave height) The most frequent and intense wave energy came from 225°-270° (the west-southwest direction), and 23% of annual wave energy came from 247.5°. The wave rose was modeled 40 km offshore from the Goodnews Bay entrance using wind and ice data from 1984 to 2014 by the U.S. Army Corps of Engineers Wave Information Studies (USACE 2019b).

term water level records exist; indirect approximations (based on measured vertical land motion in combination with regional sea surface trends from satellite altimetry) suggest that relative sea-level trends are presently negligible on a multi-decadal timescale (DeGrandpre 2015). Waves enter the bay between two barrier spits, most often arriving from the west-southwest direction (Figures 1-2). Offshore sea ice typically reaches the bay entrance between November and January, which, when present, may help to impede significant storm surge build-up (Figure 3). The Goodnews River and Bay tend to completely freeze over from late fall until spring, regardless of offshore ice conditions, providing protective ice cover during the fall storm season (U.S. Fish and Wildlife Service 1986). When the bay and river ice become destabilized prior to a storm, flooding and erosion can occur; such was the case during the 11 November 2011 Bering Sea storm.

METHODS

The coastal hazard analysis of Goodnews Bay used remotely sensed image and elevation data, enhanced by on-site measurements and written and oral accounts, to focus on two hazards: shoreline change and coastal flooding. The site was visited in August 2015, 2016, and 2017 to perform topographic surveys, take water level measurements, and to collect local observations through personal communication with residents. Using real-time kinematic global navigation satellite systems (GNSS), 20 cross-shore elevation profiles were measured at approximately 1 year intervals to detect recent changes in the beach and bluff. These profiles were also used to compute the beach slope and bluff height for the wave impact hour calculation (Figure 4 A).

Shoreline change analysis

Shoreline change analysis is typically accomplished by identifying one representative shoreline feature (e.g. wet/dry line, bluff top edge, vegetation line) in orthorectified imagery, then measuring the change in position of that feature through time (Moore 2000). Measuring small changes and achieving more confident change rates requires co-registered, high-resolution (ideally ≤1m ground sampling distance), orthorectified images (Maio *et al.* 2012). At least two image datasets that meet these requirements exist for most coastal Alaska communities: (1) 1940s to 1960s black and white aerial photographs from the United States Air Force, and (2) 1970s to 1980s aerial photographs from NASA's Alaska High Altitude Aerial Photography Program. Contemporary image sources include State of Alaska Division of Community and Regional Affairs community profile maps from a mid-2000s comprehensive community mapping campaign, satellite imagery, and site-specific aerial surveys (Overbeck *et al.* 2017a).

The majority of high-resolution imagery and elevation models available for

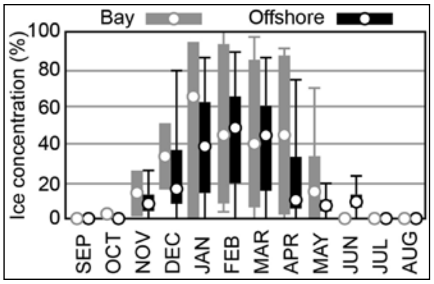

Figure 3 (left). This box plot compares monthly offshore ice concentration (1979 to 2016; National Snow and Ice Data Center) to that observed within Goodnews Bay (1982 to 2015; estimated from Landsat). Circles represent the median concentration, and tails are the minimum and maximum. January through April tend to have the greatest concentrations, but variability was high both offshore and especially inside the bay.

Table 1.
Storms reported to have caused damages in Goodnews Bay.

Storm date	Description
1920s	Community relocates due to flooding and storms.[1]
1969	Storm causes flooding of airstrip up to 0.15 to 0.31 m.[3]
1974: November	Large storm floods community.[2]
1979: 8-9 November	Large storm causes flooding from storm surge. Three houses flooded and unbalanced, one is destroyed. Estimated 1.8 to 3 m of bank erosion, and “flood depth” of 2.4 to 2.7 m. Previous airstrip narrowed (noted that flood water commonly floods previous airstrip). Residents claimed worst storm-driven waves in 20 years. 36 m/s (80 mph) winds reported in the region, 26.2 m/s (59 mph) winds measured in Bethel.[2, 3]
1982	Flood occurs.[3]
1984: February	Erosion of gravel bank fronting community due to heavy rains. The creek bridge washed away, and the creek froze.[3]
1989: 17 August	Strong winds from the south cause storm surge and flooding, high water goes over airstrip (noted that flooding occurs annually).[3]
2003: 16 November	Storm surge causes damage to boats.[4]
2011: 11 November	Large storm causes flooding from storm surge. Surge erodes bluff, damages airstrip, airport fence, property and homes, and displaces one family. Six to twelve boats are damaged or missing. Several Conex shipping containers with construction supplies washed out to mud flats. 44.7 m/s (100 mph) winds reported.[2, 4, 5]

1) Himes-Cornell *et al.* 2013
2) Terenzi *et al.* 2014
3) Buzard 2017 (Appendix II: ADCE Flood Plain Management)
4) Buzard 2017 (Appendix I: photos of damage)
5) Denning-Barnes 2011

Table 2.
Summary of images used for shoreline delineation.

Date	Type	Source	Scale/ resolution	Post-processed pixel size (m)	Ut (m)
1957: 4 June	Aerial	US Air Force	1:42,800	1.10	2.53
1983: 19 August	Aerial	NASA AHAP	1:65,500	1.26	2.71
2012: 28 June	Satellite	Worldview-2, Digital Globe	0.61 m	0.61	2.41
2016: 5 May	Aerial	Fairbanks Fodar	1:1,200	0.20	0.72

Alaska coastal communities are either publicly available for download at earthexplorer.usgs.gov, elevation.alaska.gov, or available by request from the Alaska Division of Geological & Geophysical Surveys Coastal Hazards Program (dggs.alaska.gov/hazards/coastal). The 1957 U.S. Air Force and 1983 NASA photos were processed using Agisoft Photoscan software to create orthomosaics, then georeferenced in ESRI ArcMap (Table 2). The aerial image from the community profile map was not orthorectified by the collecting agency and could not be used for shoreline delineation (DCRA 2019b). The Worldview-2 satellite multispectral (2.09 m) and panchromatic (0.61 m) level one products were acquired in 2012. These were orthorectified using the ArcticDEM and georeferenced in ESRI ArcMap (Noh and Howat 2015; Porter *et al.* 2018). The 2016 orthomosaic and digital surface model (DSM) were produced using structure-from-motion photogrammetric methods as part of a coastal community mapping campaign (Nolan *et al.* 2015; Overbeck *et al.* 2017a).

The USGS Digital Shoreline Analysis System (DSAS) tool was used to quantify change rates (e.g. Mars and Houseknecht 2007; Thieler *et al.* 2009; Ford 2013; Gibbs and Richmond 2015; Jones *et al.* 2018). This ArcGIS software extension casts virtual transects perpendicular to vector shorelines from multiple time periods and uses distances between shorelines intersecting each transect to calculate rates of change (Thieler *et al.* 2009). The bluff top was identified as the most suitable proxy indicator for net shoreline change associated with erosion for Goodnews Bay, because reports indicated it has been eroded by coastal storms. Of the entire 2000 m coastline, the bluff was present at two segments: the 350 m armored bluff fronting the community, and the 100 m unarmored bluff north of the sewage lagoon (Figure 4 B, C). Since armor rock had not been placed on the unarmored bluff, it served as a control site, representing natural (unmitigated) erosion rates. Bluff top edges were delineated manually in ArcGIS and shoreline change statistics were calculated using DSAS: a baseline was drawn to run approximately parallel to the shoreline, transects were cast perpendicular at 5 m spacing with 100 m smoothing, and the horizontal distance

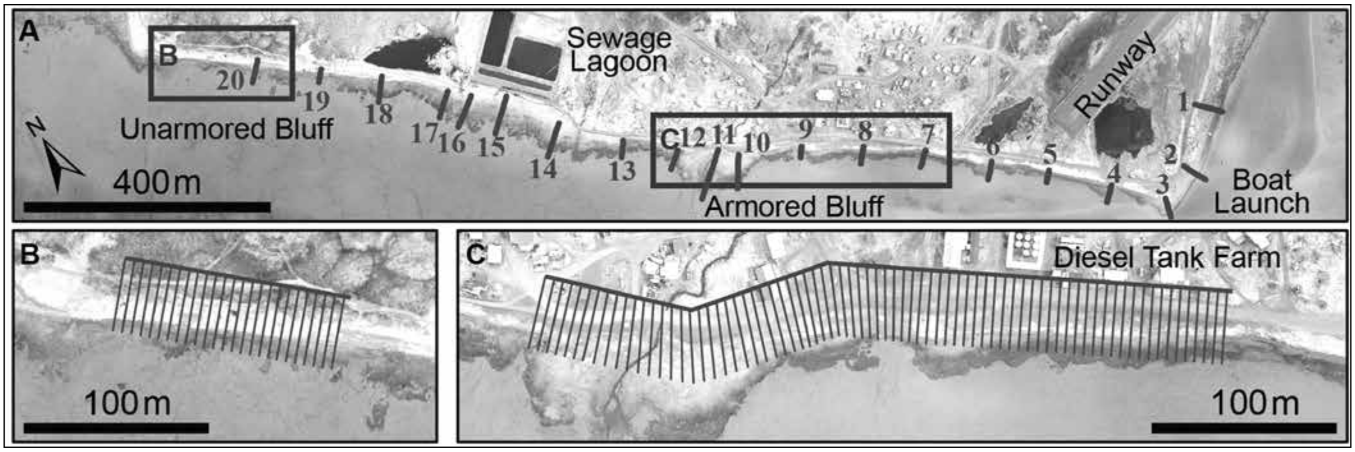

Figure 4. (A) Location of 20 cross-shore GNSS profiles from the boat launch to the unarmored bluff. DSAS transects are shown for the unarmored (B) and armored bluff (C) sections of the coast.

Equations:

$$U_t = \sqrt{{U_d}^2 + {U_o}^2 + {U_g}^2 + {U_c}^2} \quad [1]$$

$$U_p = \sum_{i=1}^{n} max(|L_{1i} - L_{2i}|, |L_{1i} - L_{3i}|, |L_{2i} - L_{3i}|) \quad [2]$$

$$U_d = U_a + U_p \quad [3]$$

$$T_f = T_{WLR} \times (F_y - C_y) \quad [4]$$

$$T_U = T_{WCI} \times (F_y - C_y) \quad [5]$$

T_f – distance of change
T_{WLR} – WLR of the transect
C_y – most recent shoreline year
F_y – future projection year

$$< \eta > = 0.35\beta_f (H_0 L_0)^{\frac{1}{2}} \quad [6]$$

$$R_2 = 1.1\left(< \eta > + 0.5\left[H_0 L_0 \left(0.563\beta_f^2 + 0.004\right)\right]^{\frac{1}{2}}\right) \quad [7]$$

$<\eta>$ – maximum setup height
β_f – beach slope
H_0 – significant wave height
L_0 – peak wave period
R_2 – 2% runup exceedance

between each shoreline was calculated. For each transect, shoreline change was measured using net shore movement (NSM) and weighted linear regression (WLR) statistics (Table 3).

Total horizontal position uncertainty (U_t) for each shoreline was calculated using the root sum of squares error (RSS) of the digitizing uncertainty (U_d), orthorectification uncertainty (U_o), georectification error (U_g), and base image ground control uncertainty (U_c) (Table 2; Eq. 1). This is a common method for summarizing uncertainty in shoreline delineation (e.g. Gibbs and Richmond 2015; Kinsman and Gould 2014; Ruggiero *et al.* 2013). Using the bluff top for the shoreline proxy eliminated other commonly factored uncertainties related to changes in the tidal regime (Boak and Turner 2005). No standard is set to fully quantify digitizing uncertainty, but shoreline studies generally assume the ability of the user to interpret features accurately is directly related to pixel size or image scale (e.g. Crowell *et al.* 1993; Ruggiero *et al.* 2013; Gibbs and Richmond 2015). Building on this assumption, we developed a user precision (U_p) factor calculated for each image by taking the mean of the maximum distances between the three repeat delineations (L_1, L_2, L_3) on each transect, i.e. the average greatest difference between three digitizing attempts (Eq. 2). The total digitizing uncertainty (U_d) was then considered to be the sum of the digitizing ability (pixel size = U_a) and digitizing precision for each image (Eq. 3).

Future shoreline positions were projected by extrapolating the WLR rate of change statistic linearly along the transect. An uncertainty footprint was calculated from the 90% confidence interval and the length of time forecasted (Eq. 4; Eq. 5). This calculation was accomplished using a custom ArcGIS tool described by Gould *et al.* (2015).

Storm surge flooding analysis

The coastal flooding analysis was conducted in three parts: (1) estimating maximum water levels from historical storms, (2) combining a numerical storm surge and tide model with a parameterized wave runup model to estimate hindcast total water levels, and (3) calculating wave impact hours. Written and oral accounts and photos identified four major storms that caused flood damage in Goodnews Bay, and these sources were used to estimate the maximum water level reached. Combining these resources with GNSS elevation measurements, the community profile map, and the 2016 DSM, the height of the 1969, 1979, 1989, and 2011 storms were estimated (Table 6; i.e. Buzard 2017).

Much of Alaska's western coast lacks direct water level or wave measurements, so marine total water level (TWL; tide + surge + wave runup) was estimated using tide, surge, and wave runup models (e.g. Kinsman and DeRaps 2012). For the tidal component, the NOAA tidal datum and astronomical tide predictions for the head of Goodnews Bay were used. The surge component was provided by the NWS Sea Lake and Overland Surge from Hurricanes model (Jelesnianski *et al.* 1992). Offshore deep-water (20 m) peak wave period and significant wave height were modeled by the USACE Wave Information Studies station 82234 (USACE 2019b). Average beach slope was calculated from our GNSS beach profile survey. These components were used with the Stockdon *et al.* (2006) parameterized wave runup equation to compute wave setup (Eq. 6) and maximum 2% runup (Eq. 7), with the error estimated to be 20% of the surge height (Jelesnianski *et al.* 1992; Taylor and Glahn 2008). To test the accuracy of this approach, results during the 2011 storm were compared to approximations made from written accounts.

Using the TWL estimate, erosion susceptibility was assessed based on how often waves reach the beach and bluff. This analysis, measured in wave impact hours (WIH), calculated the amount of time TWL exceeds the elevation of relevant coastal geomorphic features (Sallenger 2000; Ruggiero *et al.* 2001; Hapke and Plant 2010). The WIH estimate was constrained to times when offshore waves were directed toward the bay entrance (wave direction between 235° and 255°). Using the period of 2009 to 2014, when all necessary datasets were available, the TWL estimates were compared to elevations of three coastal features to determine the WIH of:

Beach erosion: MHHW≤TWL<bluff toe

Bluff collision: bluff toe≤TWL<bluff top

Bluff overtopping: bluff top≤ TWL

Mean higher high water (MHHW) was locally defined by a tide-by-tide analysis using data from a GNSS-leveled HOBO pressure gauge deployed during fieldwork, NOAA tide predictions, and the modified range ratio method for semidiurnal tides (USDC 2003; Table 5). The mean elevation of the bluff toe and top were obtained with *in situ* GNSS measurements.

Table 3.
List of DSAS Statistics (from Himmelstoss 2009).

Abbreviation	Statistic	Description
EPR	End point rate (m/y)	Distance between oldest and youngest shorelines divided by the time elapsed between them
ECI	EPR confidence interval (m/y)	Root mean sum of squares of the EPR shorelines' total uncertainties divided by the time elapsed between them
NSM	Net shoreline movement (m)	Distance between oldest and youngest shorelines
WLR	Weighted linear regression rate-of-change (m/y)	Linear regression rate of change weighted by the inverse of the squared variance in the uncertainty
WCI	WLR 90% confidence interval (m/y)	90% confidence interval for the standard error of the WLR slope
WR2	WLR R^2 value	Percentage (0.0-1.0) of variance in the data that is explained by a regression

Table 4.
Change statistics for each bluff section over the study period. Net shoreline movement (NSM) is also broken into two periods. WLR = weighted linear regression rate-of-change.

Sample period	1957-1983		1983-2016		1957-2016					
Statistic	NSM		NSM		NSM		WLR (m/y)		R^2	
	Mean	2 std. dev.	Mean	2 std. dev.	Mean	2 std. dev.	Mean	2 std. dev.	Mean	2 std. dev.
Unarmored	-0.6	1.4	-4.9	3.4	-5.5	3.4	-0.10	0.07	0.91	0.13
$Armored_{north}$	-4.2	6.3	-5.0	6.4	-8.8	5.4	-0.14	0.11	0.82	0.34
$Armored_{south}$	-2.1	6.0	0.8	4.3	-1.4	4.6	-0.01	0.06	0.37	0.61
$Armored_{total}$	-2.5	6.4	-0.5	6.8	-2.9	7.8	-0.05	0.14	0.50	0.69

Table 5.
Local tidal datums for Goodnews Bay in meters NAVD 88. The Platinum values are published by NOAA CO-OPS for station 9465396.

Tidal datum	Goodnews Bay, AK	Platinum, AK
MHHW	2.095	2.648
MHW	1.182	1.827
MTL	0.060	0.895
MSL	0.235	0.945
DTL	0.410	1.210
MLW	-1.061	-0.037
MLLW	-1.275	-0.228
GT	3.370	2.876
MN	2.243	1.864
DHQ	0.920	0.821
DLQ	0.197	0.191

RESULTS

Through these analyses, areas most at-risk to erosion and flooding were identified, and the impact of particularly strong storms (e.g. 2011) on Goodnews Bay has been quantified. The following summarizes the results of the shoreline change and storm surge flooding analyses. For a more comprehensive site-specific analysis for Goodnews Bay, refer to Buzard (2017).

Table 6.
Estimated significant total water levels associated with storm surge and flooding events.

Storm date	Elev. (m MHHW)	Elev. (m NAVD 88)
2011	3.4	5.5
1989	2.4 to 3.0	4.5 to 5.0
1979	2.7	4.8
1969	2.4 to 3.0	4.5 to 5.0

Shoreline change analysis

Minor amounts of erosion of the bluffs in Goodnews Bay were observed from 1957 to 2016 (Table 4; Figure 5). The unarmored bluff north of the community retreated between 3.4 m to 9.8 m (RSS error = 2.6 m), most of which occurred

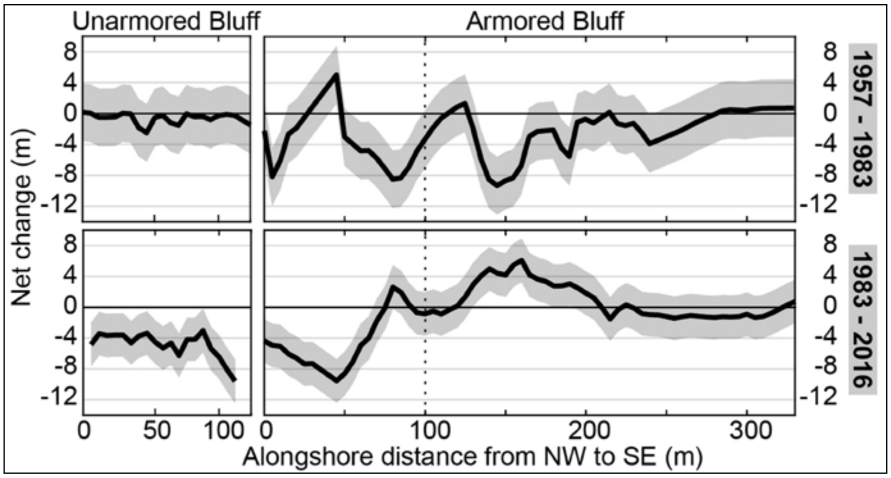

Figure 5. Graph shows net horizontal change of the bluff edge from 1957 to 1983, and from 1983 to 2016. The gray area indicates the root sum of squares error of the respective uncertainties. The dashed line separates the north and south area of the armored bluff. The unarmored bluff eroded in the recent period. The armored bluff experienced significant erosion near the creek (0 m to 100 m alongshore distance) in both periods, but the southeast section was repaired by the community, causing a positive net change in the shoreline measurement (100 m to 200 m alongshore distance).

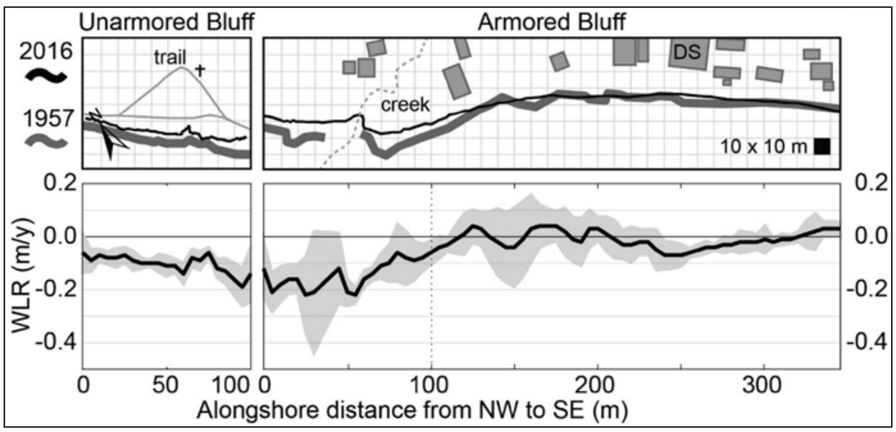

Figure 6. Map (top) shows locations of 1957 (gray) and 2016 (black) bluff top edges on a 10 m grid, and nearby buildings are digitized. The footprint size of each bluff edge represents total uncertainty. Some erosion occurred near the diesel power station (DS), but the greatest erosion happened in the creek area. The graph (bottom) shows the weighted linear regression rate of change (WLR) with the 90% confidence interval (light gray). The unarmored bluff eroded 0.1 to 0.2 m/y, whereas the armored bluff was spatially variable.

between 1983 and 2016 (Figures 5-6). The armored bluff fronting the community retreated between 0 and 15.6 m over the entire study period (Figure 6). Sections of the armored bluff that had eroded during the 1957-1983 period were repaired with new rocks by the community. This mitigation caused an "accretion" result in the shoreline change calculation (Figure 5). The analysis demonstrated that erosion was mitigated to some degree by bluff armoring, and identified areas in the community most susceptible to erosion (Figure 6). Future bluff top edge positions were projected to the years 2030 and 2050 using the WLR rate of shoreline change (Figure 7). The shoreline projections did not overlap with any current infrastructure, suggesting that the erosion is not expected to be long-term hazard to the community.

Storm surge flooding analysis

The storm surge flooding analysis involved estimating historical storm heights and mapping flood extents and impacts. The earliest documented storm impact was for the 1969 event, and the 2011 event was the most recent significant storm (as of 2018). TWL estimates of the four largest historical storms to flood Goodnews Bay suggest that the 2011 storm surge reached the highest elevation, 3.4 m above MHHW (Table 6). All four storms reached higher than the bluff toe along the entire shoreline fronting the community, and reached the lowest-lying homes. The active airport runway is constructed at a higher elevation, and only a storm reaching the same height as in 2011 would flood it (Figure 8). Most residences and infrastructure observed in the most recent orthoimage (2015) were located at least 4 m above historical flooding levels.

The numerical storm surge and tide models were combined with a parameterized wave runup model to hindcast TWL. The accuracy of the modeled TWL was measured using the 2011 storm height approximated from accounts and photos. The timing of the storm peak matched local reports, but the wave runup estimate was far higher than local observations suggested (Denning-Barnes 2011). Replacing runup with the wave setup height component of the Stockdon *et al.* (2006) equation, the TWL estimate was within 0.2 m of the 2011 storm height observations. Wave setup was therefore considered the more appropriate parameter for TWL model, and was used for the subsequent WIH analysis.

TWL was modeled over the available dataset period of 2009 to 2014 and compared to coastal features in order to analyze WIH for the armored bluff in Goodnews Bay. The total monthly WIH were greatest from October through December, which was consistent with the region's fall storm season (Figure 9) (Terenzi *et al.* 2014). All years ranged between 11 to 23 annual WIH, except for 2011 when it reached 55 hours. The November 2011 storm contributed about as many WIH as would typically occur over one year in Goodnews Bay.

DISCUSSION

This analysis was designed to identify past, current, and potential future coastal hazards using datasets common to remote coastal communities. Areas at risk of erosion were identified by measuring shoreline change and forecasting future shoreline positions. We also estimated past storm TWL heights, mapped their extent, and identified areas at-risk of storm surge flooding. The methods used were adequate for answering our research questions, but certain aspects could be improved upon when applying this analysis to other locations.

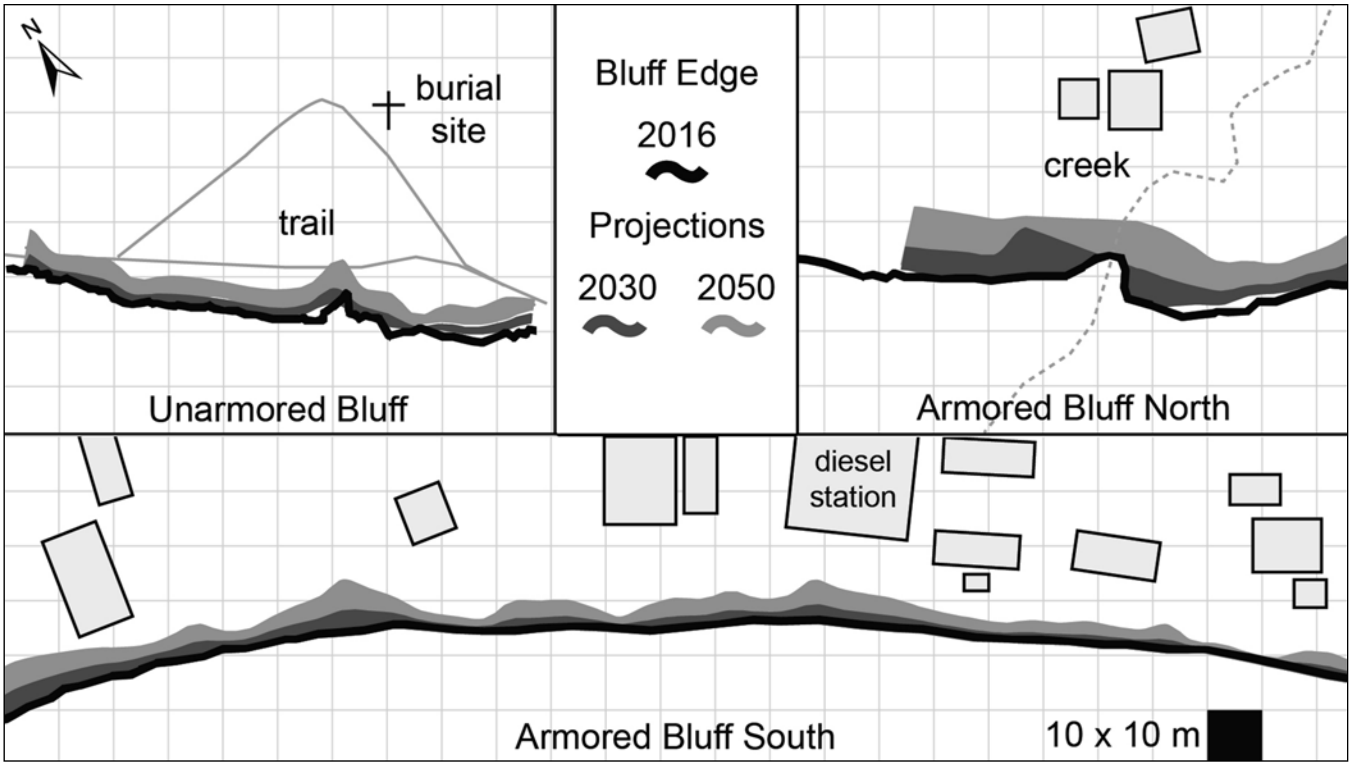

Figure 7. Future bluff positions are projected onto the digitized map for 2030 (dark gray) and 2050 (medium gray). The projection footprint represents the area that the bluff may erode to within the 90% confidence interval of the WLR. No structures were projected to be impacted by bluff erosion by 2050.

Shoreline change and mitigation

Using a combination of aerial and satellite imagery, GNSS surveys, and personal communication, the risk of erosion to the community of Goodnews Bay was identified. Bluff erosion at this location is caused by infrequent storm surge flooding, and after the 2011 storm the community replaced some eroded sections and armored the bluff with large rock. Much of the eroded area from 1957 to 1983 was replaced (Figure 5), and with this added material, the bluff fronting the community was largely net-stable over the study period (Figure 6). The unarmored bluff continued to erode throughout the study period, which suggests that the bluff fronting the community would have also seen net erosion without mitigation.

Shoreline change projections are useful for mitigation efforts and coastal infrastructure planning, and communities can save resources by better understanding how their shoreline responds to anthropogenic modifications. In Goodnews Bay, the projections showed that erosion of the bluff edge would not reach buildings by 2050; this assumes that the community continues to respond to significant erosion by rebuilding the revetment (i.e. their mitigation strategy is effective in protecting coastal infrastructure). Across the United States, armoring is a common response to erosion, but it can have significant upkeep costs, is sometimes ineffective, and can cause undesired coastal responses (Pilkey and Wright 1988; Griggs 2005; Mason *et al.* 2012). The image-based shoreline change analysis can provide guidance for coastal hazard planning, but it must be updated as new mitigation strategies are implemented.

Storm surge flooding hazards

Flooding due to storm surge forced Goodnews Bay to relocate in the 1920s, and continues to pose risks (Table 1). This analysis tied four recorded floods into a geodetic vertical datum, allowing us to project flooded inland areas using the local elevation model (Figure 8). While all four storms flooded the airport runway when they occurred, the current runway (built in 2009) is approximately 0.5 m higher and would only be flooded by storm surge reaching the height of the 2011 event (3.4 m above MHHW). No evidence was found that storm surge flooding has ever affected the sewage lagoon or the diesel station, two coastal structures that are vital for the community. The sewage lagoon berm would be overtopped by storm surge exceeding 4.0 m above MHHW, but the diesel station is effectively outside of the flood risk zone.

Relating storm heights to land and infrastructure elevation can improve the guidance for infrastructure planning. For example, the recommended building height in the majority of coastal Alaska communities was designated as 0.31 m or 0.62 m (1.0 or 2.0 feet) above the height of the highest known flood (USACE 2019a). These flood heights were estimated by USACE (2019a) in the 1990s, but this investigation had limited information and measurement tools compared to today (e.g. survey-grade GNSS was not yet available). In absence of GNSS, the flood heights and recommended building heights in the USACE (2019a) reports are often referenced to local infrastructure, such as a high water sign on a telephone pole. These physical vertical reference markers can be altered or removed over time. Only two of the six USACE (2017) survey control marks in Goodnews Bay are still intact, both of which we occupied with GNSS (Buzard 2017). The recommended local minimum building height that USACE (2017) designated was 3.3 m above MHHW (5.4 m NAVD 88). The 2011 storm exceeded this recommended building height by 0.1 m, suggesting that this height is outdated. Based on the 2011 storm and the USACE (2019a) guidance method, the new recommended building height for Goodnews Bay should be

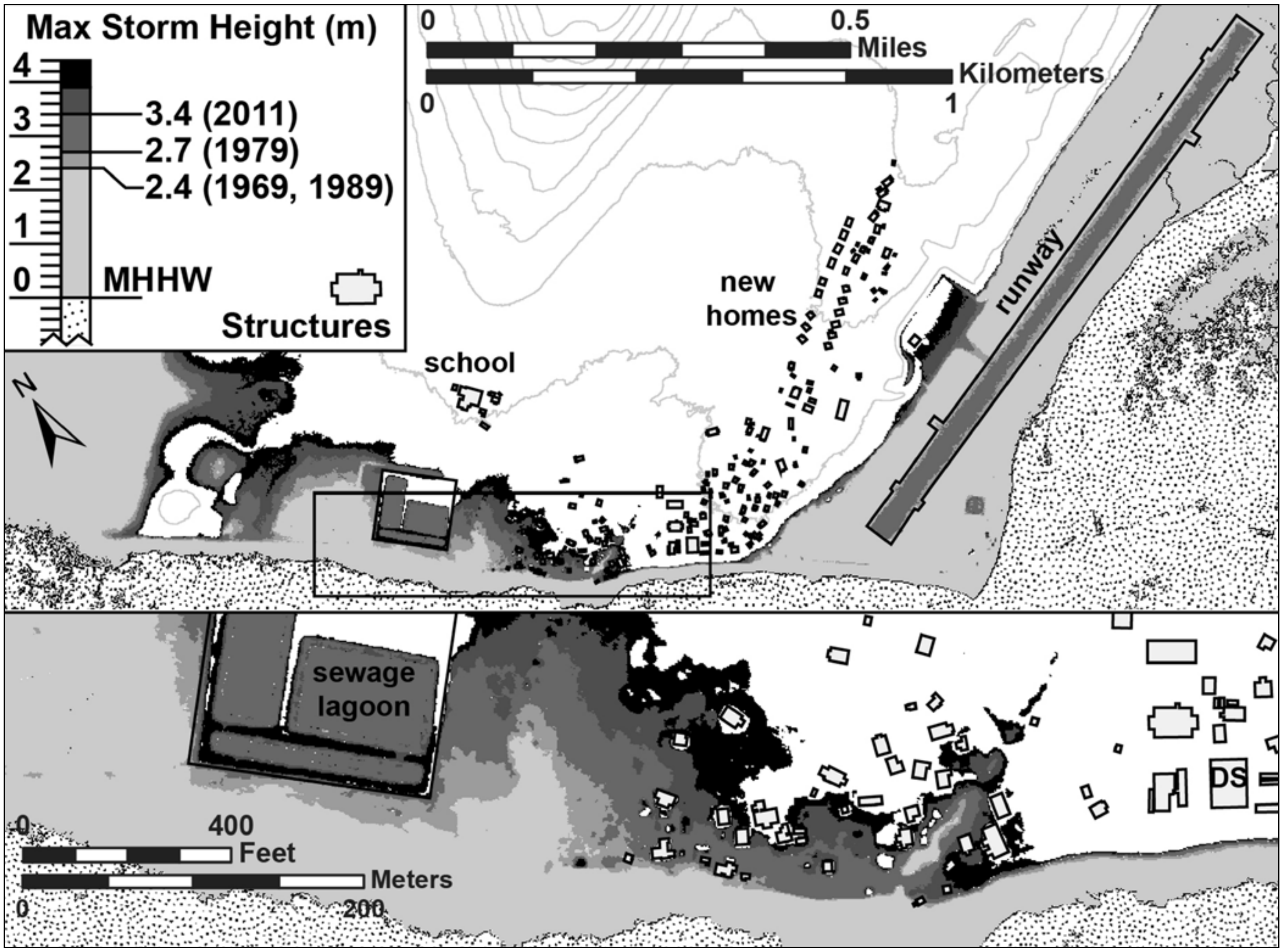

Figure 8. Map shows horizontal extent of estimated total water level of the four past storms reported to have inundated the runway (1969, 1979, 1989, 2011). All permanent structures (buildings, sewage lagoon, runway, etc.) are outlined. The two darkest zones delineate the extent of a hypothetical storm reaching up to 1 m above the 2011 storm. Contours are drawn at 10 m intervals, beginning 10 m above MSL. Storms partially surrounded the sewage lagoon, which sustained no serious damage in 2011 and could be overtopped by a storm reaching 4 m above mean higher high water (MHHW).

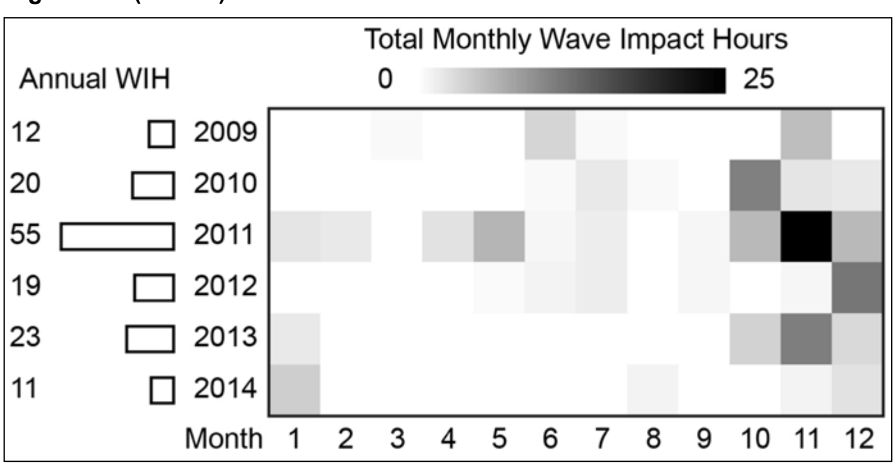

Figure 9. Heat map illustrates total hours each month when modeled waves reached the base of the bluff. The x-axis is months, y-axis years, and grid shade is wave impact hours (WIH). Darker squares represent more wave energy reaching the bluff, possibly leading to erosion. The graph (left) shows the total number of WIH per year. The November 2011 storm itself (25 WIH) exceeded all annual WIH in the study time period.

3.7 m or 4.0 m above MHHW (5.8 to 6.1 m NAVD 88). By connecting storm elevations, prior surveys, and elevation models to one consistent vertical datum, measurable with GNSS, scientists and engineers can create flood risk maps that assist communities in making informed decisions to reduce risk.

Orthorectified imagery and digital elevation models

Repeat image acquisition is essential for measuring long-term shoreline change in remote regions. Having one recent high-resolution (20 cm in our case) color image was invaluable in identifying the shoreline indicator, which helped to confirm shoreline interpretations in coarser imagery. Goodnews Bay exhibits relatively slow rates of erosion, so two images (one contemporary and one historical) would have been sufficient for quantifying bluff change. Measuring shoreline change in an area with faster or more dynamic erosion would benefit from more frequent sampling (e.g. Maio *et al.* 2012).

The 2016 orthoimage and DSM were essential for determining risk to community infrastructure. From the 2016 image, we could interpret shoreline armoring, types of infrastructure, and areas of high traffic and use. The aerial image and contours from the community profile map of 2005 were useful for identifying these features as well, but important aspects were outdated. For example, the airport runway was expanded and elevated in 2009, and it became less susceptible to flooding from storm surge. To ensure the most accurate and relevant coastal hazard analysis of a community, imagery and elevation models must be refreshed and maintained.

Site visits and GNSS surveys

Accessing remote locations can be difficult and expensive, but site visits aided every aspect of this analysis. For example, we set up meetings with community leaders and learned pertinent details about the history of storms, erosion, and mitigation efforts that helped steer the analysis to meet community needs. Flood indicators from local accounts and shared photographs were used to measure past flood heights with GNSS. The GNSS surveys were also used to evaluate the accuracy of the 2016 orthomosaic and DSM, measure the bluff top edge, calculate beach slope, measure the local tidal datum to the same vertical datum as the DSM, and determine the factor to adjust the community profile map contours into a geodetic vertical datum. While not as applicable in Goodnews Bay, a location experiencing significant beach erosion or accretion would benefit from volumetric change measurements using repeated coastal profiles with GNSS. Shoreline change analysis and flood height estimates can be accomplished without actually visiting the site, but their scope becomes limited and the results less verifiable without ground-truth measurements from GNSS and local observations.

Storm height estimates

Estimating the height that a storm surge flood reaches in a community requires careful considerations. For historical storm events in Goodnews Bay, data such as written accounts were limited in detail, such that only three of the eight flood events recorded had enough information to be approximated (Table 1). Even when accounts were descriptive enough to determine a maximum storm height, care had to be taken to use the appropriate dataset. For example, water flooded up to 0.31 m on the runway in 1969, but the runway had been reconstructed and was a different height in the 2016 DSM. Ultimately, estimating storm heights using these limited datasets provided the first quantified storm record for the community, and helped to validate TWL.

The TWL and WIH estimates helped to visualize the impact that the 2011 storm had on Goodnews Bay, especially highlighting how this storm compared to the usual annual wave energy affecting the bluffs. TWL relied on modeled tide, surge, and wave runup, which are commonly available in most Alaska communities on the west and north coast (USACE 2019b). The timing of the event peak was consistent with local accounts, but the approach overestimated the 2011 runup height. Wave runup may have been overestimated due to the difference in coastal setting between the community of Goodnews Bay and the inlet; offshore wave conditions may not be representative of the fetch-limited embayment wave conditions, due to wave dampening during translation through the inlet and bay and wave breaking over a shallow embayment. Using the wave setup output of the Stockdon *et al.* (2006) equation instead of wave runup, the TWL estimate matched the observation-based GNSS measurement of the storm height.

The WIH results were consistent with local accounts of flood and erosion activity over the study period. Noise was reduced by constraining the estimate to time periods when the offshore wave direction entered the narrow inlet into Goodnews Bay. Thus, both TWL and WIH could be modeled with some success given the available datasets, but the results require validation and careful interpretation. These methods may be less reliable for areas with greater sea ice presence, because sea ice can reduce wave energy (Overeem 2011; Vermaire *et al.* 2013).

Application of this analysis to regional coastal communities

Communities in western and northern Alaska are experiencing unprecedented coastal changes due to sea ice loss and air and ground temperature increases (Chapin *et al.* 2014). The methods in this study demonstrate the feasibility of measuring shoreline change with historical aerial images, which now exist for the vast majority of these communities. Coupled with a baseline shoreline GNSS survey and elevation model, which are relatively inexpensive to collect with contemporary technology, flood hazards can be identified as well. Beyond just quantifying the severity and extent of hazards, these datasets can in-turn be used for estimating the functional lifespan of current and future infrastructure, and can be used by the National Weather Service to improve storm surge forecast content (Overbeck *et al.* 2017b). Given the current state of warming, sea ice loss, and widespread erosion and flooding of Alaska communities, it is imperative that threatened communities have access to quantitative shoreline change and flooding analyses.

This analysis can be performed for many Alaska communities given available datasets, but several data gaps still exist that would restrict certain aspects. Quantifying flood hazards required more datasets and interpretation than the shoreline change analysis; it was crucial to have a GNSS survey, elevation model, and local knowledge and reports of flooding in order to identify risk areas and the frequency and severity of flood hazards. Most coastal Alaska communities only have one elevation model that is sufficient for this style of flood analysis (sub-meter ground sampling distance, in a vertical datum verified by ground control), and most do not have a bare-earth model meeting these requirements (e.g. typically derived from Lidar surveys). The existing elevation models allow for new avenues of hazard analysis, but will eventually need to be updated as communities continue to develop. Flood modeling also requires tide and storm surge models and elevation measurements referenced to a geodetic elevation, which are not available for many communities. Temporary or permanent instrumentation such as water level sensors and tidal datums are required to document these water levels. While progress on this front is being made, many communities in western Alaska are still lacking these necessary datasets, and thus lacking the capacity to receive adequate coastal hazard analyses (Overbeck 2018).

CONCLUSIONS

Coastal hazards in Goodnews Bay were mapped using a combination of written and oral accounts, survey-grade GNSS, geospatial datasets, and various oceanographic hindcast models. Storm surge is the primary hazard causing flooding and bluff erosion. The community mitigated erosion by replacing the damaged bluff with a rock revetment, but some areas continue to erode. In the future, a storm reaching the height of the 1979 or 2011 storm would inundate roads, storage areas, current residences, and the airport runway.

Many Alaska communities experience greater magnitudes of flooding and erosion than Goodnews Bay. They have similar baseline datasets, but still lack up-to-date analyses of coastal hazards that would greatly improve hazard mitigation projects. The critical need for informed hazard analyses is exacerbated by the vast changes in presence and duration of sea-ice and permafrost that affect coastal flooding and erosion across the Arctic. As this paper demonstrates, the tools are available to conduct thorough hazard assessments for the majority of communities.

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