Report of Investigation 2021-1

COASTAL FLOOD IMPACT ASSESSMENTS FOR ALASKA COMMUNITIES

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Hooper Bay residents identify the flood height of the November 1974 storm. Source: U.S. Army Corps of Engineers Flood Information Papers, photo taken by community member of Hooper Bay.

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Department of Natural Resources
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Contents

Figures

Tables

Conversions

1 meter = 3.281 feet

Abbreviations

ft = feet
DCRA = Division of Community & Regional Affairs
DGGS = Division of Geological & Geophysical Surveys
DSM = digital surface model
DEM = digital elevation model
FEMA = Federal Emergency Management Agency
MHHW = Mean Higher High Water
NFIP = National Flood Insurance Program
NWS = National Weather Service
Orthoimagery = orthorectified aerial imagery
UAF = University of Alaska Fairbanks
USACE = U.S. Army Corps of Engineers

Additional Information

The DGGS Coastal Hazards Program is committed to mapping and monitoring erosion and flooding in Alaska's coastal communities. Resources include shoreline change assessments, high-resolution orthoimagery and digital elevation models, online and interactive flood visualizations, and community-based monitoring information. Visit our website to see data for your community at dggs.alaska.gov/hazards/coastal/ or make observations at Alaska Water Level Watch at www.facebook.com/AlaskaWaterLevelWatch/.

COASTAL FLOOD IMPACT ASSESSMENTS FOR ALASKA COMMUNITIES

Richard M. Buzard[1], Jacquelyn R. Overbeck[1], Jonathan Chriest[2], Karen L. Endres[2], and Edward W. Plumb[2]

Abstract

Coastal communities in Alaska experience frequent storm surge flooding, yet the majority do not have a clear and consistent record of flooding. Local and statewide flood mitigation decisions require a clear understanding of flood risk, but the risk for many communities has not been adequately determined due to the difficulty of discovering information or interpreting flood impacts. One key dataset that is commonly missing is a complete list of all known flood events, along with flood heights relative to a consistent vertical datum, for each community. Water level sensors are largely absent in rural Alaska so determining the height of past events requires more creative efforts.

This report introduces a method for estimating historical storm heights and flood impact categories for individual communities relative to infrastructure and a local tidal datum. Community-based observations and written accounts are used to estimate the height of recorded flood events. Flood impact categories are defined using National Weather Service terminology and are based on the elevation of residences, airstrips, and other critical infrastructure. Flood category heights and storm heights are listed in two tables, providing weather forecasters with fast decision support tools to help determine how communities should prepare for incoming storms.

This initial publication includes reports for Golovin and Hooper Bay, and additional community assessments will follow. Community-specific reports include a flood category map showing current infrastructure, and a graphic relating infrastructure heights with previous floods. The report explains how each storm height was measured, and provides a bibliography of sources that were used to make those estimates.

INTRODUCTION

Most coastal communities in western Alaska have experienced and documented storm impacts during the last century, but there was not a consistent way to measure storm surge flooding heights. By understanding how frequently storms reach a certain height (such as with a flood recurrence interval), communities can develop plans to reduce flood damages through mitigation projects or by moving out of the floodplain. Comparing flood events relative to each other and to infrastructure requires that all heights are known relative to one reference (for example, a tidal datum, geodetic datum, or building). Relating past storm impacts to a consistent vertical datum also helps weather forecasters estimate the potential severity of an incoming storm, which in turn increases community capacity to avoid storm damage.

Flood mapping for many Alaska communities has not been conducted to date, largely due to a lack of critical baseline data such as measured topography and fluctuations of the land-water interface at the coast (tidal datums geodetically tied to digital elevation models). Alaska has the widest gaps in the National Oceanic and Atmospheric Admin-

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istration (NOAA) National Water Level Observing Network (NWLON; NOAA, 2014). NWLON stations measure water levels to create a long-term record of flooding and these datasets are used to estimate the statistical return interval of floods (for example, the 100-year flood). Elevation data necessary to model flood inundation extents were also not available before modern efforts to map Alaska's coast. In recent years (2016–2019), the Alaska Division of Geological & Geophysical Surveys (DGGS; Overbeck and others, 2017), NOAA's Office for Coastal Management, and the U.S. Geological Survey (USGS) collected an unprecedented amount of high-quality orthoimagery and elevation data over northern and western Alaska (DGGS, 2020a). With these high-resolution datasets, ground features and reference marks are visible, making it possible to identify flood extents based on photographs alone (Overbeck, 2017). These innovative mapping, data collection, and data processing efforts provide the foundation upon which flood impact maps can now be created for small, remote communities along Alaska's coast.

Communities analyzed using our methodology are required to have an elevation model and a tidal datum tied to a geodetic datum. Because these data were only recently collected or made available, there are many more communities where this type of assessment could be conducted than are included in this report (fig. 1). Additional reports will be released as communities are analyzed by DGGS. There are still communities that lack datasets (fig. 1), so additional baseline data must be collected to assess them.

This report summarizes the methods used to create community-specific coastal flood impact assessment reports. The community reports detail

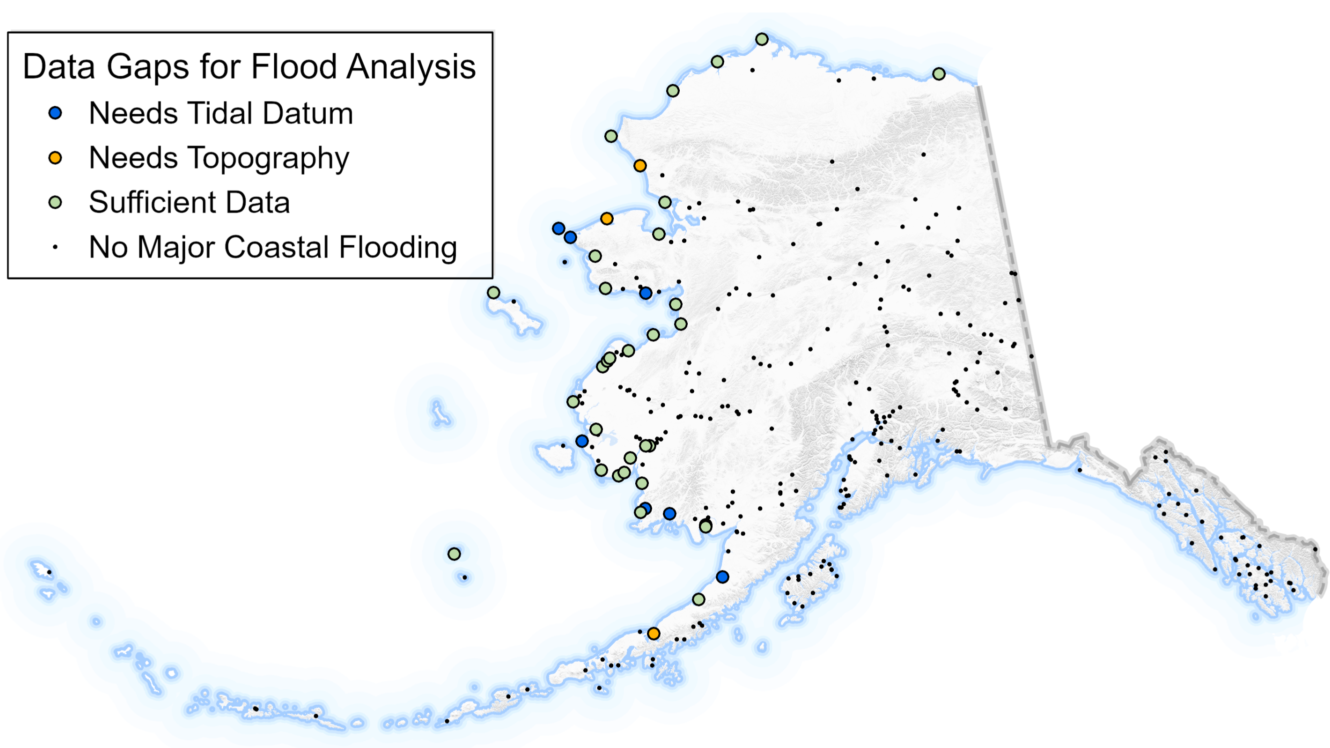

Figure 1. Availability of datasets necessary for flood impact analysis. Many communities have sufficient data (green), but several are still missing a tidal datum (blue; DGGS, 2020b). Three communities are only missing a topographic model (orange). The color-indicated communities are known to have experienced major coastal flood impacts, and the remaining communities (black) either have not experienced major coastal flooding or have not been assessed.

historical storm observations in heights above mean higher high water (MHHW) and show mapped flood impact areas for the community. Conversion factors are provided to reference heights to mean lower low water (MLLW) and orthometric height. Flood impact categories represent the height water would need to reach in order to cause minor, moderate, or major flooding impacts, and can be referenced to NOAA National Weather Service (NWS) forecasts. We also created an online and interactive storm impact visualization tool tailored for each community. The tool displays the current NWS forecast storm surge elevation and allows the user to toggle on elevation contours to simulate flood extent. Mapping tools can help planners make decisions that improve safety and resilience, such as determining safe building areas and developing effective emergency plans.

BACKGROUND

Hurricanes and nor'easters cause the most destructive and expensive disasters in the United States (NOAA National Centers for Environmental Information, 2020). Like the eastern U.S., Alaska's western and northern communities also experience disastrous storm surge from Arctic and extra-tropical cyclones. Alaska comprises numerous isolated rural communities spread along the coast, and storms have the capacity to cause widespread damage. For example, a storm that occurred in November 2011 resulted in a disaster declaration for 37 individual Alaska communities spanning over 1,300 miles of coastline, which is more coastline than the western contiguous U.S. (U.S. Office of the Press Secretary, 2011). Two years later, a smaller storm resulted in a disaster declaration for 23 communities along an even longer segment of the coast (Federal Emergency Management Agency [FEMA], 2020). Storms tend to occur in fall or winter when temperatures are below freezing and there are minimal daylight hours, compounding hardship during the aftermath. Even the smaller and more frequent storms cause significant flooding and erosion damage in many coastal communities, leading to mitigation projects and even partial or total relocation of community infrastructure (Division of Community and Regional Affairs [DCRA], 2019a). Sea ice can reduce storm surge (Overeem and others, 2011; Vermaire and others, 2013) but the rapid decline in sea ice extent has left coastal communities vulnerable to storms for longer periods than those observed in the historical record (Chapin and others, 2014; Thoman and Walsh, 2019; Walsh and Chapman, 2015).

Many government reports have identified flooding and erosion as threats to Alaska communities, particularly those on the west coast (Immediate Action Working Group, 2009; U.S. Army Corps of Engineers [USACE], 2009; U.S. General Accounting Office, 2003; U.S. Government Accountability Office, 2009; University of Alaska Fairbanks Institute of Northern Engineering [UAF] and others, 2019). In a statewide assessment focused on erosion, communities on the west coast made up 21 of the 26 locations (81 percent) identified as "Priority Action" (erosion is an imminent hazard to community viability; USACE, 2009). Storm surge flooding was the principal driver of erosion in 98 percent of coastal communities. While flooding was not the focus of the report, USACE (2009) explain that "...numerous communities with erosion problems less urgent than those of Priority Action Communities also experience severe flooding." They conclude that ".. an analysis similar to the [baseline erosion assessment] that incorporates flooding is needed" (USACE, 2009). No such effort has been conducted to date.

Flood history in western Alaska is poorly documented. For many communities, the only floodplain assessments were conducted by USACE in the 1990s. The resulting reports have served as the best available flood information for planning purposes and are referenced in many community planning documents, but the entire collection is not accessible online (USACE, 2019, 2020). These assessments included estimates for the height of the flood of record and other flood events. The flood of record was used to map a floodplain contour and determine the recommended building height for many communities (DCRA, 2019b). Almost 30 years later, that determination is still used as the baseline in planning documents by most communities in western Alaska even though many have experienced at least one flood higher than the previous record. The assessment was conducted before Global Positioning System technology and the current National Tidal Datum Epoch, so current storm forecasts cannot be compared to the flood of record. If communities are expected to effectively plan for flooding, they need an up-to-date analysis of flood events that can be related to current infrastructure.

In the contiguous U.S., the National Flood Insurance Program (NFIP) managed by FEMA has been a catalyst for the development of flood risk information. Most western Alaska communities have not benefited from FEMA flood mapping and mitigation activities due to a significant lack of data and resources. Of more than 40 Alaska coastal communities that have experienced major flooding, only 6 participate in the program (Dillingham, Emmonak, Kotzebue, Nome, Shishmaref, and Togiak). Of these participants, few have used NFIP flood insurance. The Northwest Arctic Borough (2019) explains, "The Northwest Arctic Borough (NWAB) has been an active NFIP participant since 05/17/2005… However, the NWAB has never been mapped to receive FEMA issued Flood Insurance Rate Maps (FIRMs) that delineate their floodplain." Shishmaref joined NFIP in 1998 and received its first FIRM in 2001, but has never made a claim (City of Shishmaref, 2015). Lake and Peninsula Borough (2015) has FIRMs but has made no claims for flood insurance since joining NFIP in 2004. Communities exploring the possibility of relocation face more challenges; while the Northwest Arctic Borough participates in NFIP, the City of Kivalina (2015) explains, "At this time, due to lack of public services and the inevitable relocation of the village, implementing flood regulations in [Kivalina] is unlikely." In *The State and Federal Response to Storm Damage and Erosion in Alaska's Coastal Villages,* U.S. Congress (2008) explained that, "With the high costs in rural Alaska and low population benefit, developing a project or relocation effort with a positive benefit-to cost [sic] ratio is difficult to impossible. Without a positive benefit-cost ratio, a project is not eligible for [FEMA grant] funding consideration." Given the current lack of data required to be eligible for NFIP, and the lack of incentive to collect such data, a FEMA flood mapping campaign is not anticipated for western Alaska communities.

Those without flood insurance can still receive non-emergency disaster assistance if they have a local hazard mitigation plan (HMP; FEMA, 2019). FEMA-approved HMPs are also required for communities to be eligible for federal post-disaster funds. The majority of coastal communities now have HMPs, which often serve as the best available source for flood information. However, these plans tend not to document all available flood events; do not collect, verify or assess flood heights or dates; and sometimes fail to retain pertinent information when the plans are updated. While HMPs are a valuable resource for understanding coastal hazards, they have not reliably contained a complete or consistent flood record.

National, state, and local governing bodies rely on documented flood events for hazard planning, post-disaster recovery, and engineering mitigation solutions, yet no single resource exists that quantifies flood risk for Alaska communities. Understanding local historical flood impacts is vital for community resilience. This project is the first effort to create a comprehensive flood information resource based on observed events.

METHODS

The community-specific flood assessments include two primary analyses: (1) estimating historical storm heights based on written and photographic accounts of past storms, and (2) determining flood impact category by evaluating the heights of storm-generated flooding that would result in three levels of impact (minor, moderate, and major) as defined by the NWS (www.weather.gov/aprfc/terminology). In other parts of the U.S., numerical models of overland storm surge flooding are used to model the physical processes that result in storm surge inundation. This type of modeling requires many datasets that are not yet available in rural Alaska. Since these dynamic models cannot be developed, our methods for defining flood impact areas rely on observations of past events. This analysis required the following information or datasets for each community:

- Reported events (written accounts, water level sensors, photos, flood staffs, etc.)
- Mapped location of community infrastructure
- High resolution orthoimagery (< 40 cm pixel size)
- Digital elevation or surface model (DEM or DSM)
- Tidal datum (geodetically tied to orthometric height)

Historical Storm Height Estimates

We estimated storm heights from flood observations—typically written accounts and/or photographs. To be quantifiable for this assessment, an observation must describe flooding in a way that could be measured using a ground height. For example, if a source reported the height of water at a crossroad, the elevation of that crossroad can be measured from a DEM. Because ground height or heights and locations of infrastructure may change through time, we took care to account for any such changes that would affect the estimate. Flood descriptions can be difficult to interpret and convert to storm heights and flood impacts. For this reason, the rationale for each estimated water height and its uncertainty is recorded in detail in the Historical Flood Record section of the community-specific reports.

Most flood heights were estimated using a DEM or DSM to interpret peak flood height. For sources that described instantaneous water level or a high water line left on the ground, either a polygon or line was drawn onto the elevation model to estimate the elevation. We used the same method for reported "damage," but the estimated elevation is considered a minimum possible flood height because often the amount of detail in the description was insufficient to determine how high above ground level the water reached.

Calculating uncertainty for each storm height estimate depended on the type of observation used. Uncertainty is defined by the Joint Committee for Guides in Metrology (2008) as a "parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand." When possible, we estimated uncertainty to the 95 percent confidence interval (CI) using either the root-mean-square error or root-sum-square, as appropriate. These statistical methods are most commonly applied to large areas with many measurements (for example, polygons of elevation data representing an entire road or runway).

When uncertainty could not be estimated using these approaches, we employed the upper-lower bounds method of uncertainty propagation (University of North Carolina, 2018). This process uses the highest and lowest reasonable values of measurements to define the range of uncertainty, then assigns the middle value of that range as the final estimate. For example, if a source stated that water reached a specific road but did not reach a nearby building, the flood height would be estimated as halfway between the road height and building ground height. The uncertainty would cover the vertical range between them.

For written observations of water height, we used the number of significant figures to evaluate uncertainty (University of North Carolina, 2018). For a reported water height with one significant figure (for example, "the water reached 3 feet"), the implied uncertainty at the 95 percent CI was assumed to be one unit (3 ± 1 feet of water at the 95 percent CI). For an estimate of one unit, the uncertainty was 0.5 units (for example, 1.0 ± 0.5 feet of water at the 95 percent CI)—making the assumption that the observer could reasonably say that the water was less than 2 feet deep and more than 0 feet deep, but could not distinguish an exact height between 0.5 feet and 1.5 feet.

There are multiple components to water levels that combine to cause flooding. Beyond the regular tide level, atmospheric pressure and sustained winds can cause a change in water level called storm surge. As storm surge reaches the coast and waves break, water can run up on a beach, temporarily reaching heights above the storm surge level. This process is called wave runup. Storm estimates in this report were generally described as "still water levels" (for storm surge levels), because this best represents the height of standing flood water. We also estimated wave runup when possible. It is critical to differentiate these types of observations because wave runup can reach much higher than the still water level. Coastal communities are often situated where some structures are vulnerable to wave runup, so we used storm observations and scientific judgment to identify runup risk.

Flood Impact Categories

Flood impact categories are used by the NWS to define flood risk and communicate it to the public. The designated categories are minor, moderate, and major. In advance of a coastal flood, water level predictions help advise the flood impact that may occur. A flood advisory is triggered when a storm is forecast to cause minor flooding, and a flood warning is issued for moderate or major flooding. In populated areas, the categories are based on the height of flooding required to reach certain types of infrastructure. This practice is used because the same water level height will have different societal impacts depending on how high infrastructure is. For example, one community might have the lowest-lying homes at 6 ft above MHHW, whereas homes in another community are 10 ft above MHHW. If a 6 ft (MHHW) storm surge were to occur, the first community may experience moderate impacts while the second would not.

For this assessment, we defined flood impacts in a way that applied to most rural Alaska communities. Alaska communities are generally small in population and geographic extent, and are separated by large enough distances that each requires its own set of public utilities. Communities typically have one each of the following: power generation facility, airstrip, drinking water source and treatment facility, and wastewater facility. Without a backup option, the loss of one public utility or access to transportation services can cause disaster for the community. These common and vital facilities were used for determining flood impact categories. Other impact indicators included residences, access roads, and property that would be damaged by flooding.

Using NWS terminology, we developed a questionnaire-style guide to determine the elevation thresholds of flood impact categories (table 1). We defined categories based on the height required for a flood to cause a specific impact. Assigning categories also considered context from storm histories and community planning documents. The feature at lowest height within a flood category was typically used as the category threshold. For example, if the drinking water source was at 7 ft MHHW and the fuel storage tanks were at 8 ft MHHW, then the major flooding category would be triggered when a flood was forecast to reach 7 ft MHHW.

COMMUNITY-SPECIFIC PRODUCTS

This report documents methods used to quantify community-specific flood risk and is a companion to individual reports for coastal communities. Each community report includes an introduction, a description of past flood impacts, and a summary of the results of the analyses in two tables: One for flood categories and infrastructure, and one for the storm history. A map sheet shows the extent of minor, moderate, and major flood levels relative to community infrastructure.

The report then describes the process of analysis, including a description of datasets available, the method for determining flood impact categories, methods used to estimate storm surge flood heights, and a rationale for decisions. Appendices for each report contain direct quotations from storm-related accounts that were used to estimate storm heights, and any additional tables or figures that communicate how storm heights and flood impact levels were determined. See table 2 for a summary of these items.

Each community-specific report contains—in table format—the results of the historical flood analysis and height designation of flood category indicators. The table of flood impact category indicators shows the elevation of critical or commonly referenced features in the community (table 3). Each flood category is defined as a single height cutoff (the minimum height to which water must rise to trigger that category). Features are listed in order from highest to lowest elevation. Infrastructure that may be at risk of wave runup is identified with a symbol. Wave runup has the potential to reach higher than a forecast height. Infrastructure considered not at risk of storm surge flooding are listed in gray. These determinations are informed by the historical flood analysis, proximity to the coastline, and the ground elevation model.

Historical flood heights are listed in a separate table. Storms are ordered from highest to lowest elevation, and the colors represent the flood category that the storm would trigger if it occurred, given current infrastructure heights. Infrastructure may have changed over time, so storms may have caused different impacts when they occurred. These changes are noted in the summary.

Each community report is accompanied by a map sheet that displays flood impact areas, infrastructure, and a flood staff that shows flood height

Table 1. Flood impact category guide. During the risk assessment, the assessor answers "At what height..." followed by each question in the list. If heights were not available from prior geospatial surveys, they were estimated using the same measurement methods as historical storm elevation estimates. The appendix explains how each individual question was decided.

Major flooding: At what height...	
1.	Have several buildings been flooded with over 1 foot of water?
2.	Have the fuel storage or power generation facilities flooded?
3.	Has the airstrip been completely inundated?
4.	Has flood water reached the drinking water source?
5.	Has flood water reached wastewater facilities?
Moderate flooding: At what height...	
1.	Have several buildings been flooded with up to 1 foot of water?
2.	Have people in the lowest area(s) been evacuated to higher ground due to flooding?
3.	Has flood water cut off access to larger parts of town?
4.	Has flooding closed the airstrip?
Minor flooding: At what height...	
1.	Has water come into yards, or under elevated buildings?
2.	Has flooding reached property (such as vehicles, not homes) in low lying areas?
3.	Has flooding reached roads or the airport runway, but remained low enough to safely travel?

Table 2. Outline for community-specific reports.

Report Section	Description
Overview	Brief introduction to flood hazard at community.
Summary	Summary of findings, including a table of infrastructure heights and a separate table of historical storm heights, color-coded by flood category.
Map Sheet	Map of flood categories, including flood staff with reference to storm history and infrastructure height.
Data	List of all available mapped and tidal datasets used for the analysis. If elevation conversions were made, they are listed in this section.
Flood Impact Categories	Evaluation of flood category indicators and the final determination of flood category heights.
Historical Storm Record	List of estimated storm heights, from the oldest to the most recent flood event, with a discussion of how each estimate was calculated.
Acknowledgments	Recognize funding sources and people who contributed to the investigation.
References	Citations for all resources used for the report.
Appendix A: Storm-Related Accounts	Annotated list of all documents and publications (online and print) that contained information used to estimate storm heights. Includes direct quotes from storm-related accounts.
Appendix B: Flood Category Calculation Figures	All tables and figures that show how data were used to calculate flood impact categories.
Additional Appendices (if needed)	Information pertinent to the report that is not readily available online.

categories as illustrated by the schematic in figure 2. Colored zones represent the area that would likely flood if water were to reach the height that triggers each storm category. For the example, in figure 2 and table 3, if water were to reach 5.0 ft MHHW, then all areas in the yellow zone would be at risk of flooding, but the red and purple areas would not be expected to flood. If water were to reach 7.0 ft MHHW, the yellow zone would be flooded, the red zone at risk of flooding, and the purple zone would not be expected to flood. Floods above 9.8 ft MHHW would be categorized as major. Technically there is no "upper limit" for the major flood category. However, to more accurately communicate flood risk, the upper limit was defined using either the the higher of the highest observed or modeled water level. Heights of other critical infrastructure that are above this level are shown in gray on the flood staff.

DISCUSSION

The results for Golovin and Hooper Bay, the first two communities assessed, identified many storms and provided a clearer understanding of flood risk than found in other existing documents. The following discusses the successes and caveats of this method for storm estimation and flood risk categorization. In addition, we compare these results to the current understanding of flood risk for coastal Alaska communities.

Comparing Sources and Interpreting Storm Descriptions

The most common sources describing storm surge flooding are written descriptions and, more recently, photographs. These are found in local or multi-jurisdictional HMPs, USACE (2020) floodplain reports, USACE (2009) baseline erosion assessments, and storm surge observations (for example,

Table 3. Example of infrastructure heights and flood categories. Infrastructure that may be subject to wave runup is indicated by a wave runup symbol. Purple = major, red = moderate, yellow = minor. Gray represents infrastructure not expected to be impacted by coastal flooding, given the local flood history.

	Elevation Feature	Elevation (ft MHHW)	Vertical Uncertainty (ft)	Subject to Wave Runup
Other	Wastewater facility	15.0	0.5	
	Airstrip	14.5	1.0	
	Drinking water source	14.0	0.8	
	School	13.6	1.0	
Major	Several buildings	10.5	1.0	
	Fuel tanks	9.8	0.5	
	Major	9.8	0.5	
Moderate	Airstrip use or access	8.2	0.3	
	Access way to larger parts of town	8.2	0.3	
	Lowest residences	7.0	1.0	
	Moderate	7.0	0.3	
Minor	Lowest building	7.0	0.3	
	Access road threatened	5.5	0.8	
	Beach property	5.0	0.5	
	Minor	5.0	0.5	

Figure 2. Schematic of flood impact categories in relation to tide staff. Flood category heights are determined based on infrastructure impacts as defined in table 3.

Wise and others, 1981). Many other sources provide greater detail for specific locations or regions: news reports, publications by scientists and various entities, online blog posts, and community-based observations tracked by Alaska Water Level Watch (2020).

The list of past floods was not complete in any single source. As an example, the sources used for Golovin are compared in table 4. There were 23 storms identified between 1900 and 2019. The local HMP from 2008 mentioned 71 percent of all known storms in its time period, and had more content than any other resource. The updated 2015 HMP only mentioned 50 percent of known storms, losing information on 4 storms from the previous HMP. Other documents were surprisingly sparse, such as the USACE flood information found online, which mentioned only 13 percent of known storms (USACE, 2019). Ultimately, no single source provided a full list of storms, demonstrating the need to investigate multiple sources when evaluating storm impacts.

Written descriptions of storm heights are often limited in detail, and most storms only have one unique description that is copied across multiple reports. Typically, the source describes the peak height of the storm, so the maximum height of the flood can be estimated. However, if impacts are not described in relation to physical features or infrastructure, the report cannot be used. This was the case for many storms in the early to mid-1900s, which were only described using the cost of damages (Wise and others, 1981).

The majority of storms were estimated with an uncertainty that ranged between one to two feet. The uncertainty was influenced by the timing of the observations, the clarity of the source description, and the measurement method itself. Uncertainty may also be due to the inherent inaccuracy of representing flooding of an area with a single height value, since the effects of sustained wind, waves, and overland flow can cause water to reach different heights in different areas at the same time. Wave runup has the potential to reach several feet higher than still water, but still water better represents the general height of flooding on the community scale. Distinguishing wave runup from still water was critical.

Addressing Data Gaps and Priorities

Flood categories can be determined for communities that have orthoimagery, digital elevation or surface models, a tidal datum that is geodetically tied, and local observations of storm surge flooding. Currently, of 41 communities that experience minor to major coastal flooding, 10 are missing datasets necessary to complete this analysis (fig. 1). Seven of those have an elevation model and are only missing a geodetically-tied tidal datum. Even in the absence of a tidal datum, analyses can be performed for these communities using orthometric heights or a local infrastructure datum. If a tidal datum is collected in the future, the results of the flood analysis can be converted to the local tidal datum. Given available elevation datasets, storm heights can be estimated for at least 38 of the 41 flood-vulnerable coastal communities identified.

As previously stated, most flood-vulnerable Alaska communities lack a clear historical record of the frequency and severity of flooding. A flood return interval is commonly used to communicate risk, but can only be calculated using continuous observations over at least 20 to 50 years. The majority of vulnerable communities have no long-term water level measurements. The most recent attempt to estimate return intervals for multiple locations in western Alaska was completed by Chapman and others (2009). These results provided valuable insight into the timing and severity of storms, but validation data was nonexistent for the majority of communities because they did not have water level observations. Community-based observations of past and current flooding can help inform and validate future modeling efforts and flood return interval calculations. For this reason, it is imperative that communities share their experiences with flooding and continue to document events.

Communities can greatly improve the current understanding of flooding and increase their capacity to mitigate flood hazards by continuing to document flooding, and also by incorporating modern monitoring equipment. Recent efforts have been made by DGGS to monitor flood water levels autonomously and provide a means to report flood levels referenced to a vertical datum (dggs.alaska.gov/hazards/coastal/monitoring.html). Flood observations can be shared with the state Coastal Hazards Program by submitting photos and written accounts to Alaska Water Level Watch (at www.facebook.com/AlaskaWaterLevelWatch).

Improving Hazard Analyses for Alaska Communities

So long as hazard information remains difficult to find and interpret, statewide attempts at hazard assessments will have trouble accurately and equally representing all communities. Comparing resources is necessary for accurately determining risk and avoiding contradicting and false statements. For example, the City of Kivalina (2007) HMP mention the unreliability of return interval models at the time, pointing out that every model severely over-predicts flooding as compared to community observations. Chapman

Table 4. Comparison of storm or flood mentions by source for Golovin. A black box represents a storm mentioned by that source. A gray box represents a storm not mentioned by that source, even though the storm occurred in the period that the source evaluated. The white region represents time beyond the scope of the source. The bottom row is the summary of the listed sources and others, showing a total of 23 mentioned storms from 1900 to 2019. The total number of storms is unknown because there is not a long term water level record.

Source	# of storms in report	Percent given time period	Percent of total storms	Storm surge flood events (23 total)																						
				1900-SEP-12	1913-OCT-05	1945-OCT-28	1946-OCT-25	1960-OCT-02	1974-NOV-10	1977-SEP-12	1992-OCT-05	2002-OCT-08	2003-SEP	2003-NOV-01	2004-OCT-19	2005-SEP-22	2008-JAN	2009-NOV-11	2011-NOV-08	2012-OCT-05	2013-NOV-09	2016-OCT-29	2016-DEC-30	2017-OCT-13	2019-FEB-11	2019-AUG-03
Local HMP* Update	9	50%	39%																							
Local HMP	10	71%	43%																							
USACE Online Flood	3	15%	13%																							
USACE Erosion	4	31%	17%																							
USACE Print Flood	3	38%	13%																							
Wise and others (1981)	4	57%	17%																							
Chapman and others (2009)	3	38%	13%																							
These and all sources	23	?	?																							

* Hazard Mitigation Plan

and others (2009) developed models for the region with more realistic return intervals for Kivalina. Glenn Gray and Associates (2010) summarized five separate 100-year floodplain estimates for Kivalina that ranged between 8.3 and 16.3 ft above MLLW, and specifically suggested that the updated HMP should use Chapman and others (2009). Despite this suggestion, the update by City of Kivalina (2015) only cited the older, inaccurate models, and made no mention of Chapman and others (2009). Without a thorough literature review, one may not be aware of the best available data when trying to determine how at-risk a community is, which has implications when prioritizing mitigation actions among many communities (UAF and others, 2019). Communities are misrepresented when local knowledge and best available information are not properly documented. Inaccurate claims of imminent destruction can lead to improper planning and misallocation of resources (Mason and others, 2012), and even decline in mental health (Willox and others, 2015; Yoder, 2018). It is crucial that hazard assess-ments thoroughly review literature and use local observations to verify or disavow the findings of other studies.

Hazard assessments can be further complicated by the combined threat of hazards. For example, Kivalina, Shishmaref, and Shaktoolik experience major erosion damages from storm surge, but little to no infrastructure flooding. However, the most recent statewide threat assessment (UAF and others, 2019) ranked all three at higher risk of infrastructure flooding than many communities where flooding is so severe that it has forced partial or total evacuation, including Napakiak, Galena, Emmonak, and Kotlik. Places where storm surge causes erosion, but not flooding, may have been incorrectly marked at much higher flood risk. In addition, the flood information may not have been accurate or up to date, such as the Kivalina example above. In contrast to the challenges of finding and interpreting several resources, some at-risk communities were considered by UAF and others (2019) to have little to no flood risk, or not having enough information. For example, Goodnews Bay, Kwigillingok, and Nunam Iqua were ranked least at risk of flooding, even though all have experienced major flooding that led to destruction of infrastructure and homes, and partial relocation.

The current challenges of assessing hazards signifies that there is a widespread need for comprehensive, community-specific analyses that examine all available data and combine it in a clear and quantifiable way with full documentation. Such an analysis will represent the current best understanding of flood hazards, from which under-represented communities can identify and address data gaps. After improvements based on local input, the analyses will become the best-available resource for local hazard information. Such an effort can ultimately lead to greater prioritization of mitigation resources, improving community resilience statewide.

CONCLUSIONS

Using recently acquired imagery and elevation datasets, we developed a method to measure the height of historical floods relative to current infrastructure. Flood impact category heights were defined using NWS terminology, and can be used to communicate forecast flood events to communities. All resources were carefully assessed, and the rationale for scientific judgment was documented in detail. We initially analyzed two communities—Golovin and Hooper Bay—with results included in this report (https://doi.org/10.14509/30573). However, this method can be performed for 28 more communities that have necessary baseline data, and 8 more communities that are at risk of coastal flooding but do not have tidal data. By compiling storm histories and using modern methods for tying storm-induced flooding to community infrastructure and elevations, this analysis provides the most concise and descriptive view of local flood impacts to date, which can be used for local hazard mitigation planning, post-disaster recovery, and engineering mitigation solutions.

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APPENDIX: SOURCE DATA FOR FLOOD CATEGORY QUESTIONS

The following questions (in bold type) were used to evaluate how a storm would be categorized based on direct quotes from NWS documents (in italics).

Major flooding

1. **Have several buildings been flooded with over 1 foot of water?**
   This is an important metric, but is also the hardest to quantify. It depends on how many buildings constitute "several" for a given community. It also requires knowing the finished floor height, which is mostly undocumented in western Alaska.
   - *"many buildings flooded, some with substantial damage or destruction"*
   - *"infrastructure destroyed or rendered useless for an extended period of time"*
   - *"multiple homes are flooded or moved off foundations"*
   - *"Numerous structures will flood with sufficient depth to result in major damage. The most vulnerable homes and businesses near the waterfront could be severely damaged or destroyed… Generally, 2–4 feet of inundation (depth of water above ground level) is expected in low lying areas."*
2. **Have the fuel storage or power generation facilities flooded?**
   Most small coastal communities only have one power source, and this is a vital resource.
   - *"the airstrip, fuel tanks, and the generator station are likely flooded"*
   - *"fuel tanks may float and spill and possibly float downstream"*
   - *"loss of transportation access, communication, power and/or fuel spills are likely"*
3. **Has the airstrip been completely inundated?**
   Complete inundation implies that repairs and/or debris removal would have to be done before the airstrip could be used again.
   - *"the airstrip, fuel tanks, and the generator station are likely flooded"*
4. **Has flood water reached the drinking water supply?**
   This metric will be aided by communication with the community and quantifying the history of past events that contaminated drinking water.
5. **Has flood water reached wastewater facilities?**
   Most communities have sewage lagoons for wastewater disposal, and if flood waters are contaminated with lagoon water then there may be a health risk.

Moderate flooding

1. **Have several buildings been flooded with up to 1 foot of water?**
   This runs into the same caveats as with major flooding: the term "several" is based on the community itself, and finished floor heights are mostly unknown.
   - *"several buildings flooded with minor or moderate damage"*
   - *"Widespread flooding of locations may occur near the waterfront including some damage to vulnerable structures."*
   - *"Ponding of water behind dune structures will result in some flooding of roads and vulnerable structures."*

2. **Have people in the lowest area(s) been evacuated to higher ground due to flooding?**

   If people have to leave their homes to be safe, it is classified as a moderate flood.

   - "elders and those living in the lowest parts of the village are evacuated to higher ground"
   - "A few evacuations may be needed in the most vulnerable areas."

3. **Has flood water cut off access to larger parts of town?**

   Generally, this is when access is cut off to lower residences or vital infrastructure.

   - "*water over the road is deep enough to make driving unsafe*"
   - "*water deep enough to make life difficult, normal life is disrupted, and some hardship is endured*"
   - "*Numerous road closures due to flooding and/or overwash debris. A few areas could become isolated due to the flooding of roads.*"

4. **Has flooding closed the airstrip?**

   Most communities have one airstrip. For this analysis we assume it is closed if flooding makes landing unsafe or if access to the airstrip is cut off.

   - "*airstrip closed*"
   - "*access to the airstrip is cut off or requires a boat*"

Minor flooding

1. **Has water come into yards, or under elevated buildings?**

   The NWS considers this "inconvenience or nuisance flooding," and there is no danger to people.

   - "*water over banks and in yards*"
   - "*no building flooded, but some water may be under buildings built on stilts (elevated)*"
   - "*one or two homes in the lowest parts of town may be cut off or get a little water in the crawl spaces or homes themselves if they are not elevated*"

2. **Has flooding reached property (such as vehicles, yards) in low lying areas?**

   Important property, such as untethered boats and tractors, are sometimes left on the upper beach area and may be at risk of damage or flooding from minor flooding events.

   - "*personal property in low lying areas needs to be moved or it will get wet*"

3. **Has flooding reached roads or the airport runway, but remained low enough to travel safely?**

   - "*Small part of the airstrip flooded, and aircraft can still land*"
   - "*Flooding of parking lots, parks, and roads with only isolated road closures expected*"