COMMUNITY-BASED MONITORING: SHORELINE CHANGE IN SOUTHWEST ALASKA

By

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Abstract

Arctic amplification has resulted in increased coastal hazards such as erosion in Alaska. The remoteness of the southwest Alaska coastline hinders frequent coastal hazard surveys, requiring alternate methods for measuring change throughout the year. This study documents and evaluates a community-based monitoring program in two southwestern Alaskan communities including Chignik Bay and Dillingham. The program entitled, Stakes for Stakeholders, has been running successfully since 2016 and continues to engage with rural communities to measure and map coastal change. The Stakes for Stakeholders program promotes self-advocacy and equips local participants with the tools, information, and resources needed to respond to increasing coastal hazards. This method engages local partners through data collection, training, and reviewing and revising resulting products to address local priorities. Community engagement consists of biannual video conference meetings, annual site visits, and miscellaneous communication (i.e., calls, text messaging, and emails). Baseline data was collected with community partners in the form of coastal topographic profiles and measurements collected at locally identified monitoring sites. The process of establishing, operating, and maintaining these sites is documented in various protocols and workflows produced in this study. As part of the research, locally prioritized data products were created. One such product was a hazard assessment report that was drafted for the community of Chignik Bay outlining all relevant coastal hazards to which the community is susceptible. Assessment rubrics were drafted and used to evaluate the efficacy of the program. These evaluations highlighted some of the most relevant community-based monitoring takeaways and pointed towards areas that needed improvement. Results from this study document a successful community-based monitoring (CBM) program and serve as a model for State and Federal research agencies and Arctic and sub-Arctic communities looking to respond to global climate change.

Table of Contents

List of Figures

List of Tables

Page

List of Appendices

Acknowledgements

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Chapter 1 Introduction

Due to global climate change, coastal hazards have increased worldwide with Arctic and sub-Arctic regions experiencing the highest rates of change and impacts (Cohen et al., 2014; Pörtner et al., 2022). This phenomenon known as Arctic amplification is equated to warming at twice the global rate resulting in major environmental shifts along the coastline (Cohen et al., 2014; Koenigk et al., 2020). Some of the most notable changes include the decline of sea ice, increasing flooding and erosion, permafrost degradation, and sea-level rise (Buzard et al., In Press; Li et al., 2020; Pörtner et al., 2022). Sea ice extent has declined in the past decade, increasing land exposure to open water and wave action (Frey et al., 2015; Li et al., 2020), while permafrost degradation is leading to unstable shorelines increasing susceptibility to erosion and land collapse (Manson & Solomon, 2007; Osterkamp, 2007; Sepp & Jaagus, 2011). Permafrost thaw and decline in sea ice have also increased land exposure and vulnerability to storms, thereby increasing flooding extent and erosion rates along the coast (Bogardus et al., 2021). Compounding these changes is the acceleration in the rate of sea-level rise which is leading to a translation of coastal hazards further inland (Cazenave et al., 2014; Magnan et al., 2022).

The State of Alaska has warmed at a faster rate than the rest of the United States (Taylor et al., 2017). Results of the warming trend include warmer, longer summers; shorter, milder winters; and increased storm impacts (Berman & Schmidt, 2019; Melvin et al., 2017), all of which are negatively affecting rural coastal communities. Approximately 83% of Alaska's population lies along the coast (NOAA, n.d.). While most of this population lies in cities, the remainder live in sparsely populated areas often along rivers and coastal embayments. These predominately Indigenous communities lack access to major road systems and other essential services that sometimes hinder the research needed to inform an effective response. Due to their remoteness and other challenges to conducting research in the region, there is a paucity of environmental datasets that would allow one to accurately assess coastal hazards and risks (GAO, 2003). These issues manifest as limited high-resolution aerial imagery, digital elevation models, and coastal topographic surveys; a lack of water level data; costly research trips; and incompatible weather and nearshore conditions for sensitive instrumentation. All of this leaves rural coastal communities without the information needed for planning and informed decision-making.

One way to address these challenges is through community-based monitoring (CBM; Danielson et al., 2021; Glenn, 2022; Kouril et al., 2016). CBM focuses on addressing local priorities using standardized environmental monitoring methods in trusting partnerships between multiple stakeholders such as Tribal organizations, State agencies, and academic institutions (Eicken et al., 2021; Eitzel et al., 2017; Tebes, 2005). CBM provides the platform for co-developed research and education activities improving adaptive strategies for climate resilient communities (Bronen et al., 2020; Buzard et al., In Press).

There has been a great deal of work in the Arctic and sub-Arctic delineating evidence-based practices and guidance for designing equitable, sustainable, and impactful CBM programs (Danielsen et al., 2021; Gofman, 2010; Johnson et al., 2016; Kouril et al., 2016; Sigman et al., 2015). Key features of successful CBM programs include; centering on local values and priorities; the inclusion of local and Indigenous knowledge; adequate training opportunities; simple and standardized methods; the presence of a local champion; a clear link between monitoring data and local decision making; collegial and collaborative relationships between local monitoring teams and supporting professional scientists; access to technology; good communication feedback loops; and adequate funding and equitable compensation for monitoring work in communities (Danielsen et al., 2021; Gofman, 2010; Johnson et al., 2016; Kouril et al., 2016; Sigman et al., 2015).

While the broad features and underlying concepts of Arctic and sub-Arctic CBM have been well studied, the main mechanisms of project workflows and methods to evaluate the local fit and the success of the projects have not, to our knowledge, been published publicly. The aim of this study was to make visible some of the inner workings of a well-established CBM program to show what these design elements look like in practice and what potential improvements could be made. These methods are demonstrated throughout this study.

1.1 Research Goal and Objectives

The goal of this study is to advance the application of CBM methods to measure coastal change in rural coastal communities. To achieve this goal four objectives are defined:

1. Develop sustainable and reciprocal partnerships with local environmental observers to identify local priorities, gain guidance through Indigenous Knowledge holders, and collaborate in research activities.
2. Conduct baseline topographic surveys and install, operate, and maintain monitoring sites.

3. Develop and refine written protocols and workflows to efficiently organize and process CBM data.
4. Develop community prioritized data products that inform planning and decision-making.

1.2 Background

In an initial flooding and erosion assessment by the Government Accountability Office (GAO) in 2003, 184 of 213 Alaska Native villages were identified as experiencing some level of erosion and flooding (GAO, 2003; GAO, 2009). In an updated GAO report published in 2022, 70 of 200 Alaska Native communities are said to experience "significant environmental threats" from hazards such as erosion, flooding, and permafrost thaw (GAO, 2022). The shift in intensity of the threats between these two reports reflects the fact that recent environmental shifts likely driven by global climate change are leading to increased infrastructure damage and pose health risks to rural coastal communities (Melvin et al., 2017). Historically, Indigenous communities lived nomadic lifestyles and moved with their resources (Dinero, 2005; Pearce et al., 2015). Since the introduction of permanent residencies, this is no longer an option. In addition, Alaska Native communities are disproportionately affected by the negative impacts of climate change (Maldonado et al., 2014; Pearce et al., 2015; Wildcat, 2013). Communities that are closely tied to the land for subsistence and traditional food, commercial livelihoods, and cultural practices, such as the remote Alaska Native communities along the coastline of Bristol Bay, have much at stake in the face of rapid environmental change (Billiot & Mitchell, 2019; Jones, 2019; Maldonado et al., 2014; Pearce et al., 2015; Wildcat, 2013). The combination of these factors introduces unique challenges to closing these data gaps.

With a lack of a designated hazard mitigation agency in Alaska, there is an increasing need for multi-stakeholder collaboration, local datasets for self-advocacy, and funding proposals to support planning and mitigation in these underrepresented communities. One such agency working to fill these data gaps is the Alaska Division of Geological and Geophysical Surveys Coastal Hazards Program (DGGS). The DGGS engages in ongoing investigations that focus on understanding how the coastline has evolved and how it responds to hazardous events and long-term changes (DGGS, n.d.). The DGGS works to foster scientific partnerships that improve the quality and quantity of coastal data that are necessary to fuel informed decision-making throughout the State (Overbeck et al., 2020).

The foundational research that culminated in this thesis began in 2016 with the start of the *Stakes for Stakeholders* CBM program (Buzard et al., 2019b; Glenn, 2022). *Stakes for Stakeholders* includes developing reciprocal partnerships with Tribal and City governments within rural coastal and riverine communities to implement accurate measurement protocols to map, quantify, and monitor erosion and flooding. This program has been led through DGGS, the University of Alaska Fairbanks Arctic Coastal Geoscience Lab (ACGL), and the Bristol Bay Native Association and is now active in over a dozen communities across western Alaska. Local partners are paid Tribal Environmental Coordinators as part of the Environmental Protection Agency's Government Assistance Program (GAP; ANTHC, 2016). To generalize the application of this CBM program, environmental coordinators will be referred to as environmental observers from this point onwards. This thesis highlights the collaborative work of the ACGL and the environmental observers in the Bristol Bay region.

1.3 Study Sites

This study focuses on two communities in Bristol Bay (Figure 1.1). Dillingham, a community of over 2,000 people (Alaska Demographics, n.d.) located at the mouth of the Nushagak river, and Chignik Bay, a community of around 44 year-round residents located on the southeastern side of the Alaska Peninsula in the Gulf of Alaska (GOA; Alaska Demographics, n.d.).

Located on the southwestern shores of Alaska, Bristol Bay encompasses 103,600 km^2 and houses one of the largest salmon fisheries in the world (UTBB, n.d.). Bristol Bay contains 31 Federally recognized Tribes composed of Yup'ik, Dena'ina, and Alutiiq people (UTBB, n.d.). The region is thought to have been first occupied by Siberian peoples crossing the Bering land bridge and waters 11,500 years ago, and perhaps longer (Waters & Stafford, 2013). These Indigenous communities have stewarded lands and waters for millennia (Giddings, 1960). Russian settlers date back to the late 1700s, followed by American settlement after being purchased from Russia in 1867 (LOC, n.d.). Two years after Alaska's purchase, the first cannery was established in Bristol Bay (Clark et al., 2006). The rise of canneries introduced western styles and a western economy (NPS, n.d.). It also introduced diseases such as the Spanish flu of 1918 that devastated Native Alaskan populations (NPS, n.d.; Troll & French, 2021). To this day, canneries have influenced socioeconomic systems and Indigenous traditions throughout southwest Alaska (Clark et al., 2006; Troll & French, 2021).

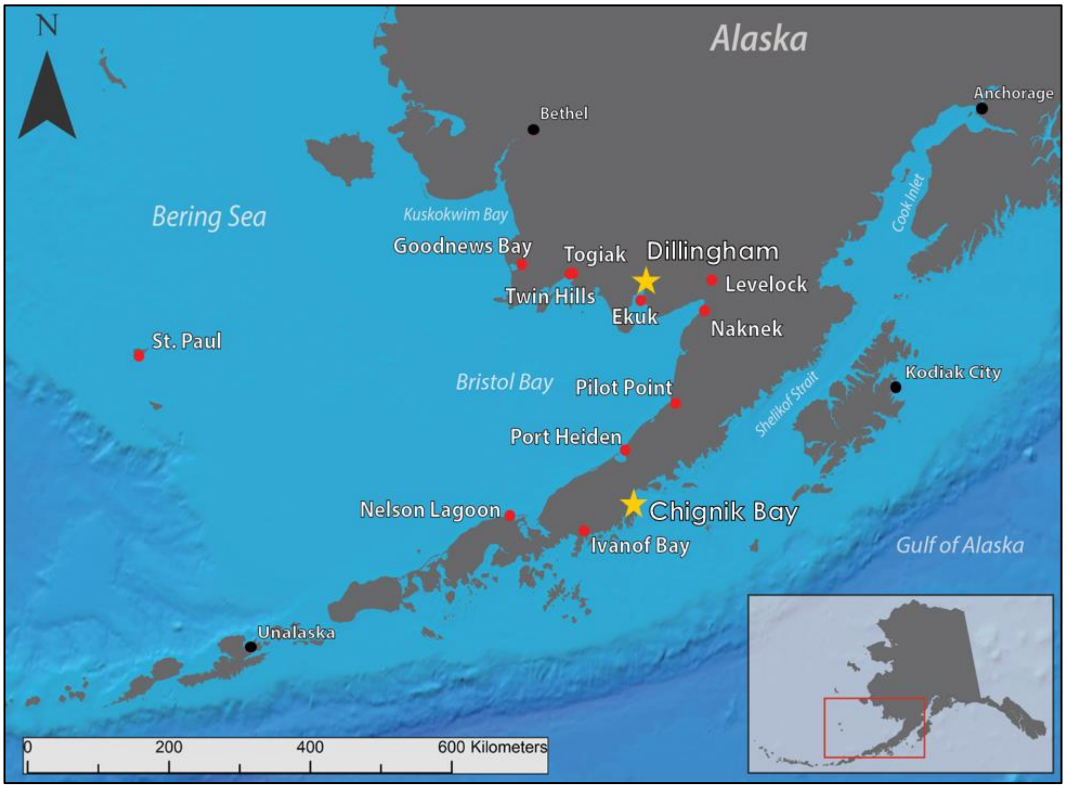

Figure 1.1 Map of CBM Sites in Bristol Bay and the Gulf of Alaska. Gold stars represent study sites, Red circles indicate communities participating in a community-based monitoring program with the Arctic Coastal Geoscience Lab (ACGL), and black circles represent regional hub communities.

Bristol Bay is a tide-dominated environment with semidiurnal tides ranging from 2 m at the mouth of the bay to more than 5 m at its head in Dillingham (Wise et al., 1987). Having an inverse relationship with the tides, wave energy is greatest at the mouth of the bay, near Nelson Lagoon, and grows weaker as it travels to the head, near Dillingham (Wise et al., 1987). With the Pacific current's warm intrusion moving through the Aleutian Islands and cutting through the bay's mouth, the region is a catcher's mitt for cyclonic storms (Sharma et al., 1972). This produces extreme storm events with strong winds and large waves that can reach up to 9 m at some locations (Wise et al., 1987). These factors combine to create significant storm events that can last days (Bogardus et al., 2021; Buzard et al., 2020).

The GOA is a mixed energy system dominated by strong storms (Stabeno et al., 2004). The terrain around the coastal GOA causes storms in the region to linger, even in the later stages of their lifecycles (Wilson & Overland, 1986). In the western GOA the Alaskan Stream, driven by wind and freshwater runoff, controls circulation along the shelf (Stabeno et al., 2004). This circulation in addition to complex bottom water topography, results in a highly productive coastal zone, promoting larvae dispersal and the introduction of ocean waters to juvenile salmon (Hermann et al., 1996; Napp et al., 1996).

The coastal geology of the two study sites is very different. In Bristol Bay the area is primarily made up of unconsolidated sediments consisting of glacial drift, alluvium, and lacustrine sediments with limited areas of exposed rock (Sharma et al., 1972; Wilson et al., 2015). In the western GOA, unconsolidated surficial sediment is composed of mostly glacial drift, marine deposits, and alluvial fan and floodplain deposits with the most prominent geology being rugged and sharp coastlines composed of a mixture of solid rock and loose sediment (Riehle et al., 1977). Both sites may experience tectonic and isostatic uplift or subsidence, which can influence local erosion rates (DeGrandpre & Freymueller, 2019; Kaufman & Manley, 2004). Both Bristol Bay and the GOA communities are located in a region that is tectonically active on the Aleutian Megathrust subduction zone. Bristol Bay communities are oriented away from the main fault while the GOA communities are directly facing the main fault, making them more susceptible to these tectonically driven hazards (Pulpan & Kienle, 1979; Rogers, 1977).

Chapter 2 Methods

Details of the methods and process in this manuscript are spread across four objectives. These objectives are separated into three sections: 1) community engagement 2) baseline datasets and CBM sites and 3) CBM workflows, protocols, and data products.

2.1 Community Engagement

To develop sustainable and reciprocal partnerships with local partners, annual site visits were carried out to establish CBM sites, conduct coastal topographic surveys (Figure 2.1), stake-ranging and time-lapse camera site maintenance (Figures 2.2 & 2.3), and training. These annual trips served to strengthen the relationships with participating communities while allowing for the collection of baseline and repeat topographic data at a high spatial and temporal resolution. Community meetings held during site visits were a valuable way to interact with the communities. Community meetings hosted by environmental observers and Tribal leaders were events that gathered residents to guide CBM activities and provide a platform for knowledge exchange. These meetings often took the form of a cookout or potluck to encourage greater participation and a less formal atmosphere. ACGL scientists shared knowledge of operating professional surveying equipment and erosion monitoring methods while local environmental observers and other participants shared long-term observations and stories of past impacts and extreme weather events.

Between visits, the local environmental observers gather shoreline data and maintain monitoring sites. Biannual teleconference meetings are held with each community to provide updates, discuss site visits, and gain feedback on the program and the data products. This feedback was used to revise data products to be included within a comprehensive hazard assessment report. The community participants often provided updates on the recent local environmental conditions (e.g., large storm impacts), monitoring activities, and technical issues such as camera maintenance. These meetings also opened the conversation to discuss new areas of concern. Figures 2.1, 2.2, 2.3 outline the workflow for the described processes.

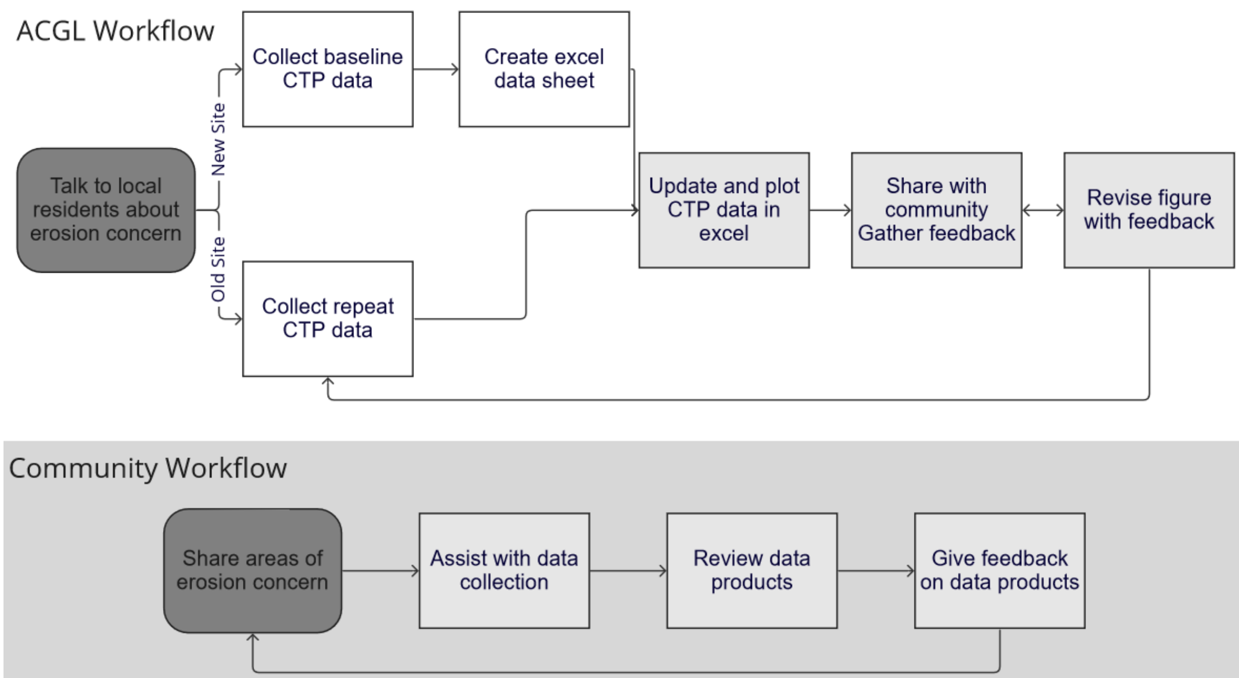

Figure 2.1 Process of coastal topographic profile (CTP) data collection, data product creation, and revision laid out in order of operation for both lab (top) and community (bottom) workflows.

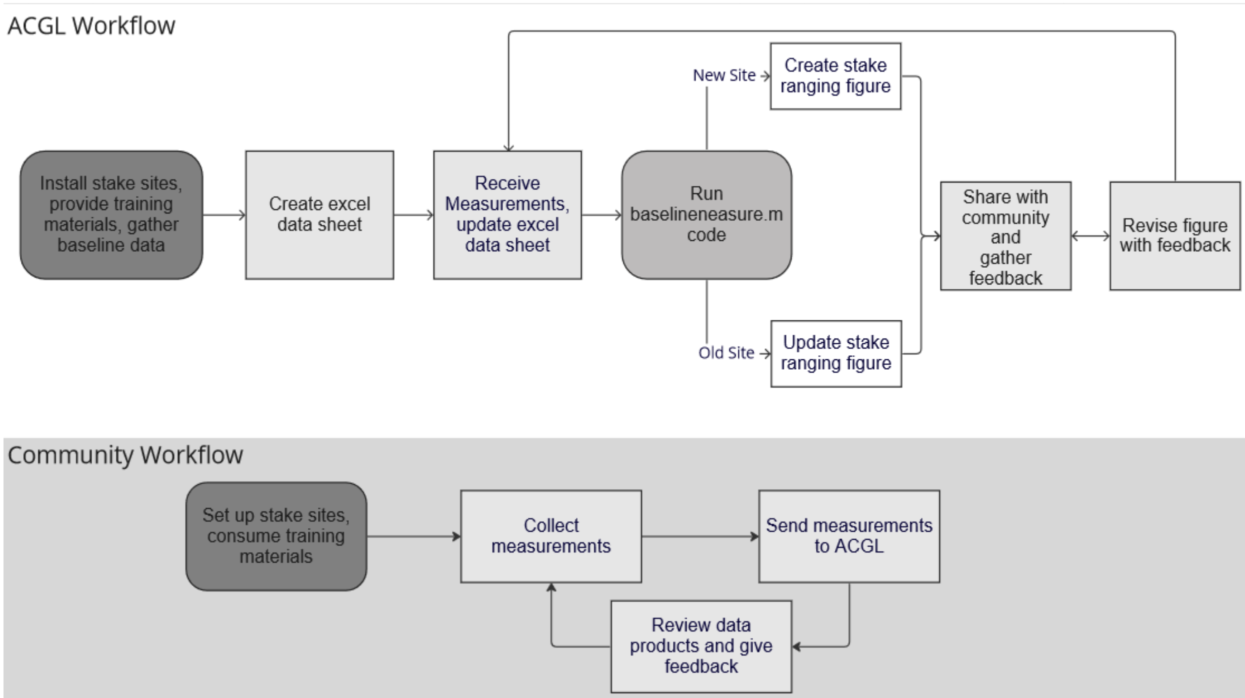

Figure 2.2 Process of stake ranging site installation, data collection, data product creation and revision laid out in order of operation for both lab (top) and community (bottom) workflows.

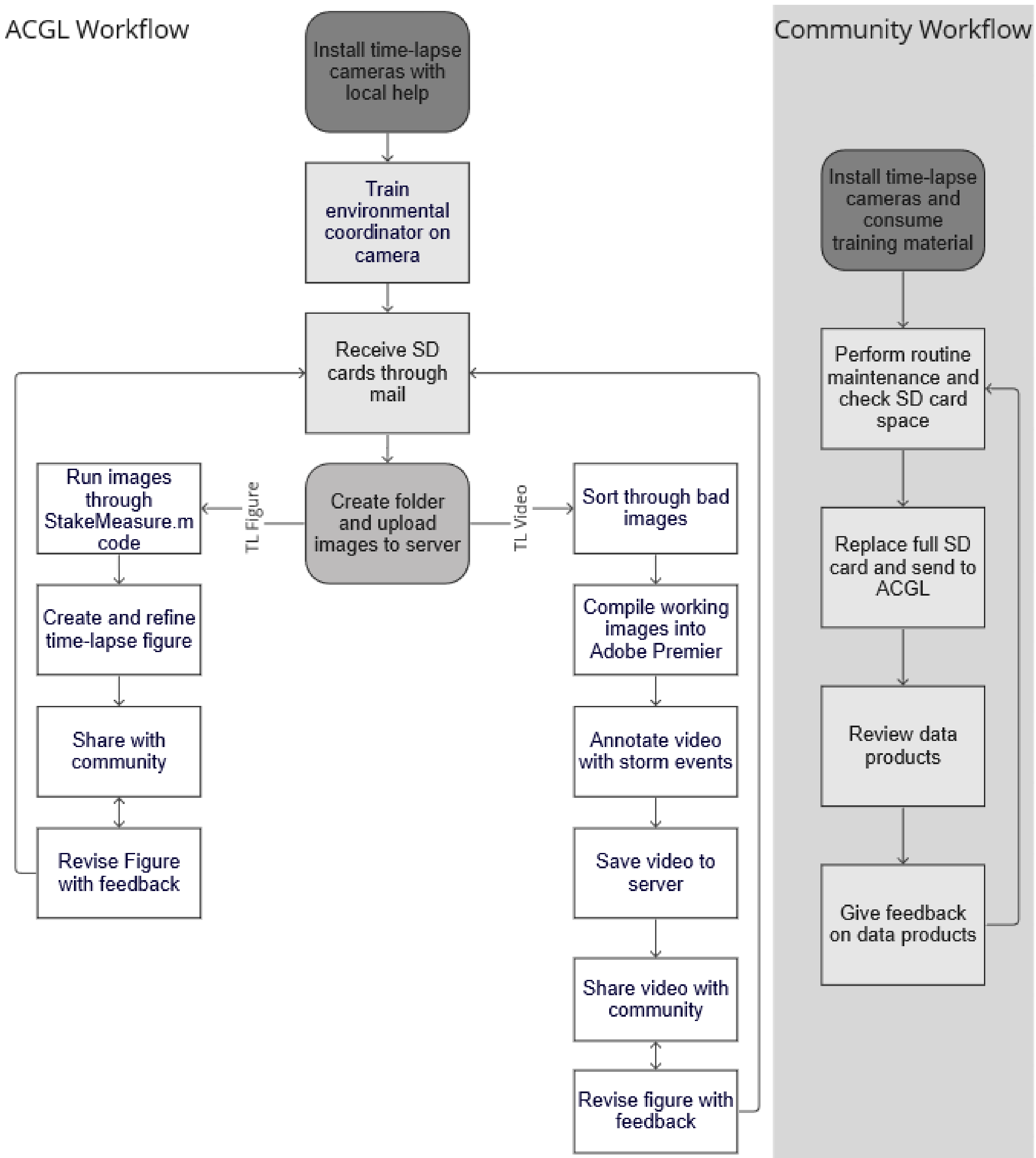

Figure 2.3 Process of time-lapse camera site installation, data collection, data product creation, and revision laid out in order of operation for both lab (left) and community (right) workflows.

2.2 Baseline Datasets

ACGL scientists, environmental observers, and other participants carried out baseline coastal topographic surveys and maintenance on monitoring sites. Coastal topographic surveys were collected with a Trimble R8s, real-time kinematic-global navigation satellite system (RTK-GNSS). Cross-shore profiles were collected with the RTK system across the shoreline fronting the community with greater spatial resolution at each of the monitoring sites. Profile locations were chosen based on the presence of infrastructure; changes in sediment type or slope; and/or areas of local concern. RTK points representative of shoreline features (e.g., vegetation lines, changes in sediment, and water lines) were collected along each profile (Figure 2.4). Once the baseline dataset is collected, repeat surveys are carried out allowing for a comparison between previous years to show the change in beach shape over time. Raw data was processed by the ACGL using Trimble Business Center, MATLAB, and Microsoft Excel.

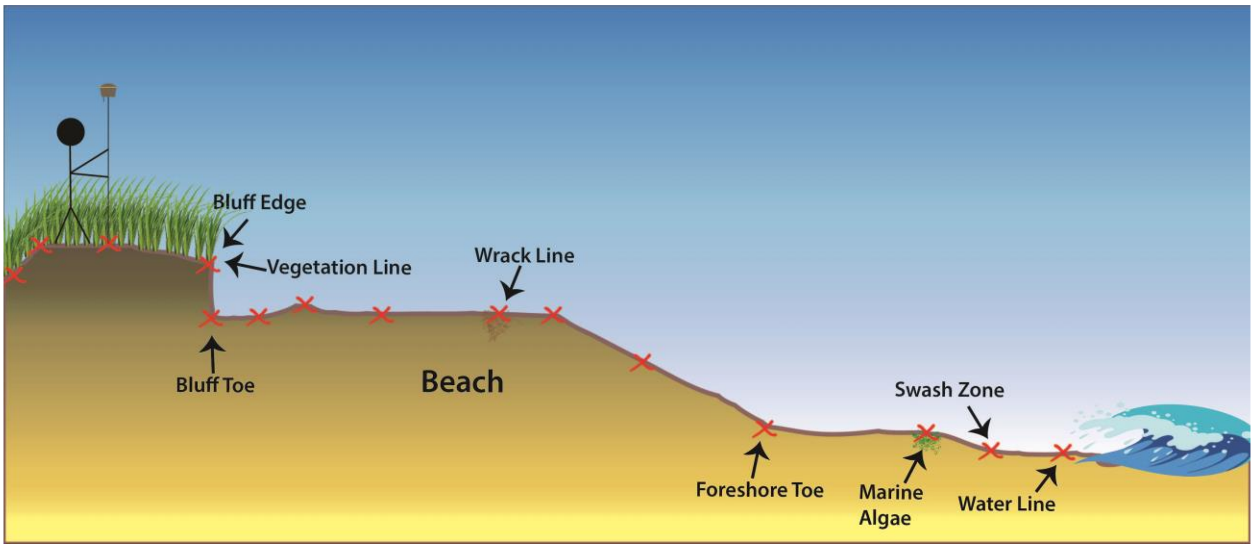

Figure 2.4 Example diagram of coastal topographic profile collection process. The user walks in a straight line (profile) perpendicular to the shoreline collecting RTK-GNSS points represented by red x's along the transect. The red x's are representative of changes in topography, vegetation, sediment type, and beach zones.

2.3 CBM Workflows and Protocols

Written protocols and workflows were developed by the ACGL to document the *Stakes for Stakeholders* CBM methods. Documents outline the various tasks and processes for data collection, processing, and management (Buzard et al., 2019a; Buzard et al., 2019b; Buzard et al., 2020). Protocols also explain how to use MATLAB codes to process stake-ranging and timelapse camera data. For example, the CBM Site Selection protocol describes the monitoring site selection process and data collection instructions (see Appendix A). Using this protocol, ACGL staff collaborate with community members to determine a monitoring site location. These protocols will continue to be updated by the ACGL to meet community needs. Some updates may include additional instructions for new equipment and/or a change in data collection methods.

2.4 Monitoring Sites

Stake-ranging data collection utilizes a tape measure and a fixed point in an area fronting an eroding feature (wooden stake, utility pole, corner of building). For this research, these fixed points will be referred to as stakes. Multiple transects with 2-3 stakes are installed (Figure 2.5). The data collector measures out from the seaward stake to the eroding feature and records the distance at each transect.

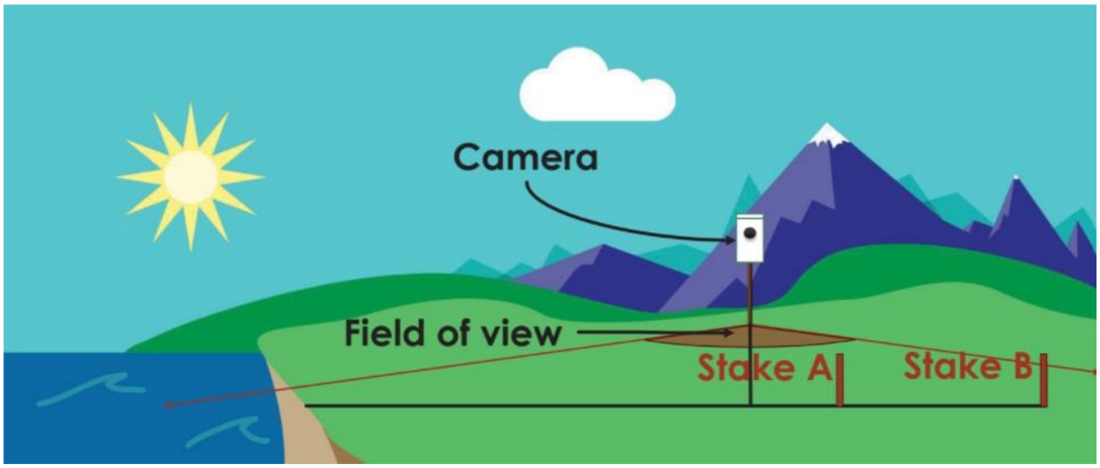

Figure 2.5 Example of time lapse camera site set up. Stakes A and B are installed near the eroding feature and make up a single transect (i.e., a line parallel to the eroding feature). A time lapse camera is installed a distance back and facing the transect to capture the two stake locations and the eroding feature in the swath of the image. Cameras take pictures hourly, and local environmental observers carry out maintenance and send in SD cards when full (from Buzard et al., 2019a).

The location of monitoring sites were chosen based on community concerns and observations of erosion such as areas fronting important infrastructure and transportation routes. Once the staked transects and camera posts are installed sites were surveyed with the RTK-GNSS and cross-shore profiles were carried out along the staked transects with RTK points taken on all the stakes and camera post. The local environmental observer and assistants visited each site two to three times per year to collect measurements and before and after extreme storm events. One of the data collection times was during the ACGL site visits. This allowed for the ACGL to provide additional training for new observers or assistants and contribute towards the site maintenance such as replacing cameras and stakes which were brought in as part of the field work.

CBM data including the transect and stake number and distance to the eroding feature is sent to the ACGL via email or postal mail. The ACGL then inputs those measurements into an Excel spreadsheet and utilizes a MATLAB code to calculate and plot measured changes (Buzard et al., 2019b). One example of a stake site is the Chignik Bay medical clinic monitoring site (Figure

2.6). This site was chosen by the local Tribal Council and is locally relevant given that the new multimillion dollar medical clinic sits on an eroding shoreline and is the only medical provider in the area.

Figure 2.6 (Left) Chignik Bay environmental observer (Ed Krauss) and ACGL student (Jessie Christian) collecting stake ranging measurements at the Chignik Bay medical clinic erosion monitoring site. (Right) Stake A at transect 1, positioned in front of the Clinic on unconsolidated sediment.

Time-lapse cameras were installed at stake-ranging sites. Protocol documents support local data collectors in their operation and maintenance (see Appendix B & C). Time-lapse camera data collection includes the camera, a tape measure, and a wooden or metal post. The camera is mounted perpendicular to the transect with at least two stakes and the eroding feature in the frame (Figure 2.5). These images are used to measure erosion and document the local environmental conditions surrounding severe erosion events (Buzard et al., 2020). In addition to using the images to calculate erosion rates, time-lapse videos were produced to support the visualization of coastal processes and drivers such as changes in sea-ice conditions and wave action. Maintenance included replacing batteries and SD cards approximately every 6-months. SD cards were sent in by local partners via postal mail along with stake-ranging measurements. After processing, results were shared with the community via email, teleconference meetings, or during in-person site visits (Figure 2.3).

2.5 Community-Prioritized Products

Products that focus on local priority areas were developed by the ACGL with data collected by environmental observers. This included a variety of graphs, maps, timelapse videos, and a draft hazard assessment report. The drafted hazard assessment report is a comprehensive document that outlines the geologic and oceanic settings, coastal hazards, products and assessment tools, and risks to infrastructure in each community. These reports were requested by communities to provide accurate and up-to-date information and data products that can be included in their FEMA required Tribal Hazard Mitigation Plans as well as funding proposals, engineering reports, and other planning documents. The hazard reports are meant to provide a go to source of information for communities including both past and current activities.

As part of effectively addressing local priorities and providing effective data products and information an assessment tool was drafted to outline the contributing social and environmental factors that contribute to the efficacy of the program. Defining the contributing factors of CBM programs contributes to a better understanding of how to run these programs and effectively troubleshoot key issues in communities where methods are not working (Huntington, 2011). I developed a literature-based 3-point rubric, modeled after Larson and Spellman (2017), to define the environmental and social factors influencing the effectiveness of CBM (Tables 2.1 & 2.2; e.g., Berkes et al., 2007; Conrad & Daoust, 2008; DeVries et al., 2016; Pollock & Whitelaw, 2005; Sharpe & Conrad, 2006; Stone et al., 2014).

To evaluate the environmental factors that affect the success of the *Stakes for Stakeholders* program, I examined the physical features defined in the coastal hazard literature, learned through our prior 6-years of work, and from previous feedback from environmental observers (Table 2.1; e.g., Berkes et al., 2007; DeVries et al., 2016; Stone et al., 2014). To determine social factors that enhance or limit the success of *Stakes for Stakeholders*, I focused on the relationships between the ACGL and the communities that support participation and communication feedback loops defined in the CBM literature (Table 2.2; e.g., Conrad & Daoust, 2008; Pollock & Whitelaw, 2005; Sharpe & Conrad, 2006; Stone et al., 2014). I then evaluated two example sites to test the rubric and look for areas of program improvement.

The environmental rubric has five contributing factors including *vegetation density, safety of the data collector*, *measurement accuracies*, *accessibility*, and *cause for concern* (Table 2.1). The *cause for concern* factor refers to the social ties to the land and the type of infrastructure located there. For example, power, sanitation, and emergency access infrastructure can increase the need for CBM. *Measurement accuracies* refers to the *definition of the eroding feature* (Table 2.1). For example, if there is a cracked bluff, this can cause confusion between data collectors and may influence the accuracy of measurements.

The social rubric has six contributing factors including *human working capacity*, *turnover time*, *support from the ACGL*, and *relationships between the ACGL staff and community partners* (Table 2.2). *Human working capacity* refers to the pool of data collectors needed to carry out the work. For example, if there are not enough people to do the work both in the communities (e.g., Tribal staff) and at the ACGL (e.g., students and staff), the program will not have the capacity to run efficiently (Johnson et al., 2016). *Turnover time* refers to the hand-off from one participant to another. Turnover in rural communities and among students is common and when one participant leaves, the time to find and train another person to do the job can halt progress. This may also cause discrepancies in the measurements between different data collectors as well as the management of the data within the lab. The *relationships between the ACGL staff and community partners* are critical to retain a monitoring program. Many key aspects must be achieved to create and maintain this relationship. One way to build these relationships is by seeking guidance from environmental observers to focus on locally relevant problems at a scale that combines the interests of local communities and research partners (Eicken et al., 2021).

Table 2.1 Rubric for assessing contributing environmental factors of a monitoring site with supporting literature.

Contributing Factors	Description	Efficacy Ranking 3	2	1	Supporting Literature
Vegetation density	Vegetation density can affect accessibility to the monitoring site	Vegetation density is low and easily maneuverable by environmental observer	Vegetation is moderately dense and requires good maneuverability skills by environmental observer	Vegetation density is high and poses a risk to environmental observer	*DeVries et al. 2016*
Clearly defined eroding feature	How pronounced an eroding feature is can affect accuracy of repeat measurements	Highly defined eroding feature does not affect accuracy of measurements amongst environmental observer	Somewhat defined eroding feature, can cause confusion amongst different environmental observer	Undefined eroding feature causes serious confusion for environmental observers, and affects data accuracy	*Berkes et al. 2007*
Accessibility and Safety	Accessibility is key for collecting data. The site must be accessible and safe	Year-round accessibility to all monitoring locations and safe access for environmental observer	Partial year-round accessibility to some monitoring locations, some inaccessible during parts of the year. Somewhat safe for environmental observer access	Accessibility limited year-round to all monitoring locations and site raises safety concerns for environmental observer	*DeVries et al. 2016*
Noticeable changing shoreline	A noticeably changing shoreline can increase the desire for CBM efforts. Different types of sediment can affect erosion rates	Noticeable active erosion; Highly erosive sediment types (e.g. silts and sands)	Somewhat noticeable erosion; Moderately erosive sediments (e.g. coarse sands, clays)	No noticeable erosion; Low erosive sediments (e.g. gravel, bedrock)	*Berkes et al. 2007*
Cause for concern	Position of critical infrastructure, residences, and other important features contribute to the desire and need for CBM	High risk infrastructure or feature	No immediate concern for infrastructure or features, though may be some in the future	No concern for infrastructure or feature	*Stone et al. 2014*

Table 2.2 Rubric for assessing contributing social factors of a monitoring site with supporting literature.

Contributing Factors	Description	Efficacy Ranking 3	2	1	Supporting Literature
Human working capacity	Monitoring programs require adequate personnel time and capacity for the program to continue.	An ample number of participants consistently willing and able to collect data	Some people consistently willing and available to collect data	Limited number of participants consistently willing and able to collect data	*Pollock & Whitelaw, 2005; Sharpe & Conrad, 2006; Conrad & Daoust, 2008*
Personnel turnover transition	Turnover and quality of transition from one environmental observer to another - or scientist to another - dictates how smoothly the program will run.	Good communication between outgoing and incoming environmental observers or scientists causes no challenges to smooth transitions	Some communication between outgoing and incoming environmental observer s or scientists causes some challenges to smooth transitions	Limited communication between outgoing and incoming environmental observers or scientists causes challenges during personnel turnover creating significant data gaps and breaks in relationships	*Stone et al., 2014*
Training	Training provided by scientists is needed for local environmental observers to fulfill their role as data collectors and visual observers. The accuracy in which data is collected is also determined by this factor. Written and digital training support materials allow for successful data collection year-round.	Training materials are easily accessible, understandable, up to date, and locally relevant to environmental observers	Training materials are somewhat accessible, mostly understandable, outdated, and somewhat locally relevant to environmental observers	No training materials are available; training is provided on-site, but no further support materials are provided to environmental observers	*Pollock & Whitelaw, 2005; Stone et al., 2014*

Table 2.2 Continued. Rubric for assessing contributing social factors of a monitoring site with supporting literature.

Contributing Factors	Description	Efficacy Ranking 3	2	1	Supporting Literature
Participation of community	Optimal participation by environmental observers includes attending bi-annual meetings, collecting measurements, maintaining level of training, and the desire to continue the monitoring program.	Able to attend all meetings, upkeep training level, provide consistent and accurate measurements, and have a strong desire to continue monitoring	Able to attend some meetings, somewhat upkeep training level, provide few and somewhat accurate measurements, and have some desire to continue monitoring	Unable to attend meetings, no upkeep of training level, provides very limited and inaccurate measurements, has no desire to continue monitoring	*Pollock & Whitelaw, 2005; Sharpe & Conrad, 2006; Conrad & Daoust, 2008*
Support from Scientists	Support from scientists includes site visits, bi-annual meetings, structured and on-call communication (e.g., newsletters, email updates, etc.), and delivery of refined data products.	Able to provide annual site visits, holds bi-annual meetings, provides ample structured and on-call communication, provides and updates protocols and training material, and delivers updated data products as needed by the community	Able to provide a site visit, holds some program meetings, provides some structured and on-call communication, outdated protocols, and training material, and delivers some data products back to the community	Unable to provide a site visit, may hold some program meetings, provides limited communication, outdated protocols, and training material, and delivers few data products back to the community	*Conrad & Daoust, 2008; Stone et al., 2014*
Relationship between parties	Relationships built on trust, respect, and comfort are crucial for the integrity of a program.	Strong relationship between scientists and environmental observers. Great effort put into building a trusting and respectful environment. High comfort levels around each other	Somewhat functioning relationship between scientists and environmental observers. Some level of effort put into building a trustful and respectful environment. Some degree of comfort around each other	Limited relationship between scientists and environmental observers. Limited time dedicated to developing a trustful or respectful environment resulting in less comfort around each other	*Conrad & Daoust, 2008; Stone et al., 2014*

Chapter 3 Results

Results of this study are presented in parallel order as outlined in the objectives and methods: 1) community engagement 2) baseline datasets and CBM Sites and 3) CBM workflows, protocols, and data products.

3.1 Community Engagement

Partnerships with the ACGL and communities began in 2016 through *Stakes for Stakeholders* and have since expanded to over a dozen other locations in Bristol Bay. Introductions to new participants from both the ACGL and communities took place over teleconference meetings and in-person site visits. In-person site visits allowed relationships to be further developed, local coastal hazard priorities to be identified in the monitoring and data products, and communication across participants strengthened. Initial conversations between community members, environmental observers, and ACGL scientists allowed for the selection of monitoring site locations and later towards their establishment, operation, and maintenance. For example, in Chignik Bay, local input indicated that a portion of the main road that leads to the airport had been recently eroding making it a good candidate for a monitoring site.

Environmental observers facilitated formal and informal meetings between ACGL scientists and community members with the most success occurring during public cookouts or other type of potluck settings. An example of this is the *Chignik Bay Climate Action Symposium* held in May 2022 (Figure 3.1). The meeting was held in the community center building and was coordinated by the local environmental observers and the ACGL. Flyers were put up weeks in advance to give ample time for community planning. Large prints and poster sized 11x17 maps depicting CBM sites and other datasets were prepared by the ACGL and dispersed to attendees. The meeting was potluck styled and a raffle was set up to bring in a wider audience. Tables were arranged in a "u" shape to bring focus to the speakers and allow for open discussion. The food was set up in the back along with the large print maps laid out on tables and hung up on walls. Breaks were taken between speakers and discussion time was weaved into each presentation. There were approximately 40 attendees and the meeting led to several important outcomes including new funding support and collaborations.

A great deal of local information and knowledge was also gained through impromptu conversations between the ACGL and curious residents. It was found that wearing bright survey vests while collecting data around the community helped residents identify ACGL scientists easily, and when accompanied by the local environmental observer(s), many would engage in conversation. Community members passing by were typically enthusiastic and willing to share their knowledge with ACGL scientists, giving valuable insight on points of mutual interest. These informal conversations led to new information sharing, such as high-water level locations, new areas of erosion, and other accounts of environmental change and the local response. Another factor that promoted this type of communication was the duration of the ACGL scientists stay in communities. Site visits typically lasted at least four full days, usually closer to a full week. This provided ample time to conduct field work tasks as well as engage with residents through the formal and informal meetings and conversations.

Figure 3.1 Image of the *Chignik Bay Climate Action Symposium* in 2022. Participants included local residents, Tribal, State, and City, officials, as well as representatives from private engineering firms, government agencies, and academic institutions. Data products were shared with community members, including infrastructure maps, shoreline change maps, and CBM graphs and other visualizations.

3.2 Baseline Datasets and Community-Based Monitoring Sites

The ACGL and the environmental observers collected baseline and repeat data including RTK coastal topographic profiles, stake-ranging measurements, and timelapse camera photos. Data collection was concentrated around CBM sites providing data with high spatial and temporal resolution. Surrounding areas within the community were collected more broadly. The number of coastal topographic profiles collected varied due to the size of the area, location, and changes in beach characteristics (e.g., sediment type, general beach morphology). Three stake-ranging sites were established in each community. Time-lapse cameras were placed at stake sites where there were few obstructions (e.g., vegetation, infrastructure, topography). While calculating erosion rates using the timelapse imagery provides high-temporal resolution data, there are limitations as the code is sensitive and any shift in camera view can distort erosion calculations. In addition, there are some areas where cameras cannot be used due to vegetation overgrowth or repeat vandalism.

3.2.1 Dillingham

Dillingham is one of the longest-participating *Stakes for Stakeholders* communities with 6 years of CBM data. There are 3 sites including the sewage lagoon, peat meadow, and Kanakanak flats (Figure 3.2). For each site there were three staked transects (including the camera transect) and measurements were compiled and averaged across their three transects. Based on the average of the three site transects at the sewage lagoon there has been 19.2 m (63.0 ft) of erosion over the 6 years, equating to a rate of 3.20 m/yr (10.5 ft/yr) (Figure 3.3). At the peat meadows site there has been 6.09 m (15.0 ft) of erosion over 6 years, equating to a rate of 0.76 m/yr (2.50 ft/yr) (Figure 3.4). Kanakanak flats is a newer site that was installed in 2021 and during its two years of operation there has been 3.048 m of erosion at a rate of 1.52 m/yr (5ft/yr) (Figure 3.5). Time-lapse cameras were installed at each site and images were sent in by environmental observers approximately every 6-months. Photos were compiled into time-lapse videos, published on the ACGL YouTube channel, and sent to community partners via email or flash drive (Figure 3.6).

Dillingham has 40 coastal topographic profiles that were collected over the course of 6 years (Figure 3.7). These profiles are concentrated around CBM sites. Many of these profiles start at major roads, residences, and critical infrastructure. Repeat profiles at the CBM stake sites have been collected over time to measure the change in shoreline position (Figures 3.8, 3.9, 3.10). The sewage lagoon has 6 years of data showing around 25.0 m (82.0 ft) of shoreline retreat during that period, or approximately 4.12 m/yr (13.5 ft/yr) (Figure 3.8). The peat meadow has 6 years of data and has experienced about 2-3 m (6.56-9.84 ft) of shoreline retreat over that period, or 0.3-0.5 m/yr (0.98-1.64 ft/yr) (Figure 3.9). Kanakanak flats is a newer site with 1 year of data collection showing about 2 m (6.56 ft) of shoreline retreat (Figure 3.10). Comparing coastal topographic profile erosion rates with community measurement rates reveals similar values. For example, coastal profile 36 (Figure 3.8) shows an average erosion rate of 4.12 m/yr (13.5 ft/yr) and community stake ranging measurements at the same location shows 3.91 m/yr (12.8 ft/yr).

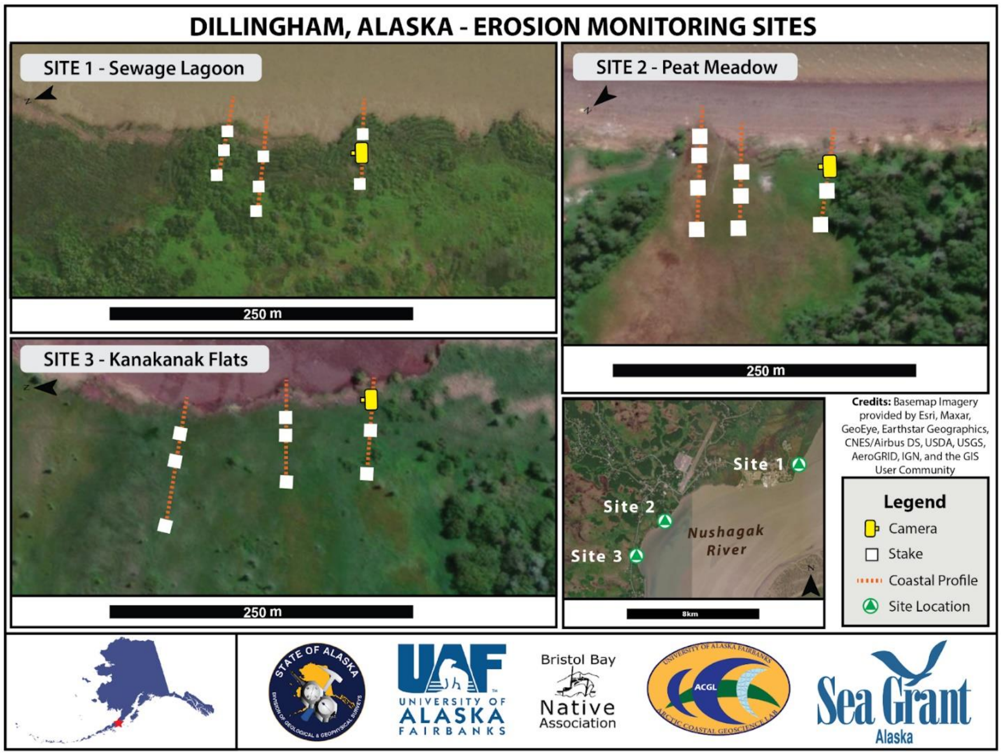

Figure 3.2 CBM site map in Dillingham, Alaska. Updated stake and camera locations are represented by the white boxes and the yellow rectangle, respectively. Coastal topographic profiles are represented by dotted orange lines.

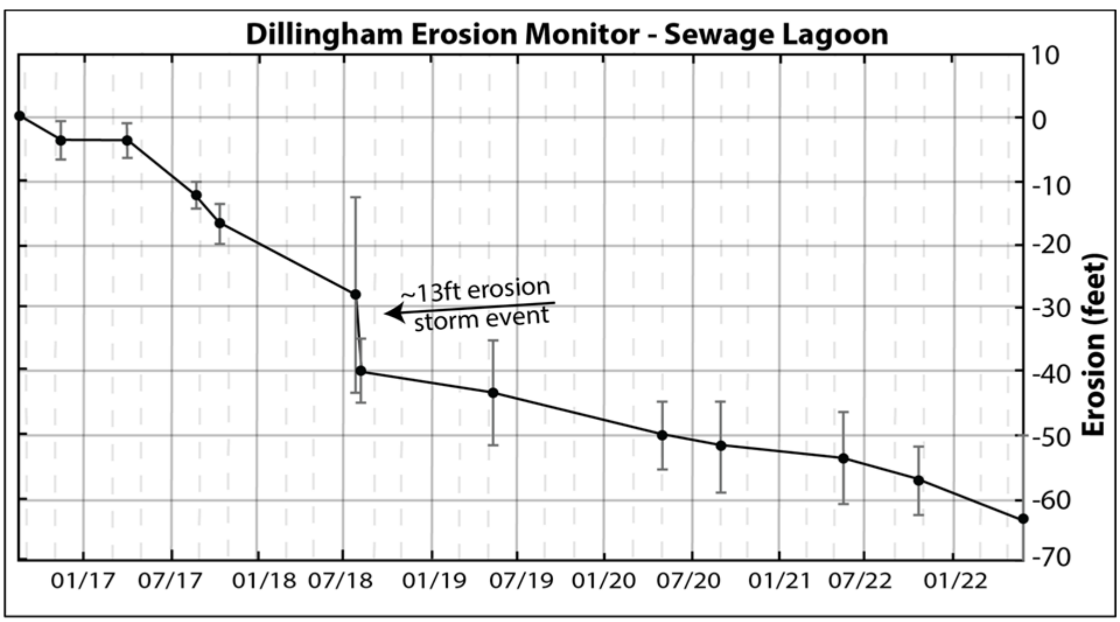

Figure 3.3 Averaged CBM stake site measurements at the Sewage Lagoon site in Dillingham, AK. Measurements were taken from 2016 to 2022 and are reported here in feet as they are delivered to community partners. The graph shows erosion distance over time. Notice the pre and post storm measurements in August 2018 that documented about 3.96 m (13 ft) of erosion in that single event.

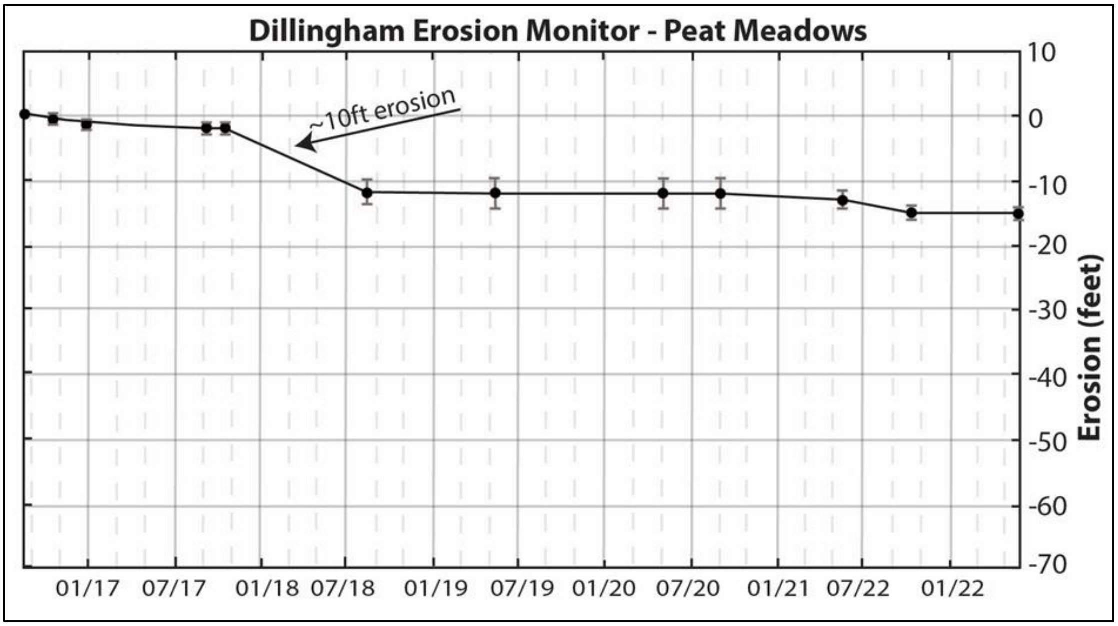

Figure 3.4 Averaged CBM stake site measurements at Peat Meadows site in Dillingham, AK. Data were taken from 2016 to 2022 and are reported here in feet as they are delivered to community partners. The graph shows erosion distance over time. The area has been relatively stable except for a sudden increase in 2018 with 3.05 m (10 ft) of erosion occurring over that year. Local observations indicate this increase in erosion was due to a series of extreme storm events.

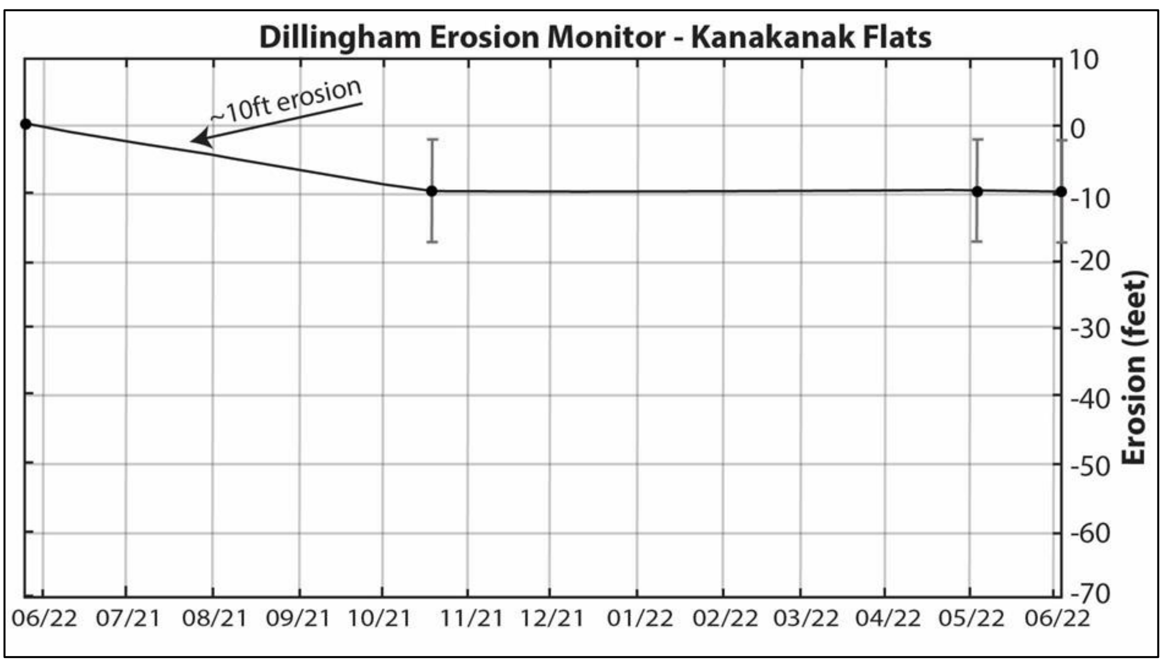

Figure 3.5 Averaged CBM stake site measurements at Kanakanak flats site in Dillingham, AK. Data were taken from 2021 to 2022 and are reported here in feet as they are delivered to community partners. The graph shows erosion distance over time. There was an increase in erosion around the year 2021, with 3.05 m (10 ft) of erosion occurring over 5 months.

Figure 3.6 Time-lapse picture and compiled video of the Sewage Lagoon stake site. Notice white stakes in background. Images taken at Dillingham sewage lagoon from May 2019 to November 2019 make up a revealing video that documents wave action and erosion resulting from a single storm event. (URL: https://youtu.be/M0zNXxNGhig).

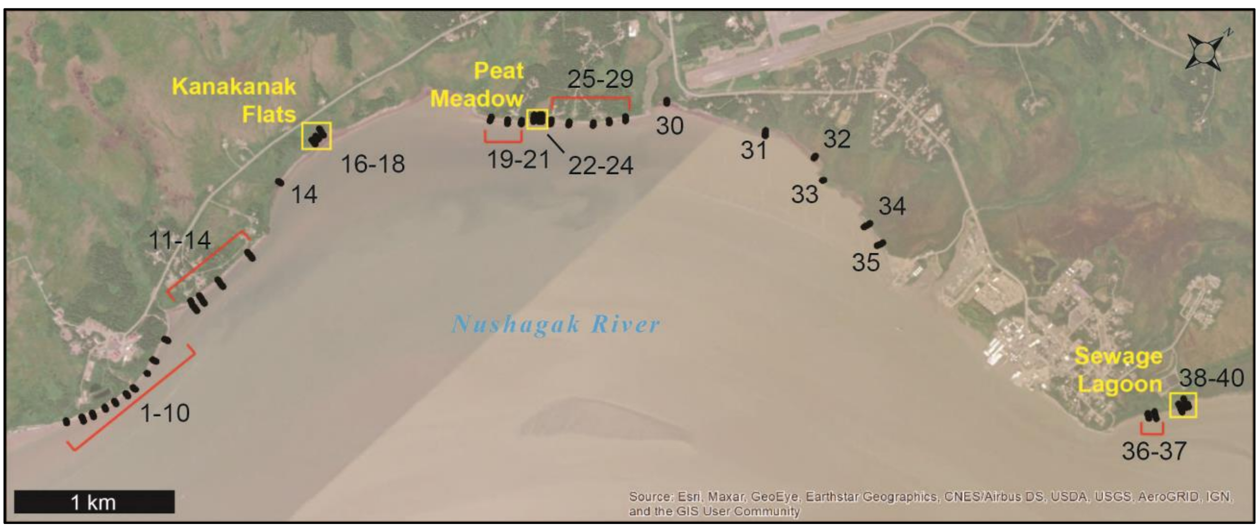

Figure 3.7 A total of 40 coastal topographic profiles were collected at Dillingham. Yellow boxes represent stake sites.

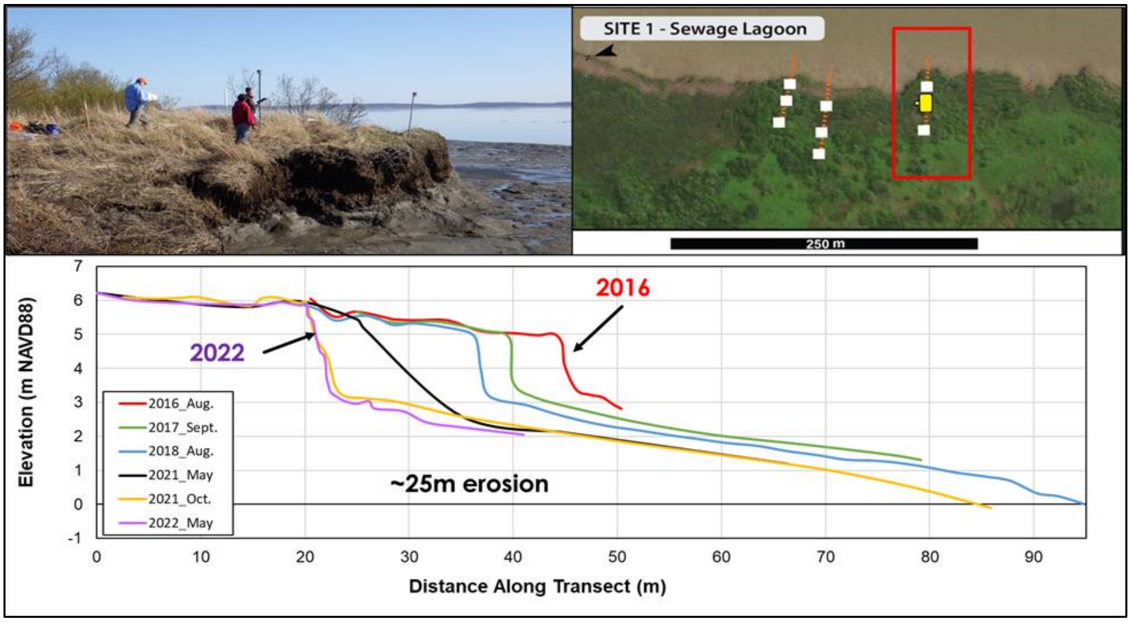

Figure 3.8 Coastal Profile 36 located at the sewage lagoon site in Dillingham, AK. (Top Left) On site image of the sewage lagoon site location. Environmental observer, Rene Roche, and ACGL scientists collecting coastal topographic profile at the location. (Top Right) Erosion monitoring site map for the Sewage Lagoon. The red box indicates which transect the coastal topographic profile was collected at. (Bottom) Data were taken from 2016 up to 2022. From 2016 (red) to 2022 (purple) there was approximately 25 m (82.0 ft) of erosion.

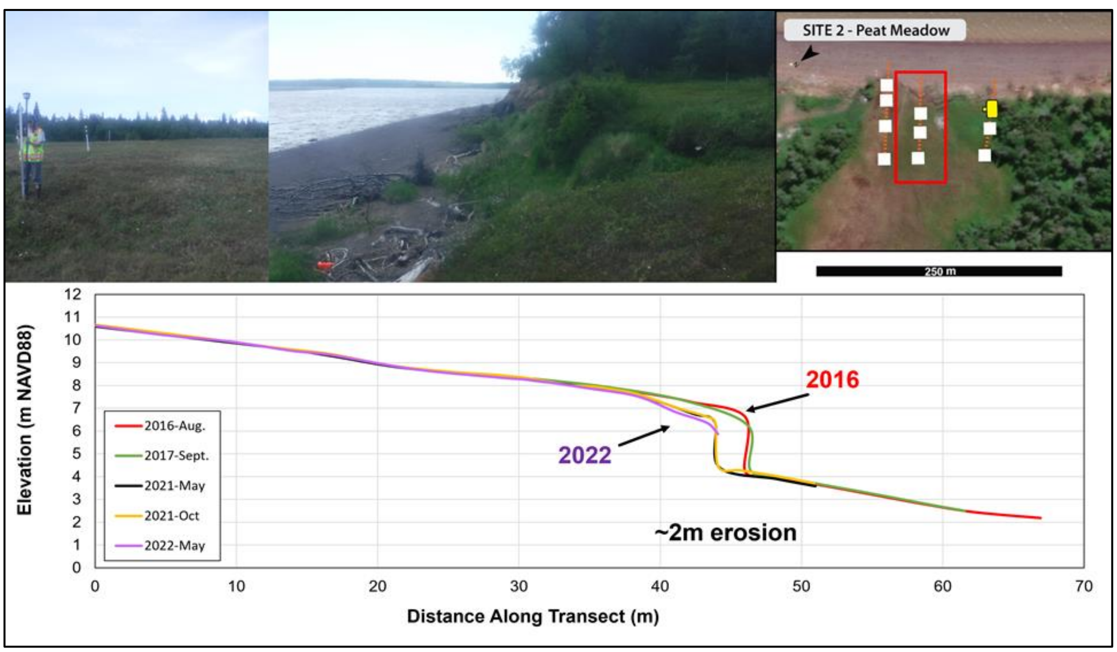

Figure 3.9 Coastal Profile 23 located at the peat meadow site in Dillingham, AK. (Top Left and Center) On site image of the peat meadows site location. (Top Right) Erosion monitoring site map for the peat meadows site. The red box indicates which transect the coastal topographic profile was collected at. (Bottom) Data were taken from 2016 up to 2022. From 2016 (red) to 2022 (purple) there was approximately 2 m (6.56 ft) of erosion.

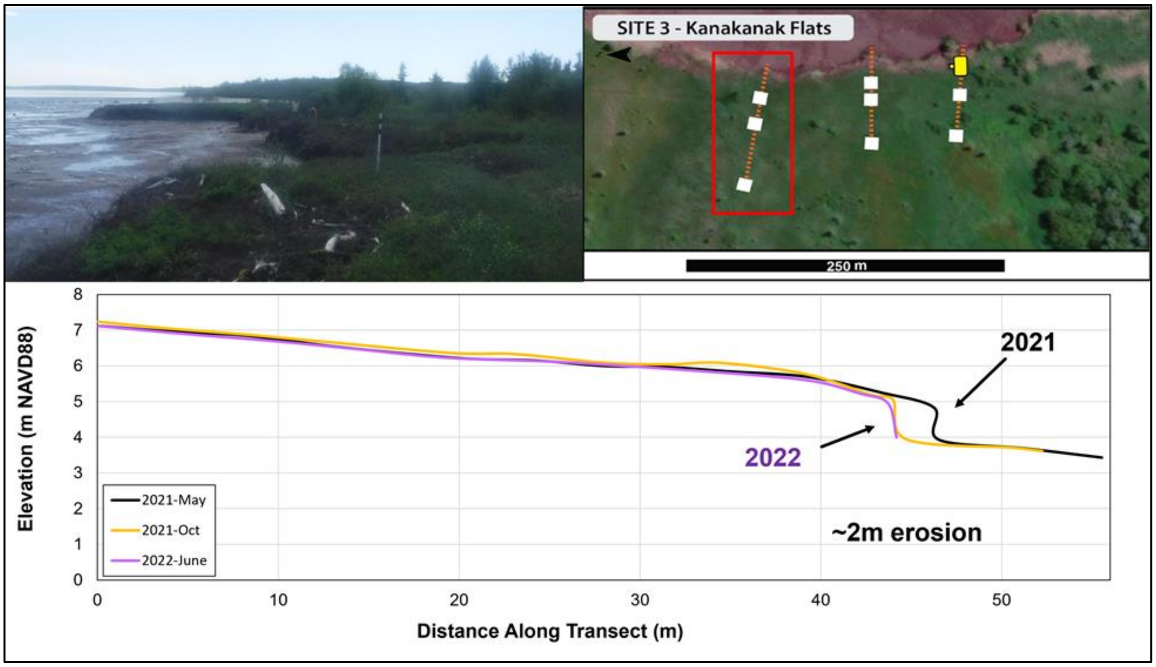

Figure 3.10 Coastal Profile 18 located at the Kanakanak flats site in Dillingham, AK. (Top Left) On site image of the Kanakanak flats site location. (Top Right) Erosion monitoring site map for the Kanakanak flats site. The red box indicates which transect the coastal topographic profile was collected at. (Bottom) Data were taken from 2021 up to 2022. From 2021 (black) to 2022 (purple) there was approximately 2 m (6.56 ft) of erosion.

3.2.2 Chignik Bay

Chignik Bay has participated in the *Stakes for Stakeholders* program for 4 years. There are 3 CBM sites: the airstrip, the medical clinic, and the Tribal office (Figure 3.11). The airstrip site has 4 stake transects and 1 camera. The average distance of erosion at the site was 0.65 m (2.13 ft) in 4 years equating to a rate of 0.16 m/yr (0.53 ft/yr) (Figure 3.12). The clinic site has 2 staked profiles with 1 camera. There was an average distance of erosion across the two transects of 0.3 m (1 ft) over 4 years equating to a rate of 0.08 m/yr (0.25 ft/yr) (Figure 3.13). It is important to note that the two transects at this site are very different in that one is positioned along an area of unconsolidated sandier sediments and the other is on rip rap with the shoreline armored by large boulders. These transects were installed to view the efficacy of the rip rap. The Tribal office site is new and only has baseline data. Time-lapse cameras were installed at each site. These images were sent to the ACGL and compiled into time-lapse videos, published on the ACGL YouTube channel, and sent via email or flash drive to the communities (Figure 3.14).

Chignik Bay has 33 coastal topographic profiles that were collected over the course of 4 years (Figure 3.15). These profiles cover the full extent of the road accessible areas of the community and are concentrated around residences, roads, and critical infrastructure. Repeat profiles at the CBM stake sites have been collected over time to measure the change of the shoreline position (Figure 3.15). Many of the coastal topographic profiles show relative stability due to the rockier composition of the sediment but erosion areas do exist. A representative profile taken near the clinic shows approximately 0.5 m (3.28 ft) of erosion over the course of 4 years validated by the CBM measurements (Figure 3.16).

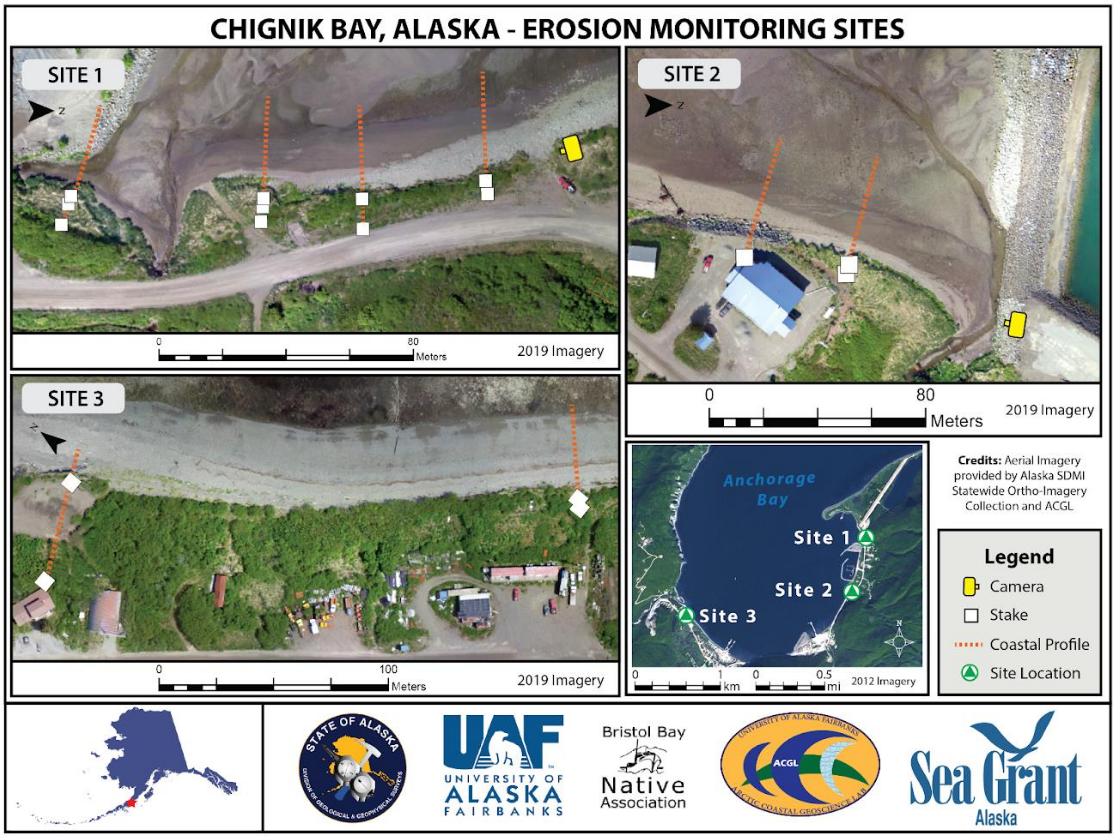

Figure 3.11 CBM site map in Chignik Bay, Alaska. Stake and camera locations are represented by the white boxes and the yellow rectangle, respectively. Coastal topographic profiles are represented by dotted orange lines.

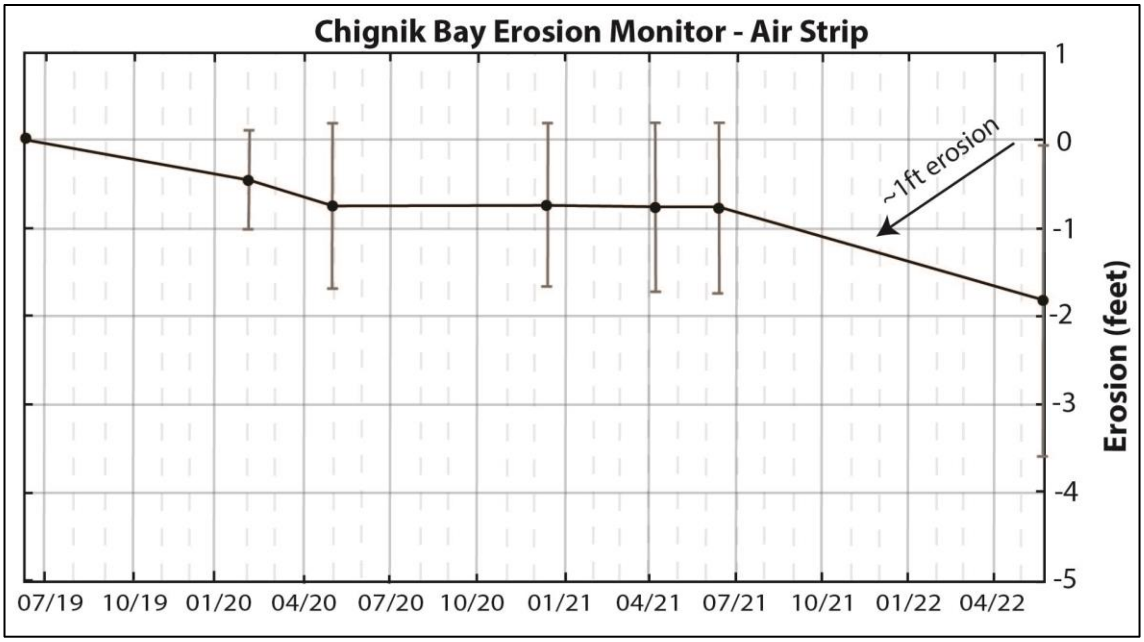

Figure 3.12 Averaged CBM stake site measurements at the air strip in Chignik Bay, AK. Data were taken from 2019 to 2022. Erosion rates are relatively consistent. There was an increase in erosion from June 2021 to June 2022.

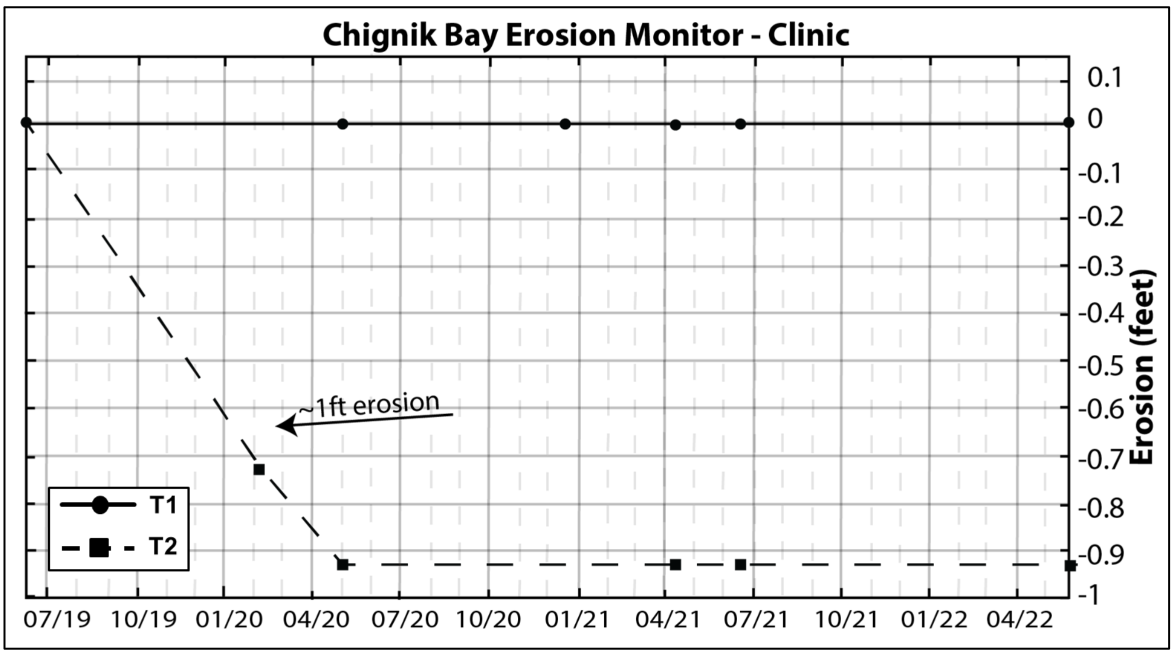

Figure 3.13 Individual CBM stake site measurements at the medical clinic in Chignik Bay, AK. Data were taken from 2019 to 2022 and are reported here in feet as they are delivered to community partners. Riprap was placed in front of a section of the clinic, while the remaining area is unconsolidated sediment. T1 is positioned on riprap in front of the clinic. T2 is positioned on unconsolidated sediment in front of the clinic. There was about 0.3028 m (1ft) of erosion at T2 between 2019 and 2020. Otherwise, this site has thus far been relatively stable.

Figure 3.14 Time-lapse picture and compiled video of the clinic site. Images taken at Chignik Bay from June 2019 to May 2022. (URL: https://youtu.be/3SjWLrm6vOw).

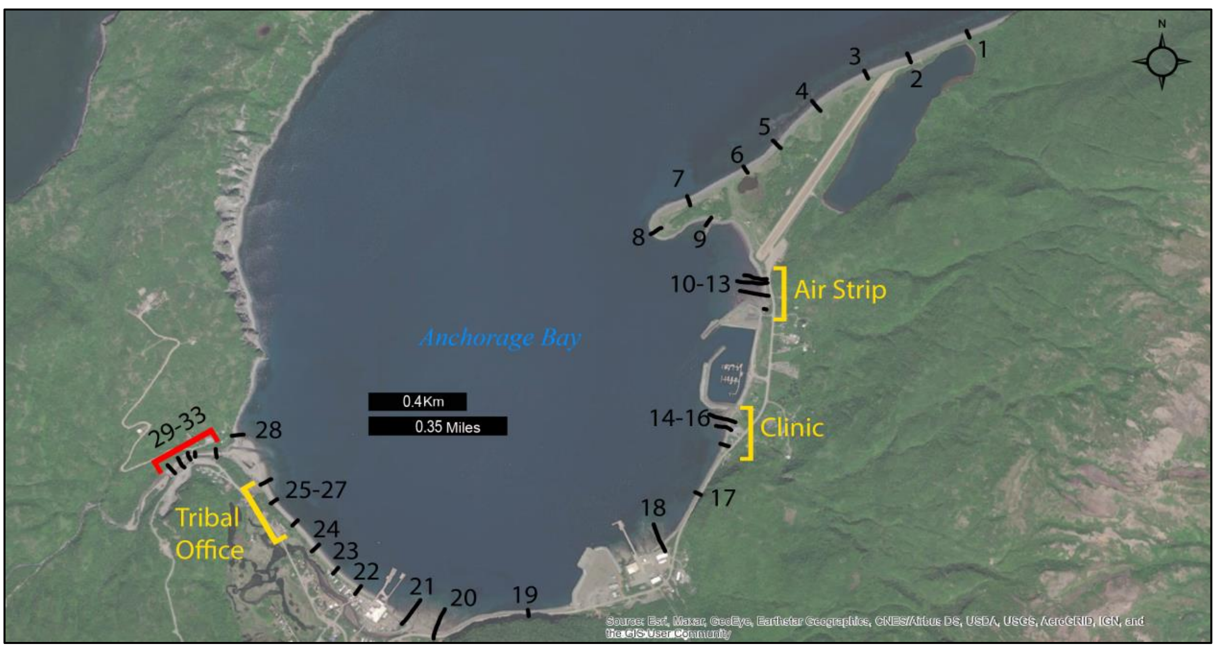

Figure 3.15 A total of 33 coastal topographic profiles were collected at Chignik Bay. Yellow brackets represent stake sites.

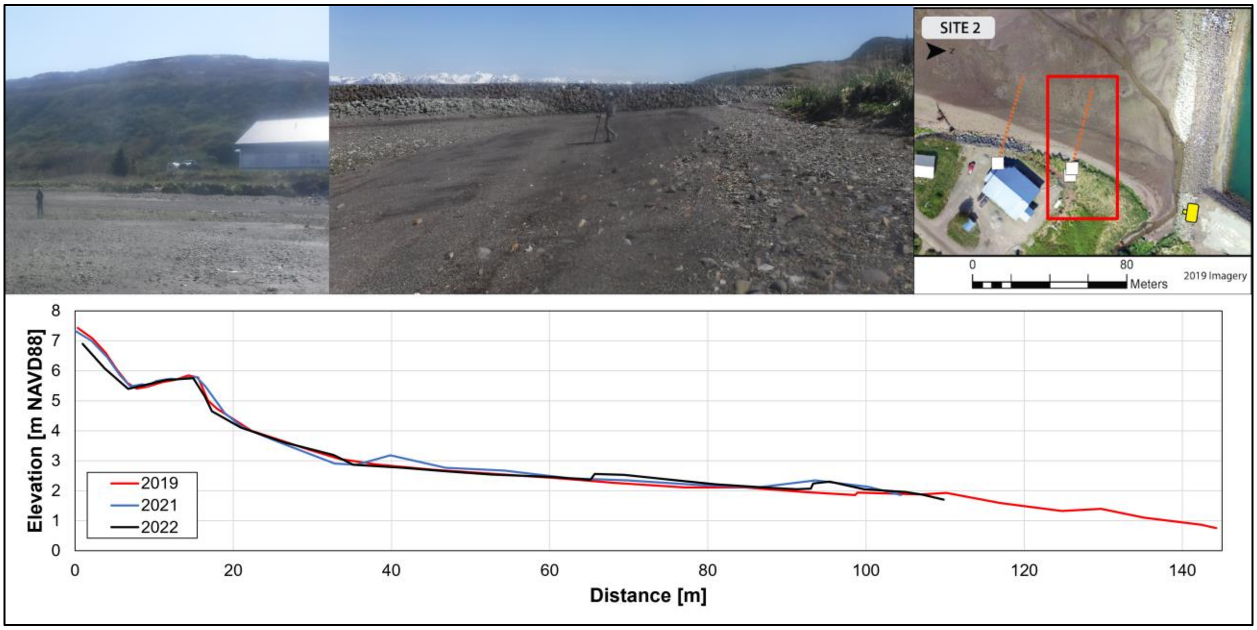

Figure 3.16 Coastal Profile 15 located in Chignik Bay, AK. (Top Left and Center) On site image of the sewage lagoon site location. ACGL scientists collecting coastal topographic profile at the medical clinic location. (Top Right) Erosion monitoring site map for the medical clinic. The red box indicates which transect the coastal topographic profile was collected at. (Bottom) Data were taken from 2019 up to 2022. From 2019 (red) to 2022 (black) there was approximately 1 m of erosion.

3.3 Community Prioritized Products

3.3.1 Hazard Assessment Report

As part of this thesis a hazard assessment report for Chignik Bay was drafted and delivered to the community (Figure 3.17; Appendix D; Christian et al., 2023). The 64-page report outlines the geographic overview, natural hazards and mitigation efforts, data products, assessment tools, identified coastal hazard areas, a summary of findings, data gaps, and future work. This report highlights the most at-risk areas in the community and serves as a reference for making decisions on mitigation efforts. It also compiles a bibliography of all previous hazard reports and other resources available. For example, an ongoing project being led by a private engineering firm is conducting geotechnical assessments in Chignik Bay on at-risk infrastructure and have utilized data from this hazard assessment report to develop their mitigation strategies.

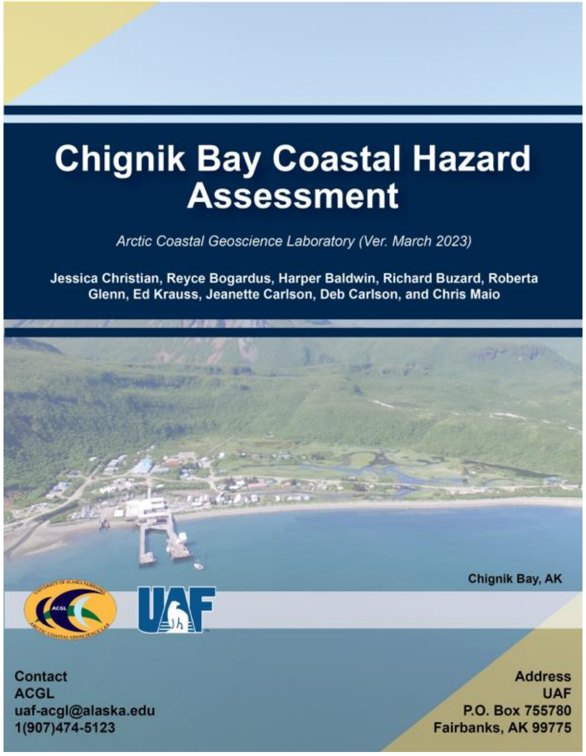

Figure 3.17 Cover of draft Hazard Assessment Report for Chignik Bay, AK.

Some example figures within the hazard report include a regional geologic setting map and orthoimagery, and a digital surface model (DSM) (Figures 3.18 & 3.19). The city of Chignik Bay is built upon predominately bedrock, however there are some areas underlain by unconsolidated sediment (Figure 3.18). These areas include the airstrip and the residential section of town. Structures built atop unconsolidated sediment increases these areas susceptibility to erosion. Another important product in the hazard assessment report is the DSM (Figure 3.19). The model was derived from roughly 2,400 aerial photographs taken from 100 m (330 ft) altitude with a FC300S camera aboard a DJI Phantom 3 Advanced UAV (Christian et al., 2023). The orthomosaic imagery is the highest resolution imagery the community has, which is crucial for future mapping projects.

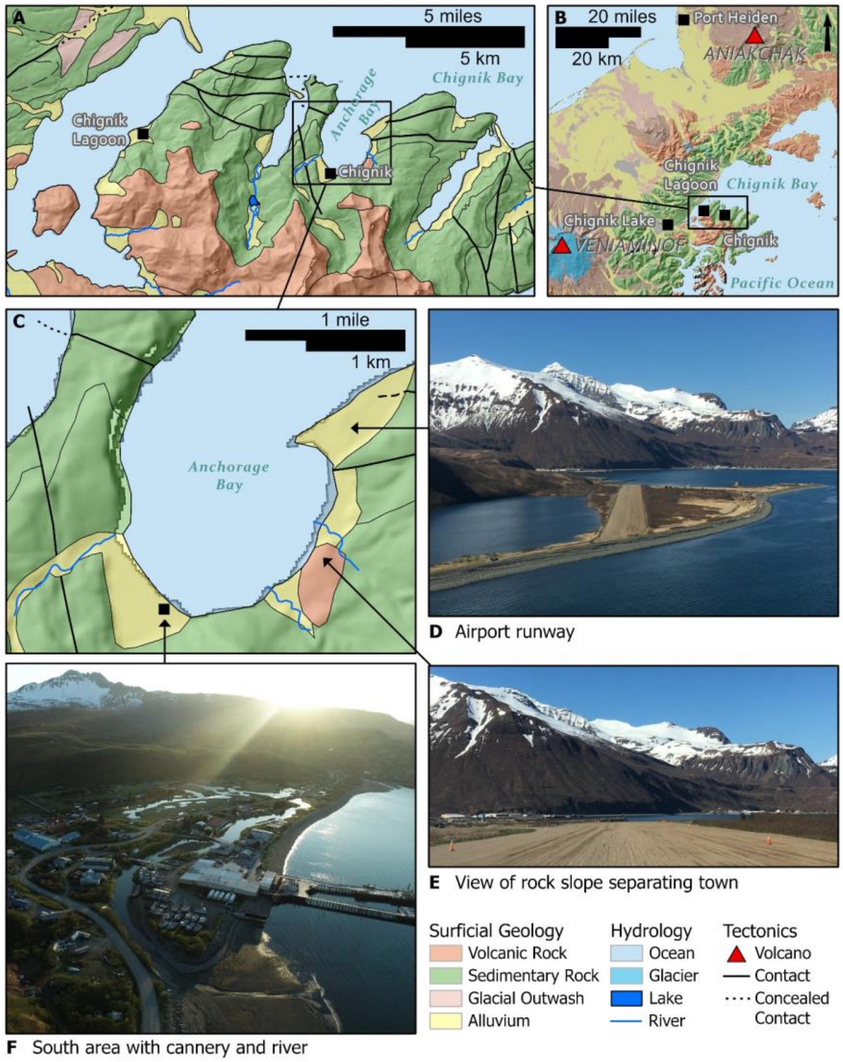

Figure 3.18 Surficial geology of Chignik (from Detterman et al., 1981). (A) The Chignik Bay area comprises sedimentary and volcanic rock with scattered alluvium deposits. Numerous faults exist. (B) This region is near two historically active volcanoes. (C) Anchorage Bay has mountainous hard-rock formations with three zones of unconsolidated sediments where Chignik is built. (D, E, F) Examples of Chignik in relation to surficial geology (from Christian et al., 2023).

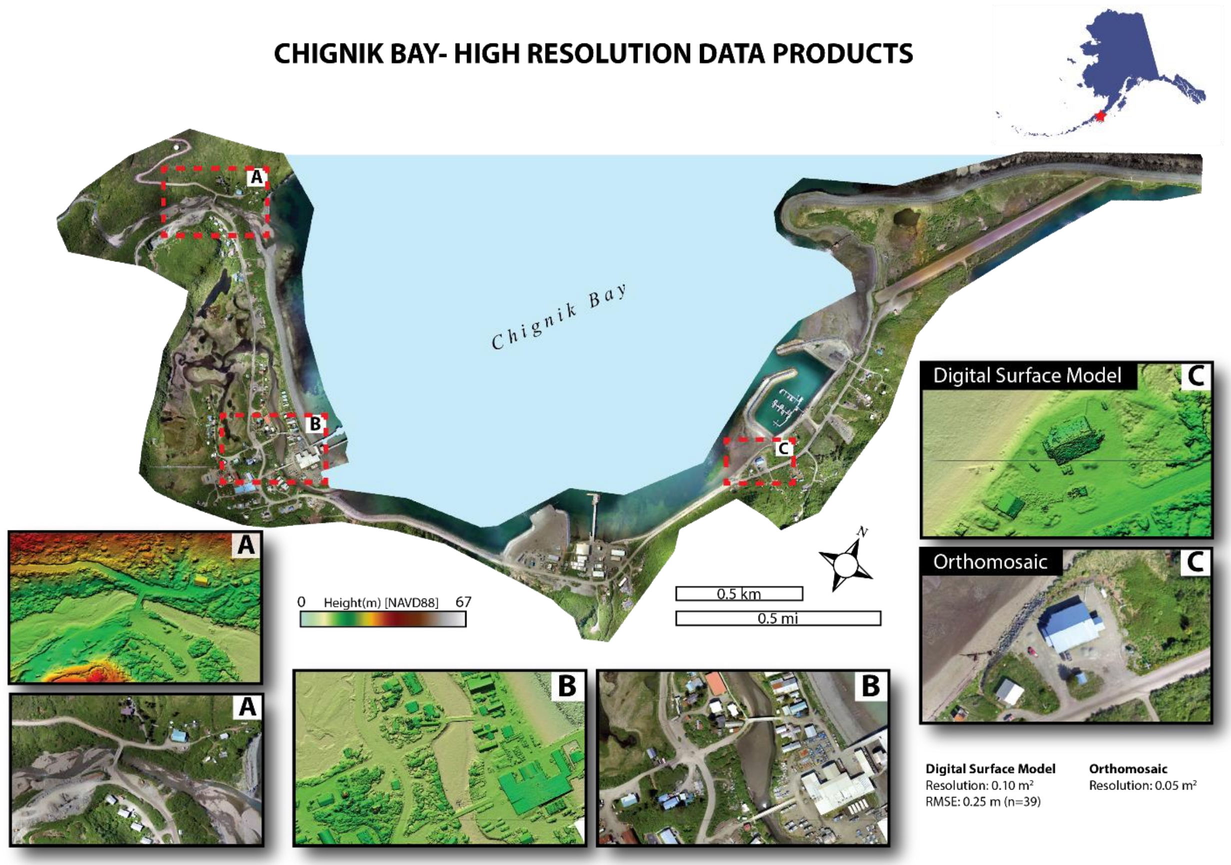

Figure 3.19 Orthomosaic and DSM of Chignik Bay generated using UAV imagery in 2019. The orthomosaic has a resolution of 0.05 m^2. The DSM has a resolution of 0.10 m^2 and a Root Mean Square Error of 0.25 m (n=39). UAV data products are shown for three locations (A-C) with examples of both DSM and orthoimagery data layers. (A) The bridge over Indian Creek is an area of interest as residents have reported flooding and erosion. (B) This residential area has been reported to flood during spring tides. (C) The clinic is another site of interest to community members as reports of erosion have been made.

3.3.2 CBM Assessment Rubrics

The variability and sometimes contrasting social and environmental conditions observed in Dillingham and Chignik Bay allowed for the assessment rubrics to be tested. For example, environmentally, Chignik Bay is more susceptible to tectonic activities and associated hazards whereas Dillingham is more susceptible to erosion and flooding. The wide variety of coastal hazards and environmental settings in each region requires a broader look into the type of CBM program that is effective for managing each threat. An example of the contrasting social conditions is the duration of participation in the CBM programs over different time periods. For example, Dillingham has been participating for 7 years while Chignik Bay has been participating for 4 years.

This indicates the efficacy of prolonged engagement in the success of these programs. Though these rubrics provide a baseline assessment, there are some factors that are more applicable than others depending on the community (Tables 3.1 & 3.2).

The community of Chignik Bay is an example where there is not a significant amount of change in the shoreline position, at least in comparison to the changes observed in Dillingham and other Bristol Bay communities (Buzard et al., In Press). However, given the fact that there is infrastructure positioned only a few meters from the eroding bluff, these areas are still of a concern to residents and warrant monitoring activities. Chignik Bay had the highest score in relationships and community participation. Discussions with residents revealed that erosion is not the community's main concern; however, the environmental observers are dedicated to continuing the monitoring program, which strengthens self-advocacy and long-term datasets that may be applicable for future research in the region. The lowest score in the Chignik assessment is in support from scientists. Protocols were provided for measuring; however, data products were not delivered in a timely manner. With a limited staff dedicated to creating these data products for the communities, delays in offering products were consistent.

The community of Dillingham is an example where there is severe erosion occurring with major land loss and significant risks to infrastructure. They also have a team of environmental observers working for both BBNA and the Curyung Tribe as well as scientists from the local community college. For these reasons, these factors have the highest scores in the assessment. Some of the lowest scores for Dillingham are from site accessibility and safety as well as support from scientists. Similar to Chignik Bay, with a lack of dedicated personnel at the ACGL, product distribution was slow. In addition, the sewage lagoon and Kanakanak flats sites are located in areas that are difficult to access requiring a hike over difficult terrain through high vegetation density. There have also been reports of bear traffic by the monitoring sites as well as timelapse images documenting their presence on the beach. This puts the local data collectors' safety at risk and results in another layer of safety precaution that can hamper regular data collection.

Table 3.1 Environmental and social factor assessment for Dillingham, AK. Each of the 3 CBM sites were assessed using the levels created for each characteristic.

Environmental Contributing Factors	Sewage Lagoon	Peat Meadows	Kanakanak Flats	Social Contributing Factors	
Vegetation density	2	3	2	Human capacity	3
Clearly defined shoreline, vegetation line, feature, or bluff edge	3	3	3	Personnel turnover transition	3
Accessibility and Safety	3	3	3	Training	3
Noticeable changing shoreline	3	3	3	Participation of community	3
Cause for concern	3	3	3	Support from Scientists	2
				Relationship between parties	3

Table 3.2 Environmental and social factor assessment for Chignik Bay, AK. Each of the 3 CBM sites were assessed using the levels created for each characteristic.

Environmental Contributing Factors	Airstrip	Clinic	Tribal Office	Social Contributing Factors	
Vegetation density	3	3	2	Human capacity	2
Clearly defined shoreline, vegetation line, feature or bluff edge	2	3	3	Personnel turnover transition	3
Accessibility and Safety	3	3	3	Training	3
Noticeable changing shoreline	2	2	1	Participation of community	3
Cause for concern	3	3	3	Support from Scientists	2
				Relationship between parties	3

Chapter 4 Discussion

The discussion is presented in parallel order as outlined in the objectives, methods, and results: 1) community engagement 2) shoreline change in Bristol Bay and the Gulf of Alaska 3) assessment & analysis tools and 4) future work. Details of community engagement efforts are assessed. Then, shoreline change in Bristol Bay and the Gulf of Alaska is examined in the long and short-term and its implications for communities. Then, the assessment and analysis tools detail the Hazard Assessment Report and the use of the Assessment Rubrics. Future work consists of ongoing projects, potential projects, and limitations throughout the study followed by potential solutions.

4.1 Community Engagement

Relationships between the ACGL and community partners were the backbone of this research with site visits being the most effective time for relationship building. Communication between site visits through phone calls and email was critical for maintaining relationships throughout the year but also presented challenges and inconsistencies. Site visits were conducted during the spring and summer months given data collection was not possible during periods of snow cover. Consistently traveling during the same months each year allowed the data to be comparable. However, it can be difficult to balance the timing of trips as spring and summer are some of the busiest times of the year for community residents, as these are key months for commercial fishing and subsistence harvesting. These activities kept community residents busy, which left a limited time window for meetings with ACGL staff. Having open communication and keeping a flexible schedule was key to maintaining a strong relationship and optimizing the work done. Many meetings with community residents were spontaneous and brief but provided valuable insight into community priorities. Staying in communities for 4-7 days also allowed enough time and flexibility to both achieve research and engagement goals.

The most difficult time for communication was between site visits. Teleconference meetings were not always ideal as bandwidth in many locations was weak, although recent infrastructure advancements in broadband in rural Alaska communities may alleviate this challenge in the future. The best way to contact environmental observers and local data collectors was through phone calls or email. Data sharing was also challenging as many of the files shared by the ACGL were too large to download on the community internet. The best way to share products was by sending flash drives with physical copies of the products to environmental observers. Another effective method was publishing products on larger host websites. For example, time-lapse videos were posted to the ACGL YouTube channel and water level data was posted on the Alaska Water Level Watch and the Hohonu water level website (AWLW, n.d.; Hohonu, n.d.). Posting products on these larger websites provides a more reliable and accessible method for public access.

4.2 Shoreline Change in Bristol Bay and the Gulf of Alaska

Coastal topographic profiles and monitoring sites point to Dillingham exhibiting the fastest shoreline change and Chignik Bay exhibiting the slowest shoreline change. This variability can in part be attributed to two primary factors including the differing geologies (e.g., bedrock vs unconsolidated sediments, and sediment types) and coastal settings (e.g., wave regimes, precipitation patterns, role of sea ice, and presence of permafrost).

The city of Dillingham is underlain by unconsolidated sediments such as well-sorted Quaternary alluvial, glacial, and dune sand and silt deposits, which contribute to increased erosion rates (Beikman, 1974; Bogardus et al., 2022). The Dillingham area is also underlain by isolated masses of permafrost (Hartman & Johnson, 1984). As the shorelines erode and permafrost is exposed, thermos-erosional processes lead to increase erosion rates in the area. The changing sea ice regime in Bristol Bay also impact erosion rates in Dillingham given wave impact hours are increasing due to a shorter sea ice season (Bogardus et al., 2022; Buzard et al., In Press). While none of the results point to a specific factor, based on local observations and pre- and post-storm measurements collected at the CBM sites it is clear that storm driven surge and wave action play a major role in driving erosion in Dillingham (Buzard et al. In Press). This was observed at the sewage lagoon site when during a single storm CBM measurements documented over 4 m of erosion took place, which is over half the annual average (Figure 3.3). Timelapse imagery further supports the case that the majority of erosion is occurring during storms that coincide with high tide.

Most of the surficial geology in Chignik Bay is bedrock, promoting a relatively stable shoreline and coastal configuration (Christian et al., 2023). Much of the coastline fronting infrastructure are also heavily armored with boulders. Based on the CBM measurements and local observations, significant erosion events in Chignik Bay have not occurred yet. Flooding seems to be one of the more frequent and consistent concerns along with earthquakes and tsunamis. Community members have reported frequent flooding in the residential area along with the area near Indian Creek. This creek separates the community and if obstructed the town is separated. This presents a huge issue as the most accessible high ground lies on the south side of the bridge. This high ground is used as an evacuation route for tsunamis. Being so close to these faults also presents the possibility of sudden tectonic uplift or subsidence, which may influence erosion rates in the future (DeGrandpre & Freymueller, 2019).

4.3 Assessment Rubrics

The environmental and social factor rubrics were used to evaluate areas of success and those that need improvement. While this is not a comprehensive program evaluation, which would ideally be conducted by an external evaluator, it is nonetheless a useful tool in self-evaluation. The rubrics are also applicable tools for other CBM programs in scoping out the suitability of a potential monitoring site as well as assessing the human capacity needed on both the program staff and community collaborator sides of the CBM workflows.

Based on the results, this study identified program improvements were site specific. For example, vegetation density at the site as well as the type of eroding feature (bluff, vegetation line, or highwater line) were factors that influenced both the accessibility of the site and the accuracy of measurements between different data collectors and the annual repeat measurements through time. Local partners from Dillingham and Chignik Bay reported confusion in collecting measurements in areas where there were cracks in the bluff or slumps in front of the shoreline with the most common question being where on the eroding feature should the measurement be taken. For example, if a tuft of grass was curling downward over the bluff do you measure to its most seaward point or where the slope changes on the bluff? To alleviate this issue, ACGL scientists were able to recommend using the break in slope at the bluff edge when the vegetation line was not distinct.

Another important characteristic to take into consideration is the noticeability of erosion at the monitoring site. If there is no noticeable change, data collection may seem unnecessary over the time scale of the typical data collection, which appeared to be the case in the Chignik Bay sites. This demonstrates that the interval between measurements should vary between sites. For example, in Dillingham, to keep up with the high erosion rates it is necessary to take measurements at least three times a year while in Chignik Bay once or twice per year is likely enough. The one exception to this is when there is the opportunity to collect measurements before and after a storm event. This can be a difficult task in the face of and aftermath of an extreme storm event, but the data is critical to deciphering the drivers of change at each location. Data from pre and post storm collection was some of the most revealing of this project (Figure 4.1).

Figure 4.1 Images from time-lapse camera at Dillingham, AK sewage lagoon site. The top image was taken in July 2018. The bottom image was taken in May 2019. CBM measurements revealed 18 feet of erosion over the 10 months, with 13 feet being from one storm. Notice in the lower image the vegetation has been washed over during a recent storm event.

Using the rubrics, I was able to reflect on possible solutions to these issues, which can influence the long-term retention of environmental observers. Possible ways to address this issue include spreading out data collection across the shoreline to capture some areas with more rapid change, even if they aren't threatening infrastructure. For example, shorelines of finer, unconsolidated sediments tend to erode much faster than rocky and consolidated shorelines. Another possible strategy is to emphasize with community monitoring teams the benefit of "no change data" and the concept of long-term data to serve as a baseline of change.

In our evaluation of the social factors influencing the CBM success at our two sites, it was found it was very important that there was investment in maintaining a pool of people with the time, interest, and capacity to conduct the regular erosion measurements. Chignik Bay has a much smaller population than Dillingham limiting the possible number of environmental observers and assistants. CBM programs must align the program commitments to the motivations a community member might have in taking on stewardship of the monitoring site.

Motivations of environmental monitoring programs generally fall into five themes: values (wanting to contribute to science or society while helping the environment), personal development (learn about the environment, gain technical skills, connect with their place), career development or recognition (gain experience or recognition related to career interest), social connection (feeling a part of a community), and recreation (having fun by doing science outside; i.e., Robinson et al. 2021). To justify the time commitment, a CBM program could create opportunities within the program to connect with other communities involved, opportunities for recognition, and opportunities for broader technical training (drone piloting, shoreline assessments, etc.).

While there were many challenges throughout the program, there were a few factors that stand out the most (Table 4.1). These include community capacity, data overload and processing time, community involvement, and data archiving, accessing, and sovereignty. One of the most common issues in the CBM programs was the lack in human capacity. Turnover time between environmental observer/local data collector positions was long and generally caused wide time gaps between data collection and meetings. To mitigate this issue, being prepared to deal with this turn over and having a plan is critical. People in communities have many obligations and do not always have the time to collect data or attend meetings. Planning consistent meetings ahead of time as well as having back-up collectors would help solve this problem. It would also be beneficial to broaden the network within the community. This can help speed up communication when it falls through. If the local data collector position has been changed, or empty, and the ACGL was not aware of this change, reaching out to other community members may help fill in this information. For example, Dillingham has three active environmental observers, making data collection relatively consistent. The only exception to this is during winter, when accessibility to the sites is limited.

The second most common issue of the CBM program was the data overload for the ACGL. There were and continue to be a myriad of large monitoring datasets that are collected throughout the years. A lack of a consistent organization and processing can slow down the time data products are delivered. One solution is having specialized positions for each of these operations. Having a position strictly for data management, and another for data processing can help keep data organized and minimize confusion within the lab. Another consideration that was found was deciding who to invite to community meetings. As previously mentioned, local partners often wear different hats within their community, making their time limited and valuable. It is important to understand the purpose of a community meeting before holding one. This helps avoid wasting community members' time and streamlines meeting agendas and outcomes.

The final takeaway revolves around data archiving, access, and sovereignty. This factor is a combination of data management, community involvement, and community capacity. Before promising products to communities, understanding how the products will be shared, accessed, and who they belong to is critical (Carroll et al., 2020; Walter & Suina 2019). Having conversations about data sovereignty with local partners helps both communities and scientists understand who owns the data and products. Also discussing how communities want to receive their data can avoid complications years into a CBM program.

Table 4.1 CBM Takeaways outlining greatest setbacks as seen in this study's findings.

Problem	**Potential Solutions**
Capacity of Communities	- Create turnover training material - Broaden relationships within community - Have a succession plan
Data Overload and Processing Times	- Specialized data management position(s) - Data management system
Broaden Community Involvement	- Be aware of audience during meetings - Have accessible data sharing method and communication avenue (Facebook, personal website, newsprint)
Data Archiving, Access, and Sovereignty	- Know fate of data - Plan out reproducibility before promising products

4.4 Hazard Assessment Report

This report examines environmental conditions in Chignik Bay and promotes self-advocacy within the community (see Appendix D). Self-advocacy takes form through local environmental observers' role in data collection and operation of erosion monitoring sites. The main use of these reports was to provide an all-encompassing hazard resource for communities. The hazard assessment report for Chignik Bay will aid in local decision-making and maps and other graphics included as part of the report are used in Tribal Hazard Mitigation Plans and within funding proposals directed at the Bureau of Indian Affairs Tribal Resiliency Program. Comprehensive datasets were also provided for engineering firms working with the community on mitigation, and development. ACGL students collected, processed, and analyzed the datasets. These results showcase how CBM programs provide training opportunities for the next generation of geoscientists as well as local environmental observers.

4.5 Future Work

The Stakes for Stakeholders program continues to evolve and the written protocols for the program developed through this study will allow for a smooth transition between personnel and the evolution of erosion and hazard monitoring. Ongoing work includes integrating various environmental monitoring technologies into CBM programs including water level sensors, weather stations, and wave buoys. Efforts to expand school outreach programs in communities are also being worked on. These school programs engage middle and high school students in the process of coastal hazards research in their communities.

4.6 Broader Impacts

The results of this research contribute to the lack of shoreline data in southwest Alaskan communities as well as providing an in-depth investigation into CBM methodology. While there have been numerous CBM programs throughout the Arctic, this research lays out the inner mechanisms and realities on the ground (Danielsen et al., 2021; Gofman, 2010; Johnson et al., 2016; Kouril et al., 2016; Sigman et al., 2015). These inner workings are laid out in a digestible and replicable manner (Tables 2.1 & 2.2), along with the most relevant CBM takeaways (Table 4.1). Shoreline change rates for Chignik Bay and Dillingham were quantified through community measurements. As a result of this work, communities have been able to reach out to engineering firms and other funding agencies for mitigation efforts and the expansion of other research projects. In addition, long-lasting relationships were forged between the ACGL and local partners.

Chapter 5 Conclusions

Throughout this CBM program, relationships were the biggest contributor to success. Site visits proved to be the best form of community engagement as it enhanced the opportunities for relationship building. During visits, ACGL scientists were able to collect and share data with environmental observers and other participants and engage with the residents through formal meetings and informal conversations. Between site visits, communication was upkept through phone calls, email, and teleconference meetings. Though this presented some challenges with poor bandwidth in communities, patience, and persistence from both the ACGL and the environmental observers kept communication strong. Some best practices for community engagement include keeping open communication between and during site visits, staying in communities long enough to engage with local members, and being considerate of community schedules.

The CBM program resulted in 3 monitoring sites being installed and maintained in both Dillingham and Chignik Bay. Sites in Dillingham have resulted in 6 years of shoreline data and 40 coastal topographic profiles. Coastal topographic profiles and community measurements revealed similar erosion rates through time, further solidifying the validity of CBM methodology (Buzard et al., 2020; Conrad & Hilchey 2011; Eitzel et al., 2017; Glenn, 2022; Overbeck et al., 2017; Pollock & Whitelaw, 2005). Sites in Chignik Bay have resulted in 4 years of shoreline data and 33 coastal topographic profiles. Through the CBM sites, it was determined that there have thus far only been minor erosion events in Chignik Bay, compared to Dillingham. In addition, the effectiveness of the armored bluff in front of the medical clinic was able to be seen through these sites (Figure 3.13).

The hazard assessment report for Chignik Bay outlining relevant coastal hazards was drafted and given to local environmental observers. The document identifies at risk areas such as the Indian Creek bridge connecting the town, the main road by the airstrip, and the clinic sitting atop a steep bluff. The hazard assessment report acts as a comprehensive reference for past and ongoing mitigation efforts and hazards in the area. Once published, the report will be used by private engineering firms and their effort to identify at risk infrastructure in the community. The assessment rubrics allowed for the evaluation of the CBM programs (Tables 3.1 & 3.2). This evaluation allowed the ACGL to reflect on some of the issues of the program and come up with possible solutions. These relationships, built on trust and respect, boosted information sharing between local partners and the ACGL and resulted in a more effective CBM program. This research outlines and emphasizes the importance and value of collaboration between rural coastal communities and research agencies.

With climate change impacting rural coastal communities in Alaska along with the unique challenges presented conducting research in the arctic, reliable and collaborative methods are required to resolve these issues (Glenn, 2022). CBM provides a robust method for collecting high resolution datasets while including local partners in scientific research that results in actionable outcomes (Danielsen et al., 2021; Glenn, 2022).

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Appendices

Appendix A. Stake-Ranging Site Selection, Maintenance, and Collection

Coastal Erosion Monitoring – Stake Ranging Sites

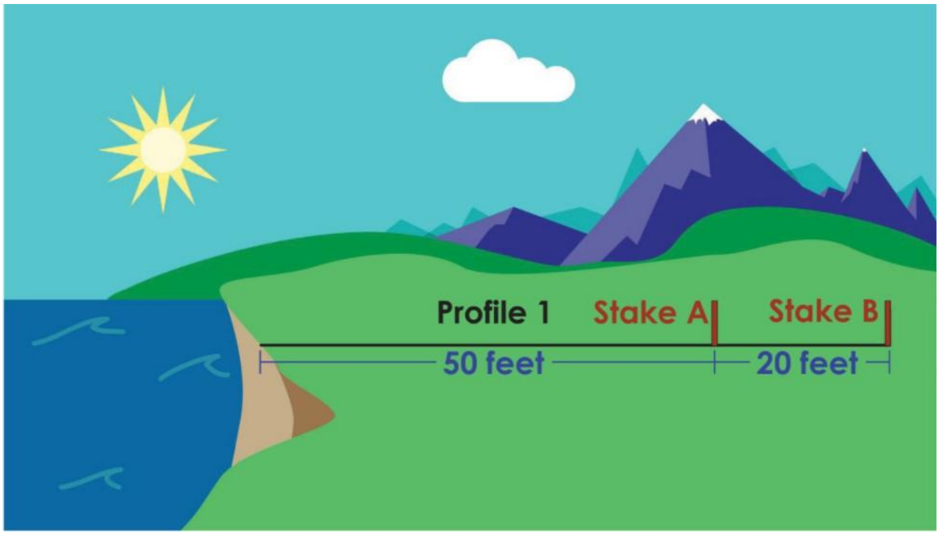

Figure 1. Example site set up for stake ranging. Figure taken from community monitoring pamphlet by Buzard et al. 2019.

Site set up

To set up an erosion monitoring site, you will first need to locate your site of interest. To select a site keep a few things in mind: Is the erosion noticeable? Is the area located near important infrastructure or does it bear local or cultural significance? Is the area safe and accessible year round? Is the area heavily vegetated?

Once you have chosen your location, you'll need to establish transects along the shoreline or coastline. It is recommended that you establish at least 2-3 transects perpendicular to the shoreline. This is so that if one transect fails, there are others to fall back on. **Figure 1** illustrates an example of what a monitoring site may look like. Visible permanent markers must be placed perpendicular to the eroding feature (ex. Vegetation line, a scarp, or the edge of a bluff). These permanent markers may be wooden stakes, buildings, utility poles, etc. It is recommended that stake A, or the stake closest to the eroding feature, be placed at least 50 feet from the eroding shoreline and the following landward stakes be placed 20 feet from the seaward stake. You may have as many stakes in a transect as you think necessary, however, at least three should be installed to begin with. To ensure the stakes are visible, paint them a bright color and label them. Once the stakes or reference markers have been installed, draw a site map showing a top down view of your transects in a notepad designated for the monitoring project. It does not have to be perfect, but it should show the shoreline or coastline, the transects, and each stake. Next, measure the distance between each marker and the distance from the seaward stake to the eroding feature and record these in your notepad. Take pictures of the site as well as observing the environmental conditions and write these down.

Measurement Collection

IMPORTANT REMINDERS: When taking measurements be sure to record the stake name before you begin. The stake name will be located along the side of the stake (ex. 2A - is the first stake in transect 2). Also - be sure to record significant changes in the environment (i.e., if the bluff looks cracked, the shoreline looks eroded, etc.) even the most seemingly simple observations are helpful. When a stake is lost at sea, be sure to record this as a note and send it with the measurements. Keeping track of the transect history at each site will help us track the erosion easier and make the future continuation of this project smooth.

Figure 2. Example of measuring from a stake to an eroding bluff at Chignik Bay, AK.

Locate the site reference point (this could be a wooden stake, a utility pole, or even a building). After recording the name of the stake, take your measuring tape and walk straight out to the eroding feature (ex. Vegetation line, a scarp, or the edge of a bluff) as seen in **Figure 2**. Record the number on the measuring tape at the edge of the eroding feature. If you run into a bluff where the edge is cracked, but not detached, measure from the crack of the bluff, not to the tip of the broken chunk of shoreline. If you measure to the edge of the broken chunk, the measurement will not accurately represent the shoreline change as the measurement may depict accretion. After you have the measurement, look around and consider the environment. Ask yourself - have there been any significant changes? Be sure to record these observations as these small notes help us get an idea of the environment since we cannot be there. Go out and collect measurements every 3 months and when possible before and after big storm events.

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Appendix B. Time-lapse Camera Protocols (Bushnell Trophy HD)

Coastal Erosion Monitoring – Time-lapse Camera Settings

Camera Type: Bushnell Trophy HD

NOTICE: The camera settings may vary slightly depending on the camera type. If there are settings on this instruction sheet that do not appear in the camera settings, ignore them. In some cases, there may be two options, for example the image size. Choose whichever option appears in the settings of the camera.

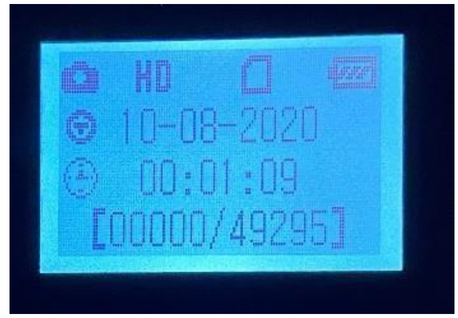
Make sure the **SD** card is inserted before you begin setting up the camera. Switch camera to **OFF**. Switch to **SETUP** mode. Press the **MENU** button to start changing the settings.

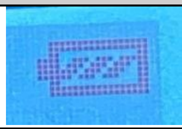
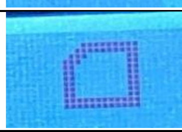
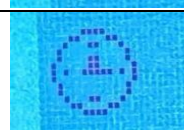
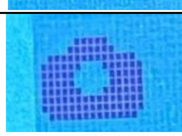
Pressing the **RIGHT** or **LEFT** key scrolls through the different *parameters* while pressing the **UP** or **DOWN** keys changes the *settings* of the current displayed parameter. Once you have set the parameter accordingly, select the **OK** button to save it. It is important to select **OK** once you change a parameter setting, otherwise it will not save! When you are done, press **MENU** to go back to the home screen.

The adjacent image shows one type of camera configuration for the power and control panel. Depending on your camera this maybe be different. To the left of the line are the power options: **OFF** (located at the bottom of the switch) turns the camera off, **SETUP** (located in the center of the switch) allows you to set the different parameters, **ON** (located at the top of the switch) turns the camera on and it starts capturing photos according to its settings. To the right of the line are the different keys: **LEFT** and **RIGHT** keys are located to the sides of the **OK** button, **UP** and **DOWN** keys are located above and below the **OK** button, the **MENU** key is on the bottom left of the control pad. For the field scan option, once you select it, use the down arrow to scroll through the different options.

PARAMETER	**SETTING**
Clock	(enter local time)
PreSets	Advanced
Mode	Camera
Image Size	HD or highest MP (16M)
Image Format	Full Screen
Capture Number	1 Photo
LED Control	Low
Camera Name	(SKIP)
Video Size	(SKIP)
Video Length	10S
Interval	60M
Sensor Level	Low
NV Shutter	High
Camera Mode	24hrs
Format	(SKIP)
Time Stamp	On
Field Scan	ON "A" set to 00:00 and 12:00 "B" set to 13:00 and 23:00 "interval" set at "60M"
Coordinate Input	Off

The adjacent image below is the home screen that should appear once you switch the camera to **SETUP** mode. The top right corner shows the battery level, the top right center shows that the SD card is inserted and recognized, the top left center will show the "Image Size" setting which should be set to "HD", and the top left corner shows the "Mode" the device is set to: "Camera" mode will show the camera icon as seen above (make sure it is showing the camera), "Video" mode will show, "Hybrid" mode will show a camera with a +. Along the left side of the home screen there are two other icons; the "T" in a circle shows that "Time Stamp" is turned on. The analog clock shows that the field scan is on and set.



Home screen Symbol	Meaning	Home screen Symbol	Meaning
	Battery Level		Hybrid Mode
	SD card inserted		Time Stamps ON
	Image Size		Field Scan ON
	Camera Mode		Video Mode

Battery Replacement and Maintenance

Batteries should be replaced approximately every 6 months depending on the displayed battery level. If all the batteries are removed at once the camera settings will need to be completely re-entered. To avoid this – ONLY TAKE OUT HALF THE BATTERIES AT A TIME. ONCE YOU REPLACE THESE WITH NEW ONES REMOVE AND REPLACE THE SECOND HALF. This way the camera will always have power and the settings will not be reset.

The outer camera lens should be cleaned occasionally with a soft cloth and cleaning agent (alcohol, Windex, etc.). Be careful not to scratch this!

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Appendix C. Time-lapse Camera Protocols (Wingscape TimelapseCam Pro)

Coastal Erosion Monitoring – Time-lapse Camera Settings

Camera Type: Wingscape TimelapseCam Pro

NOTICE: The camera settings may vary slightly depending on the camera type. If there are settings on this instruction sheet that do not appear in the camera settings, ignore them. In some cases, there may be two options, for example the image size. Choose whichever option appears in the settings of the camera.

Make sure the **SD** card is inserted before you begin setting up the camera. Switch camera to **OFF**. Switch to **SETUP** mode.

Pressing the **RIGHT** or **LEFT** key scrolls through the different *parameters* while pressing the **UP** or **DOWN** keys changes the *settings* of the current displayed parameter. Once you have set the parameter accordingly, select the **OK** button to save it. It is important to select **OK** once you change a parameter setting, otherwise it will not save! **OFF** (located at the bottom of the switch) turns the camera off, **SETUP** (located in the center of the switch) allows you to set the different parameters, **ON** (located at the top of the switch) turns the camera on and it starts capturing photos according to its settings, **Playback** allows the user to view images on the SD card. To the right of the line are the different keys: **LEFT** and **RIGHT** keys are located to the sides of the **OK** button, **UP** and **DOWN** keys are located above and below the **OK** button, the **MENU** key is on the bottom left of the control pad.

PARAMETER	SETTING
Clock	(enter local time)
Photo or Video	Photo
Time lapse Interval	1 hour
Time lapse Program	1
TL Program #1 Start Time	Always on
Security Code	00000
Temperature Unit	Farenheit
AC connected	No
Wi-fi SD card	No
Camera Name	Skip
Imprint Info	Yes
Video Length, Video Quality	Skip
Photo Quality	Enhanced
Managed Memory	Do Not Overwrite
Erase All Images	No
Reset Factory Defaults	No

Battery Replacement and Maintenance

To Access the battery compartment, hit the **EJECT** button on the bottom of the camera face. Batteries should be replaced approximately every 6 months depending on the displayed battery level. If all the batteries are removed at once the camera settings will need to be completely re-entered. To avoid this – ONLY TAKE OUT HALF THE BATTERIES AT A TIME. ONCE YOU REPLACE THESE WITH NEW ONES REMOVE AND REPLACE THE SECOND HALF. This way the camera will always have power and the settings will not be reset.

The outer camera lens should be cleaned occasionally with a soft cloth and cleaning agent (alcohol, Windex, etc.). Be careful not to scratch this!

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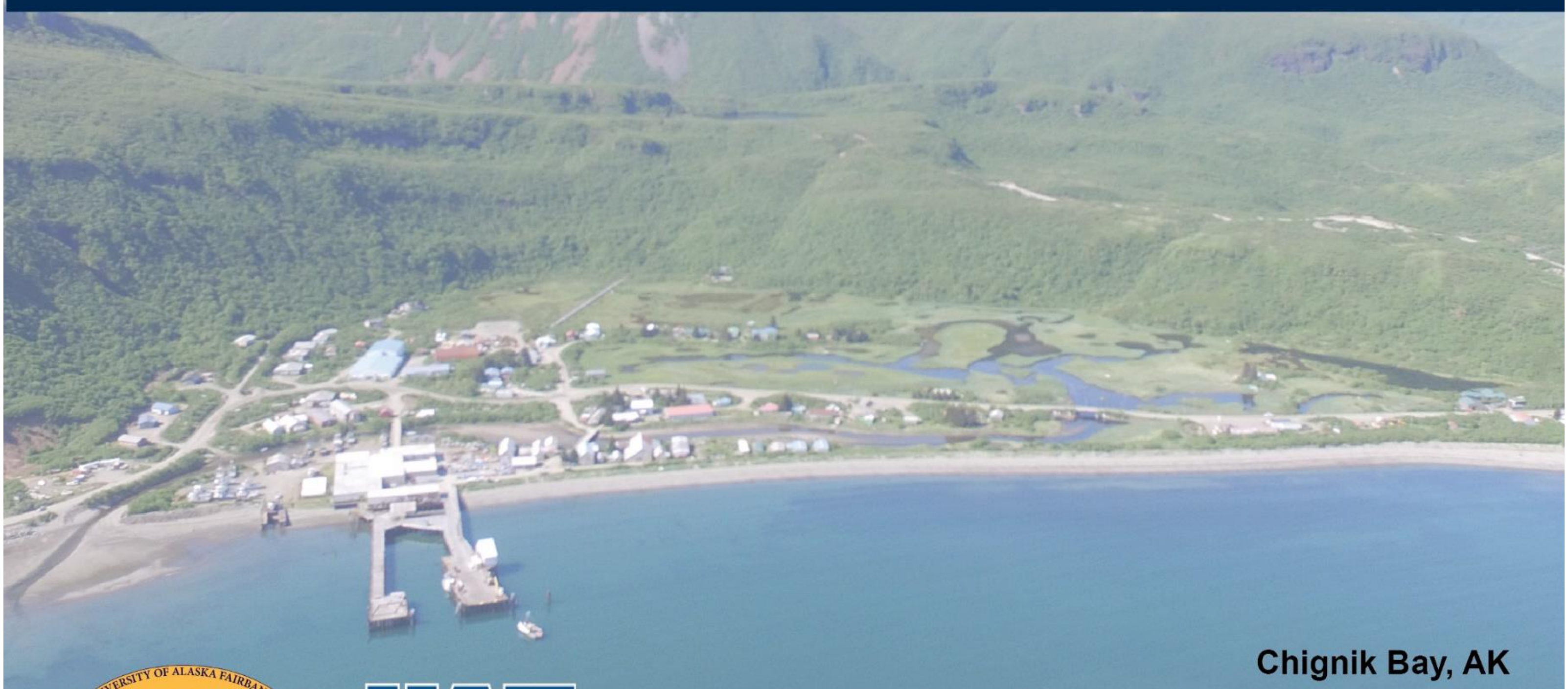
Appendix D. Chignik Bay Hazard Assessment Report (DRAFT)

Chignik Bay Coastal Hazard Assessment

Arctic Coastal Geoscience Laboratory (Ver. March 2023)

Jessica Christian, Reyce Bogardus, Harper Baldwin, Richard Buzard, Roberta Glenn, Ed Krauss, Jeanette Carlson, Deb Carlson, and Chris Maio



Chignik Bay, AK

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STATEMENT OF INTENT

This report is meant to contribute accurate information and high-resolution map and data products to inform erosion and flooding mitigation efforts. It is our goal that this report will aid in local decision making, provide maps and graphics for research funding opportunities, and be an information source for FEMA Hazard Mitigation Plans. We have compiled an assortment of existing data sources (DGGS, UAF-SNAP, etc.) that provide information on current and projected environmental changes. Additionally, numerous datasets have been collected, processed, and analyzed by the ACGL. This work was primarily carried out by undergraduate and graduate students within the ACGL, providing training opportunities for the next generation of geoscientists. Local environmental coordinators have also played a major role in the baseline surveys, operation of erosion monitoring sites, as well as this document. All data and products will be provided by the ACGL upon request. This report is meant to supplement more detailed geotechnical surveys, such as those carried out by contracted engineering firms.

ACKNOWLEDGMENTS

This research has been supported and/or funded through multiple contributors. These include local Tribal Environmental Programs through the Environmental Protection Administration (EPA) Indian General Assistance Program (IGAP), Alaska Sea Grant (ASG), the National Science Foundation (NSF), the Bristol Bay Native Association (BBNA), the Bureau of Indian Affairs (BIA), the University of Alaska Fairbanks (UAF) Geophysical Institute, and the Alaska Division of Geological and Geophysical Surveys Coastal Hazards Program (DGGS). We also thank the long-term contributions made by Susan Flensburg, Gabriel Dunham, and Nicole Kinsman.

We would like to thank the Chignik Bay Tribal Council as well as Jeanette Carlson, Debbie Carlson, and Ed Krauss for their continued efforts to collect monitoring data, their local observations, and assistance during field work. We greatly appreciate your knowledge and support and look forward to our continued collaboration.

DISCLAIMER

The hazard assessments in this report are based on a compilation of data we collected, as well as the data made available to the Arctic Coastal Geoscience Lab (ACGL) through external agencies and bodies. The maps and products within have been created from analysis of this information using modern techniques and based on the best information currently available. However, they do not necessarily show the greatest extent of coastal flooding or erosion suffered in the past, or likely to be suffered in the future. There are also other uncertainties associated with each analysis and mapping product. As such, the ACGL does not warrant or represent that the maps are free from errors or omissions, nor do we accept any liability in relation to the quality or accuracy of the flood and erosion maps. In particular, the ACGL does not warrant that land not shown as being subject to inundation or erosion, is free from flood waters or erosional processes.

The extent of coastal flooding maps is based on the coastal topography at the time of survey. Changes in coastal landform that have occurred since the date of survey, as well as potential future landform change are not reflected in the coastal flood mapping. The maps reflect flooding and erosion associated with coastal processes, and as such do not represent flooding and erosion caused by storm rainfall, including surface run off, storm water network overflow, and river flooding.

We have not assessed or mapped coastal hazards outside of the surveyed areas shown in this report. For areas where only one type of coastal hazard (flooding / erosion) has been mapped, it should be assumed that any unmapped coastal hazard has not been assessed. Where only coastal flood risk has been mapped it should not be assumed that no coastal erosion hazard exists, and vice versa.

The tsunami inundation map has been completed using the best information available and is believed to be accurate; however, its preparation required many assumptions. Actual conditions during a tsunami may vary from those assumed, so the accuracy cannot be guaranteed. Areas inundated will depend on specifics of the earthquake, any earthquake-triggered landslides, on-land construction, tide level, local ground subsidence, and may differ from the areas shown on the map. Information on this map is intended to permit state and local agencies to plan emergency evacuation and tsunami response actions. The map is not appropriate for site-specific use or for land-use regulation. Interpretation of the tsunami inundation map(s) by qualified experts is strongly recommended.

Finally, this work is preliminary and is subject to revision. It is being provided due to the need for timely "best science" information. Accordingly, these maps should not be relied upon as the sole basis for the making of any decision in relation to potential coastal hazard risk. The assessment is provided on the condition that neither the ACGL nor the University of Alaska Fairbanks may be held liable for any damages resulting from the authorized or unauthorized use of the assessment.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACRONYMS AND ABBREVIATIONS

ACCAP	Alaska Center for Climate Assessment and Policy
ACGL	Arctic Coastal Geoscience Laboratory
ADLWD	Alaska Department of Labor and Workforce Development
AHAP	Alaska High Altitude Photography
AIJ	Alaska Institute for Justice
AOOS	Alaska Ocean Observing System
ASOS	Automated Surface Observing System
DCRA	Division of Community and Regional Affairs
DGGS	Division of Geological and Geophysical Surveys
DSAS	Digital Shoreline Analysis System
DSM	Digital Surface Model
ESRI	Environmental Systems Research Institute
GIS	Geographic Information System
GLONASS	Global Orbiting Navigation Satellite System
GNSS	Global Navigational Satellite System
MHHW	Mean Higher High Water
MHW	Mean High Water
MSL	Mean Sea Level
NASA	National Aeronautics and Space Administration
NAVD88	North American Vertical Datum of 1988
NIR	Near infrared
NOAA	National Oceanic and Atmospheric Administration
NSM	Net Shoreline Movement
RGB	Red, Green, Blue
RSLR	Relative Sea Level Rise
RTK	Real-time Kinematic
SECD	Strategic Economic and Community Development
SfM	Structure from Motion
SVTM	Single Value Threshold Map
UAV	Uncrewed Aerial Vehicle
USACE	United States Army Corps of Engineers
USGS	United States Geological Survey
UTM	Universal Transverse Mercator
WCI	Weighted Confidence Interval
WEAR	Waste Erosion Assessment and Review
WIS	Wave Information Study
WLR	Weighted Linear Regression
WMO	World Meteorological Organization
WR2	Weighted R Squared

GLOSSARY

Definitions were pulled from the United Nations Office for Disaster Risk Reduction.

Capacity	the combination of all the strengths, attributes and resources available within an organization, community or society to manage and reduce disaster risks and strengthen resilience.
Disaster risk	(referred to as risk): the potential loss of life, injury, or destroyed or damaged assets which could occur to a system, society or a community in a specific period of time, determined probabilistically as a function of hazard, exposure, vulnerability and capacity.
Disaster risk assessment	(referred to as risk assessment): A qualitative or quantitative approach to determine the nature and extent of disaster risk by analyzing potential hazards and evaluating existing conditions of exposure and vulnerability that together could harm people, property, services, livelihoods and the environment on which they depend.
Exposure	the situation of people, infrastructure, housing, production capacities and other tangible human assets located in hazard-prone areas.
Hazard	a process, phenomenon or human activity that may cause loss of life, injury or other health impacts, property damage, social and economic disruption or environmental degradation.
Mitigation	the lessening or minimizing of the adverse impacts of a hazardous event.
Resilience	the ability of a system, community or society exposed to hazards to resist, absorb, accommodate, adapt to, transform and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions through risk management.
Vulnerability	the conditions determined by physical, social, economic and environmental factors or processes which increase the susceptibility of an individual, a community, assets or systems to the impacts of hazards.

1. LOCAL NARRATIVE

1.1 LOCAL NARRATIVE

"The community of Chignik 'Anchorage Bay' is located on the south shore of the Pacific side of the Alaska Peninsula. Chignik Bay is the hub community of the Chignik sub-region and provides the residents in our neighboring villages of Chignik Lagoon, Chignik Lake, Perryville, and Ivanof Bay with essential infrastructure, including an airport, three docks, small boat harbor, Trident Seafoods, and the Harris Sub-regional Clinic. Freight is barged from Seattle on Coastal Transportation vessels, and the Alaska State Ferry Tustamena provides more affordable transportation to and from Kodiak, Homer, and Anchorage. Additionally, the Harris Sub-regional Clinic is staffed by a Mid-level Practitioner to provide a higher level of medical care to residents in our region.

"Our community experiences coastal bank erosion and flooding from storm events, which is threatening and damaging infrastructure, (e.g. Harris Sub-regional Clinic, tank farms on the East and West sides of the village, the airport, road culverts, and bridges, tsunami escape road, road to the airport, clinic and power plant. There are invasive plants and alders taking over traditional berry harvesting area. Warming of seawater temperature is affecting salmon runs, and all other species of fish and wildlife, and frequent high levels of PSP has prohibited subsistence clam digging, bidarki picking, and octopus hunting in traditional areas."

Jeanette Carlson
Secretary
Chignik Bay Tribal Council

Debbie Carlson
Treasurer
Chignik Bay Tribal Council

1.2 ADDITIONAL LOCAL OBSERVATIONS

<u>Summary of interview with Chignik Intertribal Coalition, Consultant Hazel Nelson:</u>
This meeting was held through Zoom and began at 10 AM, ending about 11:30 AM. The Chignik Bay Tribal Council (CBTC) was represented by Jeanette 'Chickie' Carlson, CBTC Secretary and Environmental Coordinator; and Debbie Carlson, CBTC Tribal Administrator. The group discussed answers to these questions jointly in a conversation that highlighted old and new information that also helped inform other ongoing efforts towards building resiliency for the Chignik Bay Tribe. They offered their Tribal Hazard Mitigation Plan and Action Plan for additional information to help inform this BIA TRP grant and to help reduce redundancy. The tribal members are very knowledgeable, involved and passionate about building tribal resiliency. They are already working on researching key environmental concerns and furthering mitigation and action plans for the tribe.

What changes in the environment have you observed or that have occurred in the recent past or over your lifetime in your home area?

“When we have high winds now, its higher than ever, the storms seem bigger. The recent 100 mph winds occurred during sub-zero temperatures, it knocked the power out and some people had no electricity.

“The erosion on the beach is very bad. Concerned about the clinic and the East end of the runway. The breakwaters have created two deep holes from eddies, at one end of the harbor and the other by the clinic. They are safety hazards. There’s erosion by the city dock from the big storms. There are a lot of big cracks in the road that goes to the dock.

“Indian Creek is now so wide that the bridge structures beneath it may collapse, they need to be inspected. The earthquakes and aftershocks have caused all four of the bridges to move and they need inspection for structural safety. If there is a big earthquake and the bridges collapse, then a tsunami, there will be nowhere to go to escape.

“The road to the hill is for tsunami protection and it also goes to the dump. There are steep ditches on both sides of that road along with unstable edges on the corners of the road which are very unsafe. People have already gone off the edge and been medevac’d out with serious injuries.

“The clinic has had damage from the big 8.2 earthquake, the aftershocks and it needs inspection.

“This past summer there were more fish (salmon) up Indian Creek than ever before, Roderick Carlson, CBTC Tribal President caught several silvers in there in October. In the deep creek behind Chickie’s house she saw some salmon and a land otter that was trying to catch them. There are also a lot of sticklebacks there and Kingfishers are catching them.”

All Alaskan tribes rely on key animals, birds, fish and plants and berries – these are key species necessary for food and/or for commercial sale. In the air, lands, or waters that your community relies on please identify the <u>key</u> species you are most concerned about.

“People in Chignik Bay had little to no salmon this summer unless it was brought in from another area.

“This year, there was a good berry harvest, but there is a lot of fireweed, lupine and alders overgrowing traditional berry picking areas. Alder is growing like weeds, it’s so bad that people can’t see each other while they’re berry picking, and are worried about not seeing bears or wolves, and worried about safety. Alder is also growing up all over town and around town.

"There are two wolves that have moved into the local area, and they are seen where people pick berries.

"We used to have ducks that people hunted but they don't stay over anymore. Very little ptarmigan, it's been 5, maybe 8 years since someone went ptarmigan hunting because they don't flock up here anymore. Someone saw two, recently though."

Have you been thinking about how to protect and strengthen your community's future? Would you like to create a plan or add to existing plans that define how to live a sustainable life along with the rapid changes happening in your area?

"For the past several years the Chignik Bay tribe and city have been discussing climate change and already made progress in building resilience for the tribe and community. There are several grants that the local government entities have applied for and are in different stages of completion and award. They are already working on a BIA Tribal Climate Resilience Planning grant with Bristol Engineering Services, Danielle Dance as a consultant to complete the work. Chignik Bay's IGAP grant has Bristol Bay Heritage Land Trust Executive Director, Tim Troll as a consultant, along with his partner, UAA Research Geographer, Marcus Geist working on the development of a watershed plan to identify and map areas important for the survival and harvest of local subsistence resources, places of cultural and historical significance, and other values in the Chignik, and which includes the communities of Chignik Bay, Chignik Lagoon, Chignik Lake, Perryville, and Ivanof Bay. Chignik Bay's IGAP grant also has UAF Arctic Geoscience Lab Director, Chris Maio of UAF as a consultant conducting baseline coastal erosion assessment studies, which include time-lapse photos/digital mapping for annual coastal hazard assessment reports. He will also provide technical support to write a QAPP-Site Specific Sampling Plan."

Hazel Nelson
Consultant
Chignik Intertribal Coalition

2. GEOGRAPHIC OVERVIEW

2.1 WESTERN GULF OF ALASKA REGION

The Gulf of Alaska encompasses all water from the east shore of the Alaska Peninsula to southeast Alaska. The Gulf is a semi-enclosed basin with circulation dominated by the Alaska Coastal Current and the subarctic Alaska Gyre. The current is characterized by its relatively warm water, low salinity, and freshwater core from freshwater runoff from the mountains surrounding the Gulf of Alaska (Stabeno et al. 2004; Stabeno et al. 2016). The western region includes the area of several megathrust earthquake ruptures, including the southwestern extent of the M9.2 1964 rupture—the second largest earthquake ever recorded (Zimmermann et al. 2019). The landscape of this region has been sculpted by subduction zone tectonics and multiple glaciations (Zimmermann et al. 2019).

2.2 CHIGNIK BAY

Chignik Bay is one of seventeen communities in the Lake and Peninsula Borough. It lies 724 km (450 mi) southwest of Anchorage and 418 km (260 mi) southwest of Kodiak (DCCED 2018) (**Figure 1**). The city comprises 11.7 square miles of land and 4.3 square miles of water (Chignik Bay Tribal Council 2019). Kalwak, the original village of the current land of Chignik Bay, was destroyed in the late 1700s during the Russian fur boom (Chignik Bay Tribal Council 2019). The word “Chignik” is a Sugpiak word for “big wind,” and the village of Chignik Bay was named after the body of water it overlooks. The community was established in the late 1800s as a fishing community and became an incorporated city in 1983 (DCCED 2018). Coal mining occurred from 1899 to 1915. The city is located at the head of Anchorage Bay, which itself is in the larger Chignik Bay.

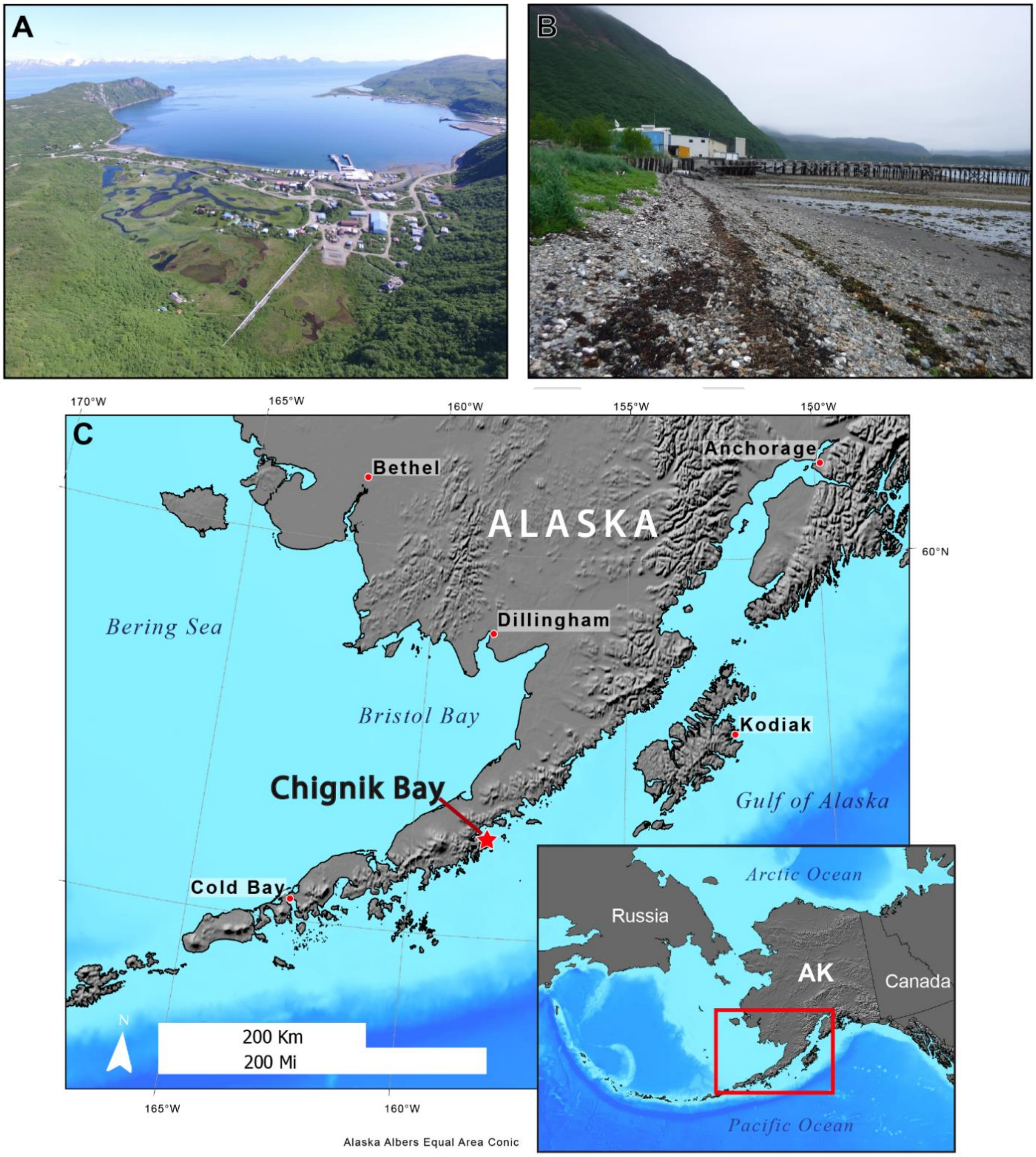

Figure 1. Regional context of the Chignik Bay, AK study site. (A) Aerial view of Chignik Bay. (B) Beach and cannery. (C) Regional map showing Chignik Bay's location in Alaska.

2.3 COMMUNITY INFORMATION

According to the 2017 State of Alaska Department of Commerce, Community, and Economic Development, Chignik Bay has a population of 96 – down from 188 as reported in the 1990 Census. The majority (57.14%) of the population is Alaska Native. The 2010 census reported 41 households with an average household size of three people (DCCED 2018).

2.3.1 Infrastructure Description

The community of Chignik Bay spans approximately 2.5 miles long with a state road connecting the main community with the airstrip and dock system. According to the 2010 census, 41 of 105 housing units are occupied (note: some of these may be seasonal homes not built to be lived in year-round).

There are several tank farms located around the community. There are three active tank farms: the east power plant tank farm, Trident tank farm, and the school tank farm. The east power plant tank farm contains six fuel tanks and is located 165 ft from Anchorage Bay (CIAP WEAR Trip Report, 2014). It acts as a fuel station for the community, and it supplies fuel to the east side power plant. The Trident tank farm contains eight fuel tanks and is located 60 ft from Anchorage Bay. It provides fuel for the Trident Seafoods Corporation (CIAP WEAR Trip Report, 2014). The school tank farm, located behind the school, provides fuel for the school. The site is located 1,200 ft from Anchorage Bay (CIAP WEAR Trip Report, 2014).

The city landfill has been in operation since 1996. It is unpermitted and only accepts municipal waste (CIAP WEAR Trip Report, 2014). This site is 1,000 ft from the west side of Anchorage Bay and 2,000 north of the main residential area (CIAP WEAR Trip Report, 2014). Indian creek holds a dam and a reservoir that treats water for all homes and the school. Piped sewage is held in community tanks and discharged through ocean outfall lines (CIAP WEAR Trip Report, 2014).

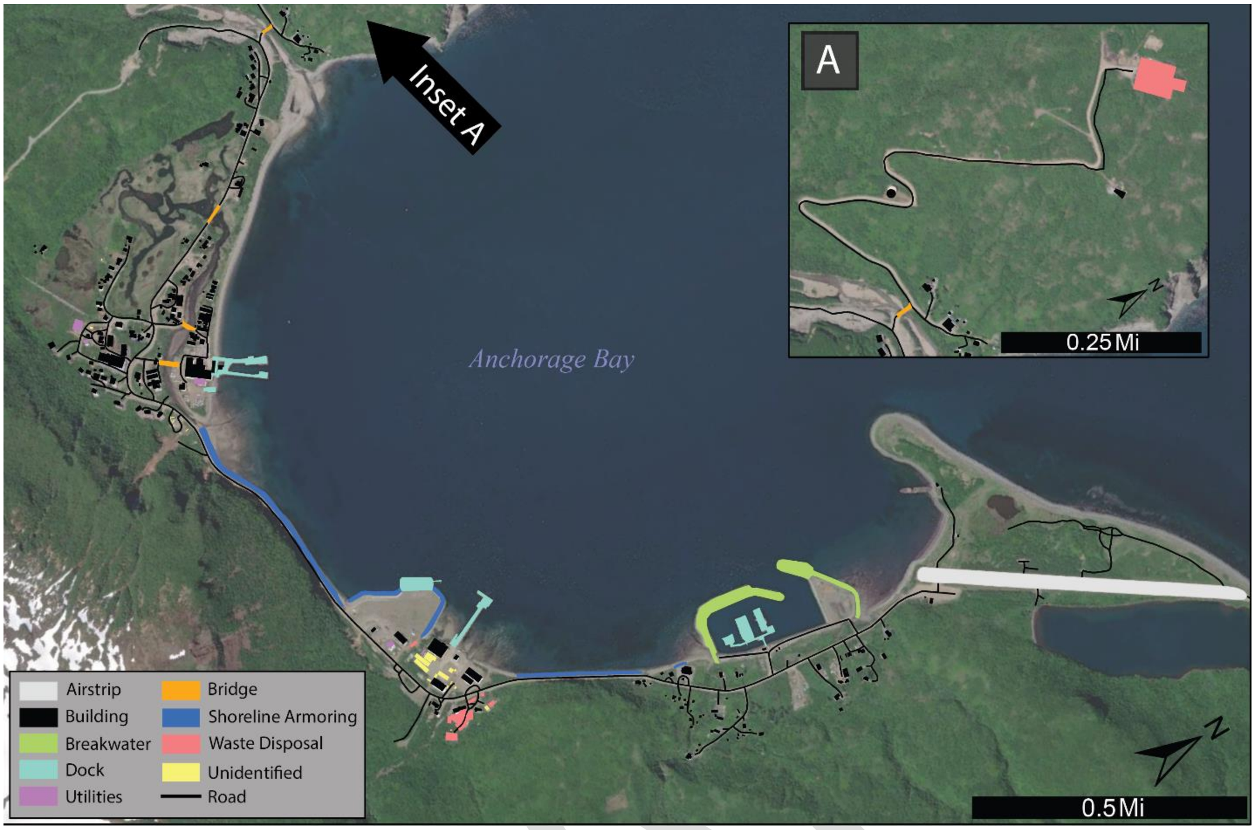

Figure 2. Map showing the building and utility infrastructure of Chignik Bay. (A) The extent of the community, (B) The waste disposal site. Data are displayed over ArcGIS base imagery provided by Esri.

2.3.2 Transportation

The primary methods of transportation within the community are four-wheel drive vehicles followed by all-terrain vehicles. Skiffs and air transportation are typically used to travel to surrounding communities. The unpaved road system consists primarily of sands. There is a 1.2km long by 23m wide gravel airstrip in the community with regular air traffic typically scheduled three days a week (HDR, 2011). There is an 80m long dock in the eastern section of the community with berthing areas large enough to receive commercial barges as well as a smaller boat loading ramp for smaller watercraft (HDR, 2011).

2.3.3 Economy

The main source of employment comes from the local government and health services with other manufacturing, construction, information, professional and business services, trade, transportation, and utilities (ALARI, 2018). The primary source of food for the community comes from a subsistence lifestyle (DCCED, 2018). The median household income in the community was $75,417per the Alaska Demographics 2021 report.

2.4 GEOLOGIC SETTING

Chignik is built on the Pacific side of the Alaska Peninsula, a volcanic arc formed by subduction zone processes. The city is approximately 30 miles east of Mount Veniaminof and 40 miles southwest of Mount Aniakchak, two historically active volcanoes (**Figure 3**). The U-shaped Anchorage Bay comprises sedimentary and volcanic rock formations with regions covered by unconsolidated alluvium. Three major sedimentary rock formations make up the bulk of the bay. The small dome of volcanic rock found in Anchorage Bay is an intrusive rock. The volcanic rocks covering the sedimentary formations south of Chignik are an unconformity from the Meshik Formation. Most of the surficial geology is hard rock, promoting a stable shoreline. Much of the city is built atop unconsolidated alluvium (silt, sand, and gravel) deposited by streams. There are several faults identified in the area.

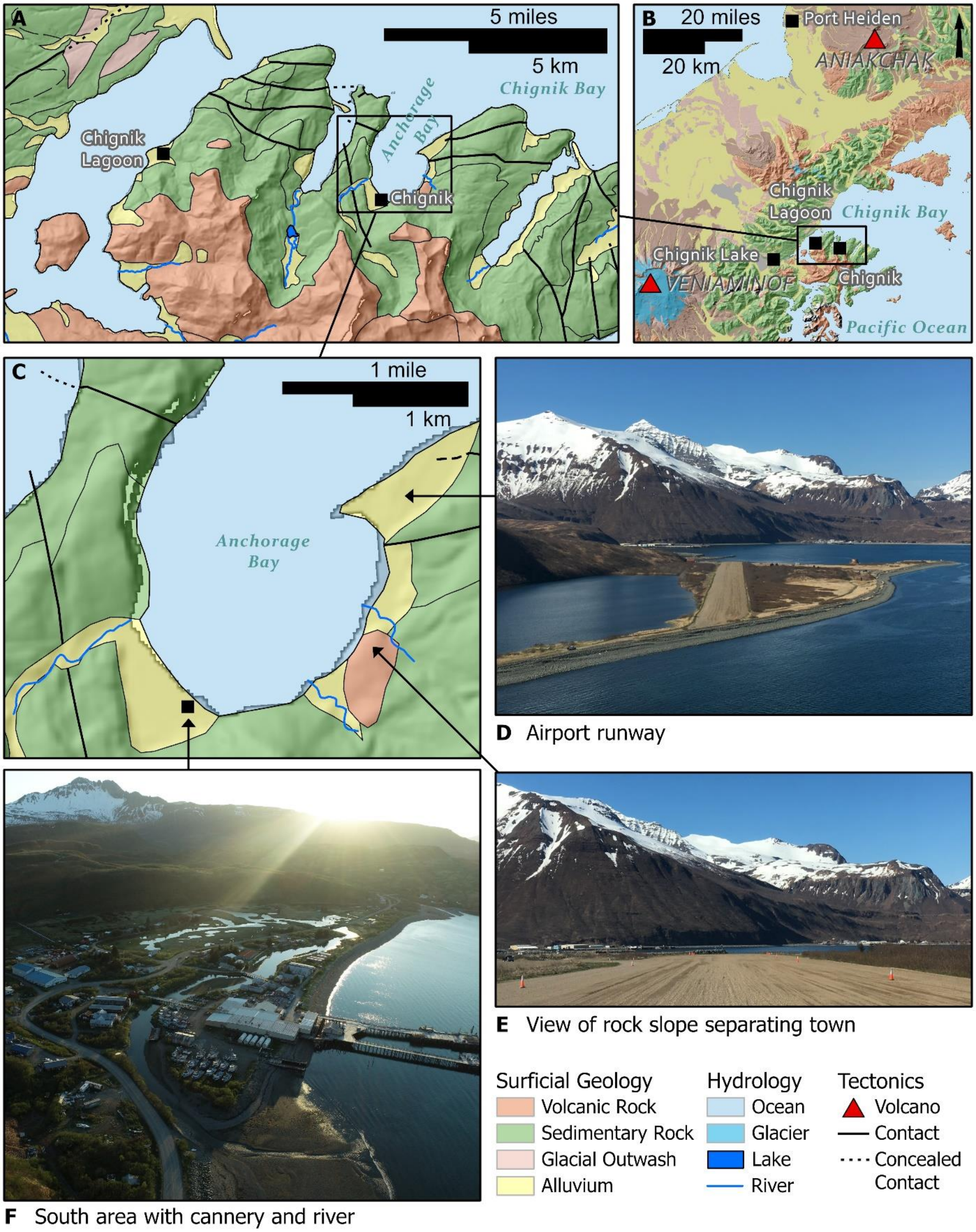

Figure 3. Surficial geology of Chignik (from Detterman et al., 1981). (A) The Chignik Bay area comprises sedimentary and volcanic rock with scattered alluvium deposits. Numerous faults exist. (B) This region is near two historically active volcanoes. (C) Anchorage Bay has mountainous hard-rock formations with three zones of unconsolidated sediments where Chignik is built. (D, E, F) Examples of Chignik in relation to surficial geology.

2.5 CLIMATE AND METEOROLOGY

2.5.1 Temperature Regime

Temperatures across Alaska have increased between 1970 and 2019. Southwestern Alaska and the Aleutian Island chain have observed temperature increases of between 2 and 5 °F over this period which could have significant ecological and physical impacts (**Figures 4, 5, 6**). Seasonal trends show an increase in temperatures, especially in regard to fall (**Figures 7 & 8**). The four warmest falls have all occurred within recent years and the warmest year exceeding the warmest summer temps (**Figures 7 & 8**).

Chignik Bay is located within the southwest maritime climate zone, characterized by persistently overcast skies, high winds, and frequent cyclonic storms (DCCED, 2018). Annual precipitation averages 127 inches, with an average annual snowfall of 58 inches (NOAA, November 2013). The average winter temperatures range from 21 to 50°F, and the average summer temperatures range from 39 to 60°F. Extreme temperatures range from as high as 76°F to as low as -12°F have been recorded (NOAA, November 2013).

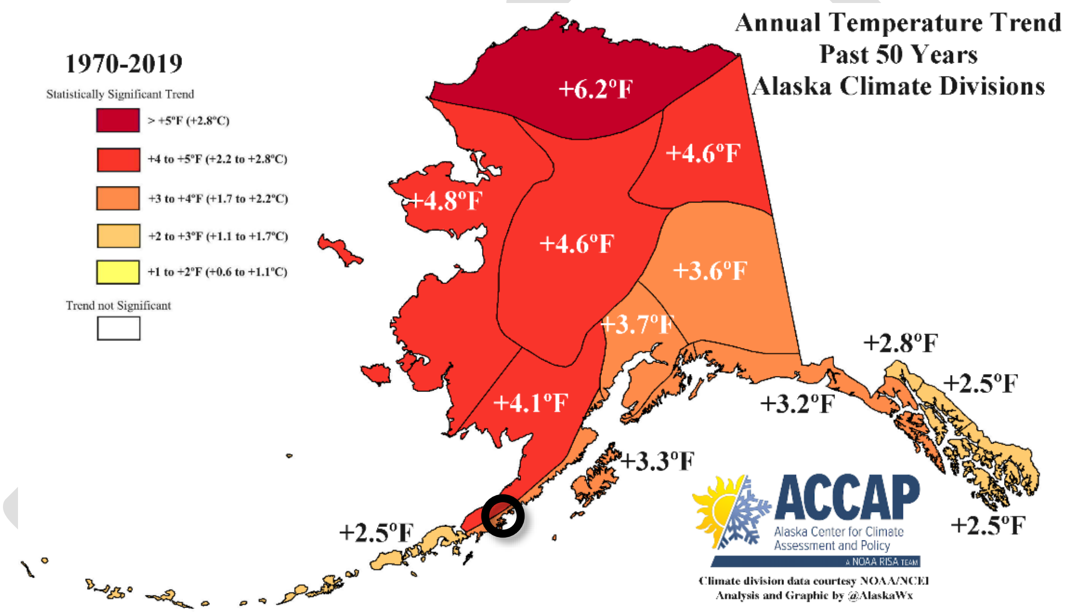

Figure 4. Annual temperature increase in Alaska between 1970 and 2019. Chignik Bay (black circle) has a 1.2°C (3.7°F) increase in temperatures over 49 years. Figure courtesy of Rick Thoman and ACCAP (URL: https://uaf-accap.org/air-temperature/).

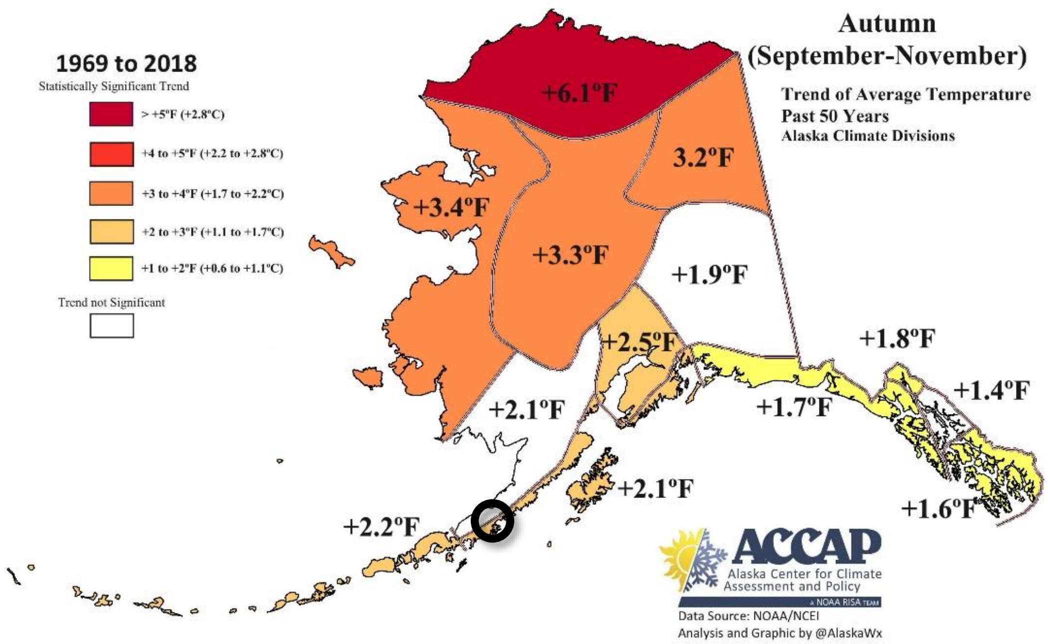

Figure 5. Autumn temperature increase in Alaska between 1969 and 2018. Chignik Bay (black circle) has a 1.2°C (2.2°F) increase in temperatures over 49 years. Figure courtesy of Rick Thoman and ACCAP (URL: https://uaf-accap.org/air-temperature/).

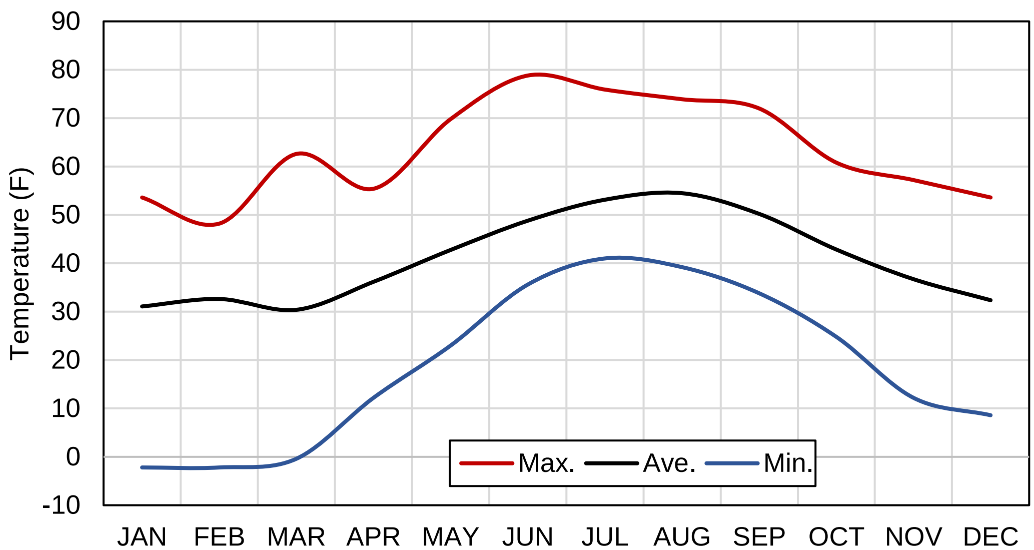

Figure 6. Temperature trends in Chignik Bay between 1997 and 2022 based on a local airport temperature gauge. Temperature data is from ASOS (URL: https://mesonet.agron.iastate.edu/request/download.phtml?network=AK_ASOS).

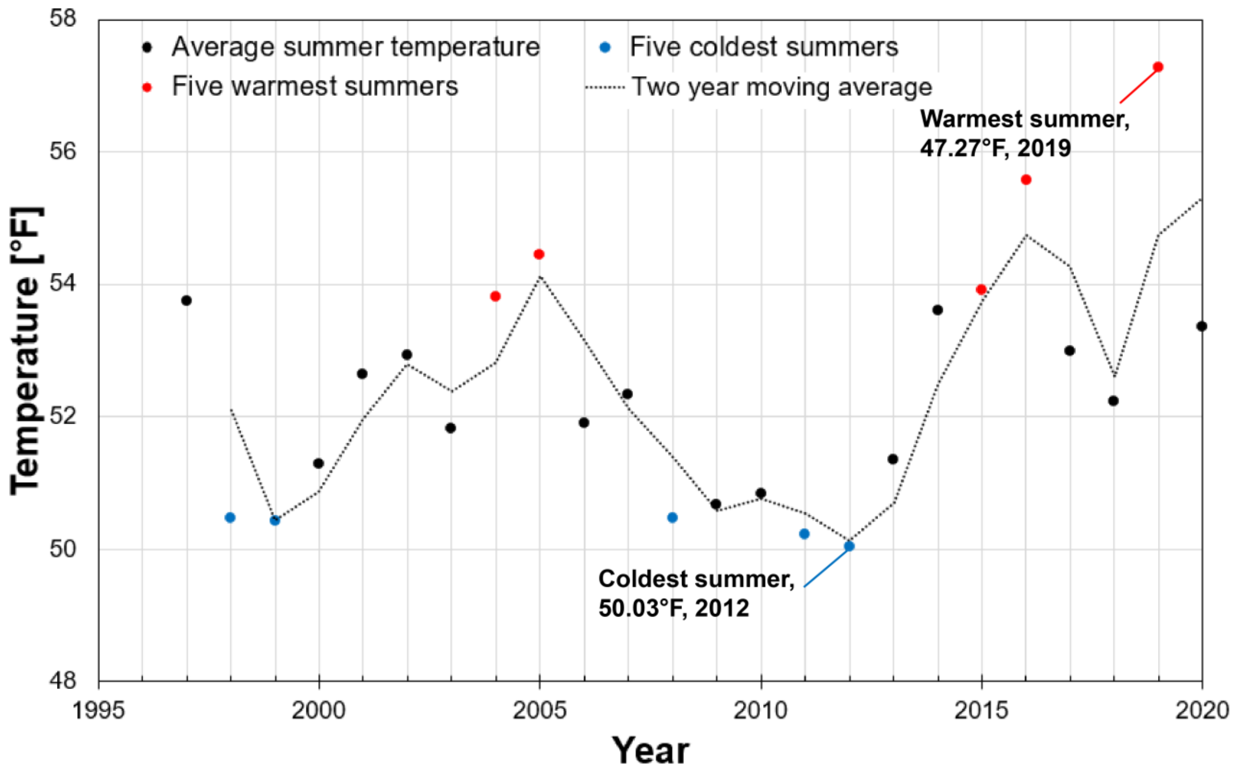

Figure 7. Mean summer (June-August) temperatures in Chignik Bay between 1997 and 2020 based on a local airport temperature gauge. The average summer temperature is 11.4°C (52.4°F). 2019 had the highest average temperature of 14.0°C (57.3°F), while 2012 had the lowest average temperature, at 10.0°C (50.0°F). Temperature data is from ASOS (URL: https://mesonet.agron.iastate.edu/request/download.phtml?network=AK_ASOS).

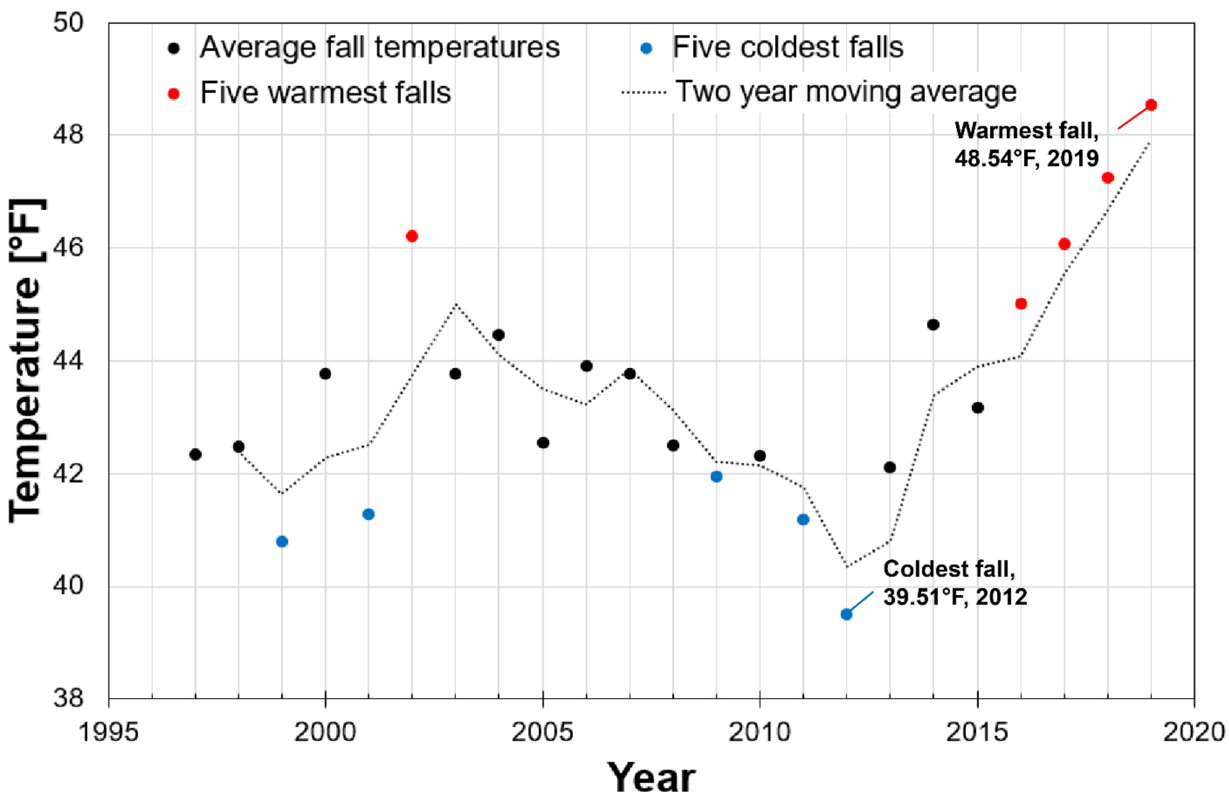

Figure 8. Mean fall (September-November) temperatures in Chignik Bay between 1997 and 2020 based on local airport temperature gauge. The average fall temperature was 6.4°C (43.5°F). The highest average fall temperature was 9.2°C (48.5°F) in 2019, while the lowest average temperature was 4.2°C (39.5°F) in 2012. Temperature data is from ASOS (URL: https://mesonet.agron.iastate.edu/request/download.phtml?network=AK_ASOS).

2.5.2 Wind Regime

Records of wind strength and direction at Chignik Bay were compiled from ASOS via the Iowa State University Environmental Mesonet (**Figure 9**). The dataset was recorded at the Chignik Bay airport (SID: PAJC) and spans 27 years. The plotted data show that winds predominantly prevail from the northwest and are strongest during the winter months, whereas prevailing wind direction is more variable during the summer months.

Chignik wind measurements from 1996 through 2023 shows winds average 9.3 mph and most commonly blow from the northwest (**Figure 9**). Winds are strongest during the winter months (**Figure 10**). The windier part of the year is from October to April, with average wind speeds of more than 10.3 mph. December is the windiest month of the year, with an average hourly wind speed of 11.1 mph. The calmer time of year is from May to September, with average wind speeds of 7.9 mph. The calmest month of the year is July, with an average hourly wind speed of 6.7 mph. Prevailing wind direction is more variable during the summer months.

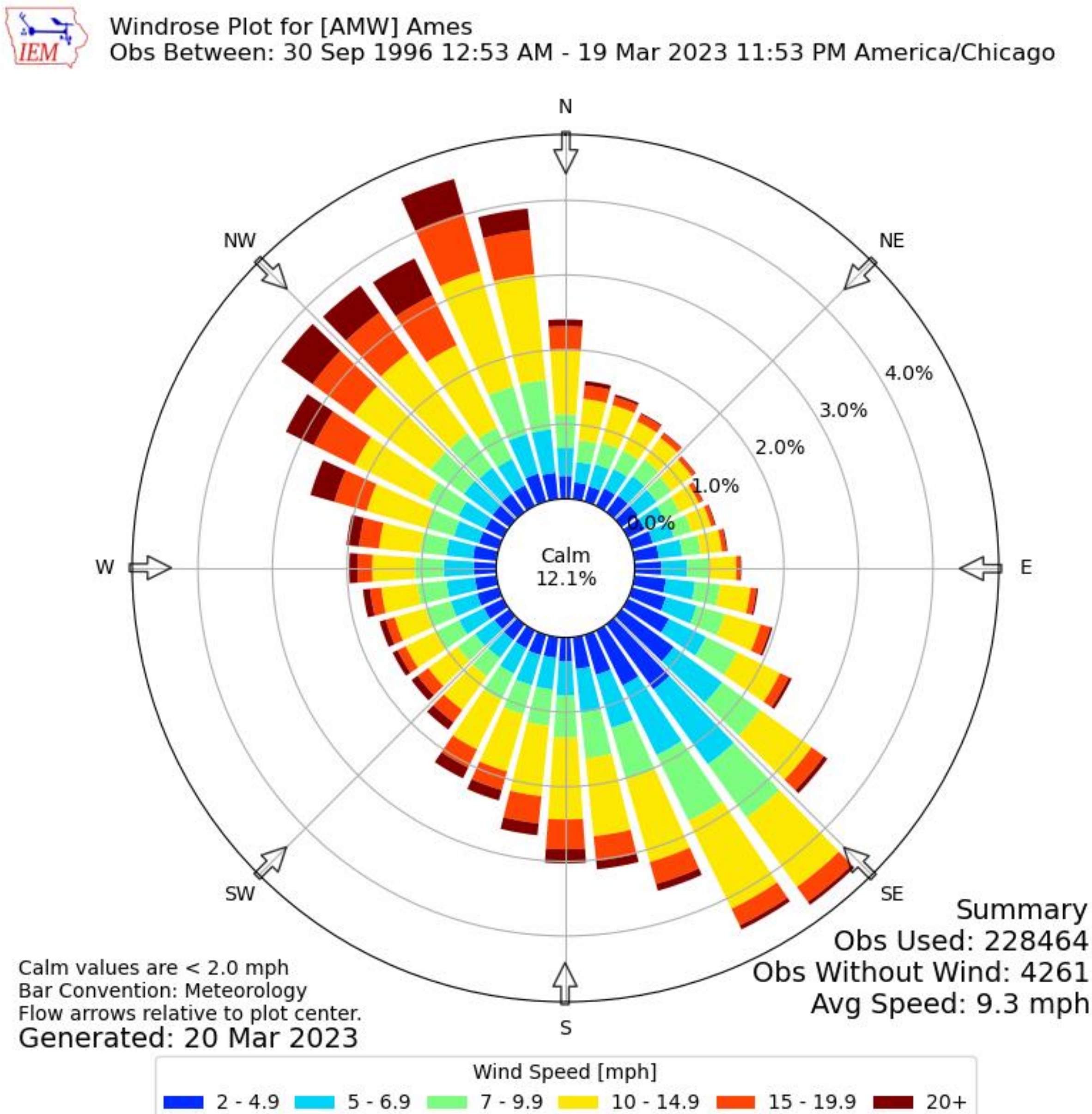

Figure 9. Average yearly wind rose for Chignik Bay computed from 1996 through 2022. Spokes point in the compass direction from which winds traveled. Colors within each spoke denote wind speed bins and the length of the spokes denote the frequency of occurrence. Wind is most frequent from the northwest and can exceed 20 mph (URL: https://mesonet.agron.iastate.edu/ASOS/).

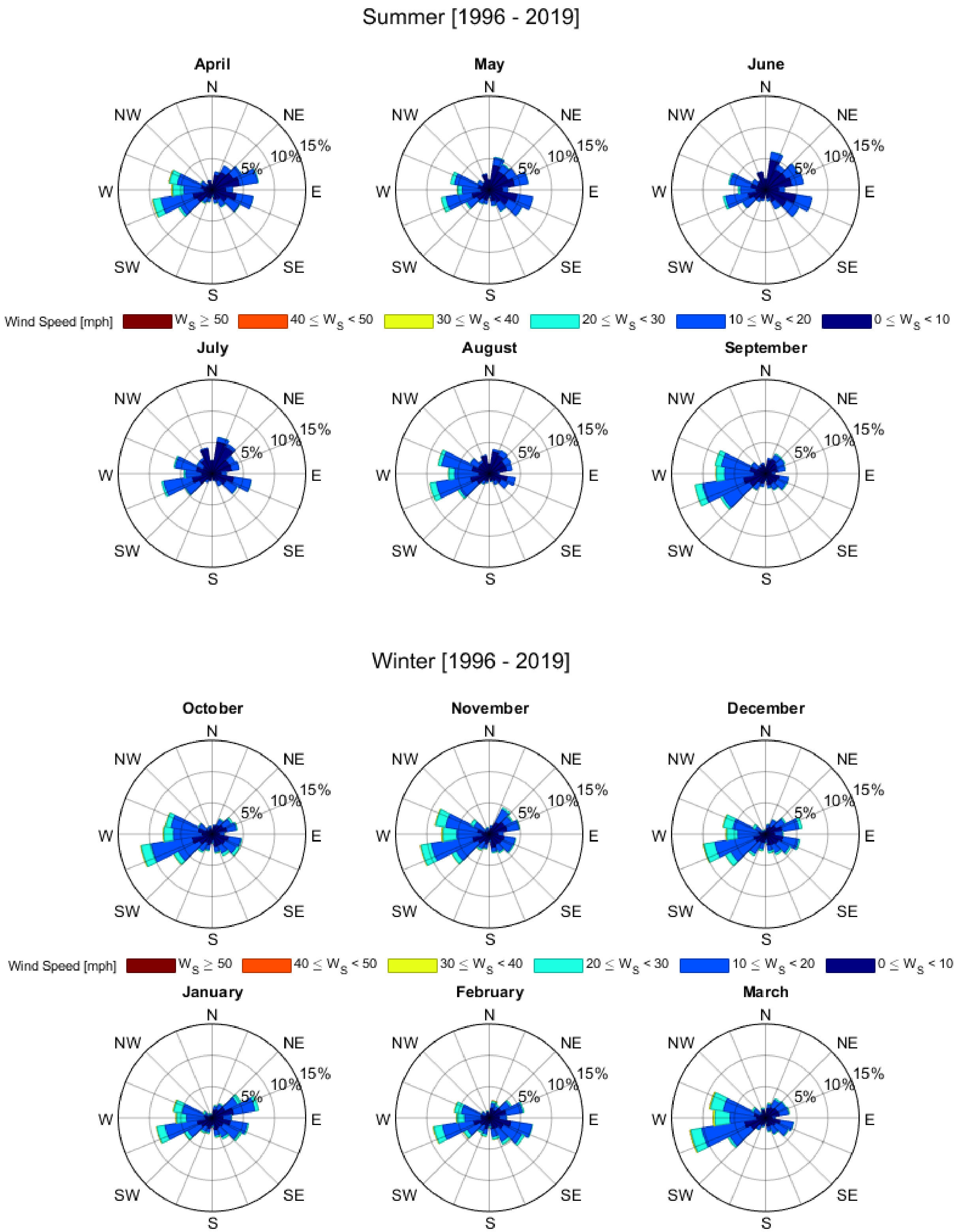

Figure 10. Averaged monthly wind roses for Chignik Bay (1996-2019). Spokes in each plot point in the compass direction from which winds traveled. Colors within each spoke denote wind speed bins and the

length of the spokes denote the frequency of occurrence. For example, in January, 10 mph to 20 mph winds were common and prevailed from the west. (URL: https://mesonet.agron.iastate.edu/ASOS/).

2.5.3 Storm Regime

Cyclones reaching the Gulf of Alaska most often come from the Pacific Ocean. According to the Beaufort Wind Scale, an extratropical cyclone is categorized as a storm when the wind speed attains values greater than 53.7 mph (24.5 m/s; WMO, 1970). Storms can last anywhere from 12 to 200 hours (up to >8 days), depending on the season and local geography, and can vary in size from mesoscale (≤1000 km) to synoptic scale (>1000 km). Storms are often associated with damaging winds (Mesquita et al., 2010) and/or strong precipitation in the form of rain and snow (Sorteberg and Walsh, 2008).

Chignik Bay is in a region of moderate to high storm track density, especially during fall (Stabeno et al., 2004; **Figure 11**). Storms in the region linger due to surrounding mountains that inhibit eastward progression (Wilson and Overland, 1986). Winds in the region are cyclonic typically from the fall season throughout the spring (Stabeno et al., 2004). While wind data has not been well recorded, there have been max wind speeds of almost 67mph with gusts of over 100mph recorded (ASOS, 2023).

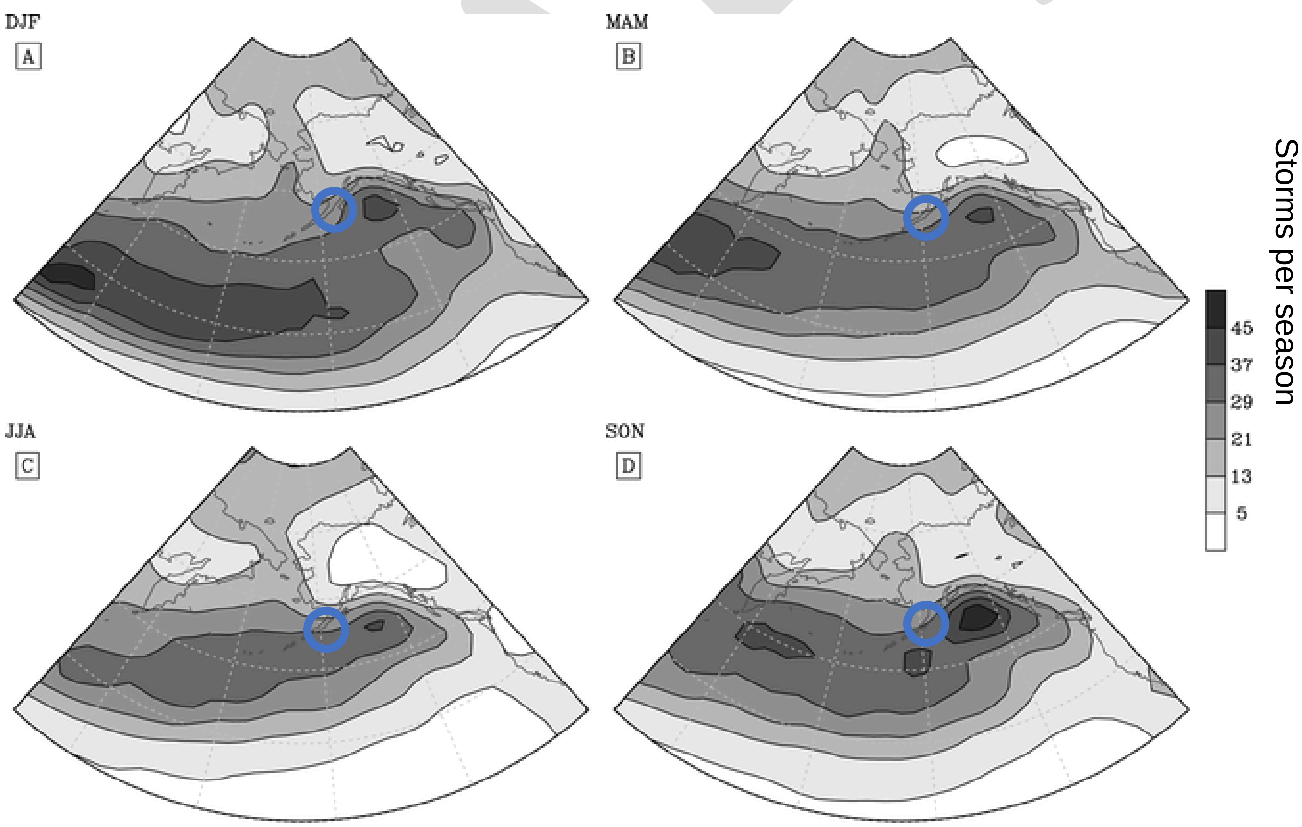

Figure 11. Storm track density climatology in the North Pacific from 1948/49 to 2008. (A) winter (DJF), (B) spring (MAM), (C) summer (JJA), and (D) autumn (SON) seasons. Units: Storms (10^6 km^2 season)$^{-1}$. Location of Chignik Bay is noted by the blue circles. Notice that Chignik Bay observes greater than 21 storms per season on average (after Mesquita et al., 2009). (URL:https://doi.org/10.1175/2009JCLI3019.1).

2.6 OCEANOGRAPHIC SETTING

2.6.1 Tides and Currents

Chignik has semi-diurnal tides with a great diurnal range of 8.93 ft (2.722 m; **Table 1**). The Alaska Coastal Current flows southwest (**Figure 12**).

Table 1. Tidal datum for Chignik, Anchorage Bay (NOAA station ID 9458917).

Datum	Abbreviation	Ft MLLLW	M MLLW
Mean Higher-High Water	MHHW	8.93	2.722
Mean High Water	MHW	8.13	2.477
Mean Tide Level	MTL	4.79	1.459
Mean Sea Level	MSL	4.70	1.432
Mean Diurnal Tide Level	DTL	4.47	1.361
Mean Low Water	MLW	1.45	0.441
Mean Lower-Low Water	MLLW	0.00	0.000
North American Vertical Datum of 1988	NAVD88	1.61	0.490
Great Diurnal Range	GT	8.93	2.722
Mean Range of Tide	MN	6.68	2.036

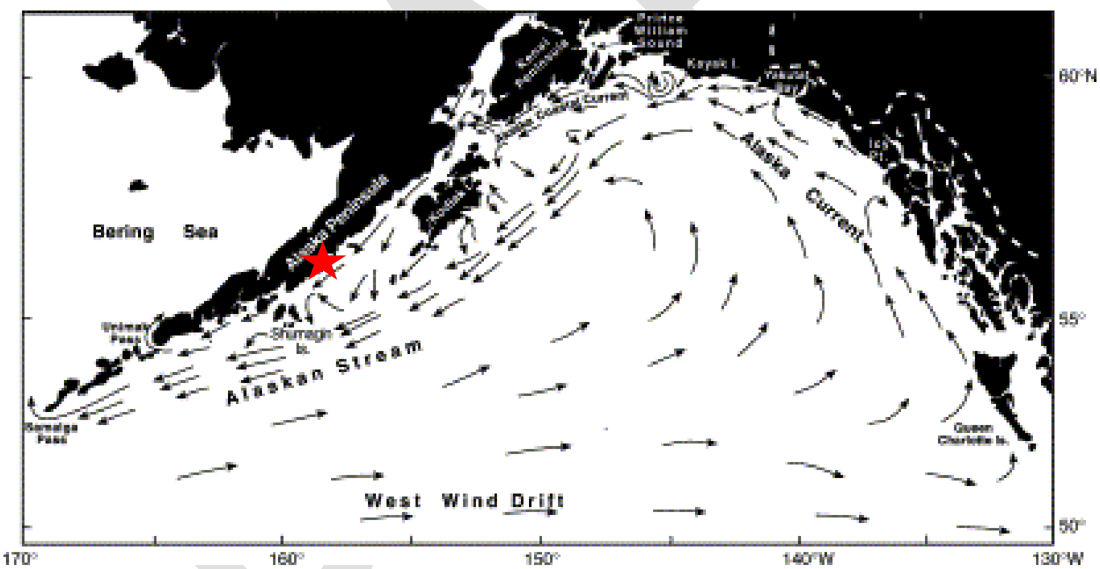

Figure 12. Map of the Gulf of Alaska. The red star represents Chignik Bay. The flow of the Alaska Coastal Current and subarctic gyre are indicated as are several geographic place names. (After Reed and Schumacher, 1986).

2.6.2 Wave Climate

The mean significant wave height (SWH) in Chignik Bay is 1.20 m (SD = 0.32 m), reaching as high as 2.49 m in December 2000 (**Figure 13**). Monthly Mean SWH is lowest in July (0.79 m) and greatest in December (1.59 m). Average annual SWH increased by 0.08 m (7%) from 1959 to 2022. Mean monthly SWH values were modeled by Hersbach et al. (2020).

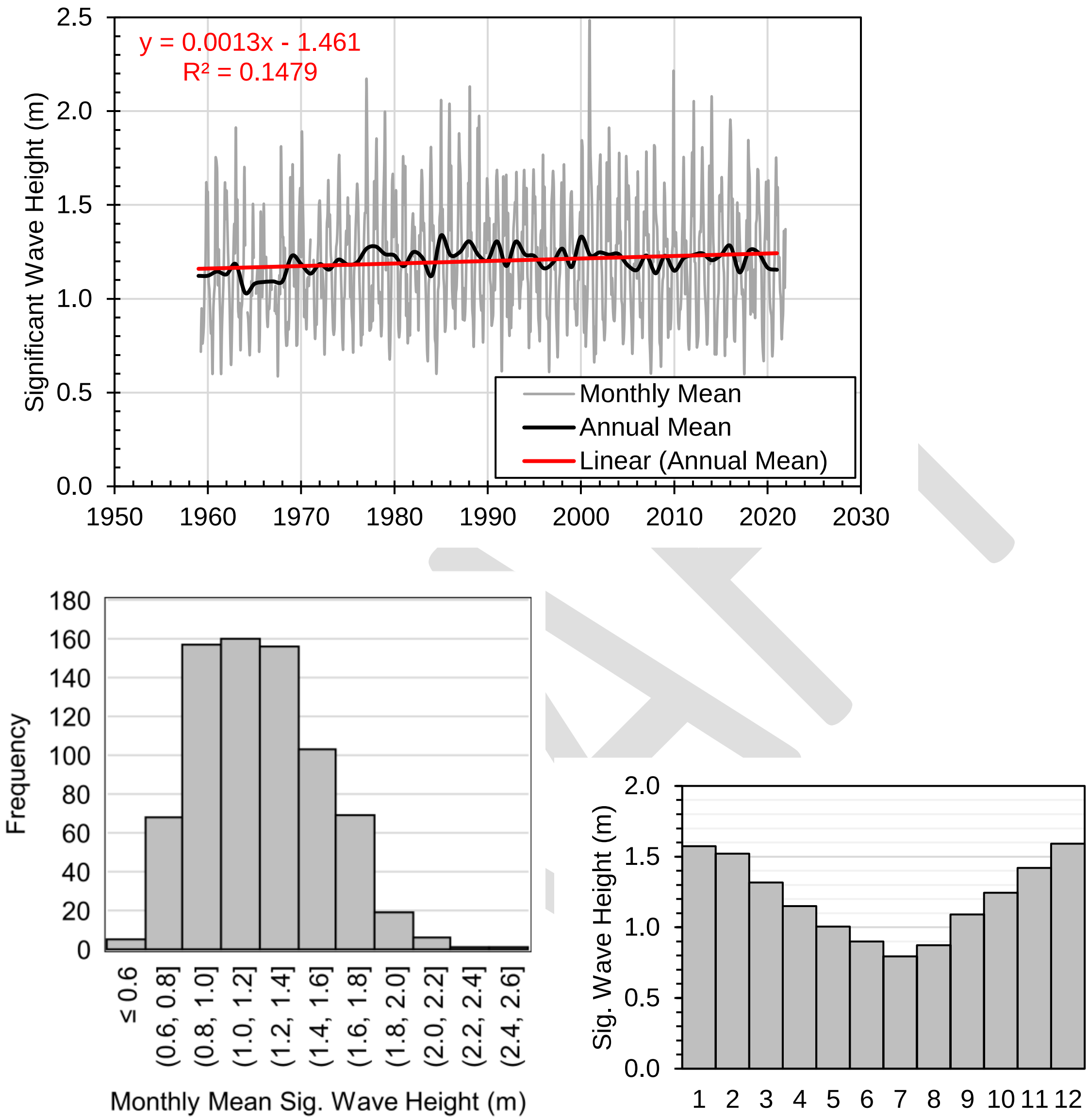

Figure 13. Significant wave height (SWH) statistics for Chignik Bay. (Top) Monthly (gray) and annual (black) mean SWH from 1959 through 2021. The linear regression of annual SWH (red) shows a slight increase but interannual variability is very high. (Bottom Left) Histogram of SWH shows the average is 1.20 m with SD 0.32 m. Values range between 0.5 to 2.6 m. (Bottom Right) Monthly mean SWH shows SWH is greatest in winter and lowest in summer.

2.7 SEA ICE

Coarse-resolution global sea ice models indicate sea ice does not have a significant presence in Chignik Bay. The model used by Hersbach et al. (2020) shows on average 1 month per year of wave-dampening sea ice existed from 1959 to 1971, but this is no longer the case. Sea ice does not play a significant role in Chignik Bay.

3. NATURAL HAZARDS AND MITIGATION EFFORTS

3.1 DESCRIPTION OF HAZARDS

The following subsections (3.1.1 – 3.1.6) describe and quantify the following natural hazards: erosion, flooding, earthquakes, landslides, tsunami, and sea level change. This list specifically pertains to *coastal* related hazards and is partially based on information in the Lake and Peninsula Borough Hazard Mitigation plan and observations by residents. As such, potential non-coastal natural hazards like volcanoes and wildfire are not examined by this report.

3.1.1 Erosion

Shoreline change is the retreat or aggradation of a shoreline as a result of sediment erosion or accretion (Mangor et al., 2017). Shoreline change can occur because of changing sediment supply, oceanographic conditions, episodic storm events, terrestrial degradation through slope failure or permafrost thaw, and other nature- and human-driven processes (**Figure 14**) (Overbeck et al., 2020). Shorelines are naturally very dynamic; however, when changes occur at or near infrastructure and land used for hunting or gathering subsistence resources, erosion can be disastrous.

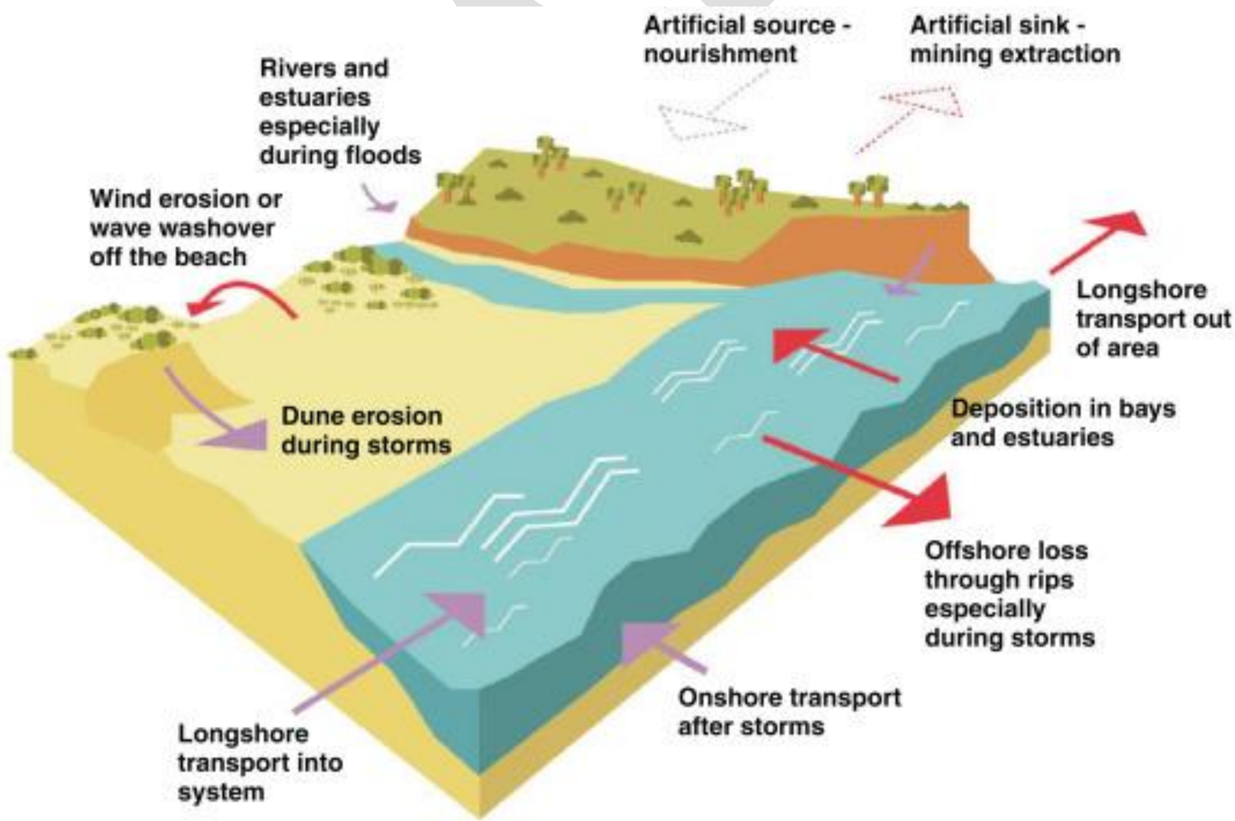

Figure 14. Components of a sediment budget for a sandy coast. From Goodwin et al., 2020 (URL: https://doi.org/10.1016/B978-0-08-102927-5.00025-4).

Riverine flooding can also occur. This may result from heavy rainfall, snowmelt, or a combination of these with a high tide or storm surge.

According to the Chignik Bay Tribal Hazard Mitigation Plan (2019), the erosion of highest concern is the spring runoff in rivers and creeks eroding through the community to the point where homes and the community's infrastructure (utilities, roads etc.) are undermined. Critical assets located near erosion areas include bridges, homes, access roads, the airport, and the clinic. Because the two parts of the community are connected via a road that has been affected by erosion, access to any asset between the two sides can be affected (Chignik Bay Tribal Hazard Mitigation Plan 2019).

3.1.2 Flooding

Coastal flooding is predominately caused by storm surge during high tide (USACE, 2009). Storms drive water to the coastline and raise water levels above normal tide levels (storm surge and wave set-up). As waves break, they can travel up the beach (wave run-up) and temporarily reach higher than the still water level (Sallenger, 2000).

Total water level (TWL) is a summation of the tide, setup, and wave run-up (Erikson et al., 2018) and can be generalized as the combination of 1) a static (or assumed static or slowly varying) mean water level associated with astronomical tides, storm surges, and wave setup; and 2) a fluctuation about that mean (swash) associated with surf beat and the motion of individual waves at the shoreline (**Figure 15**). Wave run-up can add meters to the total water level on the open ocean coast. This also controls the elevation of the primary dune toe and wave impact hours (as computed from a TWL time series; Ruggiero et al., 2001; Ruggiero, 2004).

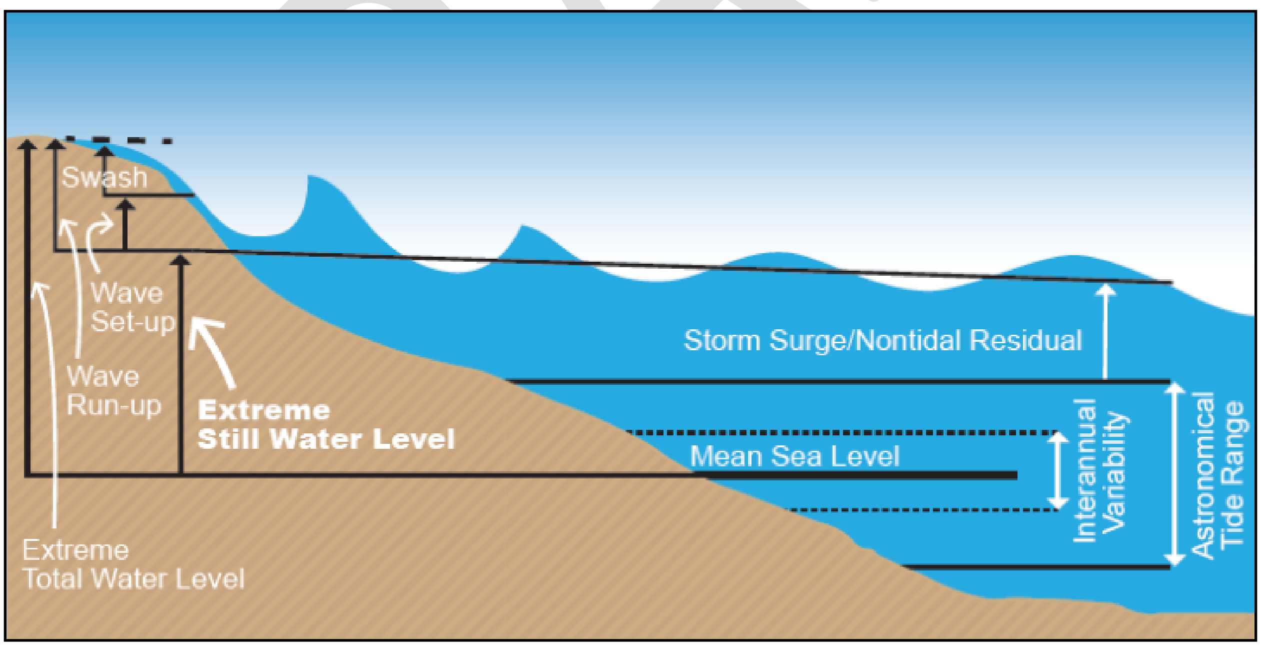

Figure 15. Diagram showing the various components of Total Water Level (TWL); waves, tides, and nontidal residuals. After Moritz et al., 2015.

The Chignik Bay Tribal Hazard Mitigation Plan (2019) explains that annual flooding occurs due to spring melt runoff and rainfall. High tide combined with spring melt can lead to flooding of low-lying areas including the airport runway. Flooding occasionally impacts homes, basements, and other structures. Roads have been built higher to prevent flooding and washouts, but issues from widespread flooding persist.

Chignik Bay does not have a clear or extensive record of the highest known flood, annual flood levels, or flood impacts (**Table 2**). These metrics are invaluable to support endeavors to reduce flood impacts. Chignik Bay does not have a water level sensor to record coastal flooding. FEMA does not have flood maps for this location. A survey of flood records and community infrastructure can be used to inform the elevation for safe construction and even aid in forecasting impacts from storms. A high-resolution DEM can be used to map flood extents and depths.

Table 2. Table of documented flooding events in Chignik Bay from hazard mitigation plans and USACE.

Date	TWL (m)	Cause	Impacts
2018	Unknown	Not specified	12 inches standing water in City Office building[1]
2002-OCT-23	Unknown	Heavy rain, storm surge	Damage to docks, piers, bridge, and homes.[2]
1986-DEC-31	Unknown	Not specified	Photo[2]
1948-OCT	Unknown	Storm surge	See appendix

[1]Chignik Bay Tribal Council (2019)

[2]Lake and Peninsula Borough (2015)

3.1.3 Earthquakes

The USGS produces probabilistic seismic hazard maps based on earthquake history and seismic potential based on the location, depth, and characteristics of geologic faults (**Figure 16**;Wesson et al., 2007). These maps indicate the probability of an earthquake event exceeding a certain measure of ground acceleration, which correlates with the most intense shaking experienced during an earthquake event. The USGS standardizes acceleration into three measures: peak ground acceleration (PGA), 0.2 second spectral acceleration (SA), and 1.0 second SA. Each of these is measured in %g, or percent of the force of gravity. PGA measures particle movement at ground level, whereas SA describes the maximum acceleration in an earthquake on an object – specifically a damped, harmonic oscillator moving in one dimension. 0.2-0.6 second SA is applicable to buildings with less than seven stories. As such, we utilize PGA and 0.2 second SA.

An earthquake with a magnitude of above a 7.0 on the moment magnitude scale is considered a major earthquake (Michigan Technological University, 2021). The Community is located approximately 512 miles southwest of the 1964 earthquake epicenter, the largest recorded earthquake in Alaska. The community is not located on any mapped fault lines. The largest earthquake that has occurred within a 75 miles radius of the community was a magnitude 8.2 on the Richter scale, located 28.5 miles away on the Alaska Peninsula in July 2021 (Chignik Bay Tribal Hazard Mitigation Plan

2019). The closest earthquake to occur near the community above a magnitude 2.5 was a magnitude 2.8 earthquake that occurred 1.7 miles away in June 2006 (USGS 2018).

The most severe earthquake felt in the Community was the Great Alaska Earthquake of 1964 (Alaska Earthquake Center 2018). This earthquake had a recorded magnitude of 9.2 on the Richter scale, making it the second largest recorded earthquake in the world.

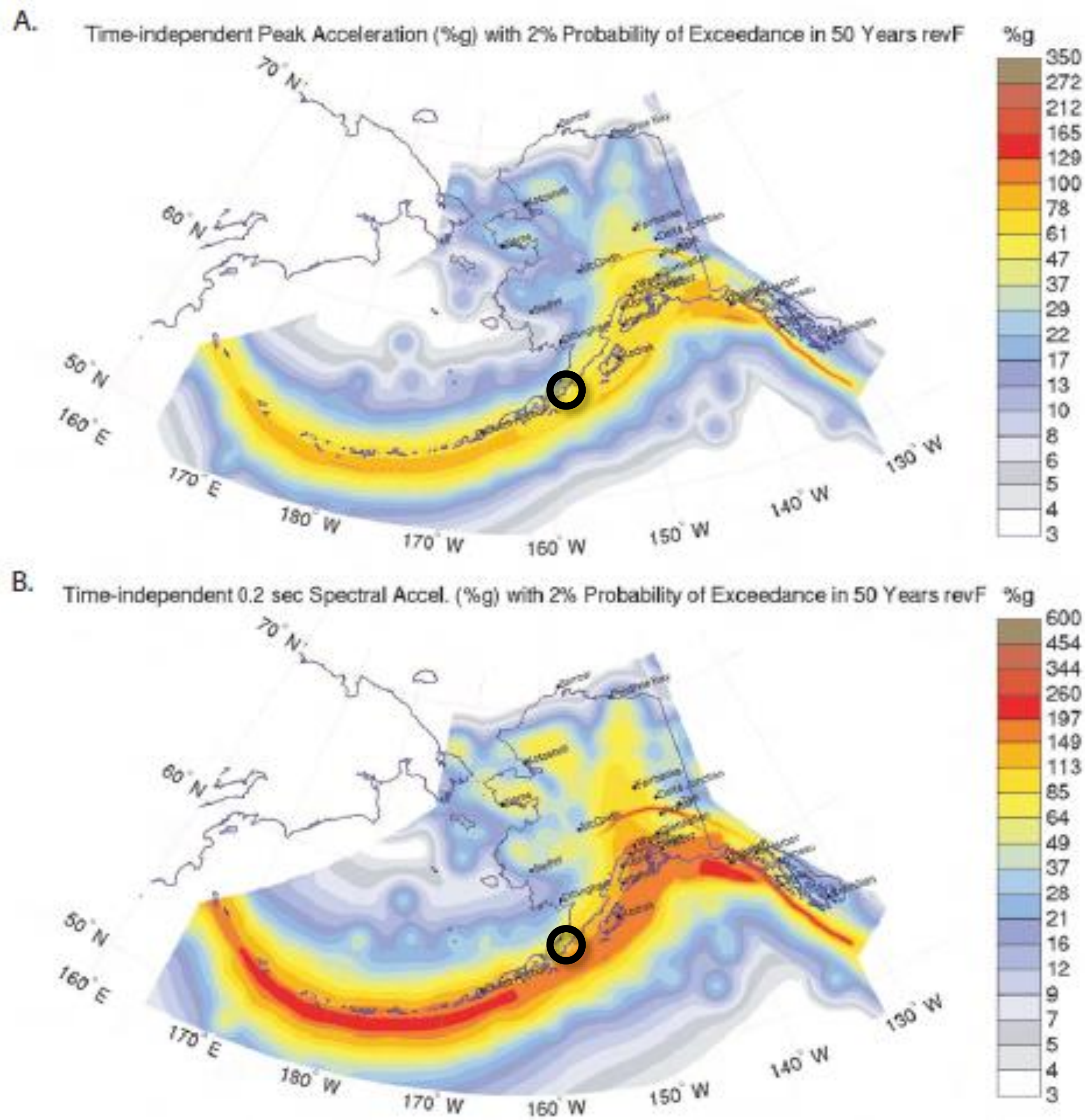

Figure 16. Earthquake probability in Alaska . Probabilistic ground motion with a 2-percent probability of exceedance in 50 years for peak ground acceleration (A), 0.2 second spectral acceleration (B). Nelson Lagoon noted by blue circle. (URL: https://www.usgs.gov/natural-hazards/earthquake-hazards/hazards).

3.1.4 Mass Land Movement

An avalanche is the movement of snow and debris down a slope by force of gravity. Avalanches occur when the stability of the slope changes from stable to unstable. This can be caused by storms, earthquakes, volcanic eruptions, rapid temperature changes, and other human activities. Steep slopes and long slopes have a higher probability to slide.

A landslide is the movement of a mass of debris, rock, or earth by force of gravity down a slope (Cruden and Varnes 1996). This can be caused by storms, earthquakes, volcanic eruptions, fire, erosion, and other human induced activities (Gariano and Guzzetti 2016). Steep slopes and long slopes have a higher probability to slide. Landslides cause infrastructure and property damage, environmental disturbance, and possible injuries and fatalities (Petley 2012).

According to the Chignik Bay Tribal Hazard Mitigation Plan (2019), avalanches occur on the mountains surrounding the community. The areas above the road sections that connect the two sides of the community have long, steep slopes. When avalanches occur, access to critical infrastructure for residents on opposite sides of the avalanche is cut off (Chignik Bay Tribal Hazard Mitigation Plan 2019). For example, the airstrip and medical clinic are located at the north end of town and is accessible only by the main road that runs along the base of steep slopes. If access to this road is obstructed, the airstrip becomes inaccessible to the southern end of the community. In 2002, such was the case when an avalanche obstructed the main road to the airport, separating the north and south ends of town for 2 weeks.

Landslides occur on the mountains surrounding the community (Chignik Bay Tribal Hazard Mitigation Plan 2019). In addition to landslides, large boulders and rocks fall from these steep slopes and pose a threat. Falling boulders or rocks can hit travelers, or land on the road causing a road hazard. When landslides occur, they cut off access to critical infrastructure and can wash out the road. Reportedly, large masses of soil and large rocks slough off or topple down onto the road (Chignik Bay Tribal Hazard Mitigation Plan 2019).

3.1.5 Tsunami

A tsunami is a large, fast-moving wave caused by the displacement of a large volume of water. They can be triggered by earthquakes, volcanic eruptions, submarine landslides, and onshore landslides. Tsunamis caused by earthquakes are generated from the epicenter offshore. With adequate detection, this usually allows warning times of minutes to hours. Tsunamis generated by eruptions and landslides are called “local tsunamis” and have little warning time. Local tsunamis can potentially reach much higher in the area they were generated. For example, the 1964 earthquake caused tsunami waves up to 90 ft (27 m), but a landslide in Valdez Inlet caused a local tsunami reaching 220 ft (67 m). Tsunami waves can bounce off shorelines and cause complex changes to water levels. This process, called seiche, may have occurred in Chignik Lagoon in 1964. The first wave arrived 3 hours after the earthquake, but the highest wave occurred 6 to 7 hours after (Nicolsky et al., 2016).

Chignik experienced tsunamis in 1946 and 1964 that caused water elevation of 5 ft (1.5 m) and 10 ft (3 m), respectively. These were caused by subduction zone ruptures of magnitude 8.6 (1946) and 9.2 (1964). A worst-case tsunami scenario (magnitude 9.25) could result in coastal areas flooded to 80 ft (24 m) with a maximum depth of 102 ft (31 m) on Anderson Street (Nicolsky et al., 2016; **Figure 17**). Evacuations on foot could require up to 43 minutes. While the impacts would be devastating, there is a small likelihood of an earthquake of this magnitude happening any given year. Nicolsky et al. (2016) model earthquakes on the Alaska Peninsula at varying depth between magnitude 8.9 and 9.25. Since at least 1899, only one Alaska earthquake occurred in this range (1964). There were 9 earthquakes between 8.0 and 8.7 magnitude (1 every 13 years on average). The 1964 earthquake is believed to be a 500-year event and may have last ruptured in 1585. Since 1900, earthquakes of magnitude 8.0 to 8.7 have occurred every 14 years on average throughout the entire state. The epicenter location and depth have to be in the correct configuration to affect Chignik, reducing the likelihood an event would cause a tsunami. However, the tsunami generated by local landslides or seiche is also possible.

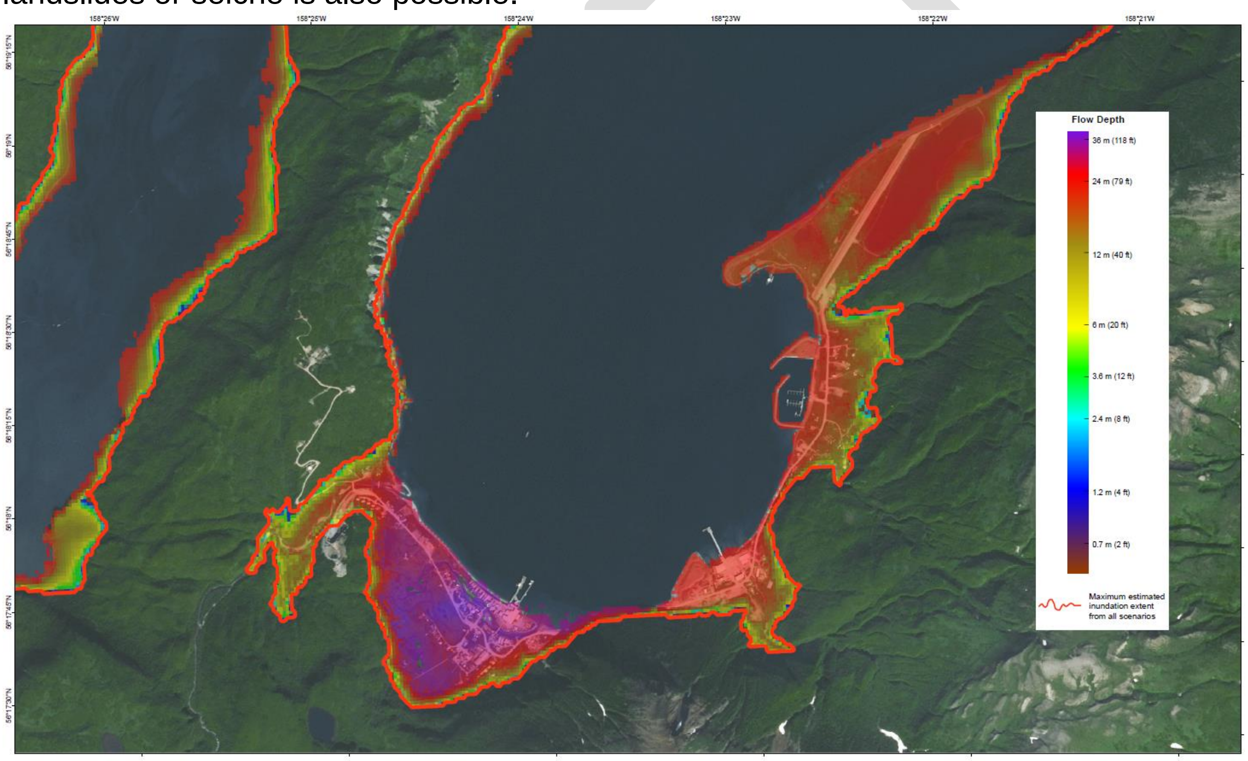

Figure 17. Tsunami hazard map of Chignik Bay (red hatched line represents hazard zone with hatch marks toward potential inundation zone). The map is not appropriate for site-specific use or for land-use regulation (CBTC, 2019).

3.1.6 Sea Level Change

A large number of studies worldwide suggest that over the past 1,000 years global average (eustatic) sea level has risen at a rate of <2mm (<0.08 in) per year (Gornitz, 1995). Eustatic sea level has risen about 21–24 cm (8–9 in) since 1880, with about a third of that occurring in the last 25 years. The rising water level is mostly due to a combination of meltwater from glaciers and ice sheets and thermal expansion of seawater as it warms. In 2019, global mean sea level was 87.6 mm (3.4 in) above the 1993 average—the highest annual average in the satellite record (1993-present). From 2018 to 2019, global sea level rose 6.1 mm (0.24 inches) (Wuebbles et al., 2017; Cazenave et al., 2018; Davidson-Arnott et al., 2019).

Sand Point is the closest geodetically referenced station, 164 km away from Chignik Bay. Relative sea level rise (RSLR) is the combination of eustatic (global) sea level rise and local land subsidence (or in some cases, rise in land elevation). This local change in land elevation has a variety of causes, such as earthquake deformation cycles, groundwater reduction or increase, oil extraction, etc. RSLR in the Chignik area is 1.35 ± 0.83 mm/yr (0.44 ft/century; **Figure 18**).

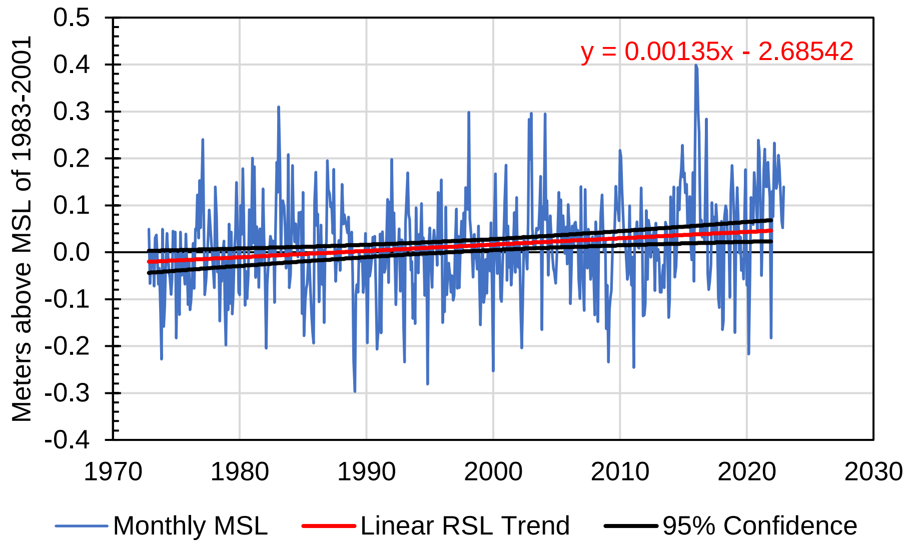

Figure 18. Monthly mean sea level (blue) from 1972 to 2022 at Sand Point (Station ID: 9459450) with average seasonal cycle removed. The long-term linear trend (red) is 1.35 mm/yr with uncertainty of 0.83 mm/yr at a 95% confidence interval (black). Water levels are relative to MSL from the National Tidal Datum Epoch of 1983 to 2001. (URL: https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=9459450).

RSLR is anticipated to accelerate due to warming, but the rate of acceleration is complex to predict due to several factors including anthropogenic actions and uncertainty about ice-sheet response. Sweet et al. (2022) anticipate a high likelihood of global mean sea level (GMSL) exceeding 0.5 m by 2100, with a <5 to 23% probability of exceeding 1.0 m if warming reaches 3 to 5ºC. Exceeding 1.5 m by 2100 is less likely given the current understanding of ice-sheet response.

RSLR projections for Chignik Bay are shown for three scenarios of GSLR by 2100 of 0.5, 1.0, and 1.5 m (**Table 3**, **Figure 19**). Levels are relative to mean sea level in 2005. There is a reasonable likelihood of 13-17 cm (0.4-0.6 ft) by 2050 and 36-80 cm (1.2-2.6 ft) by 2100.

Table 3. RSLR projections for Chignik Bay computed from global models by Sweet et al. (2022). Rows represent different RSLR scenarios depending on GMSL. Each scenario has a probability of happening

given the anticipated warming of 2ºC by 2100 and less likely but possible warming up to 5ºC. Projections are split into three dates (2050, 2100, and 2150), then subdivided into mean values and the low and high boundaries of a 95% confidence interval. Projections are in cm above Chignik Bay modeled MSL in 2005.

GMSL by 2100	Likelihood for 2 to 5ºC	2050 (cm)			2100 (cm)			2150 (cm)		
		Low	Mean	High	Low	Mean	High	Low	Mean	High
0.5 m	50 to >99%	9	13	18	24	36	47	39	61	85
1.0 m	<5 to 23%	12	17	25	59	80	93	105	160	349
1.5 m	<1 to 2%	16	24	38	92	130	148	155	224	330

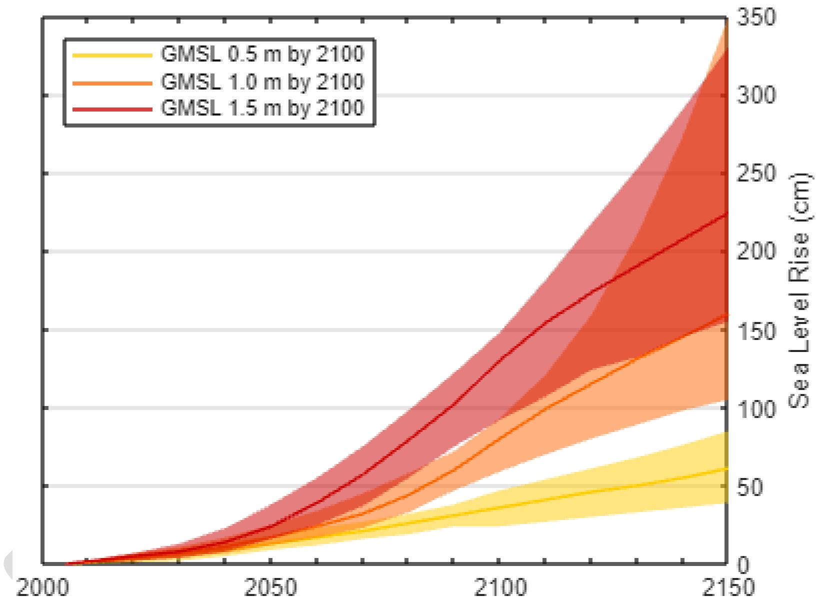

Figure 19. Graph of RSLR projections for Chignik Bay. Mean projected values are solid lines with the colored area representing a 95% confidence interval. The GMSL 1.0 and 1.5 scenarios have faster RSLR rates beginning around 2070.

3.2 PAST/ONGOING MITIGATION EFFORTS

The community of Chignik Bay has drafted a pre and post mitigation plan in the 2020 Tribal Hazard Mitigation Plan. The Community is working to protect their bridges by placing armor rock along the edges of the supports to stabilize the area (THMP 2019). As of 2022, the Chignik Bay Tribal Council has contracted Bristol Engineering to conduct their own infrastructure assessment in the community and have plans to construct tsunami shelters on both sides of the community.

4. DATA PRODUCTS AND ASSESSMENT TOOLS

This research was conducted in part to assess spatial patterns of vulnerability to erosion and flooding over long- and short-timescales, as well as to identify at-risk infrastructure in Nelson Lagoon. This was accomplished through ground-, water-, and air-based surveys coupled with computer-based processing and analysis using a geographic information system (GIS).

4.1 PREVIOUS ASSESSMENTS

Chignik Bay has two hazard mitigation plans and one assessment each for flooding, erosion, and tsunamis (**Table 4**).

Table 4. Summary of existing hazard assessments for Chignik Bay.

Date	Report	Leading Org.	Subjects
1992	High water mark survey	USACE	• Flooding
2007	Erosion information paper	USACE	• Erosion
2009	Community plan	City of Chignik Bay	• Community priorities
2014	Hazard mitigation plan	Lake and Peninsula Borough	• All hazards • Community priorities
2019	Tsunami inundation maps	DGGS	• Tsunami
2019	Hazard mitigation plan	Chignik Bay Tribal Council	• All hazards • Community priorities

The University of Alaska Fairbanks ACGL has been actively conducting coastal hazard related research a Chignik Bay since the spring of 2019 (**Table 5**). This includes a series of topographical surveys and the establishment and maintenance of erosion monitoring sites. The results of this continuing work are delivered in this report.

Table 5. Summary of ACGL community visits and field work.

Date	Individuals	Research Activities	Monitoring Activities	Outreach
May 2019	Chris Maio, Reyce Bogardus, Ed Krauss	• GNSS survey • UAV survey(s)	• Established 2 sites • Training on measurements	• Meeting with environmental program staff • Community meeting
May 2021	Chris Maio, Reyce Bogardus, Jessie Christian, Ed Krauss	• GNSS survey • Temporary pressure gauge	• Site maintenance • Establish 1 site	• Meeting with environmental program staff
May 2022	Chris Maio, Reyce Bogardus, Jessie Christian, Matthew Balazs	• Install water level gauge • GNSS survey • Install tidal staff	• Site maintenance	• Meeting with environmental program staff • Community meeting
May 2023 (planned)	Chris Maio, Michael Willis, Matthew Balazs, Sue	• Water level gauge maintenance • GNSS survey • Bathy survey(s)	• Site maintenance	• Climate Symposium

	Flensberg, Casey Ferguson	• UAV survey(s) • Survey in tide staff		• Meeting with environmental program staff

4.2 REFERENCE DATASETS

The following subsections (4.2.1 – 4.2.5) describe baseline geospatial datasets and hydrological datums as collected or compiled by the ACGL. These data contain aerial imagery, continuous elevation surfaces, as well as discrete point data. Source information and links to data portals are included in sections related to compiled data. This information is intended to assist any future environmental assessments of Chignik Bay. Data collected by the ACGL is available upon request.

4.2.1 Ground Control Points and Checkpoints

Ground control points (GCPs) and checkpoints are locations on the ground that have a precise coordinate associated with them. In photogrammetry, they are used to tie the map down to the Earth—matching the drone or satellite location data to the location data measured terrestrially. It’s important to note that GCPs are not the same as checkpoints, which are used in post-processing to validate accuracy by checking the map against the known points on Earth as captured during the survey.

At Chignik Bay, the ACGL has collected 187 GCPs or checkpoints (**Table 6**). Precise horizontal and vertical measurements were collected with a GLONASS-enabled GNSS system consisting of dual frequency Trimble R2 and R8s receivers with a TSC3 field controller running Trimble Access software. These measurements broadly fall into the following categories during three field surveys: ground control points and checkpoints, shoreline indicators, profiles, cross-spit profiles, benchmarks, and other (including waterlines, timelapse camera locations, erosion monitoring stake locations, and water level gauges).

Table 6. Summary of GPS survey points per product type and year. Unless otherwise specified, the number displayed below is the number of points of this product type taken per survey. For profiles, the number of linear profiles is listed first, with the total number of points taken at all profiles listen in parentheses.

Year	GCPs	Shoreline	Profiles	Benchmarks	Other	Total
2019	167	0	539	2	5	713
2021	20	0	689	1	8	718
2022	39	0	722	1	22	784

4.2.2 Benchmarks

Benchmarks are intended to be permanent points of reference for surveyors to verify their survey is consistent with prior work and have precise real-time coordinates during surveys. NOAA’s National Geodetic Survey (NGS) manages approximately 240,000 stations gathered over the last two centuries. This survey benchmark data is made available through the National Geodetic Survey Data Explorer (https://geodesy.noaa.gov/NGSDataExplorer/). Two main types of benchmarks exist – “vertical control points” and “horizontal control points”. Vertical control points contain a precisely measured orthometric height. The elevation is usually measured as height above sea level. Horizontal control points simply contain latitude and longitude values. Within these two broad types of survey benchmarks, there are different types of categories for horizontal control markers as described in NOAA’s Horizontal Control documentation. There are two NGS benchmarks in and around Chignik Bay (**Table 7**). One is GPS and vertical control while the other is GPS and approximate height.

Table 7. NGS benchmarks within 10 km of Chignik Bay.

Site Name	Latitude	Longitude	Ortho. Height (m)	Control Type
AI1023	56° 17' 44.87610"	-158° 24' 19.91039"	14.572	GPS and Vertical Control
AI1024	56° 18' 18.80460"	-158° 24' 59.18464"	14.583	GPS and Approx. Height

When surveyors occupy benchmarks over several hours, they measure an extremely precise position. Surveyors can upload their measurement to the Online Positioning User Service (OPUS; https://www.ngs.noaa.gov/opusmap/) to share the solution with others. This user-maintained database provides a catalog of the most reliable benchmarks. There are 3 OPUS benchmarks around Chignik Bay (**Table 8**).

Table 8. OPUS benchmarks at Chignik Bay.

OPUS Position ID	Stamping	Latitude	Longitude	Ortho. Height (m)	Last Occ.
BBFS48	DEROCCHI 2017	56° 18' 26.78396"	-158° 22' 37.74266"	5.321	2017
BBDW16	CHIG-2 USACE 2004	56° 18' 8.23604"	-158° 22' 43.91080"	4.711	2017
BBDW14	945 8917 COR 4	56° 17' 46.33526"	-158° 24' 22.70783"	5.231	2019

4.2.3 Digital Surface Model and Orthomosaic

A digital surface model (DSM) was derived from 2,400 aerial photographs taken from 100 m (330 ft) altitude with a FC300S camera aboard a DJI Phantom 3 Advanced uncrewed aerial vehicle (UAV). The survey, consisting of 9 individual flights, took place over a period of 4 days and was flown during low tide stages when it was feasible to capture as much of the beach face and mud flats as possible.

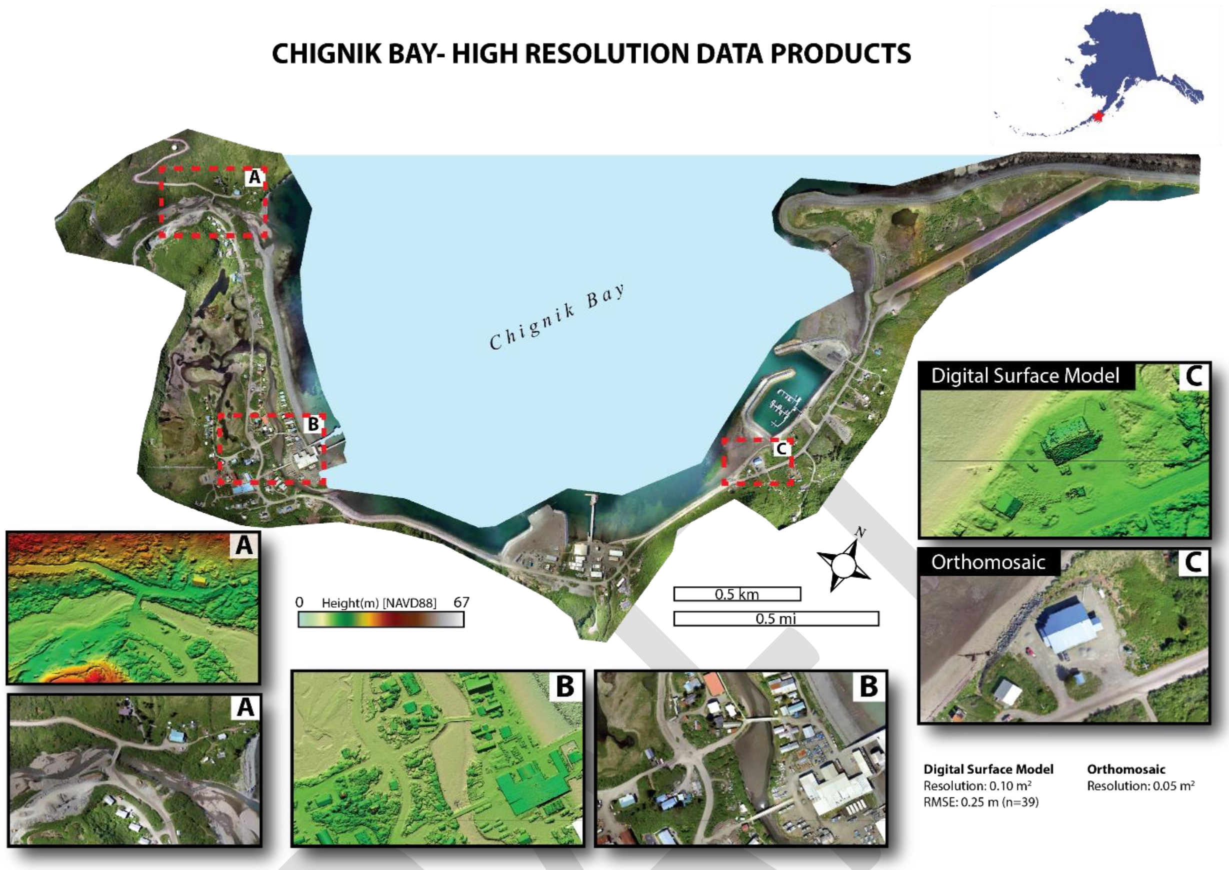

Figure 20. Orthomosaic (A&B) and DSM (C&D) of Chignik Bay generated using UAV imagery in 2019.

The survey was accompanied by an extensive ground control campaign using RTK-GNSS to vertically reference the DSM, relate elevations to the tidal datum computed for this project, and validate the vertical accuracy of the refined topographic surface. This validation was computed by comparing vertical values of the unused GCPs from the alignment phase to the resulting topographic surface. The covariance test showed a high degree of accuracy, with an average Root Mean Square Error (RMSE) of ~0.17 m (~0.56 ft) (n = 30).

4.2.4 Tidal Datums

A tidal datum is a standard elevation defined by a certain phase of the tide and is used as a reference to measure local water levels. Tidal datums are calculated from geodetically tied local water level data, which provides a necessary conversion for storm forecasting and floodplain mapping (Overbeck, 2018). Chignik Bay's tidal datum is found in **Table 1**. The tidal datum was connected to NAVD88 through the OPUS-shared benchmark with ID BBDW14 (**Table 8**).

Two water level gauges were installed in Chignik Bay. One was installed on a dock overlooking Anchorage Bay and the other was installed on a bridge over Indian Creek (**Figure 20**).

Figure 21. Map Chignik Bay water level gauges, represented by gold stars.

4.2.5 Bathymetry

The National Centers for Environmental Information (NCEI) maintains the digital data archive for all hydrographic data of the coastal waters and exclusive economic zone of the United States and its territories collected by Coast Survey. The database provides hydrographic survey products which contain additional details of the ocean floor not shown on the nautical charts. NCEI also maintains an interactive data viewer for other sources of bathymetric and ocean depth data collected by other agencies.

This interactive viewer (https://www.ncei.noaa.gov/maps/bathymetry/) allows for the identification of NOAA bathymetric data for both visualization and download. The viewer contains single beam track lines, multibeam surveys and mosaics for data visualization, the NOS hydrographic surveys, BAG footprints and shaded imagery, digital elevation models (DEMs), and coastal LiDAR datasets available.

Table 9. Overview of compiled and collected bathymetry surveys of Chignik Bay. The survey, survey type, year of acquisition, source, and datum is provided.

Survey	Type	Year	Source	Datum
H04389	Sounding Rope	1924	NOAA	MLLW
H10759	Side Scan Sonar	1997	NOAA	MLLW
W00245	Multibeam Sonar	2011	NOAA	MLLW
D00170	Multibeam Sonar	2012	NOAA	MLLW

4.3 REPEAT DATASETS

To better understand the processes that continuously shape the landscape and quantify change, repeat measurements of the surface are needed. After the first measurements of the surface are taken (known as the baseline dataset) subsequent data collected over the same location can be compared. Each survey must be accurately co-registered to the previous data to minimize error when calculating change. This report summarizes the findings from several repeat surveys including, shoreline indicators, stake measurements, cross-shore profiles, and timelapse photography.

4.3.1 Shoreline Change

A shoreline is a linear demarcation between land and water that can be represented by a visual feature or an elevation contour on the beach. Either type of shoreline (i.e., visual- or elevation-identified) can be delineated within a Geographic Information System (GIS) program (e.g., ArcGIS) based on source orthoimagery or elevation data (Overbeck et al., 2020). Shoreline data are created in the form of a vector (line) that represents the shoreline position at a particular time along a section of coast. For example, if multiple shoreline datasets are available, they can be compared visually to show how the shoreline has changed through time. The distance between shoreline vectors can also be measured to compute shoreline change distances and rates.

A long-term shoreline change study has not been conducted for Chignik Bay. Non-orthorectified aerial imagery was collected for photogrammetric mapping of Chignik Bay in 1957, 1963, 1965, 1974, 1977, and 1983. These images are publicly available from USGS and can be orthorectified (https://earthexplorer.usgs.gov/; method described by Buzard, 2021). Shoreline change is known to be relatively slow, but documenting this observation can help identify any sudden changes in erosion patterns. In addition, the pre- and -post 1964 earthquake imagery may show shoreline change from tectonics. These images can also be used to identified landslide scars.

4.3.2 Community-Based Erosion Monitoring Data

As of 2023, 13 rural coastal communities in the Bristol Bay region utilize stake ranging to monitor erosion. The Stakes for Stakeholders program trains environmental coordinators from each community in data collection (Buzard et al., 2019a). Stake ranging uses a permanent landmark or a stake (wooden or metal) to measure the distance to the eroding feature. Several transects are set up perpendicular to the eroding feature with two to three stakes along each transect. The local data collector can visit stake sites a few times a year and before and after big storms.

Two stake ranging sites were set up in Chignik Bay in May 2019 and one site in May 2021 (**Figure 22**). Measurements are collected by local environmental coordinators every 1-3 months and before and after large storms. The data collectors measure from the site reference point (typically a wooden stake, or other permanent feature) out to the eroding feature. These datasets provide a high-resolution look at the most recent shoreline change. These datasets can help better understand shoreline change in terms of recent climate settings. They can also highlight storm events in great detail. Between the start of monitoring and spring 2021, the ACGL has received six sets of measurements that are reported here (**Figure 23**). Time-lapse cameras were also set up at each site to capture images every hour (described below).

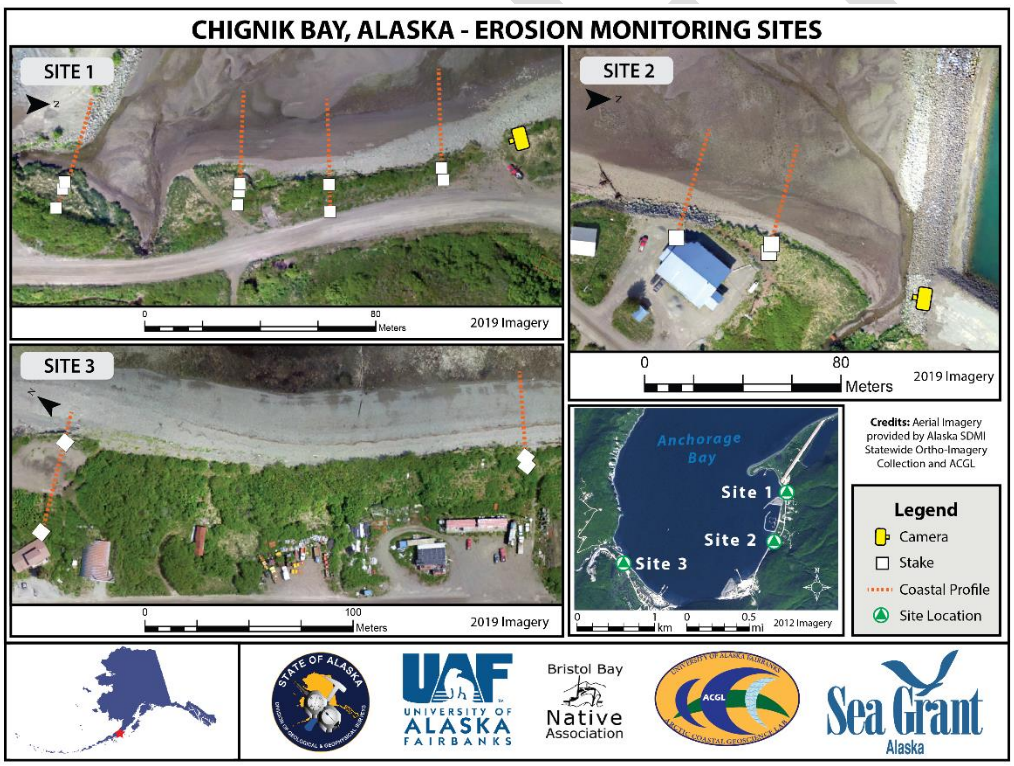

Figure 22. Map of erosion monitoring sites and stake measurement transects. Each site consists of a time-lapse camera with 2-4 staked transects where local environmental coordinators take repeat measurements.

On-site measurements for sites 1 and 2 at Chignik Bay show slower shoreline change rates with the most erosion occurring at site 1, transect 1 of 0.67 m (2.3 ft) over the past 3 years of participation, or 0.22 m (0.8 ft) of erosion per year (**Figure 23**). Most erosion occurs at Site 1, which is in front of the main road to the airport. A draft protocol of stake ranging measuring and site set up was created, describing how to set up sites, take measurements, and highlight important reminders when collecting data.

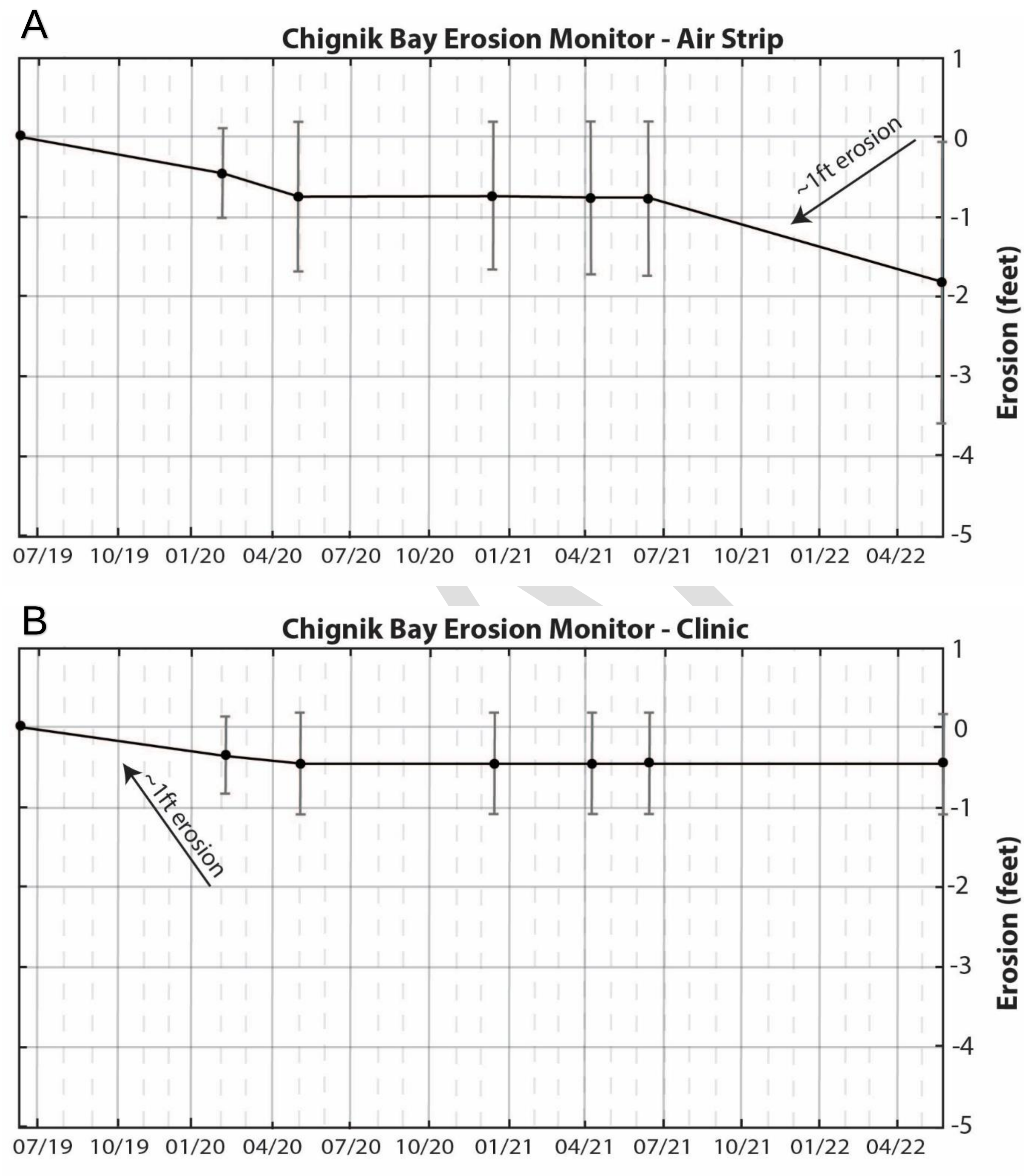

Figure 23. Graphs showing average erosion monitoring stake measurements taken by local environmental coordinators. (A) The black line represents the average of the 4 transects at the air strip site. Each dot represents community measurement. Grey error bars calculated with Excel STDEV function. (B) The black line represents the average of the 2 transects at the clinic site. Each dot represents community measurement. Grey error bars calculated with Excel STDEV function.

4.3.3 Cross Shore Elevation Profiles

Coastal elevation profiles represent the elevation of the beach from ocean (right) to land (left). When plotted through time, coastal elevation profiles can be used to understand coastal dynamics including the impacts of storms and changing ocean conditions.

Elevation profiles at Chignik Bay were collected by the ACGL along cross-shore transects at 33 locations in 2019, 2021, and 2022 (**Figure 24 & Figure 25**). Representative coastal elevation profile

Figure 24. Map showing the location of each cross-shore elevation profile. Red brackets represent CBM sites. Yellow bracket represents cross-river elevation profiles.

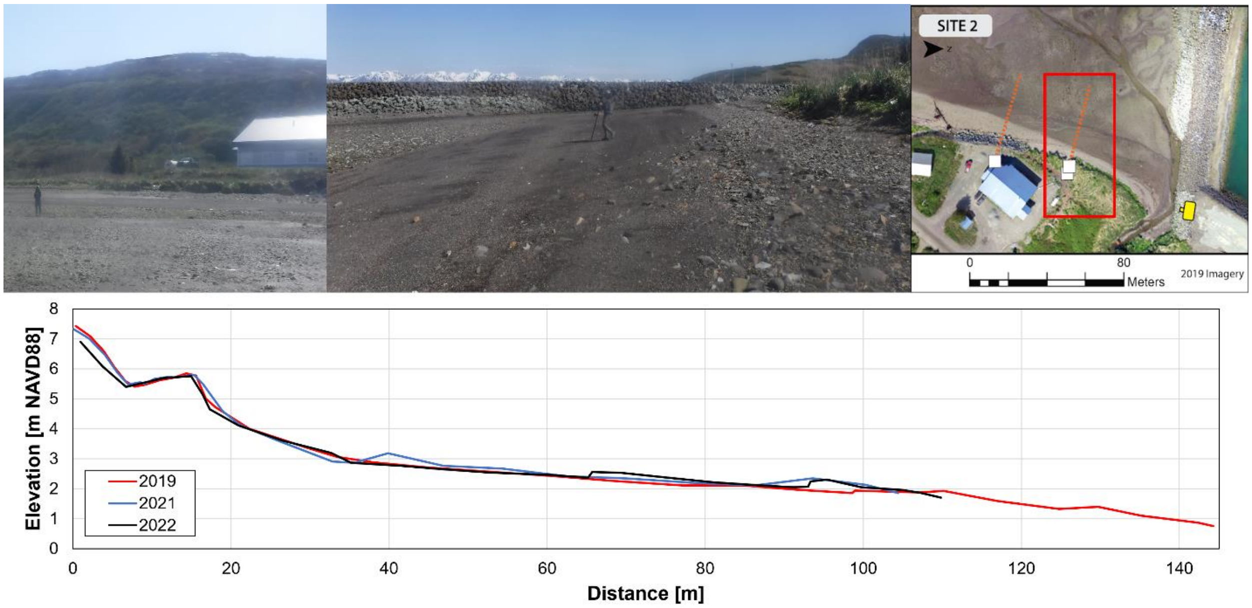

Figure 25. Example cross shore profile from the City Clinic with data plotted from 2019, 2021, and 2022. This is profile An (reference figure 22). Notice how much erosion has occurred.

4.3.4 Timelapse Photography

Time-lapse cameras were set up at two sites in May 2019 and data is currently being collected. The cameras were oriented perpendicular to a single profile at each site. Images were taken every hour and compiled into time-lapse videos (**Figure 26** & **Figure 27**). These datasets visually show change at each shoreline and can capture storm events. Erosion measurements were unable to be processed as the cameras were not secured tightly enough and the camera was frequently shifted out of place. Future site visits will require proper securing of these cameras.

Figure 26. Time-lapse picture and compiled video of erosion monitoring site 1. Images taken at Chignik L Bay from June 2019 to May 2020. (URL: https://youtu.be/5lisv9sMA1M).

Figure 27. Time-lapse picture and compiled video of erosion monitoring site 2. Images taken at Chignik Bay from June 2019 to May 2020. (URL: https://youtu.be/3SjWLrm6vOw).

4.4 HAZARD AND EXPOSURE ASSESSMENTS

Hazard maps indicate the potential for coastal hazards in a given location, such as flooding or erosion, while exposure maps indicate the proximity of infrastructure or human life to these hazards. For instance, shoreline change analysis describes coastal hazards by quantifying the spatial extent and rates of erosion along the beach, while shoreline change maps indicating areas where critical infrastructure is in close proximity to quickly eroding land constitute an exposure map.

4.4.1 Flood Maps

There is currently no flood hazard or exposure map for Chignik Bay. A flood map is created using a DEM, tidal datum connected to NAVD88, historical flood record, and impacts to infrastructure (Buzard et al., 2021). Chignik Bay has a DSM (**Figure 20**) and will receive a lidar-derived DTM. The tidal datum was connected to NAVD88 in this report's 2023 update (**Table 1**). The remaining components can be determined through GNSS surveying, community observations, and delineating infrastructure in imagery using GIS (Buzard et al., 2021a). With these components, flood maps can be created to show flood extent, severity, and likelihood. The maps would allow tide, storm, and tsunami forecasts to be related to infrastructure elevation. May 2022, a flood staff was installed on a utility pole in the flood plain of the community (**Figure 22**). This flood staff will allow residents to send in photos of flooding events. These measurements can be used to create flood extent maps.

Figure 28. Location of tide staff installed May 2022. It was installed on a utility pole near the tribal office.

4.4.2 Erosion Maps

There is currently no erosion hazard or exposure map for Chignik Bay. A coastal erosion hazard map (or shoreline change analysis) is created by measuring long-term and recent erosion rates. This is achievable as described in Section 4.3.1. An erosion exposure map is created by projecting erosion rates near infrastructure and computing the time to impact (Buzard et al., 2021b). However, if the long-term shoreline change rates are very slow it may be unfeasible to simply project erosion with reasonable confidence. The community has also performed shoreline modifications that prohibit projections of natural erosion rates. It may be impractical to attempt a community-wide erosion map, but site-specific studies can be conducted to document specific issues.

5. IDENTIFIED COASTAL HAZARD AREAS

This section identifies infrastructure at risk of erosion over spatiotemporal scales relevant to community planning; long term morphodynamic evolution is beyond the scope of this report. Identified coastal hazard areas are identified as such based on erosion rates coupled with proximity to infrastructure or otherwise cultural significant features.

Identified coastal hazard areas in Chignik Bay are as follows:

1. Indian Creek Bridge
   Local anecdotal input has pointed to erosion of the bank under the Indian creek bridge connecting the community to their tsunami evacuation route and waste disposal site. High water events from storms cause the majority of erosion according to local residents (**Figure 29**). A water level gauge was installed in 2022 and baseline data has been collected for future monitoring efforts.

Figure 29. (Left) Photo taken by Jeanette Carlson standing on Indian Creek bridge during a flood in June. (Right) Photo taken by Jessie Christian on a calm day on a berm in Indian Creek with bridge in background.

2. Road by Airstrip
   Unarmored sections of the bluff fronting the main road by the air strip are eroding. When the road is obstructed, access to the airport get cut off and transportation to and from the village slows. Coastal profiles and CBM measurements show the bluff has eroded approximately 1ft over 4 years. Residents shared information and photos of a large storm in December 2022 that

caused a large amount of erosion (**Figure 30**). Baseline data has been collected in the area for future monitoring efforts.

Figure 30. Photos taken by Andrew Anderson (Left) Main Road after December 2022 storm. (Right) Community Monitoring site located by airport after December 2022 storm.

3. Medical Clinic
   The bluff fronting the clinic is not at immediate risk, however, it is an area of concern. The clinic sits about 6 m (20 feet) away from the eroding bluff. The bluff is eroding at a rate of 0.08 m/yr (0.25 ft/yr).

6. SUMMARY OF COMMUNITY THREATS AND RESILIENCY

6.1. SUMMARY OF THREATS

- Erosion at of the main road directly threatens access throughout the community to critical infrastructure such as the airport and the medical clinic.
- Erosion around Indian creek directly threatens the integrity of the bridge connecting the community's tsunami evacuation route and their waste disposal site.
- Erosion fronting the medical clinic has been an ongoing issue but does not pose an immediate risk at this time.

6.2. COASTAL RESILIENCY

Chignik Bay faces many challenges related to coastal geohazards. The oceanographic setting means that any mitigation structures must consider waves and currents, large tides, and flooding. The climatic setting means that there is a short (seasonal) construction window for any largescale projects. However, the strongest defense against coastal geohazards at Chignik Bay has been and is its extremely proactive and hard-working people. The community has ongoing erosion monitoring efforts and numerous partnerships with state and private entities.

7. DATA GAPS AND FUTURE WORK

7.1. PRIORITY DATA GAPS

While the data products in this report describe coastal processes through their impacts on shorelines and beach profiles, a more thorough understanding of the local oceanographic setting would improve predictions regarding erosion at Chignik Bay. Additionally, improving understanding of potential storm and flooding impacts is a major goal for mitigation efforts in Chignik Bay. In order to more accurately assess these risks, additional data products are necessary, including past storm total water levels and building first floor heights (**Table 9**)

Table 10. Summary of data gaps at Chignik Bay. Applications and expected acquisitions for each item is provided.

Item	Applications	Actions	Exp. Acquisition
Water level gauge	Developing a historical index of past storm events; informing city planning and decision making. Develop tidal datum.	Install water level gauge Create local tidal datum for Chignik Bay	Summer 2022
Bathymetry	Fills data gaps on coastal erosion, aid in nearshore planning and development	Collect nearshore single or multibeam bathymetry	Spring 2023
Lidar DTM	Flood, erosion, and tsunami hazard maps	Collect ground control and check points.	2023
Wave buoy	Developing a historical index of past storm events with wave and water level data	Deploy Wave buoy Collect Wave buoy	TBD
Stream gage	Record stream elevation to inform and validate flood models	Install stream gage Survey gage	TBD
Some infrastructure heights	Relate infrastructure to flood and tsunami elevations.	Survey elevation of critical infrastructure and low-lying structures.	Spring 2023

Flood History	Identify the frequency and severity of flooding to create hazard/exposure maps and recommend building elevation.	Compile list of known floods Estimate flood elevations	Spring 2023
Orthorectify Historical Aerial Imagery	Used for long-term shoreline change mapping and identification of landslide scars and tsunami impacts.	Download imagery from Earth Explorer Process using SFM Reference to recent imagery.	Not planned.

7.2. ACGL FUTURE WORK

Continued work is being carried out to improve the hazard assessment of Chignik Bay and another field work campaign is planned for spring 2023. This will include repeat surveys, along with continued correspondence with members of the community. These datasets will feed into the comprehensive coastal hazard assessment produced by ACGL and will be updated annually.

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Citations of reports and assessments directly pertaining to Chignik Bay are bolded.

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APPENDIX

USACE (1992) high water elevation survey.

ALASKA DISTRICT CORPS OF ENGINEERS
FLOOD PLAIN MANAGEMENT SERVICES

HIGH WATER ELEVATION IDENTIFICATION

Community: **CHIGNIK**

Date of Visit: 20 November 1992

General Observations/Comments:

Chignik, also commonly called Chignik Bay, is on the south shore of the Alaska Peninsula at the head of Anchorage Bay.

Historical Record of High Water:

The highest flood of record was the flood of October 1948, which was said to have flooded the first floor of the building that is now the Chignik Bible Chapel with 13 inches of water. The 1964 earthquake has since raised the land 18 inches. More recent floods have reached, or nearly reached, the low cord of the cannery bridges crossing the former channel of Indian Creek.

People Interviewed:

Roy Skonberg

Actions Taken:

No High Water Elevation signs were placed.

Miscellaneous:

The 1948 flood elevation was estimated at 14.08 feet. Two existing temporary bench marks were employed: a spike in power pole no. 12 on the south side of Harold Skonberg's house, at elevation 15.50 feet; and a spike in a power pole nearest the south bridge abutment on West Third Avenue, at elevation 12.25 feet.

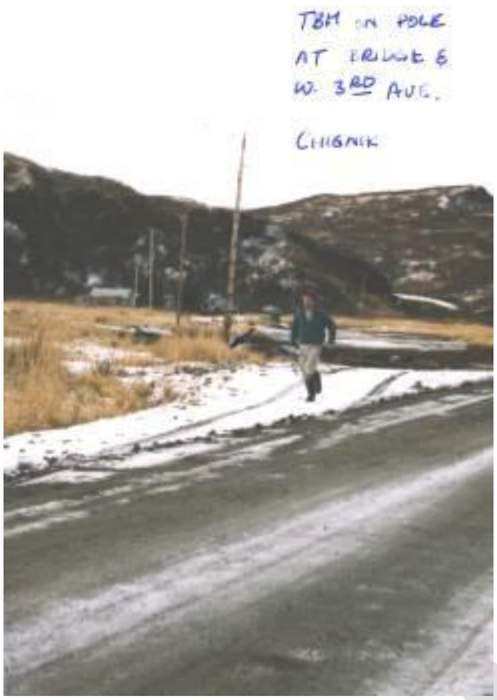
Chignik/21 March 94

Community: **CHIGNIK**

Chignik Bible Chapel.

Temporary bench mark on the power pole at Harold Skonberg's house.

Chignik/21 March 94


TBM ON POLE
AT BRIDGE &
W. 3RD AVE.
CHIGNIK