Nelson Lagoon Coastal Hazard Assessment

Arctic Coastal Geoscience Laboratory (Ver. April 2021)

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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 funded through multiple sources. These include direct support from the Native Village of Goodnews Bay Environmental Program (EPA-GAP funding), the Cooperative Institute for Alaska Research (CIFAR), Alaska Sea Grant (ASG), the National Science Foundation (NSF) (Grant # 1848542), and the Bristol Bay Native Association through the Bureau of Indian Affairs Tribal Resilience Grant.

We would like to thank the Nelson Lagoon Environmental Department as well as other community members 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. We also thank Ronnie McPherson from HDR Alaska Inc., who provided data and expertise used in this report. Thank you to Robin Bronen from Alaska Institute for Justice (AIJ) for initiating communication with the Native Village of Nelson Lagoon and moving forward efforts to monitor and record coastal change. Finally, this report would not be possible if not for the leadership and technical support provided by Jacquelyn Overbeck and Richard Buzard at the Alaska Division of Geological and Geophysical Surveys Coastal Hazard Program.

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.

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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	Unmanned 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

“Nelson Lagoon, Alaska is located on the Aleutian Peninsula on the Bering Sea coast. The community was established around 1960, the location picked for the booming commercial fishing industry in the area. The community is made up of about 95% Unangax (Aleut). Our location is an integral part of our culture providing us with all our subsistence needs. The environmental changes we have experienced here are very significant from subsistence practices being altered to erosion affecting our access to clean drinking water.

Erosion and sea level rise are the two biggest threats to our community. We have been monitoring our erosion for years. While we consider ourselves a “protect in place” community, relocation is inevitably in our future. Over the years the erosion has become faster and more significant. Higher sea levels mean more risk of flooding. The fall of 2020 is a great example of the effects from sea level rise paired with erosion and winter storms. The road to the community airstrip was partially flooded during a high tide and high winds along with a few entrances to the community from the beach. Water from the river was blown and pushed into entrances to the road and also over the bank from the inside beach onto the road to the airport. That is just one example of how the erosion and sea level rise has been affecting our community.

Our access to clean drinking water is extremely threatened due to erosion. The 2020/2021 winter was a scary one for the community’s water supply. Nelson Lagoon water comes from a fresh water lake about ten miles west from the village. The water gets pumped from that lake to the water tanks located in the village through a transmission line that is buried underground. Throughout the years the pipe has washed out a few times from erosion, but it is getting worse. This year there was about a thousand feet of line washed out in different areas throughout the beach. This caused the line to freeze in the cold winter weather meaning the water treatment plant operator was unable to pump water to the town until the line thawed out. This caused the community to go on water limits. Not knowing when the line would thaw meant we had to conserve on water until it was able to be pumped. Thankfully the water plant operator was on top of it and did not let the tanks get too low before putting out a notice to the community. The bottom line is that if this continues to get worse, which it seems that it will since we’re in a climate crisis right now, it is going to be a dire situation for our access to clean drinking water.

Subsistence is a way of life for all Alaskan Natives and other Indigenous peoples around the world. Our subsistence resources in Nelson Lagoon include caribou, duck, salmon, trout, berries, beach greens, wild celery, etc. With the climate crisis things are changing. We have gone through summers not having any berries to pick due to not enough snow in the winter. No snow also means no snow machining which affects our caribou hunting and trout fishing. Usually in the past during hunting season we were able to go out on the tundra on our snow machines to hunt. It is very difficult to drive across the tundra on a four-wheeler which makes our snowless hunting season a bigger task than it used to be. Not only that, but climate change is also affecting the time of year that the caribou are around. So, when it is caribou season there’s a chance that we won’t even see one until the season has closed and that’s when it’s illegal to hunt. We rely on these animals to feed us for the winter and this causes a lot of cultural distress within the community if we are unable to get one for our family.

Over the years we have noticed significant environmental changes in Nelson Lagoon and they only get more intense. Nelson Lagoon used to have raging winters, snow up to your knees by Halloween. The river used to freeze so well people drove their trucks across it to go trout fishing. On the Bering Sea side, the ice would build up so big there would be a literal ice wall protecting the village from harsh winter storms and high seas. Now, the river doesn't freeze and we have little to no ice on the Bering Sea side which exposes us to the harrowing affects from winter storms. The community is constantly threatened by the rising sea level, increasing erosion, warming temperatures, and the changing climate. We are on the frontlines battling this climate crisis along with the thousands of other Indigenous people on this earth."

Angela Johnson
IGAP Coordinator
Nelson Lagoon Environmental Department

2. GEOGRAPHIC OVERVIEW

2.1 BRISTOL BAY REGION

Bristol Bay is a low-salinity, meso-tidal embayment of the southern Bering Sea, with an approximate 0.2 m/km regional gradient. Tidal energy accounts for 60 – 90% of the horizontal kinetic energy produced over the Bristol Bay shelf (Kinder and Schumacher, 1981), which is characterized by water depths <120 m (<390 ft) with an average depth of approximately 50 m (160 ft) (Johnson, 1983). The shelf break is located at a depth of 180 m (590 ft). The Bristol Bay coastline of the Alaska Peninsula includes six large embayments protected from the open ocean by barrier islands and spits. The non-embayed beaches of this coastline are typically backed by dunes or bluffs of varying height that are eroded into unconsolidated deposits. Sand and gravel type beaches are typical, and they experience a wave energy regime that declines eastwards along the coastline (Kinsman and Gould, 2014).

2.2 NELSON LAGOON

Nelson Lagoon is one of six communities in the Aleutians East Borough. It lies west of the Kudobin Islands and is positioned on a barrier complex across the mouth of the Bear River which flows along the entire southern flank of the spit (**Figure 1**). It comprises 245 square miles of land and 197 square miles of water and was specifically established to take advantage of commercial fishing opportunities (Nelson Lagoon SECD, 2001). The lagoon was named in 1882 after Edward William Nelson of the U.S. Signal Corps, an explorer in the Yukon Delta region between 1877 and 1920. A Salmon saltery operated from 1906 to 1917, which attracted Scandinavian fisherman, but there has been no cannery since then. Starting in 1965 the community has been occupied year-round (Nelson Lagoon SECD, 2001).

The spit itself is approximately 19 km (12 mi) long, reaches 1,400 m (4,600 ft) at its widest point, and narrows to only 120 m (390 ft) at its narrowest point. The occupied sections of the spit range from approximately 300 m (980 ft) wide at the solid waste disposal site to 650 m (2100 ft) wide at the residential area. The vegetation over the spit is predominantly dune grass (*Leymus mollis*). A large, wave generated foredune between 4 and 13 m (13 and 43 ft) in elevation runs along the entire Bering Sea side of the spit. The elevation of this incipient dune nearest the residential section of the community is generally between 7 and 10 m (~23 and 33 ft) (**Figure 4**). There are breached portions of the seaward dune and over washing occurs during high storm-tide events, typically in the autumn and winter months. Beach morphology is more tidally influenced on the lagoon side of the spit with substantially lower foredune crest elevations (2 – 5 m; 6 – 16 ft) and extensive mud flats. As erosion advances on both sides, the spit is getting longer and narrower through time (USACE, 2007).

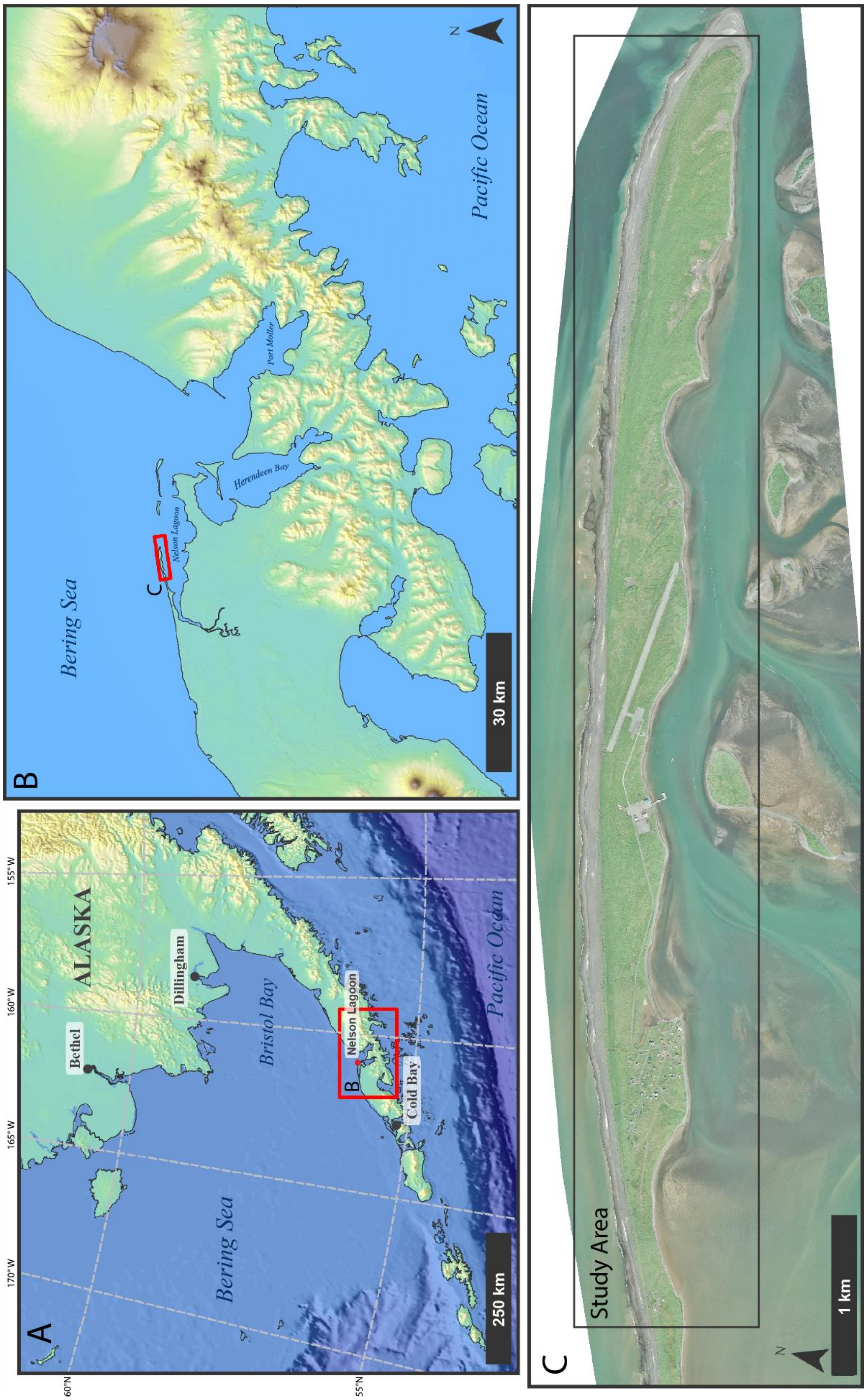


Figure 1. Regional context of the Nelson Lagoon, AK study site. (A) Bristol Bay regional map indicating community location on the Alaska Peninsula. (B) Nelson Lagoon regional oceanographic and elevation geography. (C) Nelson Lagoon study site, from which the data products from this report where generated.

2.3 COMMUNITY INFORMATION

According to the 2010 Census, Nelson Lagoon has a population of 52 – down from 83 as reported in the 2000 and 1990 Census. The majority (78%) of the population is Alaska Native. There are 32 housing units in the community, of which 22 are currently occupied. Of the 10 vacant units, 9 are for seasonal, recreational, or occasional use (HDR, 2011).

2.3.1 Infrastructure Description

Most of the buildings and facilities in the community are constructed on timber foundations and on shallow post and pad foundations at the ground surface. The base of most structures are generally skirted with plywood. In limited instances, buildings are on concrete footings. Due to the relatively high permeability of the sand, drainage problems around the structures are generally not observed. There is also no indication of significant settlement occurring at any of the buildings (HDR, 2011).

The community utilizes a combination of road systems in the interior portions of the community and the beaches for travel otherwise. The road surface is composed of medium to fine sand with low silt content. There is little in the way of fines (silt sized or smaller materials) to bind the sands together on the interior road surfaces, thus, the roads are subject to pushing and rutting (HDR, 2011). In some areas, gravel has been added to the road surface to provide a driving surface. In beach areas, driving is generally performed on moist to wet areas or areas with gravel to reduce the pushing and rutting.

The community's water system is a Class A, 38 gallon per minute water system that obtains water from a lake located approximately 16 km (10 mi) west of the community (ADEC, 2004). A four-inch-diameter pipe transfers water from the intake/pump to the community's 600,000 gallon holding tank located on a former foredune near the north side of the beach (**Figure 2**). Initially, the pipe was located above ground, but two years after construction, the line was buried approximately 0.6 to 1.2 m (2 to 4 ft) below the surface, but the location of the air valves and the pipe was not recorded, and thus the exact location of the line is generally unknown (CE2, 2002). During several erosional events, the pipe has been exposed and damaged; more than one thousand feet of pipe has been replaced due to damage. Community water lines have been replaced three times in past years due to erosion and storm damage (costs were not reported) (USACE, 2007).

Most of the community is served with individual wastewater (septic) disposal systems since there is not an identified central treatment or discharge location. The buildings in the community (**Figure 2**) are served by power and telephone lines above and below ground. Community electricity is provided by diesel generators. Solid waste disposal for Nelson Lagoon consists generally of disposing of refuse in shallow trenches approximately 1 km (0.6 mi) west of Nelson Lagoon. The refuse in the trenches is burned to reduce volume. Items such as old propane tanks, vehicle parts, and heavier metal items are segregated and stored in the solid waste disposal area (WEAR, 2015).

The fuel tank farm is located near the dock facility, approximately 1.5 km (0.9 mi) east of Nelson Lagoon. This relatively new fuel facility provides fuel storage for vehicles, power generation, and structures. The tanks are located within a bermed containment area. Buried fuel lines transfer product from the dock area to the fuel farm. Trucks and potentially other vehicles are utilized to deliver fuel oil to individual buildings.

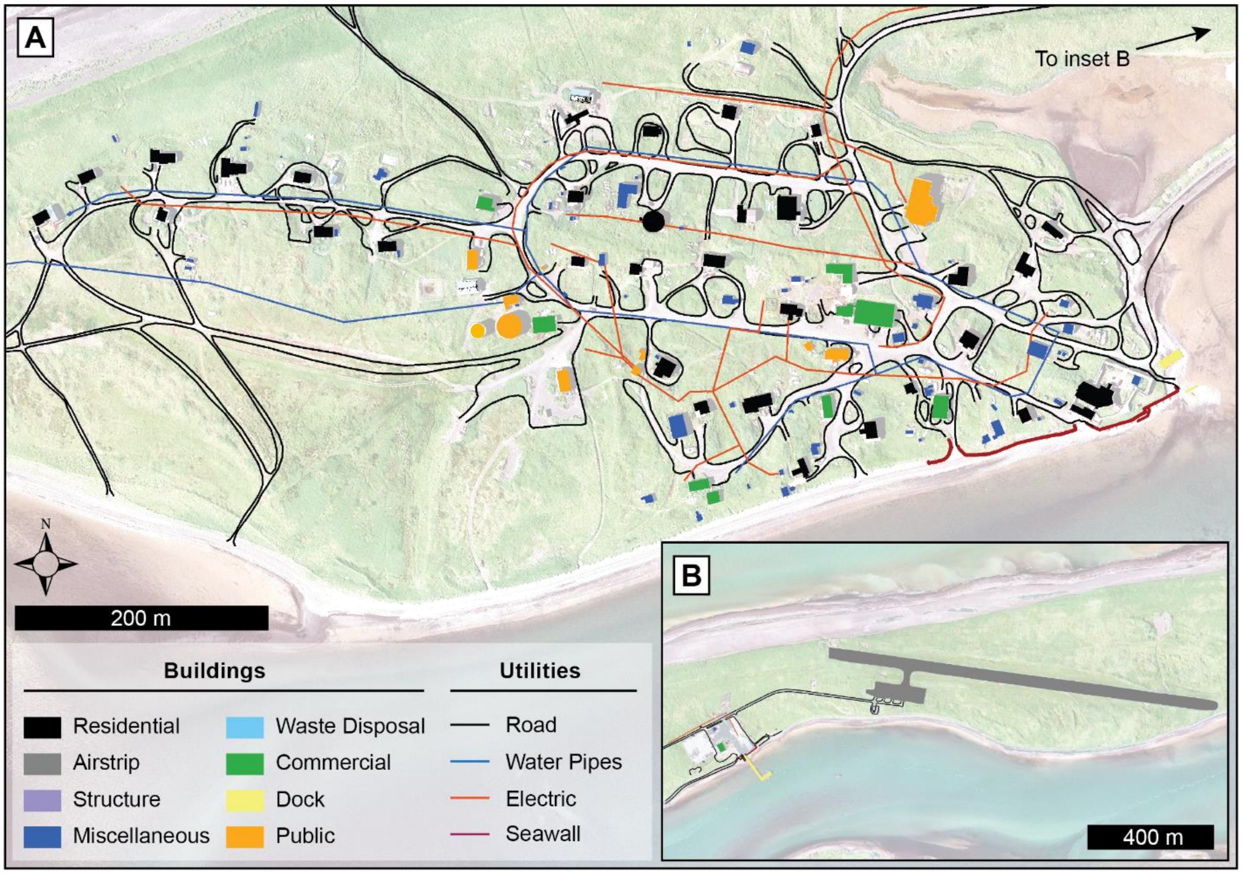


Figure 2. Map showing the building and utility infrastructure of Nelson Lagoon. (A) The residential portion of the community, (B) the tank farm, dock, and airstrip. Data are displayed over an orthoimage collected in 2013 by Kodiak Mapping Inc. (URL: https://dcra-cdo-dcced.opendata.arcgis.com/).

2.3.2 Transportation

Access to the community is generally made via two facilities (HDR, 2011):

- A State-owned 1,220m (4,000 ft) long by 23m (75ft) wide gravel airstrip, which is available year-round and located approximately 2km (1.3 mi) east of the community. Scheduled air service is generally available three days a week via Cold Bay.
- A dock facility located approximately one mile east of the community. This dock is approximately 80m (250ft) long with several berthing areas and is large enough to receive commercial barges. There is also a boat loading ramp for smaller craft.

Within the community, an unpaved road system constructed primarily of sand, as well as areas along the beaches are used by motorcycles, four-wheelers, and pickups as the modes of transport.

2.3.3 Economy

As of 2009, 23 residents hold commercial fishing permits, primarily for salmon gillnet. Some subsistence and trapping activity also occurs. Local government is the largest employment source, comprising 42% of the community's workers (ADLWD, 2011). The breakdown of employment sectors are as follows:

- Local Government (42%)
- Education and health services (19%)
- Trade, transportation, and utilities (10%)
- Professional and business services (10%)
- Financial activities (10%)
- Information (3%)
- Other (6%)

2.4 GEOLOGIC SETTING

The geology of the immediate Nelson Lagoon area is comprised of unconsolidated and poorly consolidated surficial deposits of Quaternary, Pleistocene, and Upper Tertiary age (**Figure 3**) (Wilson et al, 2015). The geology to the south predominantly consists of volcanic and sedimentary rocks of Tertiary to Eocene age (Wilson et al, 2015). The spit itself lies in a low-relief coastal plain adjacent to the inner shelf of the Bering Sea, with an abundance of unconsolidated detritus (Glaeser, 1978).

Shannon & Wilson (1993) conducted a subsurface soils investigation in which two borings were drilled to depths of approximately 13m and 11.5m (42 and 38 ft) below the mudline (HDR, 2011). In general, they observed black loose to very dense, fine-grained sand with thin layers of gravel in the borings. The density of the soils generally increased with depth.

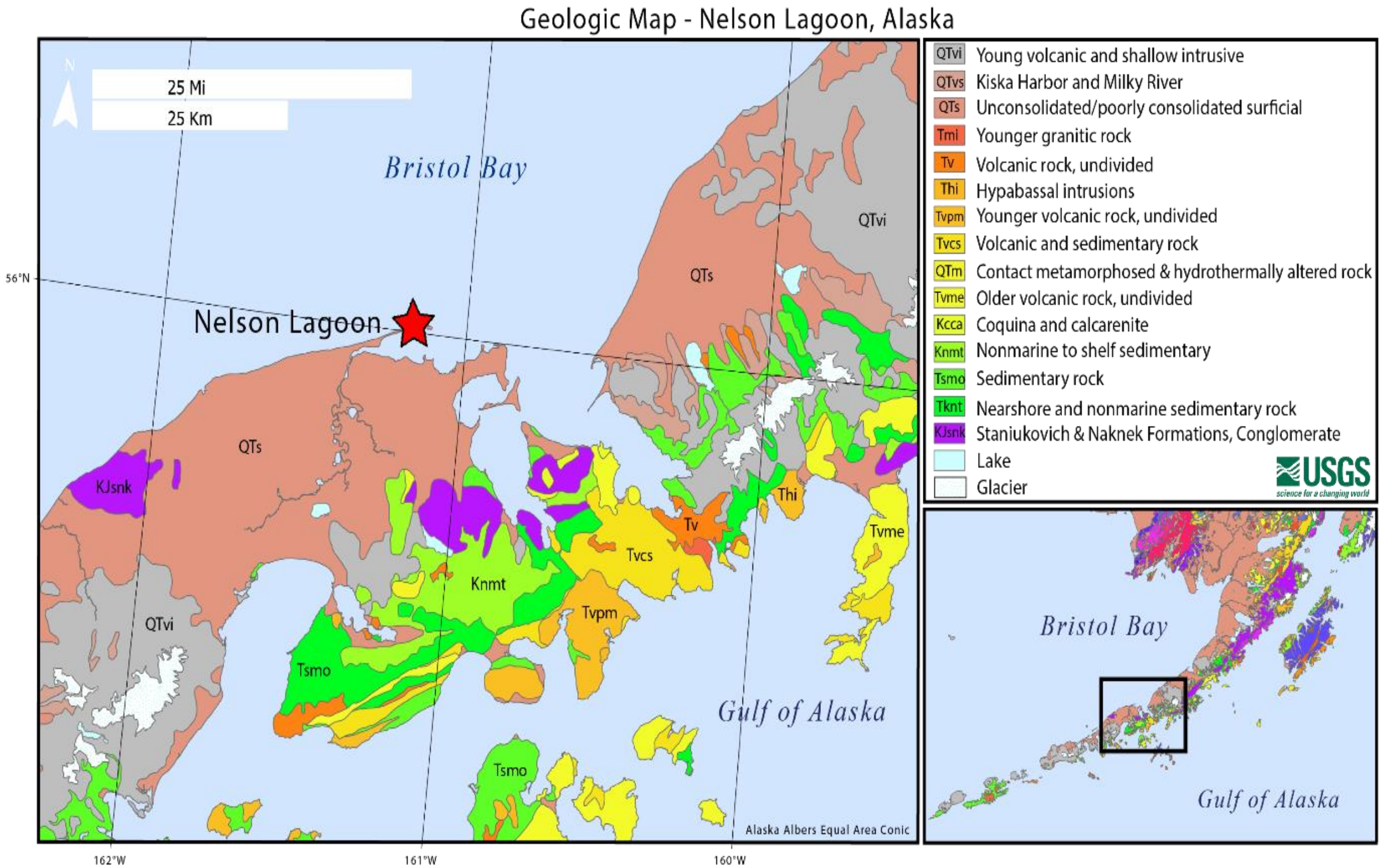


Figure 3. Generalized surficial geology of the Nelson Lagoon area (red star). Each color represents a different type or age of rock, from USGS Scientific Investigations Map 3340 - Geologic map of Alaska. Credit: Frederic Wilson and Keith Labay, USGS. Public domain. (URL: https://doi.org/10.3133/gip168).

CE2 Engineers (2002) investigated Nelson Lagoons surficial geology and found that the spit is generally composed of medium to fine black volcanic sand with "very occasional lenses of small particle-sized gravel." These sands are believed to be located on former beach ridges (**Figure 4**) that have been partially stabilized by vegetation. CE2 Engineers stated the sands are generally carried from west to east in the area. They also identify that a "tight silt layer" is evident at low tide beneath recently eroded areas.

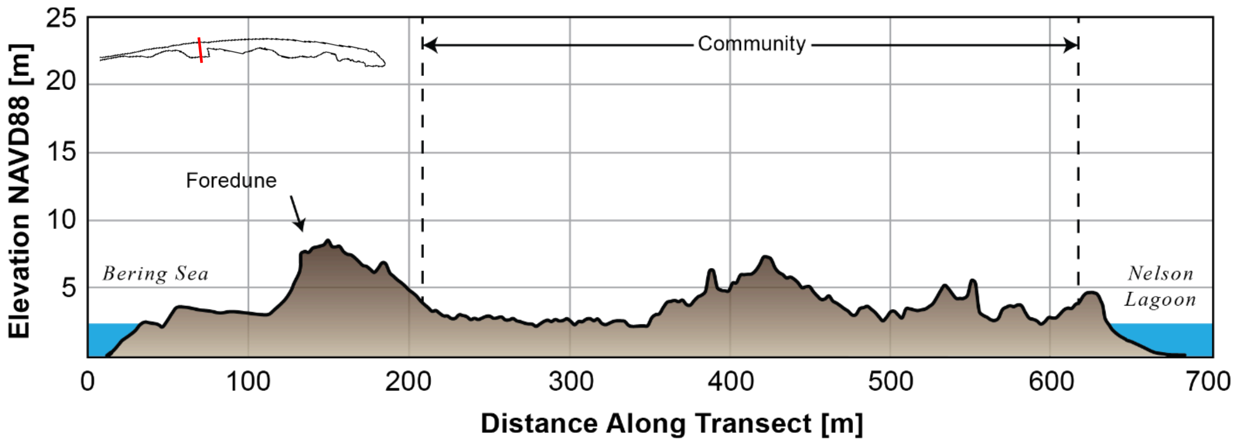


Figure 4. Elevation cross section of Nelson Lagoon. Elevation data is from 2019 and is comprised from topographic surveys and digital elevation model. Notice the different dune heights and morphologies between the Sea and Lagoon sides of the spit.

Nelson Lagoon's regional location along the Alaska Peninsula makes it part of the North American tectonic plate, which is the overriding plate of the Aleutian subduction complex. The Pacific plate is subducting along the Aleutian trench at a rate of approximately 6 to 8 cm/yr (2 to 3 in/yr) (Grow and Atwater, 1970; Cooper et al., 1976). This regional subduction has given rise to the magmatism on the Alaskan Peninsula, Unimak, and Amak Islands and the tensional Amak and Bristol Bay grabens which have formed on the continental shelf, in the tectonic back-arc area (Marlow et al., 1976).

The tectonic setting of Nelson Lagoon is unusual in that it is located in the Shumigan Gap, which is characterized by a lack of plate motion and, therefore, lack of seismic activity. The Shumagin seismic gap extends from the western end of the rupture zone of 1938 to the eastern end of the 1946 earthquake (Davies et al., 1981). The Shumagin seismic gap, had not ruptured during a great earthquake since at least 1899-1903 before a Mw 7.8 earthquake occurred in July 2020.

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 (**Figure 5**). Annual temperature increases could negatively affect permafrost, sea ice accumulation, water cycling, and habitat suitability for plant and animal life. These effects could leave communities more vulnerable to coastal erosion and geomorphic hazards as a result of decreased sea ice accumulation and thawing permafrost. In addition, important subsistence food sources could be depleted by ecological changes. Fall temperatures are significant with regard to coastal erosion specifically, as higher fall temperatures decrease sea ice formation. Fall temperatures have increased less significantly than annual temperatures, but this increase is large enough to affect sea ice formation, leaving this region more vulnerable to coastal erosion (**Figure 6**).

At Nelson Lagoon, temperature data is available from 2010-2020 via the meteorological station at the community's airstrip via the Automated Surface Observing Systems (ASOS) network (ASOS, 1998). The brevity of this record restricts the amount of long-term variation that can be assessed; however, summer and fall temperatures during these years indicate marked warming. Between 2010 and 2020, the average summer temperature in Nelson Lagoon increased from 8.28°C (46.9°F) (2012) to 12.15°C (53.87°F) (2016) (**Figure 7**). The three coldest years occurred between 2010 and 2012, and the three warmest years between 2016 and 2020. The average fall temperature in Nelson Lagoon between 2010 and 2020 was 6.73°C (44.11°F) (**Figure 8**). The warmest autumn during this period occurred in 2019, averaging 9.38°C (48.88°F), while the coldest autumn was in 2012, when the average temperature was 3.39°C (39.90°F) (**Figure 8**). The three coldest years occurred between 2010 and 2012, and the warmest three falls have occurred between 2016 and 2019. The average temperature during this warm period of 2016-2019 was 7.90°C (46.22°F).

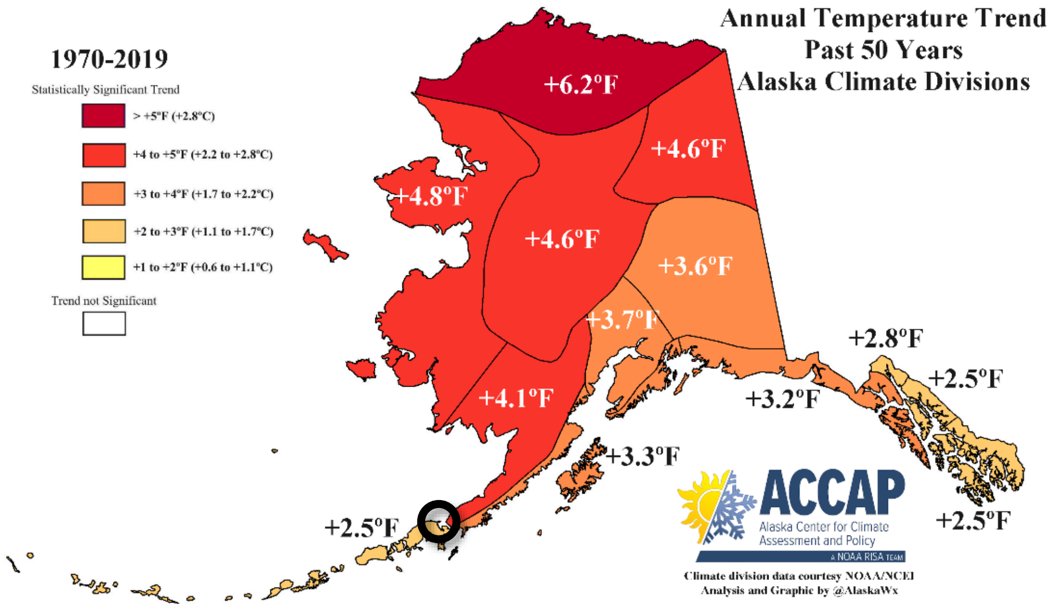


Figure 5. Annual temperature increase in Alaska between 1970 and 2019. According to the data presented Nelson Lagoon is in the area of southwest Alaska with a 1.2°C (2.2°F) increase in temperatures during the nearly 50-year period. Nelson Lagoon is in an area with a temperature increase of 1.4°C (2.5°F). Nelson Lagoon noted by blue circle. Visualization courtesy of Rick Thoman and ACCAP (URL: https://uaf-accap.org/air-temperature/).

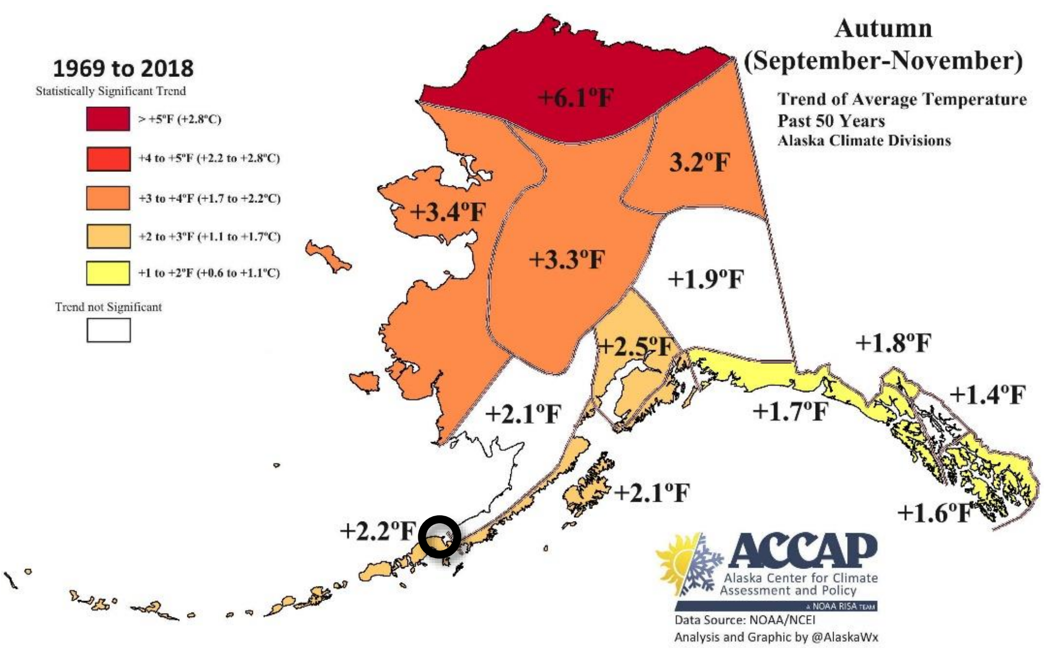


Figure 6. Autumn temperature increase in Alaska between 1969 and 2018. According to the data presented Nelson Lagoon is in the area of southwest Alaska with a 1.2°C (2.2°F) increase in temperatures during the nearly 50-year period. Nelson Lagoon is in an area with a temperature increase of 1.2°C (2.2°F). Nelson Lagoon noted by blue circle. Visualization courtesy of Rick Thoman and ACCAP (URL: https://uaf-accap.org/air-temperature/).

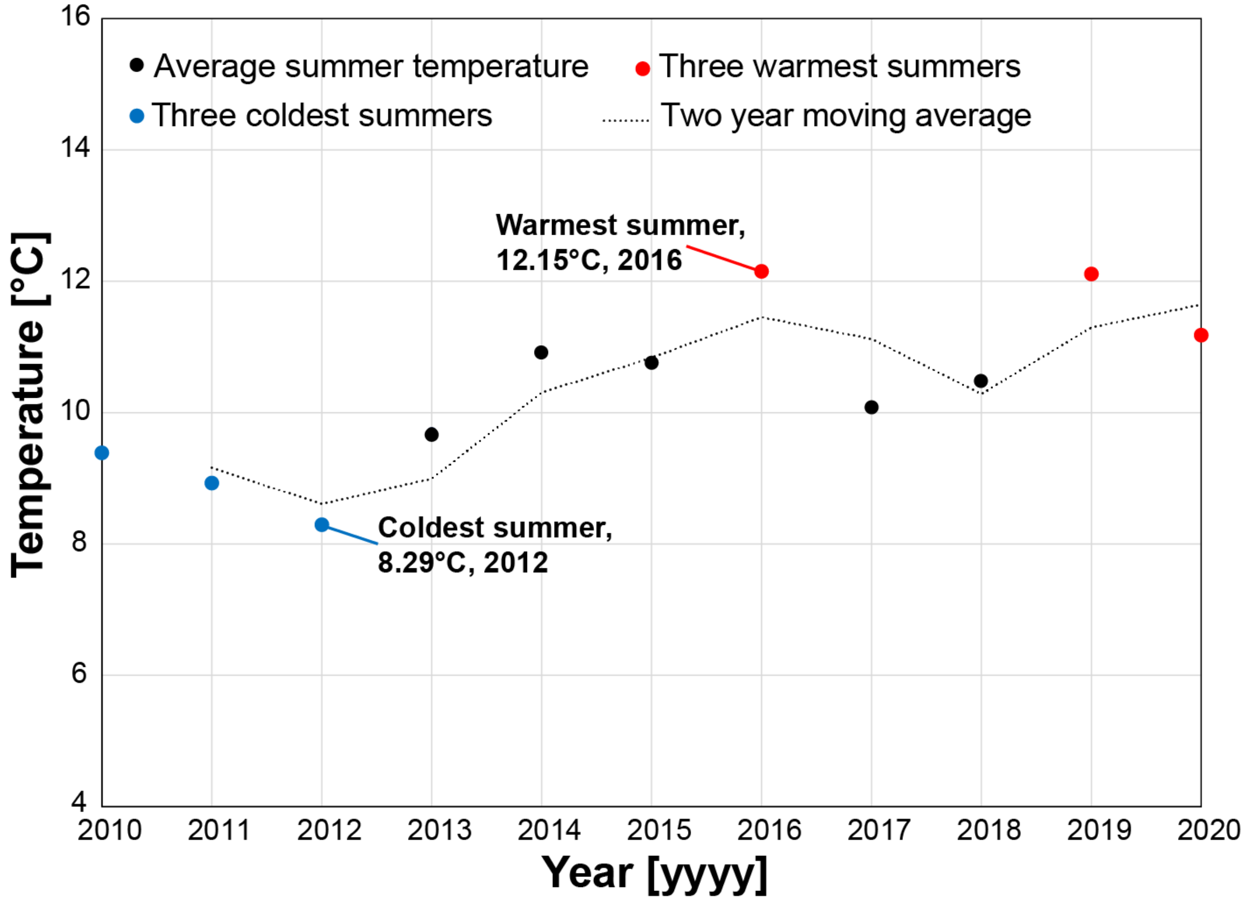


Figure 7. Mean summer temperatures in Nelson Lagoon between 2010 and 2020 based on a local airport temperature gauge. Temperature averages were calculated by taking the average of daily temperatures between June 1st and August 31st. The average summer temperature for this time period is 10.36°C (50.65°F). 2016 had the highest average temperature, at 12.15°C (53.87°F), while 2012 had the lowest average temperature, at 8.29°C (46.92°F). Daily and seasonal temperature averages were calculated from the ASOS (URL: https://mesonet.agron.iastate.edu/request/download.phtml?network=AK_ASOS).

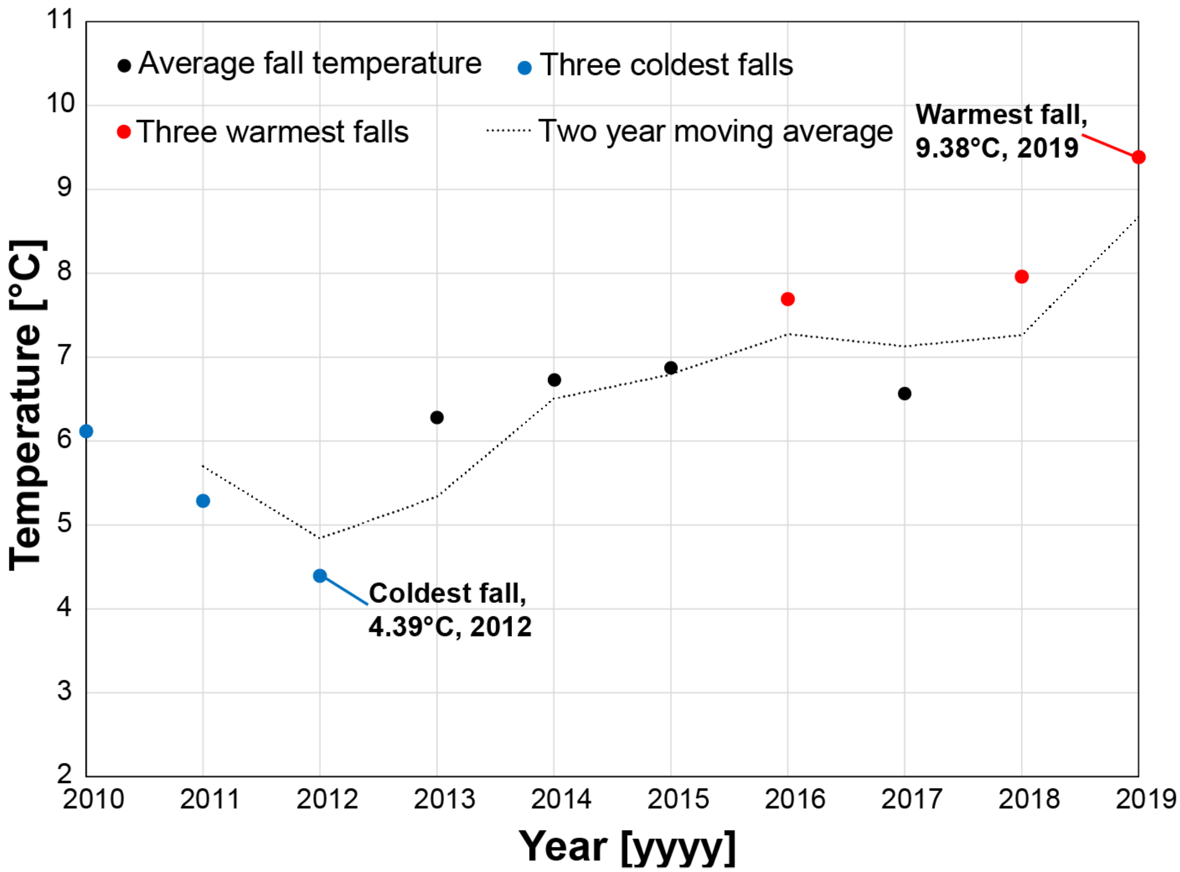


Figure 8. Mean fall temperatures in Nelson Lagoon between 2010 and 2020 based on local airport temperature gauge. Temperature averages were calculated by taking the average of daily temperatures between September 1st and November 30th. During this time, the average fall temperature was 6.73°C (44.11°F). The highest average fall temperature was 9.38°C (49.69°F), recorded in 2019, while the lowest average temperature was 4.39°C (39.90°F), recorded in 2012. Daily and seasonal temperature averages were calculated from the 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 Nelson Lagoon date back to 2010 and are also sourced from the ASOS network at the Nelson Lagoon airport (ASOS, 1998). The winds in the area are strong, averaging 20 mph, with record maximum speeds >60 mph (Brower et al., 1977). Southerly winds dominate during the summer, while northerly winds are the winter norm (**Figure 9**). However, strong winds of gale force may come from any direction at any time during the year (Mason et al., 1996). Wind speeds >50 mph have been observed during all months of the year. Wind speeds >60 mph have been recorded in February, March, April, September, October and November. Wind speeds >70 mph have been recorded in October and November. In the winter months when wind speeds are highest, the predominant wind direction is from the north and southeast. This has important implications for the wave climate of Nelson Lagoon.

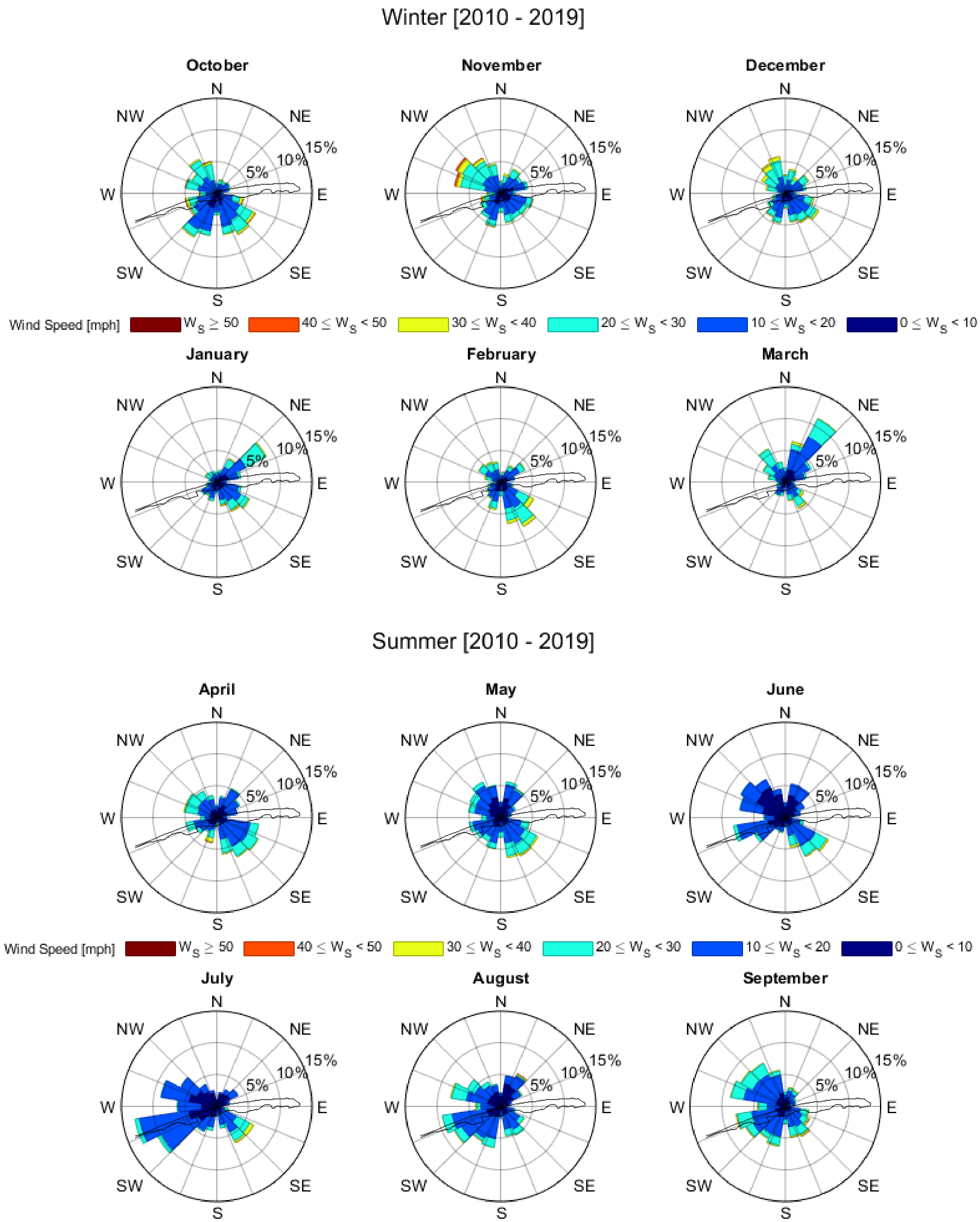


Figure 9. Averaged monthly wind roses for Nelson Lagoon (2010-2019). Spokes in each plot point in the compass direction from which winds traveled. Colors within each spoke denote wind speed bins and the length of the spokes denote the frequency of occurrence. For example, in September, 10 mph to 30 mph winds were common and prevailed from the northwest and southwest. (URL: https://mesonet.agron.iastate.edu/ASOS/).

2.5.3 Storm Regime

The center of a closed surface cyclonic circulation outside of the tropics is normally referred to as an extratropical cyclone (Jones et al., 2003; Bader et al., 2011). According to the Beaufort Wind Scale, an extratropical cyclone is categorized as a storm when the wind speed attains values greater than 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 and are an integral part of the atmospheric transport of heat, moisture (Sorteberg and Walsh, 2008), and momentum polewards (Yin, 2005; Bader et al., 2011).

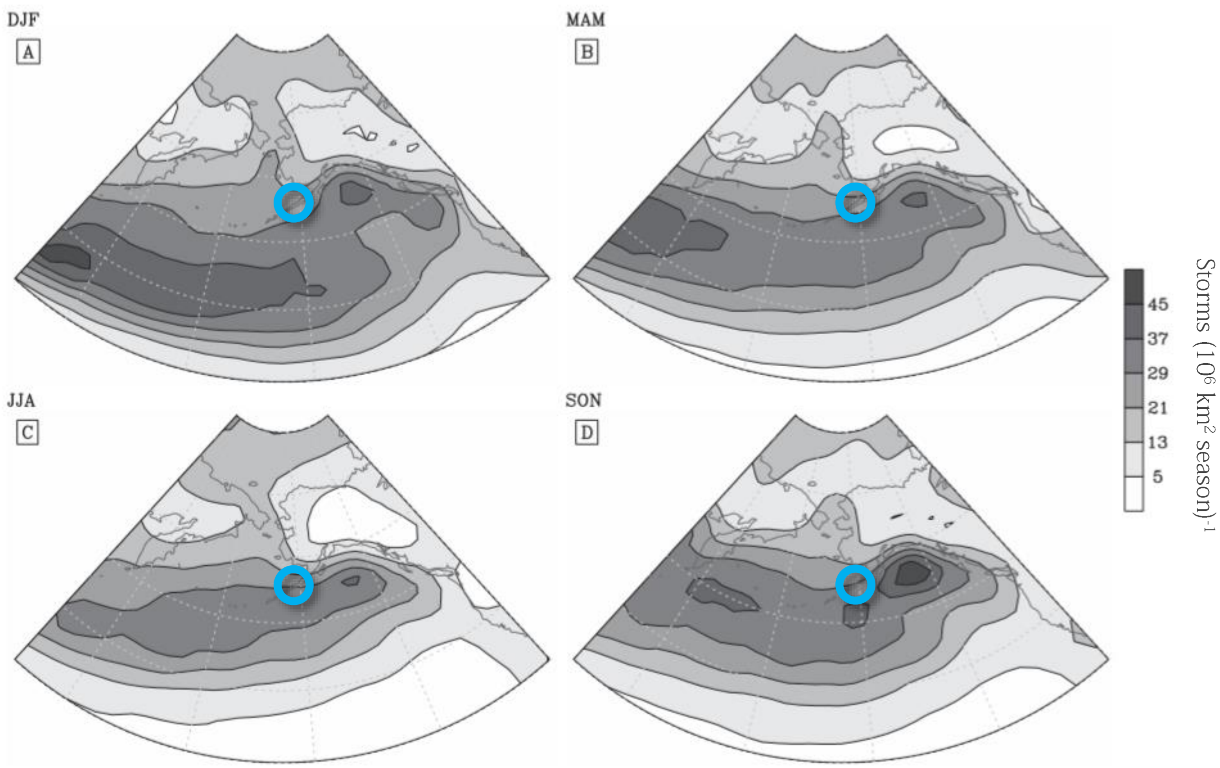


Figure 10. Storm track density climatology in the North Pacific from 1948/49 to 2008. (A) winter (DJF), (B) spring (MAM), (C) summer (JJA), and (D) autumn (SON) seasons. Units: Storms (10^6 km^2 season)$^{-1}$. Location of Nelson Lagoon is noted by the blue circles. Notice that Nelson Lagoon observes greater than 20 storms per season on average (after Mesquita et al., 2009). (URL: https://doi.org/10.1175/2009JCLI3019.1).

Understanding the trends and dynamics of coastal change in Nelson Lagoon is, ultimately, predicated on grasping both the spatial and temporal variability of storm climatologies in the North Pacific and Bering Sea (Atkinson, 2005; Rachold et al., 2005). This is because Nelson Lagoon is located in a region of substantial storm track density, especially during autumn and winter months (October – February) (**Figure 10**); with winter storms being more frequent (**Figure 10**) (Cacchione and Drake, 1979; Overland

and Pease, 1982; Sallenger et al., 1983; Mesquita et al., 2009). A study by Sepp and Jaagus (2011) found that the trend in the annual total number of cyclones in the Arctic increased by 55.8 over the period 1948–2002. There was a significant increase in the frequency of cyclones that specifically moved into the Arctic basin through the Bering Strait by Nelson Lagoon (Sepp and Jaagus, 2011). Moreover, the same study identified that the sea level pressure of Arctic cyclones showed a significant decreasing trend of 2.5 hPa (stronger storms) over the same study period.

Beach morphology and, therefore, shoreline evolution is primarily controlled by an interaction between storm frequency (surge, wave action, overwash, breaching, etc.), tidal rage, and vegetation type and extent. While overwash events brought about by storm impacts may appear to be catastrophic in the short-term, they can be considered a quasi-continuous process that shapes the coastline over longer timeframes (10^2 years) (Morton et al., 2000; Donnelly et al, 2006). As such, it is all the more important to consider storm regime shifts in tandem to sea-ice dynamics as first order drivers of overwash frequency and magnitude, as well as erosion in general.

2.6 OCEANOGRAPHIC SETTING

Nelson Lagoon is located on a wave dominated coast with a mesotidal tide regime (**Figure 11**). The lagoon is tidally connected to Herendeen Bay and Port Moller, both of which are large and deep embayments. Nelson Lagoon's energetic wave regime, coupled with its tide range, means that it is a dynamic sedimentary environment. Wave and tidal regimes, as well as sea level fluctuations at Nelson Lagoon, are explored in more detail below.

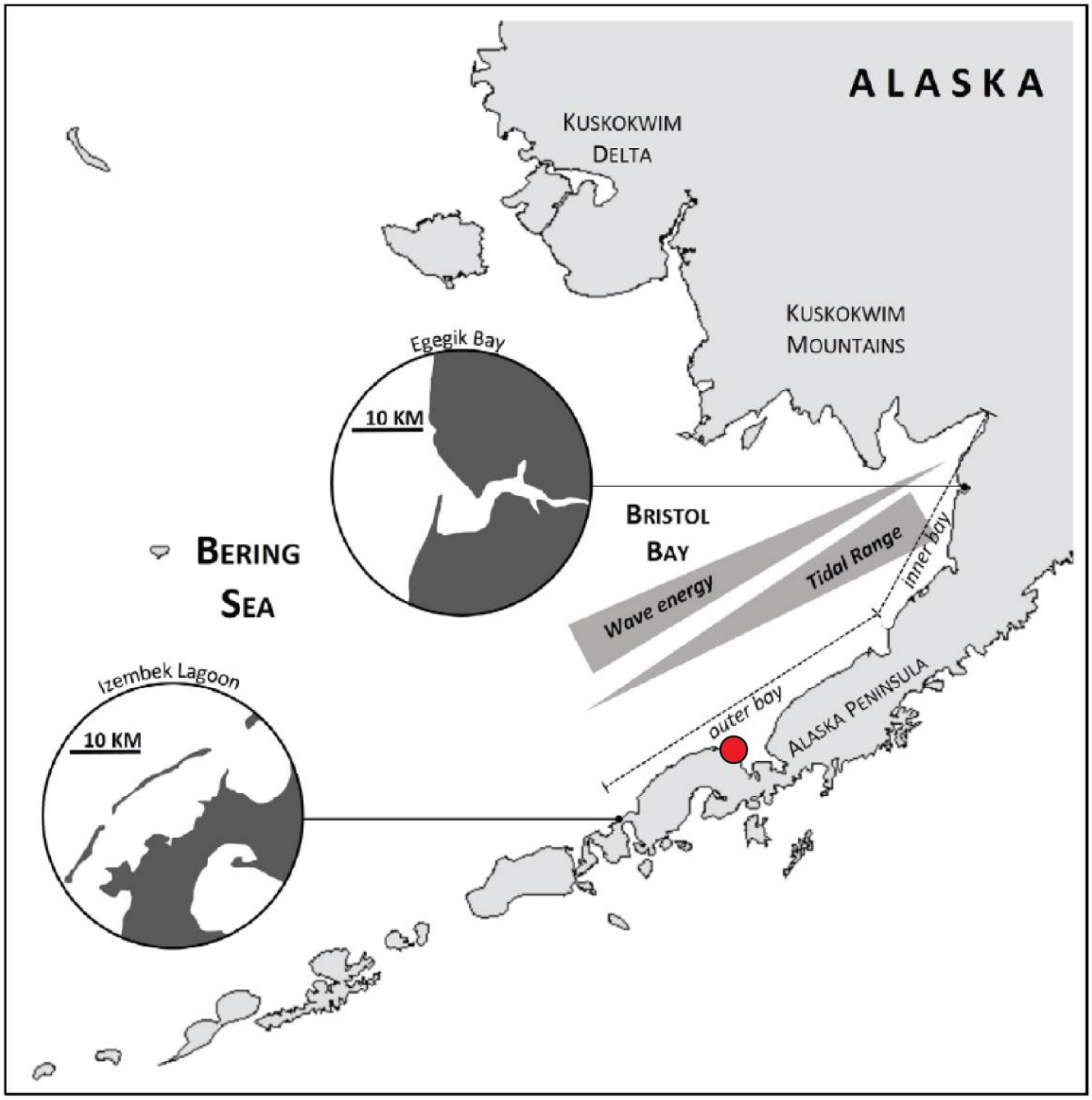


Figure 11. Graphic representation of relative strength of component marine energy (tide and wave) in Bristol Bay and the characteristic barrier morphologies in the outer (well-developed barrier islands, such as Izembek Lagoon) and inner bay (barrier spits at embayment mouths, such as Egegik Bay). Nelson Lagoon notated by the red circle (after Kinsman and Gould, 2014). (URL: https://www.arlis.org/docs/vol1/H/902693690.pdf).

2.6.1 Tides and Currents

Nelson Lagoon observes mixed semidiurnal tides with a tidal range (GT) of approximately 2.3 m (7.5ft). As such, extensive mud flats are exposed each tidal cycle. Average Mean Higher-High Water (MHHW) lies at 1.993 m (6.54ft) elevation relative to the North American Vertical Datum of 1988 (NAVD88) computed using Geoid 12B. Average Mean Lower-Low Water (MLLW) lies at -0.277 m (-0.9ft) elevation. Such water exchange between the back barrier lagoon and open ocean results in significant ebb and flood currents, with substantial sediment transport potential. HDR Alaska Inc. calculated tidal currents within Nelson Lagoon using a hydrodynamic numerical model. It was found that strong currents occurred particularly within the river channel during incoming and outgoing tides. These currents reach over 2 m/s (3.9 knots) (HDR, 2014a). However, currents next to the community were generally slight during all phases of the tide, reaching just over 0.5 m/s (1 knot).

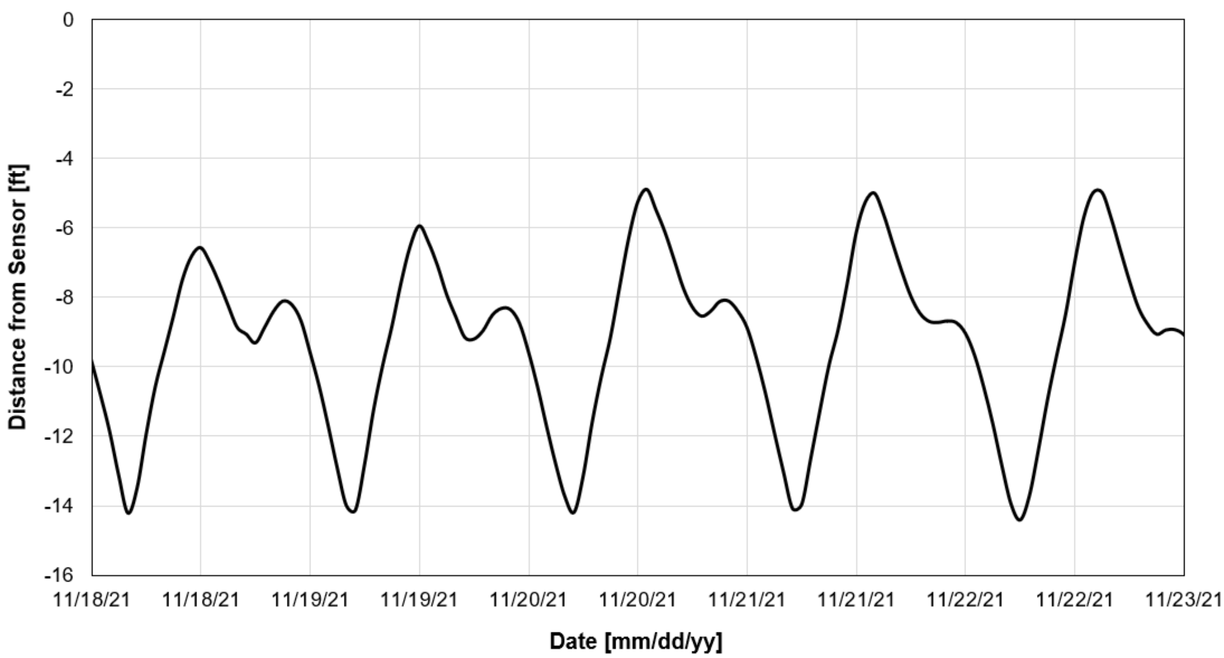


Figure 12. Example time series (11/18/21 – 11/23/21) of water level collected by a Stilltek LLC ultrasonic water level sensor at the Nelson Lagoon dock. Values represent distance from the sensor to the water surface in feet. (URL: https://stilltek.com/akdggs/nlsnlgn/).

Station: Nelson Lagoon, AK **Epoch:** 1983 - 2001
Status: Accepted (Dec 04 2019) **Datum:** NAVD88
Units: Meters

Datum	Value	Description
MHHW	1.993	Mean Higher-High Water
MHW	1.758	Mean High Water
MTL	0.988	Mean Tide Level
MSL	0.991	Mean Sea Level
DTL	0.858	Mean Diurnal Tide Level
MLW	0.218	Mean Low Water
MLLW	-0.277	Mean Lower-Low Water
NAVD88	0.000	North American Vertical Datum of 1988
GT	2.270	Great Diurnal Range
MN	1.540	Mean Range of Tide
DHQ	0.235	Mean Diurnal High Water Inequality
DLQ	0.495	Mean Diurnal Low Water Inequality

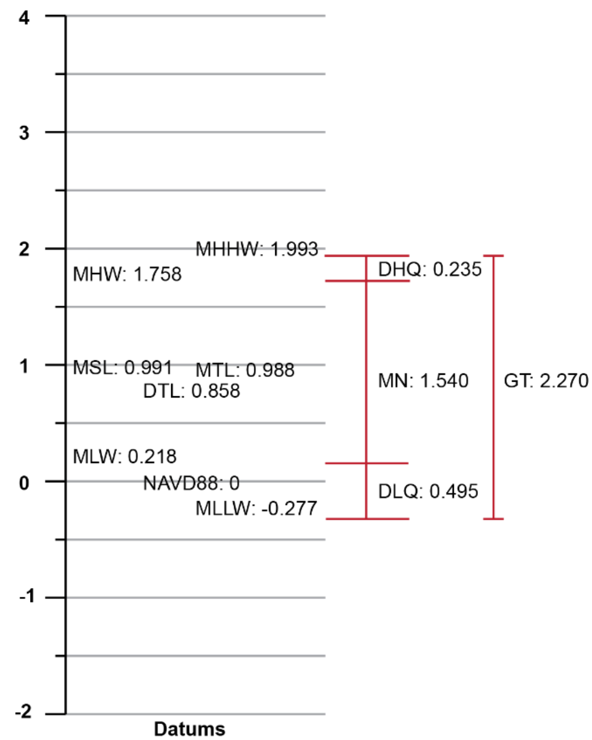


Figure 13. Tidal datum computed for Nelson Lagoon using data over a 6-month period with JOA Surveys, LLC tidal datum tool. The water level gauge was vertically referenced to a land-based datum (NAVD88).

2.6.2 Wave Climate

Nelson Lagoon lacks long-term measured surface wave data. As such, offshore wave data from the Army Corps of Engineers Wave Information Study (WIS) Station 82289 is used to characterize Nelson Lagoon's wave regime (Hubertz, 1992). This station is approximately 30 km (19 mi) north-west of Nelson Lagoon. The dominant wave height directions throughout the year are from the west and west north-west (**Figure 14**).

There is significant seasonality in the wave regime, with the winter (October – March) experiencing higher variability in both prevailing wave height and direction compared to the summer months (April – September). For example, October, November, and December have the highest occurrence of wave heights >3 m (>10 ft) while June and July have the lowest occurrence of wave heights >1 m (>3 ft). High frequency wind waves <1m (<3 ft) in amplitude are propagated across the lagoon regularly. During high southerly wind events, waves >2m (6.5ft) can be observed in the lagoon.

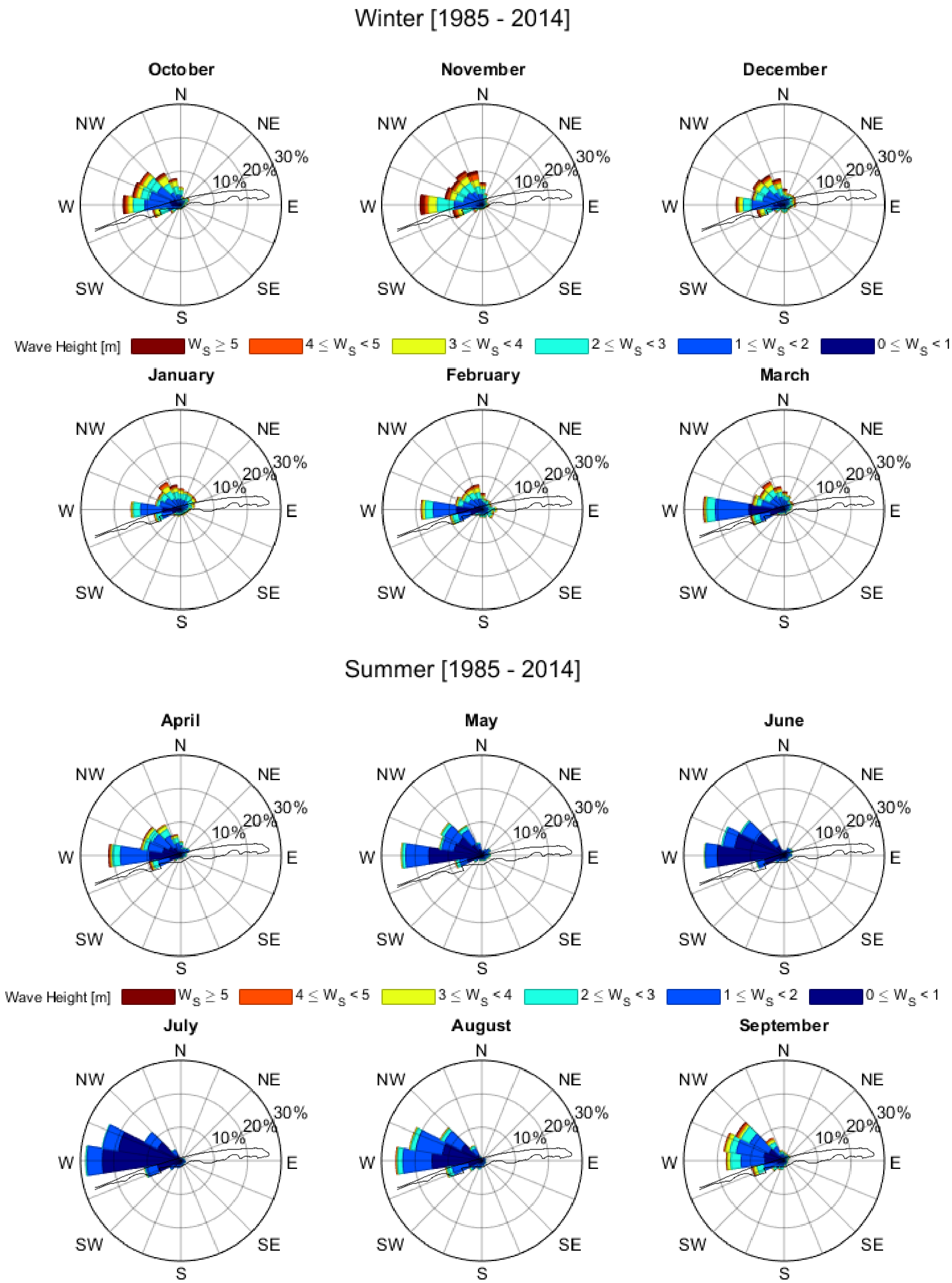


Figure 14. Averaged monthly wave roses (1985-2014) from WIS Station 82289. Spokes in each plot point in the compass direction from which waves traveled. Colors within each spoke denote wave height bins and the length of the spokes denote the frequency of occurrence. Notice wave direction is predominantly from the west and northwest. (URL: http://frf.usace.army.mil/wis/).

2.7 SEA ICE

Sea-ice extent and duration strongly influence Arctic and Subarctic coastal dynamics, and climate change is now altering the sea-ice regime of the Bering Sea (Farquharson et al., 2018). Open ocean sea-ice is an important moderator of wave fetch and water temperature, and shorefast sea-ice shields coastlines from wave action. Specifically, the extent of sea-ice has an inverse relationship with wave fetch, height, and swell size in Arctic seas (Francis et al., 2011; Overeem et al., 2011; Thomson and Rogers, 2014; Thomson et al., 2016), with the open-water season having the most wave energy available for coastal erosion and sediment transport (Overeem et al., 2011; Farquharson et al., 2018). Storms during the ice-free season generate the most geomorphologically significant wave events along Arctic coastlines and, hence, strongly influence coastal processes (Reimnitz et al., 1994; Mason et al., 1996; Forbes, 2011; Barnhart et al., 2014; Farquharson et al., 2018). Over the past three decades, there have been significant changes in the timing and extent of sea-ice cover across the Bering, Chukchi, and Beaufort Seas (**Figure 15**).

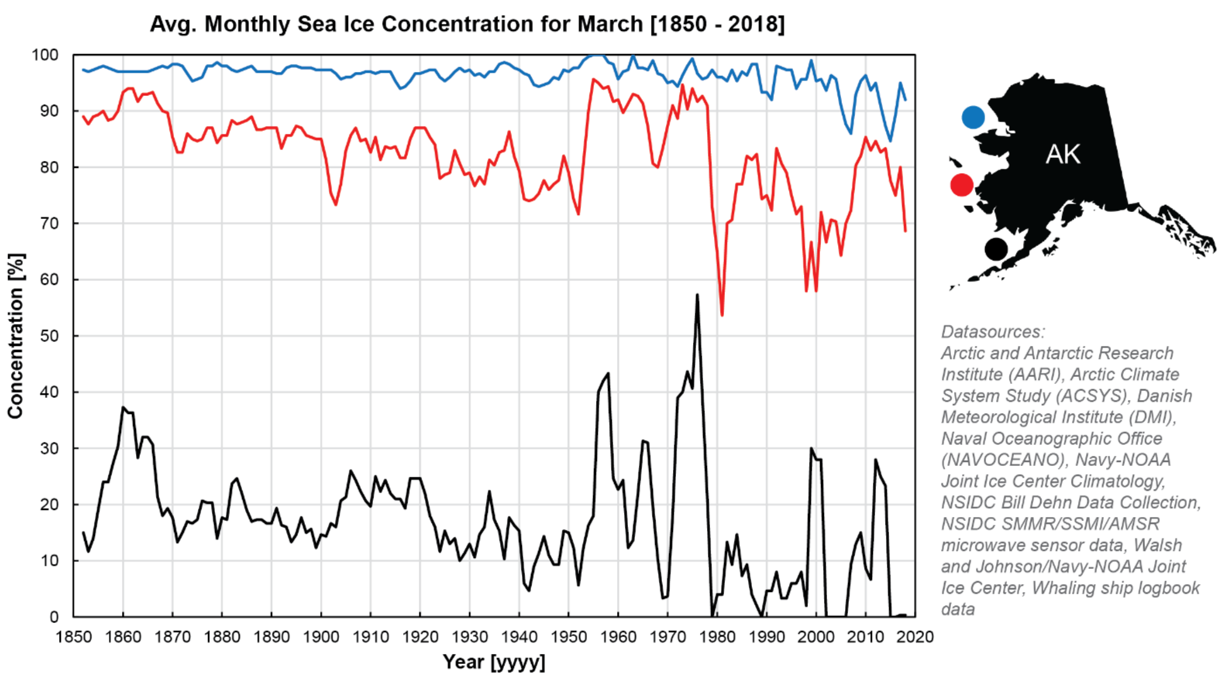


Figure 15. Sea ice concentrations for the month of March between 1850 and 2018 compiled from the Alaska Ocean Observatory Network (AOOS) Sea Ice Atlas. 0–30% indicates open water to very open drift, 30–90% characterizes open drift to close pack, and 90–100% corresponds with very close pack to compact. The black, red, and blue points in the upper right inset map correspond to the black, red, and blue sea ice time series in the main graph. Notice that sea ice in Bristol Bay (black) is no longer consistently observed each year (2000 onward). (URL: Sea Ice Atlas: Explore (uaf.edu)).

Satellite data reveal that patterns in sea-ice cover have been spatially heterogeneous through time, with significant declines of sea-ice extent in the Chukchi and Beaufort Seas, and complex multi-year variability in the Bering Sea south of St. Lawrence Island (**Figure 15**) (Frey et al., 2015). Stabeno et al. (2012) describe this multi-year variability in sea-ice cover over the southeastern Bering Sea shelf as involving oscillations between warm years (e.g., 2001–2005) with less extensive ice (driven by weak, easterly winds) and cold years (e.g., 2007–2012) with more extensive ice (driven by cold, northerly winds).

As per the extent of continuous open ocean sea ice within Bristol Bay, it generally reaches its maxima between February and March, and spatially lies roughly halfway down the Alaska Peninsula (**Figure 16**). Though, drift ice occurs south of this boundary. With significant interannual variability, landfast and/or bench ice formation in coastal shallow waters generally begins in November as far south as the Aleutian Islands.

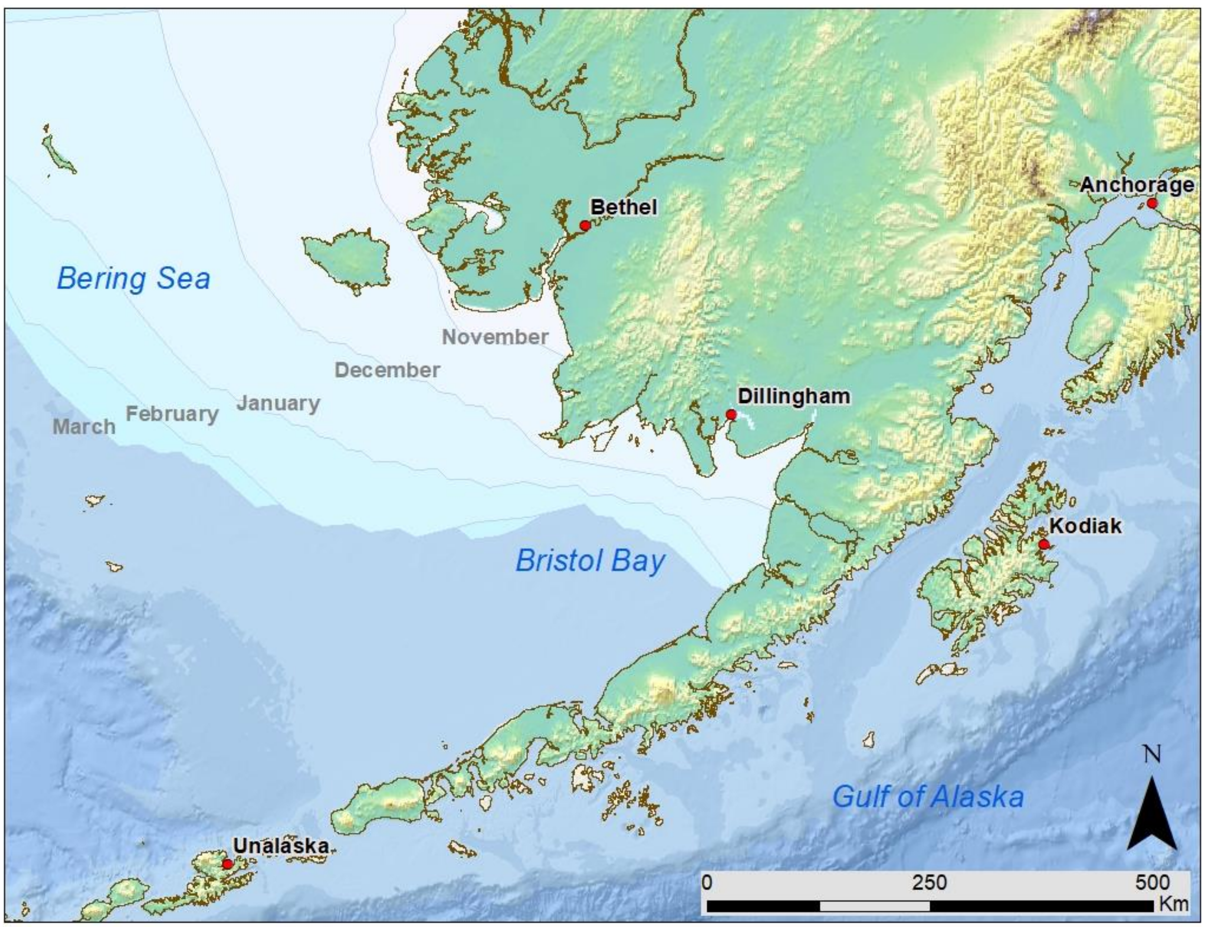


Figure 16. Average monthly sea ice extent in Bristol Bay from 1981-2010. Line data downloaded from the NSIDC and converted to polygons. (URL: https://nsidc.org/data/search/#keywords=sea+ice/).

At Nelson Lagoon, sea ice timing and spatial extent also shows extreme interannual variability. Prior to the 2000s, the lagoon would mostly freeze over each year with substantial bench ice formation along the shores which would dampen or eliminate wave impact entirely (**Figure 17**). In recent times, the sea ice regime in the lagoon has been markedly diminished as revealed from timelapse photography and local testimony.

Figure 17. Bench ice along the Nelson Lagoon sea wall in 1995. Image Credit: HDR, 2011

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 AEB Hazard Mitigation plan, consultation with U.S. Geological Service (USGS) and the Alaska Volcano Observatory (AVO) by HDR Alaska, Inc. (HDR, 2011), input from local residents, and documented past occurrences. As such, potential natural hazards at Nelson Lagoon like volcanoes and wildfire are not covered in 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 18**) (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 (Alaska Department of Homeland Security & Emergency Management [DHSEM], 2018).

Most communities in Bristol Bay are perched on tall (>20-ft-high) coastal bluffs as a result of the large tide range (macrotidal) and/or their proximity to river mouths (Overbeck et al., 2020). Communities located at river mouths in Bristol Bay are subject to erosion from coastal and riverine processes. The tall and exposed nature of the bluffs makes them vulnerable to groundwater seepage, overland runoff, and slumping. Coastal bluffs are fronted by mixed sand-gravel beaches, but the bluffs themselves are primarily composed of consolidated and/or clay-rich materials that are more resistant to wave impacts, compared to sandy beaches (Overbeck et al., 2020). During coastal storms, materials that slumped or were transported to the beach from the bluffs are eroded by waves. Waves can also cut niches at the base of the bluffs, which destabilizes the material above, resulting in new slumps.

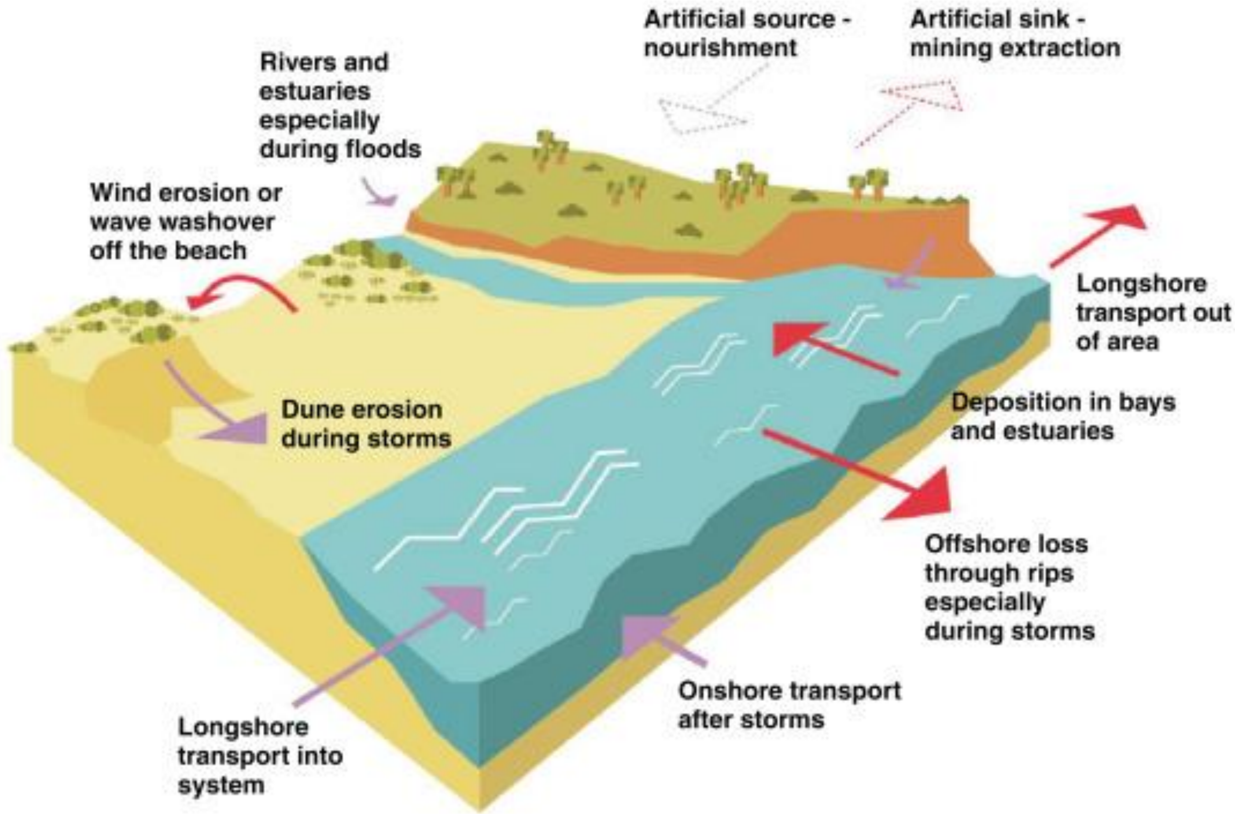


Figure 18. Components of a sediment budget for a sandy coast. From Goodwin et al., 2020 (URL: https://doi.org/10.1016/B978-0-08-102927-5.00025-4).

Nelson Lagoon's sandy beaches are fringed in the supratidal zone by foredunes up to 20 m in elevation created by sand transported by wind action (Hoyt, 1967; Davidson-Arnott et al., 2019). Wave action, however, is the primary driver of coastal change at Nelson Lagoon. Net erosion of the dunes along Nelson Lagoon has been constant for at least the last 40 years, though long-term averages of erosion along the Nelson Lagoon's foredune are generally the result of short-term severe events with substantial wave action and run-up (Nelson Lagoon SECD, 2001), when the equivalent of multiple years' worth of "normal" sediment transport can occur (i.e. Hume and Schalk, 1967; Dygas and Burrell, 1976). Shoreline erosion at and up current of Nelson Lagoon supplies a major contribution to the sediment budget of the spit, a contribution likely much larger than that of riverine input (i.e. Reimnitz and Maurer, 1979).

Erosion has impacted residential and public infrastructure at Nelson Lagoon. Most significant of which has been the community's water delivery system, though multiple private structures such as living dwellings and set net cabins have been abandoned due to shoreline change.

3.1.2 Flooding

Coastal flooding is predominately caused by long-term elevated water levels due to highest astronomical tides. Shorter-term water level fluctuations can either enhance or dampen these long-term water level fluctuations brought about by tides. During storms, changes in sea level occur as a result of wind stress on the water surface as well as deviations in atmospheric pressure leading to positive displacement of the water level (storm surge or set-up) or negative displacement (negative surge or set-down). For example, there is a change in sea level of about 1 cm (0.4 in) for every 1 millibar (roughly 0.1 kPa) in atmospheric pressure (Fu and Pihos, 1994). As a result, sea level responds not only to pressure changes associated with weather systems but also to seasonal changes in pressure (Davidson-Arnott et al., 2019). As such, tide levels are, on average, higher during the autumn which exacerbates storm surge and is when most communities in Alaska experience flood events (Fok, 2012).

In addition to elevated water caused by storm surge, waves can wash up over the beach causing inundation, breaching, and overwash (Sallenger, 2000). Wave run-up is the sum of wave set-up and swash uprush and is added to the water level reached as a result of tides and storm setup. Runup is a complex phenomenon that depends on the local water level (including surf beat or infragravity wave effects), the incident wave conditions (height, period, steepness, direction), and the nature of the beach or structure being run-up (e.g., slope, reflectivity, height, permeability, roughness) (Dean et al., 2005; Weaver, 2008).

As such, total water level (TWL) is a summation of the processes discussed above (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 19**). Wave run-up can add meters to the total water level on the open ocean coast, which is not only very important for inundation levels but 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).

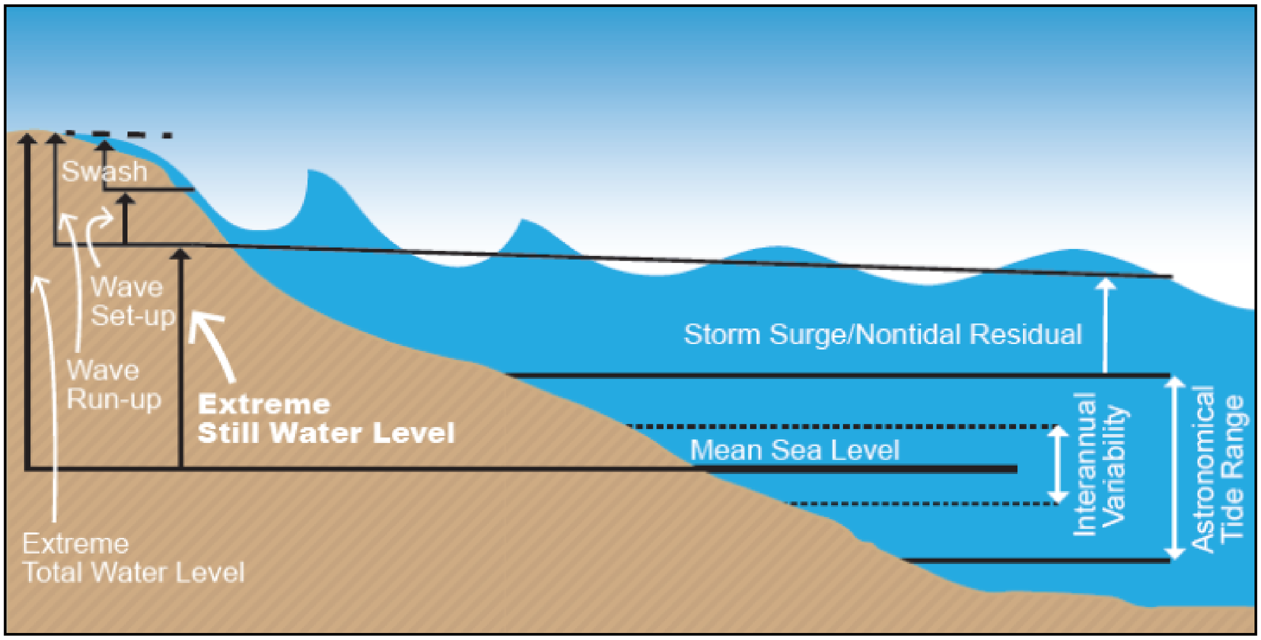


Figure 19. Diagram showing the various components of Total Water Level (TWL); waves, tides, and nontidal residuals. After Moritz et al., 2015.

Extreme TWLs in Nelson Lagoon have interfered with access to the community dock and airstrip facilities multiple times over the last 30 years (USACE, 2007). However, minimal or no data are available that document these events, which means that there are no past TWL elevations to compare future flooding events to for historical context (Buzard et al., 2020).

Table 1. Table of documented flooding events in Nelson Lagoon. Previous flood events are likely, but data on these events does not exist.

Date	TWL(m)	Uncertainty (m)	Impacts
2021.11.22	2.9	± 0.5	Road to fuel farm, city dock, and runway inundated; Foredune breached by runway

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 (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.

The probability of exceedance displayed in these maps indicates that at any given location, there is a 2% chance that an earthquake larger than the value depicted on the map occurs in the next 50 years. In Nelson Lagoon, there is a 2% chance that an earthquake with the following characteristics occurs in the next 50 years: PGA of 47%-61%g, and 0.2 second SA of 64%-85%g (**Figure 20**).

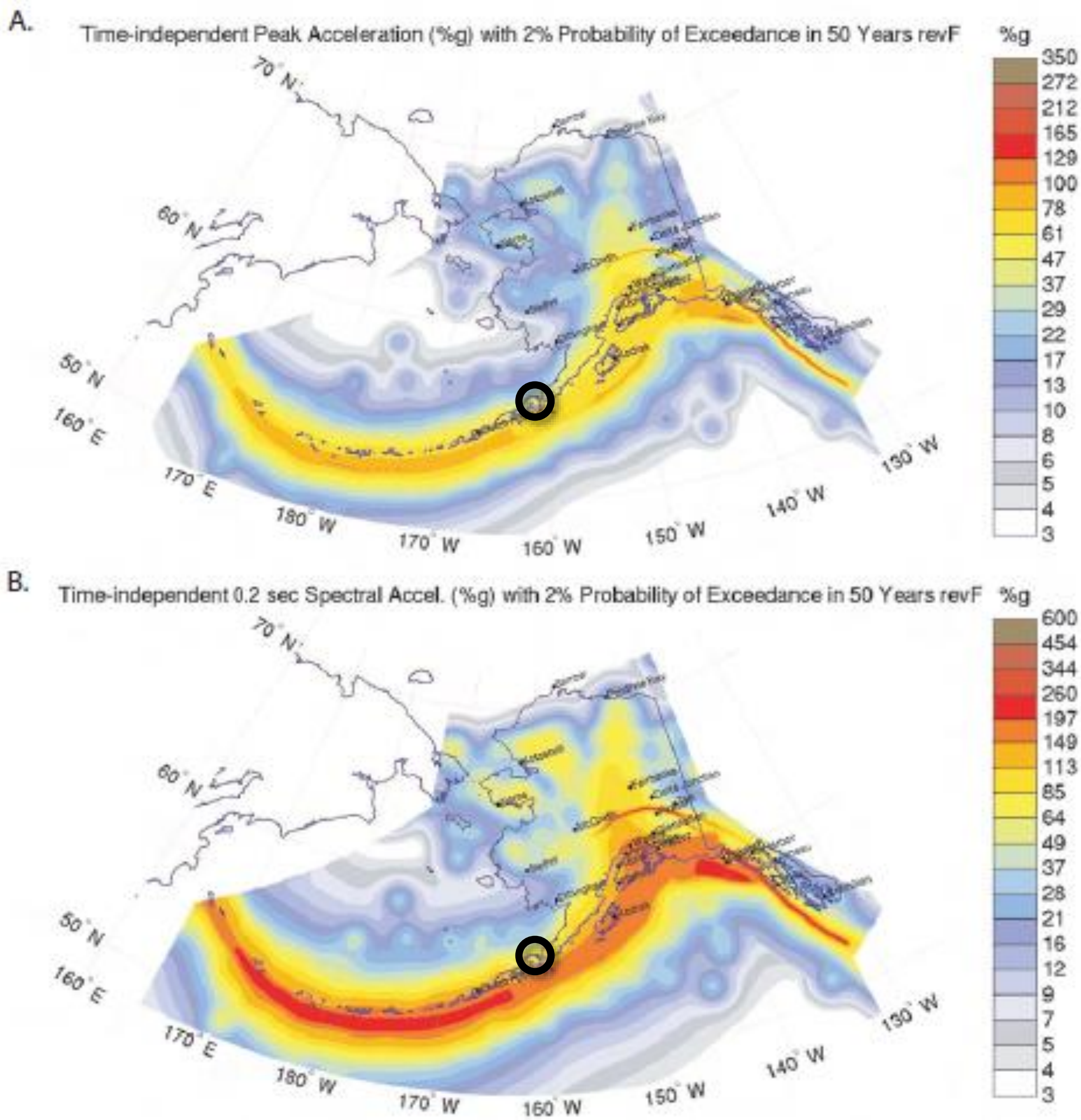


Figure 20. Earthquake probability in Alaska . Probabilistic ground motion with a 2-percent probability of exceedance in 50 years for peak ground acceleration (A), 0.2 second spectral acceleration (B). Nelson Lagoon noted by blue circle. (URL: https://www.usgs.gov/natural-hazards/earthquake-hazards/hazards).

3.1.4 Landslides

There are no known landslide geohazards at Nelson Lagoon.

3.1.5. Tsunami

Nelson Lagoon is at risk of infrastructural damage and loss of life as a result of both earthquakes and tsunamis, which are caused by seismic activity on or beneath the ocean floor. Fortunately, Nelson Lagoon is shielded from most tsunamis by the Aleutian Island chain itself, as most seismic activity occurs on the southeast side of the island chain; however, tsunami risk remains a threat. Tsunamis within Bristol Bay are likely to come from one of three sources: underwater landslides, transpacific tsunamis, or volcanic eruptions (Suleimani et al., 2020). In 2020 the DGGS conducted a tsunami hazard assessment and determined that during severe tectonic scenarios Nelson Lagoon the maximum assumed runup height above mean highest high water (MHHW) is 3.5m (11.5ft.; **Figure 21**; Suleimani et al., 2020). A surge of this magnitude would compromise much of the town's infrastructure, particularly on the lagoon side of the spit and through the center of the town (**Figure 21**).

Figure 21. Tsunami hazard map of Nelson Lagoon, produced by the Alaska Earthquake Center for the Alaska Division of Geological and Geophysical Surveys (from Suleimani et al., 2020). 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. (URL: https://dggs.alaska.gov/webpubs/dggs/ri/oversized/ri2020_001_sh001.pdf).

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).

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) (**Figure 23**). 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 Nelson Lagoon area seems to align with the global average rate, which means this signal is most likely not captured in the erosion rates measured for this project. But it is a factor that will accelerate erosion and flooding events over much longer timescales. The closest water level gauge to Nelson Lagoon that has recorded water level heights for any extended period had been NOAA's Port Moller, AK - Station ID: 9463502 (NOAA, 2020). Average monthly water levels at Port Moller station over its entire operating period show a RSLR rate of 3.15 ± 1.94 mm/yr (0.13 ± 0.08 in/yr) (**Figure 22**).

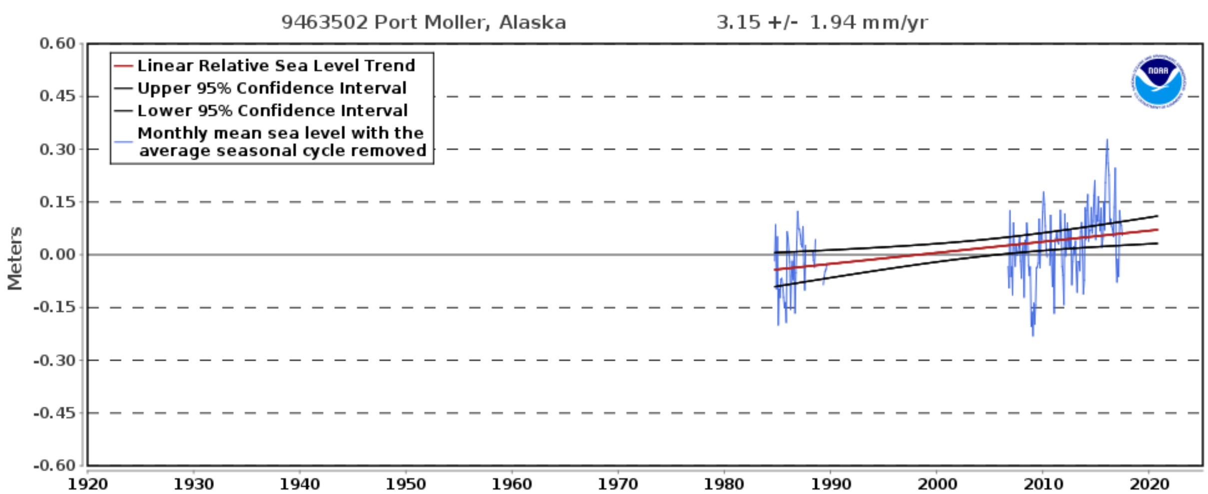


Figure 22. Monthly mean sea level from Port Moller Station ID: 9463502. The long-term linear trend is also shown, including its 95% confidence interval. The plotted values are relative to the most recent Mean Sea Level datum established by CO-OPS. The relative sea level trend is 3.15 ± 1.94 mm/yr (0.13 ± 0.08 in/yr), based on monthly mean sea level data from 1984 to 2017 which is equivalent to a change of 0.31 m (1.03 ft) in 100 years. (URL: https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=9463502).

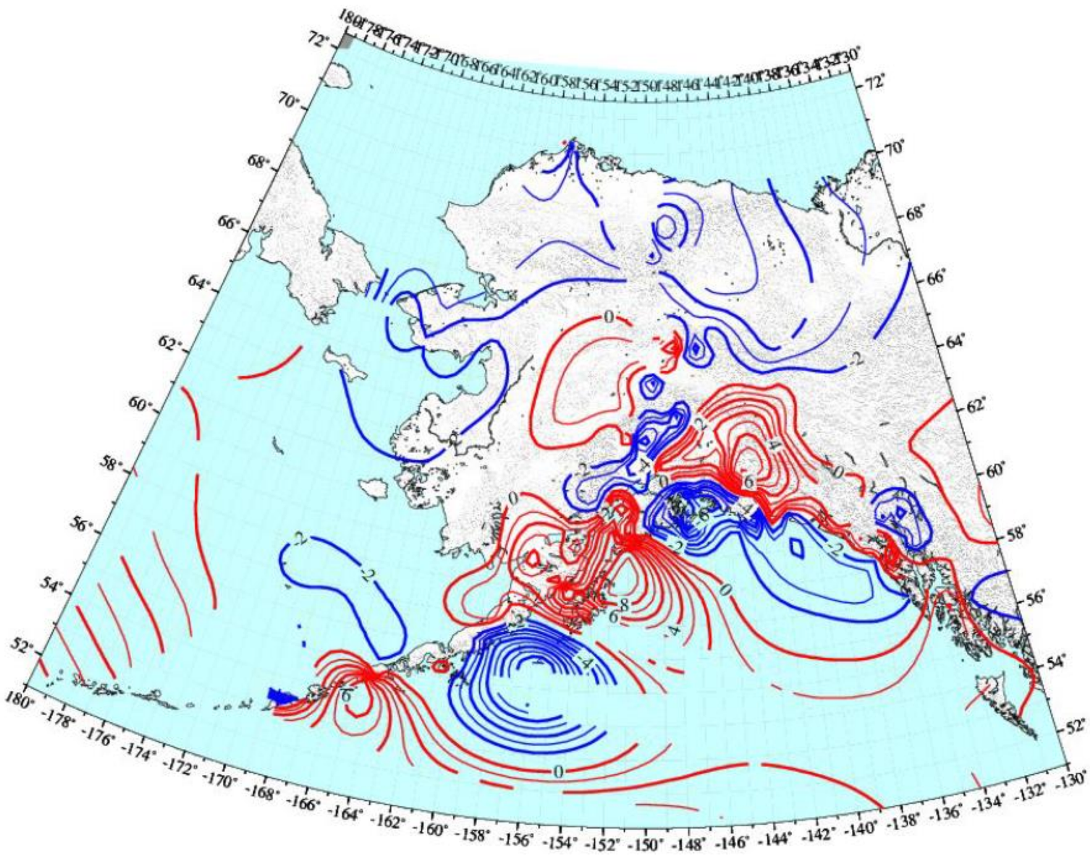


Figure 23. Predicted uplift rates with glacial isostatic adjustment subtracted, in mm/yr. This map is made by contouring vertical adjustment rates derived from various permanently operating GNSS stations across the region and subtracting signals brought about by post-glacial rebound. Contour interval is 1 mm/yr, and every other contour is labeled (from Freymueller, 2013). (URL: http://gps.alaska.edu/jeff/Snay-Freymueller-2016_GPS_velocities.html).

3.2 PAST/ONGOING MITIGATION EFFORTS

A timber seawall is already in place along a small portion of the lagoon side of the community, although it is in poor condition due to undermining and flanking. Despite its poor condition, this wall has been the primary protection for the community for almost three decades, making it, overall, a highly successful structure. In recent years, the community has installed the following major erosion protection measures along this stretch (USACE, 2007): (a) gabions along the seawall to anchor existing wood in the breakwater (**Figure 24A**), and (b) approximately 170 linear meters of sediment containers constructed with geotextile fabric (**Figure 24B**).

Figure 24. Seawall and sediment containers in place along the lagoon coastline of the community . A) the seawall and gabions, the geotextile containers can be seen on the left, and B) the geotextile containers fronting the community to the west of the seawall. May 2019.

HDR Alaska Inc. drafted plans to extend the mitigation structures to the west of the existing seawall, but also made clear that the seawall currently in place needs structural attention (HDR, 2015; **Figure 24**). No extension has taken place.

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

HDR Alaska Inc. was hired by the Aleutians East Borough in 2011 to conduct a Coastal Erosion Study Project at Nelson Lagoon. HDR produced a Historic Shoreline Erosion Map and Analysis, a Beach Profile Study, a Wave Climate Study and a 20% Preliminary Design Report (HDR, 2015). The firm collected various cross-shore elevation profiles with RTK-GNSS, conducted a shoreline evolution study using aerial imagery (HDR, 2011; HDR 2014c), and developed hydrodynamic numerical models of waves (HDR, 2014b) and currents (HDR, 2014a) for Nelson Lagoon.

Nelson Lagoon is one of 15 Alaska Native communities working with the Alaska Institute for Justice (AIJ), a community-based non-profit organization. AIJ implemented community-based environmental and social monitoring in 2015. This collaborative and multilevel documentation was carried out so that government agencies could better provide predictive rates of local environmental change as well as to assess how measured change is impacting community health and well-being.

The University of Alaska Fairbanks ACGL has been actively conducting coastal hazard related research at Nelson Lagoon since the fall of 2018 (**Table 2**). This includes a series of topographical surveys, the establishment and maintenance of erosion monitoring sites, and the collection of hydrographic datasets such as waves, water levels, and bathymetry. The results of this continuing work are delivered in this report.

Table 2. Summary of ACGL community visits and field work.

Date	Individuals	Research Activities	Monitoring Activities	Outreach
October 2018	Chris Maio, Jared Roberts, Robin Bronen, Denise Pollok	• UAV survey • GNSS survey	• Established 2 sites • Training on measurements	• Community meeting led by AIJ
May 2019	Chris Maio, Reyce Bogardus	• UAV survey • GNSS survey • Install water level gauge • Temporary pressure gauge • Wave gauge data collection • Bathymetric survey	• Site maintenance	• Meeting with environmental program staff
September 2021	Chris Maio, Reyce Bogardus, Harper Baldwin	• GNSS survey • Install wave buoy(s)	• Site maintenance • Establish new site	• Meeting with environmental program staff
October 2022 *(Planned)*	Reyce Bogardus, Harper Baldwin, Other student	• GNSS survey • Install wave buoy(s) • UAV survey	• Site maintenance	• 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 Nelson Lagoon. 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 Nelson Lagoon, the ACGL has collected 184 GCPs or checkpoints (**Table 3**).

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 (e.g. Kinsman and DeRaps, 2012; Buzard, 2017). 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 3**).

Table 3. 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 and Checkpoints	Shoreline Indicators	Profiles	Cross-spit Profiles	Benchmarks	Other
2018	64	10 km (8,950)	19 (393)	0	0	27
2019	120	2	31 (1,028)	0	0	1
2021	0	21 km (18,867)	33 (783)	9 (2,970)	0	20

4.2.2 Benchmarks

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 seven NGS benchmarks in and around Nelson Lagoon; six are purely horizontal reference points (**Table 4**). The ACGL plans to refine the coordinates provided by NGS during a site visit to Nelson Lagoon in 2022.

Table 4. NGS benchmarks within 10km of Nelson Lagoon.

Site Name	Latitude	Longitude	Geoid Height (m)	Control Type
UW0973	N 55 58 45.19704	W 161 18 33.85267	N/A	Classic Horizontal
UW0972	N 55 57 21.78346	W 161 17 18.89829	N/A	Classic Horizontal
UW0954	N 55 59 56.62890	W 161 12 15.89268	N/A	Classic Horizontal
UW1491	N 56 00 02.78576	W 161 12 12.95506	N/A	Classic Horizontal
UW0953	N 55 58 01.24536	W 161 07 55.73207	N/A	Classic Horizontal
UW1492	N 56 00 36.79355	W 161 07 56.91244	N/A	Classic Horizontal
UW7927	N 56 00 38.02456	W 161 05 52.04579	13.974	GPS Site

4.2.3 Digital Surface Model and Orthomosaic

A digital surface model (DSM) 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. The survey, consisting of 9 individual flights, took place over a period of 4 days and was carried out during low tide stages when it was feasible to capture as much of the beach face and mud flats as possible.

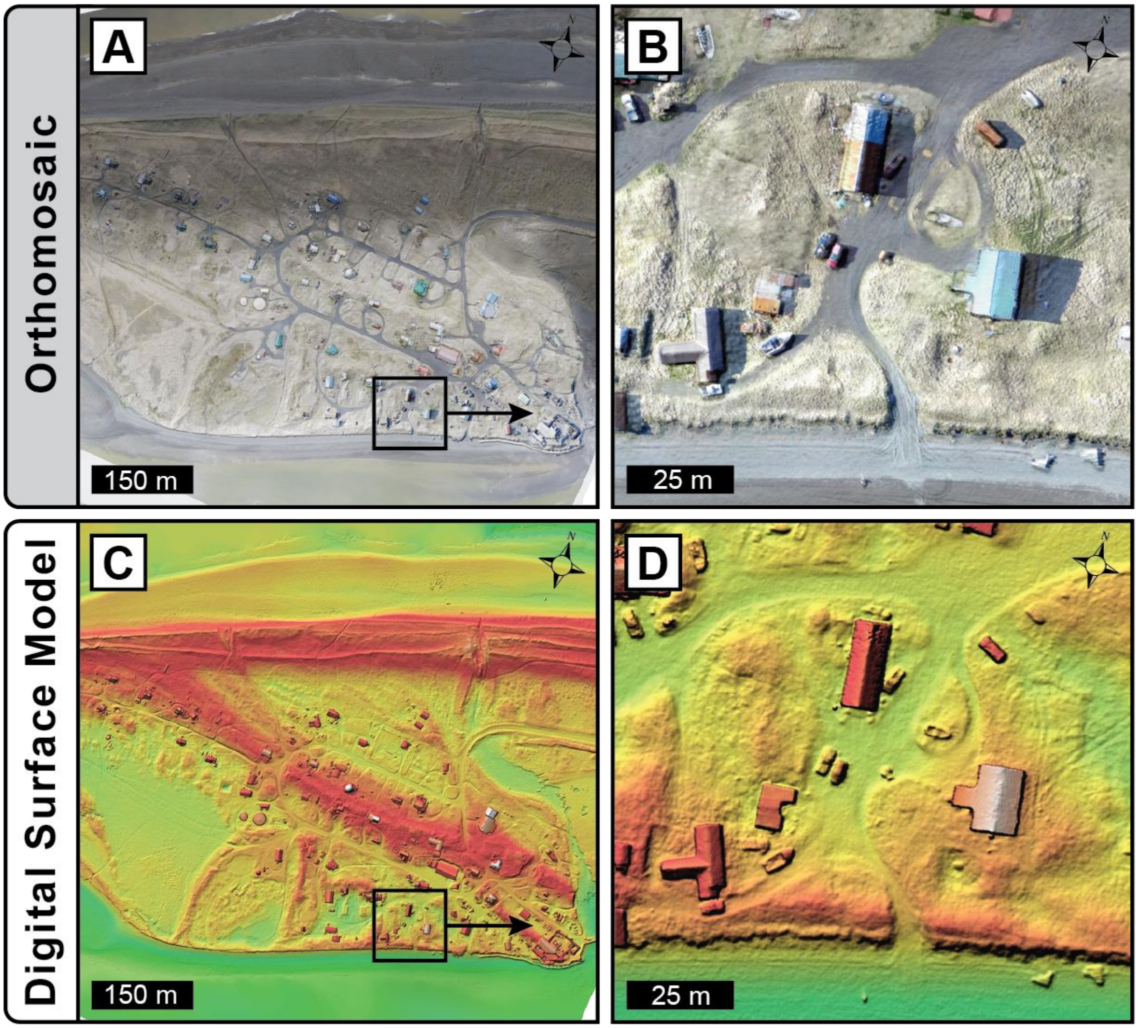


Figure 25. Orthomosaic (A&B) and DSM (C&D) of Nelson Lagoon generated using UAV imagery in 2019.

The survey was accompanied by an extensive ground control campaign using RTK-GNSS to vertically reference the DSM (Watanabe and Kawahara, 2016), relate elevations to the tidal datum computed for this project (Antunes, 2000), but also to validate the vertical accuracy of the refined topographic surface (James et al., 2017). This validation was carried out following Gindraux et al. (2017), where the vertical values of the unused GCPs from the alignment phase are compared against the refined 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).

In 2019, a water level gauge was installed and vertically referenced to a known land-based datum in Nelson Lagoon. The data is publicly available at: https://stilltek.com/akdggs/nlsnlgn/. Before then, the closest water level gauge with a computed tidal datum was approximately 40 km (25 mi) away in Port Moller, which has been non-operational since 2017 (NOAA, 2020). A tidal datum was computed for Nelson Lagoon using data over a 6-month period with JOA Surveys, LLC tidal datum tool (i.e. Spargo et al., 2006) and found that Nelson Lagoon had a great diurnal range of approximately 2.3 m (7.5 ft) (**Figure 13**). Tidal datums were computed and made relative to NAVD88, which allowed for the flooding vulnerability analysis.

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.

The ACGL as well as engineering firm HDR Alaska Inc. carried out bathymetric surveys at Nelson Lagoon, though these surveys are higher in spatial resolution yet more limited in scale than NOAA's efforts.

Table 5. Overview of compiled and collected bathymetry surveys of Nelson Lagoon. The survey, survey type, year of acquisition, source, number of XYZ points (N_{xyz}), and datum is provided.

Survey	Type	Year	Source	N_{xyz}	Datum
H08223	Single Beam	1955	NOAA	6,203	MLLW
H08488	Single Beam	1959	NOAA	7,008	MLLW
H08487	Single Beam	1959	NOAA	8,573	MLLW
H08537	Single Beam	1960	NOAA	6,347	MLLW
HDR13	Single Beam	2013	HDR Inc.	36,873	MLLW
NLG19	Single Beam	2019	ACGL	15,947	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 Indicator Position

A shoreline is a linear demarcation between land and water that can represent 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. The primary remote sensing datasets utilized for this work were orthoimagery, since not only does Alaska lack high-resolution elevation data along the coastline, but also tidal datums by which shoreline features are extracted from elevation data are not well established (Overbeck et al., 2020).

At Nelson Lagoon, the linear position of the shoreline in 1983, 2013, 2018, 2019, and 2021 has been either manually digitized over aerial imagery or surveyed in-situ with continuous topo RTK-GNSS.

4.3.2 Stake Measurements

As of 2021 over 15 rural Indigenous 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 visits each site every one to three months and before and after big storms.

Two stake ranging sites were set up in Nelson Lagoon in October, 2018 as well as two standalone profiles (**Figure 26**). 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. They can help better understand shoreline change in terms of recent climate settings, as opposed to the DSAS, which relies on historical imagery. 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 27**, **Figure 28**, and **Figure 29**). Time-lapse cameras were also set up at each site to capture images every hour (described below).

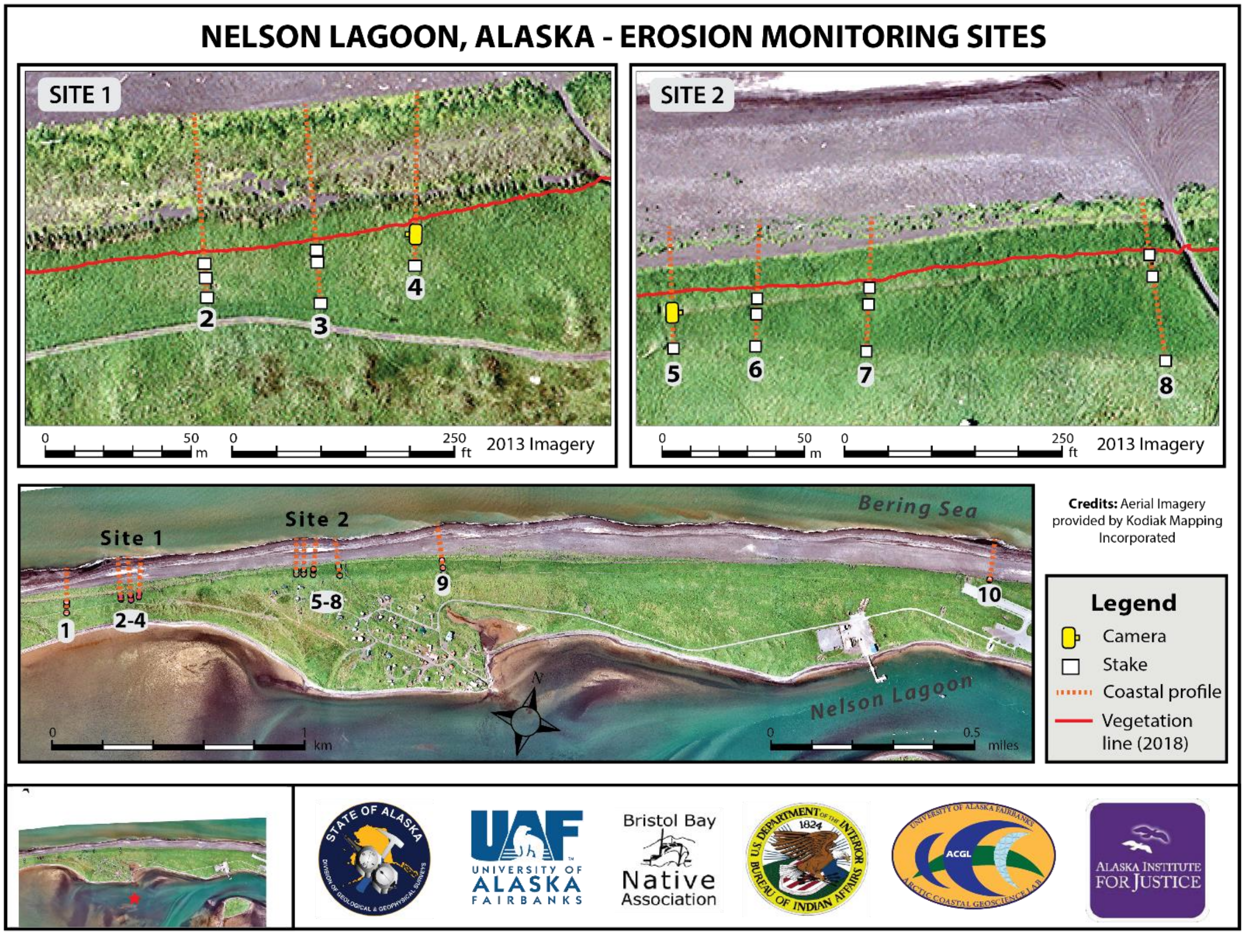


Figure 26. Map of erosion monitoring sites and stake measurement transects. The sites are located on top of a beach ridge fronting the ocean side coastline. Each site consists of a time-lapse camera with 3-4 staked transects where local environmental coordinators take repeat measurements. Important infrastructure that may be at risk from erosion includes the village dump site (Profiles 1 - 4) to the west and the airport (Profile 10) to the east.

The majority of the erosion at Site 1 (**Figure 27**) occurred between June 2020 to November 2020. Transect 4 is the closest to the access road in front of the main community and experienced the heaviest erosion losing a total of approximately 9m (30ft) from October 2018 to November 2020 (**Figure 26 & Figure 27**). The majority of that erosion occurred between June and November 2020, losing 5.8m (19ft) between the four months. Transects 2 and 3 remained relatively stable, only losing 0.3-0.6m (1-2ft) from October 2018 until June 2020 when each transect experienced heavy erosion of about 10ft and 5ft respectively. Transect 1, which is the closest to the dump, underwent the lowest loss with only 0.3m (1ft) of erosion spanning the two years of data collection (**Figure 27**).

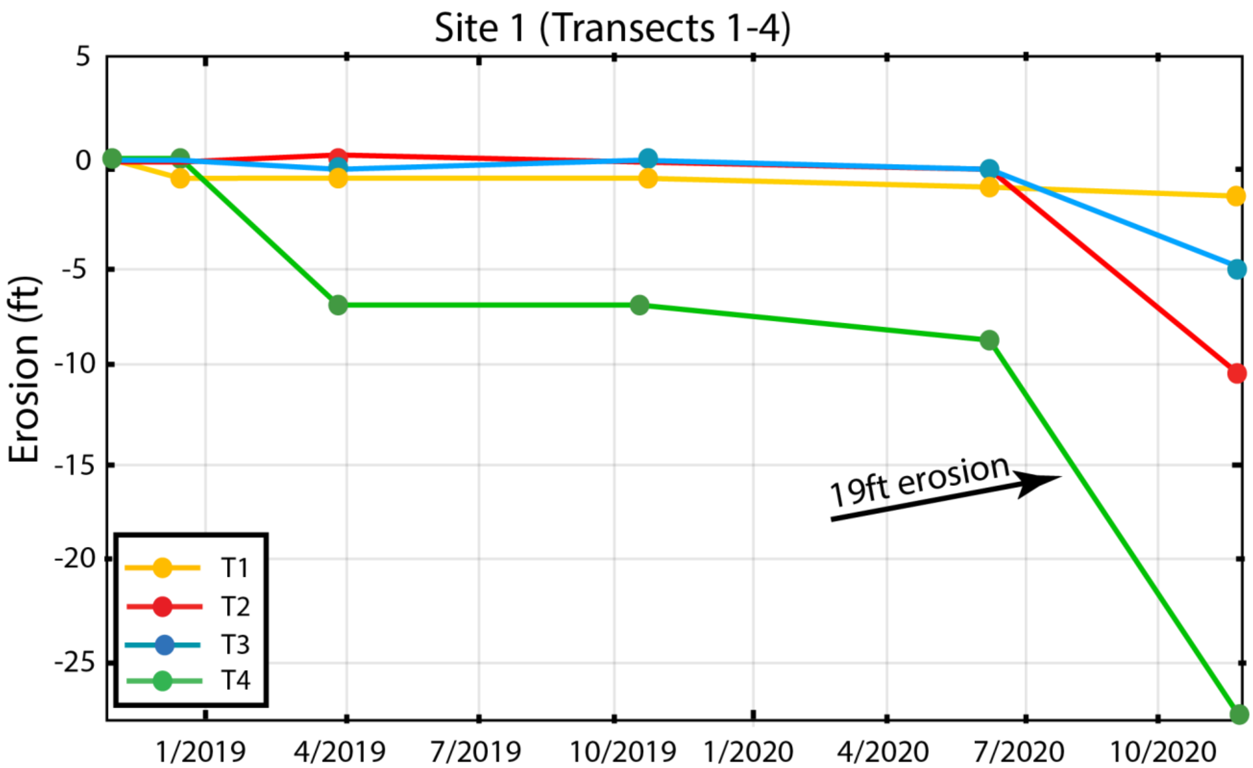


Figure 27. Graph showing erosion monitoring stake measurements at Site 1 taken by local environmental coordinators. Each transect is represented by a different colored line and the dots on the lines represent single measurements. The y-axis is the erosion in feet.

Site 2 (**Figure 28**) encountered significantly less erosion than site 1 with a max loss of 0.9m (3ft) at transect 8, nearest to the road (**Figure 26 & Figure 28**). A period of accretion ranging from 0.3m (1ft) to 0.45m (1.5ft) can be seen from December 2018 to April 2019 at transects 5 and 6, also in front of the main community, followed by 0.3m (1ft) of erosion to October 2019. They remained relatively stable until June 2020 when transect 6 lost 0.6m (2ft) and transect 5 gained 0.15m (0.5ft). Transect 7 lost less than 0.6m (2ft) of erosion from the two years of measurements (**Figure 28**).

Transects 9 and 10, the closest to the airport, experienced the least erosion **(Figure 26**). Transect 9 lost a total of 0.2m (0.65ft) and transect 10 experienced only about 0.15m (0.5ft) of total loss over the course of 2 years (**Figure 29**).

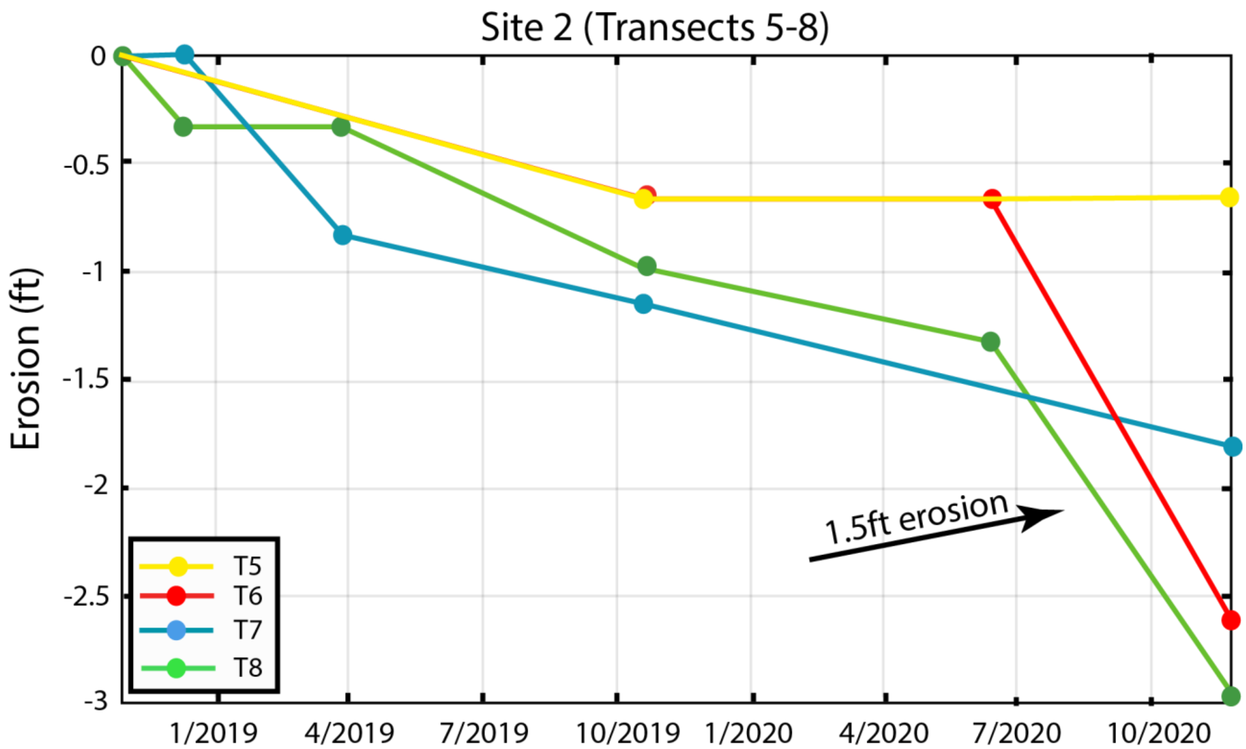


Figure 28. Graph showing erosion monitoring stake measurements at Site 2 taken by local environmental coordinators. Each transect is represented by a different colored line and the dots on the lines represent single measurements. The y-axis is the erosion in feet.

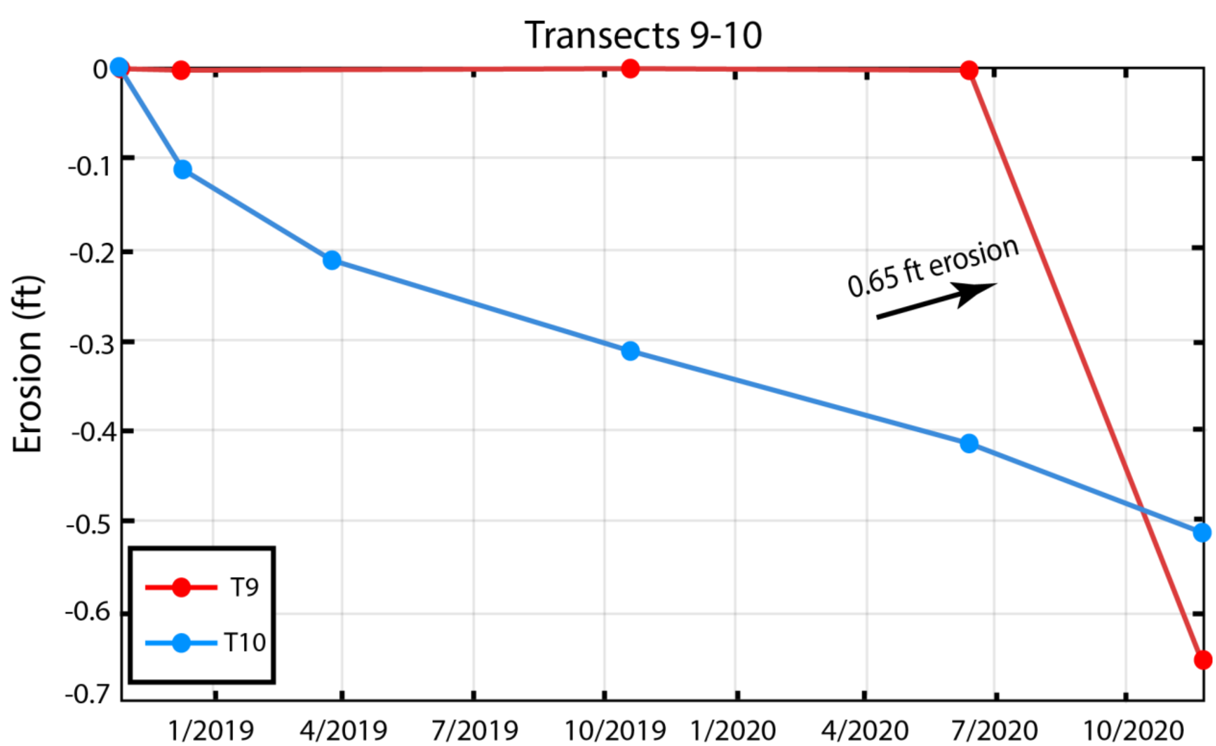


Figure 29. Graph showing erosion monitoring stake measurements at transects 9-10 taken by local environmental coordinators. Each transect is represented by a different colored line and the dots on the lines represent single measurements. The y-axis is the erosion in feet.

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 Nelson Lagoon were collected by the ACGL along cross-shore transects at 30+ locations in 2018, 2019, and 2021 (**Figure 30**). This new data builds on the datasets collected by HDR Alaska, Inc in 2014 and 2015. (HDR, 2015). A total of 30 profiles were surveyed with examples from the ocean (**Figure 31**) and lagoon (**Figure 32**) beaches (See Appendix B for all profiles collected).

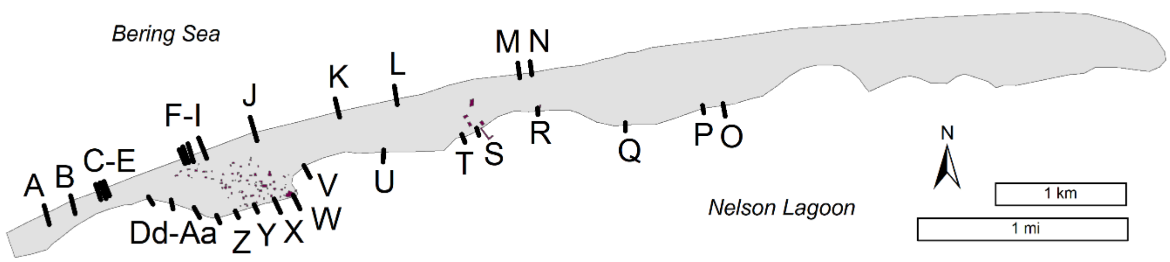


Figure 30. Map showing the location of each cross-shore elevation profile.

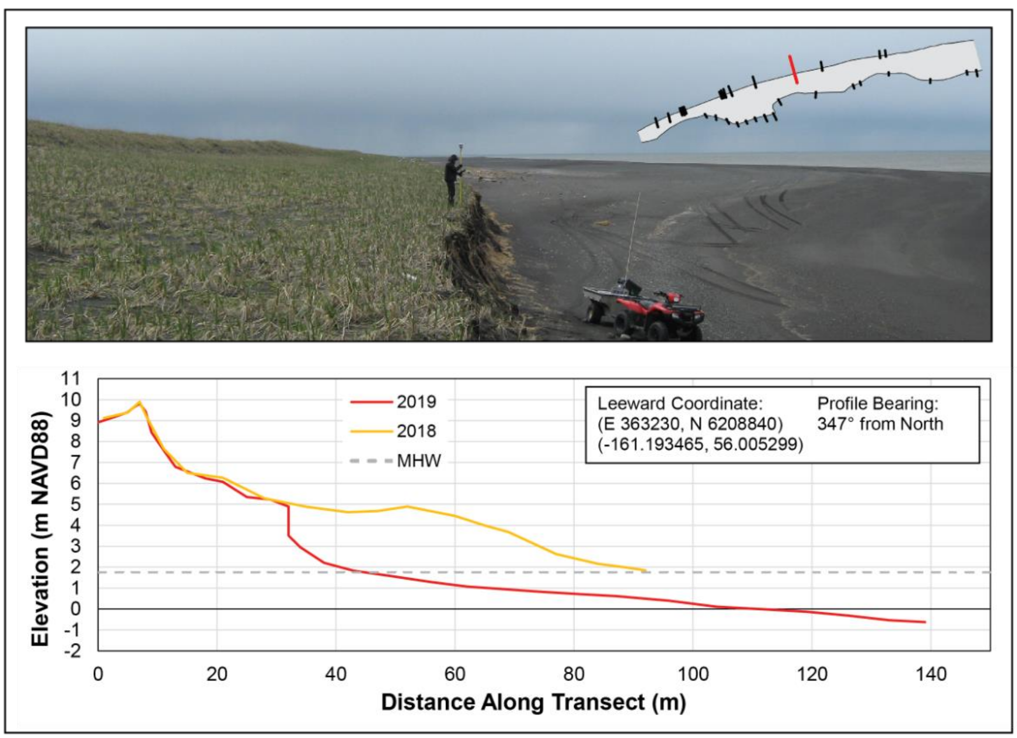


Figure 31. Coastal profile K collected along the ocean side beach . Notice up to 4 m (13 ft) of bluff eroded along this backshore windward side of the spit in one year. Displayed transect is K in figure 23.

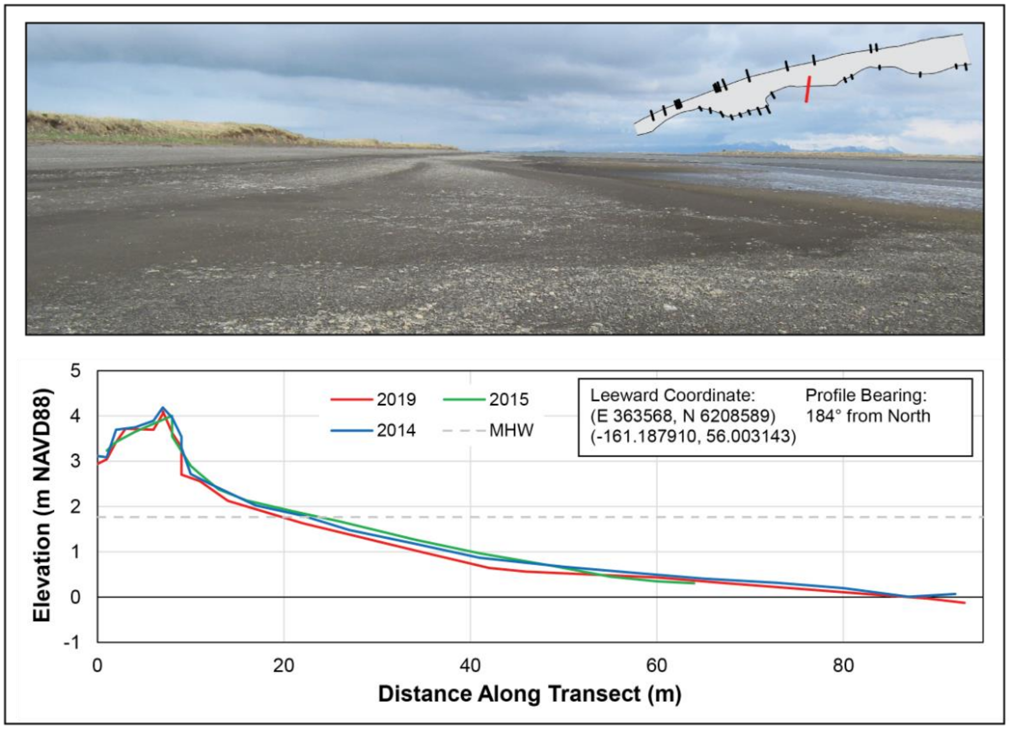


Figure 32. Coastal profile U collected along the lagoon side beach . Notice less than approximately 0.3 m (1 ft) of bluff eroded over a 5-year period along this leeward side of the spit. Displayed transect is U in figure 23.

4.3.4 Timelapse Photography

As of 2021 over 15 rural Indigenous communities in the Bristol Bay region utilize time lapse imagery for erosion monitoring. The Stakes for Stakeholders program trains environmental coordinators from each community in time-lapse imagery (Buzard et al., 2019a). Cameras are set up perpendicular to a single transect and captures hourly images, then run through a MATLAB code that calculates shoreline change.

Time-lapse cameras were set up at two sites at Nelson Lagoon in October 2018 and data is currently being collected. Displayed data below were collected at both sites between October 2018 and May 2019. The cameras were oriented perpendicular to a single profile at each site. Images were taken every hour and compiled into time-lapse videos (**Figure 33** & **Figure 34**). These datasets visually show change at each shoreline and can capture storm events. They provide a cheap alternative for shoreline change monitoring in remote locations. Erosion measurements were unable to be processed as the cameras were not secured tightly enough and the camera was frequently shifted out of place. This made running the images through the Matlab code difficult and yielded inaccurate results. Future site visits will require proper securing of these cameras.

Figure 33. Time-lapse picture and compiled video of erosion monitoring site 1 . Images taken at Nelson Lagoon site 1 from October 2018 to May 2019. (URL: https://youtu.be/r6fS1wvpeAs).

Figure 34. Time-lapse picture and compiled video of erosion monitoring site 2 . Images taken at Nelson Lagoon site 2 from October 2018 to May 2019. (URL: https://youtu.be/-FmvEXaPZvg).

4.4 HAZARD AND EXPOSURE ASSESSMENTS

Hazard and exposure assessments were generated based on analysis of the baseline datasets and repeat measurements described above. 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. These products also require analysis and integration of multiple data sources, for instance the inundation model in **Figure 35** was generated using tidal datums, DSMs, bathymetry, and mathematical modeling. Hazard and exposure assessments involve increased interpretation by researchers through the integration of multiple data products into theoretical models and the selection of certain areas that researchers deem to be at-risk. The uncertain nature of these analyses and the subjective interpretation of results should be noted when taking results into account for decision-making.

4.4.1 Flood Hazard Map

To capture spatial patterns of flooding potential, a single value threshold map was produced and color-coded based off the elevation of individual pixels above the water surface (**Figure 35**). This was done by classifying the raster surface in meter intervals so that patterns of flooding potential could be quantified in the vertical and horizontal dimensions. Elevation values were made relative to Mean High Water (MHW) (e.g. Bogardus et al., 2020).

The resultant flood hazard map provides an effective first-order method for identifying areas vulnerable to flooding based on a static ‘bathtub-style’ assessment, in that it utilizes single-value water surfaces for each mapped interval (after NOAA, 2009; Kinsman et al., 2013). It should be noted that this simplistic assessment has five main limitations: (1) surge levels are based on empirical estimates, (2) setup and runup factors along the open-ocean coast are not included in computed water levels, (3) intra-storm changes in the foreshore, such as dune blowouts are not accounted for, (4) the elevation data follows the height of vegetation, which is particularly an issue on the lagoon side of the spit most susceptible to flooding and (5) unrealistic inland ‘ponds’ of low elevation have not been manually removed. Despite these limitations, the assessment provides a first step in identifying flood-prone sections of the Nelson Lagoon spit and infrastructure susceptible to inundation of varying extents (Kinsman et al., 2013).

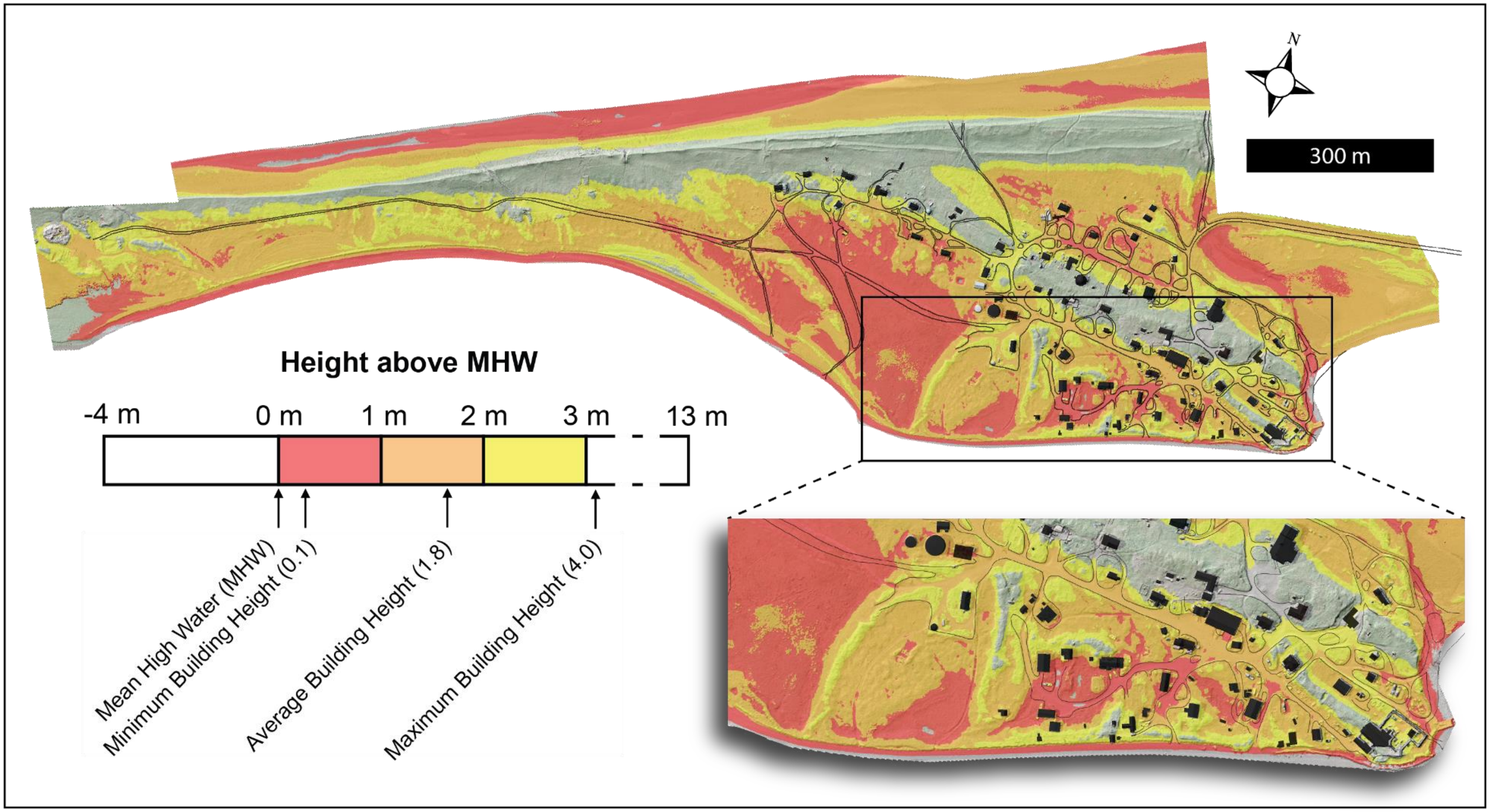


Figure 35. Single value threshold flood risk map of Nelson Lagoon residential area , color coded based off elevation in meters above mean high water. Buildings and roads are symbolized in black. The minimum, average, and maximum building heights are provided. Elevations between -4 and 0 m (-13 and 0 ft) as well as elevations between 3 and 13 m (10 and 43 ft) are transparent. Building height is the height of the ground level near the building, above which the building would be expected to be flooded, although first floor elevation surveys were not used in this analysis.

4.4.2 Infrastructure Exposure Maps

Developing accurate digital maps of community infrastructure that can be integrated within GIS assessment is an important step in assessing risks. This includes both the horizontal position in relation to the coastline and its elevation above MHW, which allow for an assessment of both erosion and flooding. Infrastructure data layers from the Alaska Division of Community and Regional Affairs (DCRA) were compiled from AutoCAD files and subsequently projected in the State Plane NAD 1983 projection system. Specific infrastructure features were extracted and saved as individual point, line, or polygon features within an ESRI geodatabase, and measurements of feature height were saved, where available (AK DGGS, Personal Communication). Infrastructure features that could be affected by flooding were prioritized, such as buildings, roads, pipes, electric lines, and solid waste disposal locations. Information about the type and purpose of each structure in Nelson Lagoon is included and allows for a practical assessment of coastal hazards and their immediate risk to community resources.

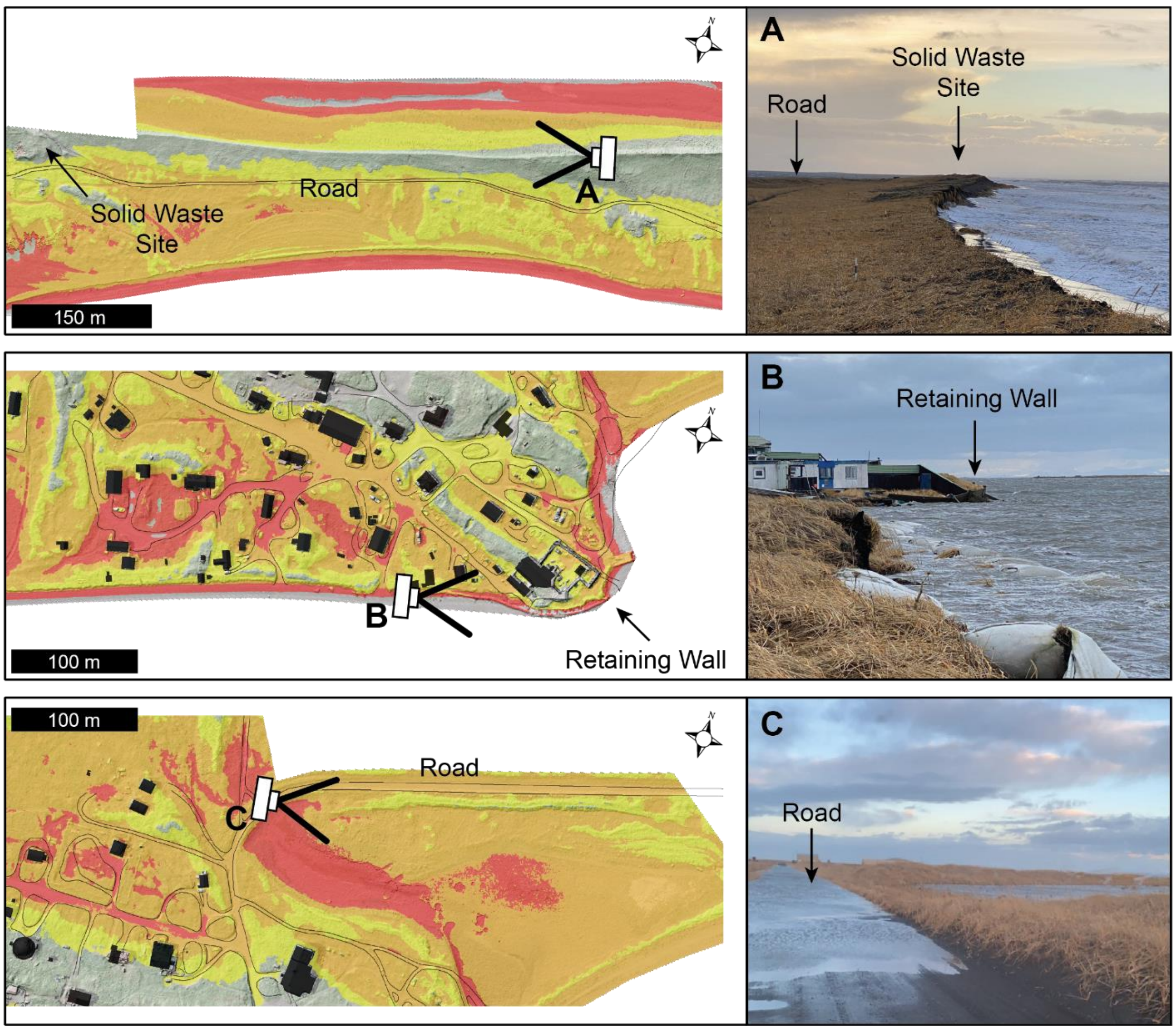
Infrastructure vulnerable to erosion was identified and categorized by extrapolating the most recent shoreline across a given shoreline section at 10-year intervals using the average WLR rate of that section. There is an assumption of linearity made in this type of analysis which introduces inherent uncertainties due to the non-linearity of many environmental processes. Infrastructure vulnerable to flooding, organized by class (i.e., residential, public, etc.), was identified and categorized by which flood height interval a given structure fell within the threshold map. The elevation values of the buildings were extracted directly proximal to the main structure of each property from the UAV elevation model. This type of analysis assumes that an area with an elevation less than a projected flood level will be flooded like a “bathtub”.

The flood hazard map identified areas of relatively high elevation safest from flooding and that serve as natural barriers to inundation. The foredune fronting the community provides a tenuous stopbank, protecting the community from storm driven or even tsunami flooding from this direction. Even so, breaching and overwash occur along the spit on the ocean side during particualry high storm-tide events. The SVTM identified another dune ridge that runs diagnal (W to E) to the modern day incipient foredune ridge, along which the community is oriented. Besides these two ridges, most of the community lies on relatively low land with most properties below 3 m (10 ft) MHW (**Figure 35**). Of the 118 structures within the area of interest, 7% of all structures fell within the 0-1 m (0-3 ft) MHW elevation interval, 40% within the 1-2 m (3-7 ft) interval, 22% within the 2-3 m (7-10 ft) interval, and 31% fell above 3 m (10 ft) MHW (**Table 6**).

A comparison of photographs documenting high storm-tide water levels and the SVTM corroborate the spatial patterns of flooding vulnerability identified by the model, but also provide a geodetically referenced elevation to the documented flood event (**Error! Not a valid bookmark self-reference.**) (i.e. Overbeck, 2017; Buzard et al., 2020).

Table 6. Overview of the building elevations in Nelson Lagoon , organized by infrastructure class. Values are approximated and represent the percentage of each infrastructure class that fell in each flood hieght interval. Flood height intervals are in meters relative to Mean High Water (MHW).

Class	0-1 m	1-2 m	2-3 m	3+ m	Total
Residential (n = 34)	9%	29%	35%	26%	**100%**
Public (n = 12)	0%	75%	17%	8%	**100%**
Commercial (n = 8)	20%	35%	10%	35%	**100%**
Miscallaneous (n = 64)	6%	40%	18%	36%	**100%**
All (n = 118)	***7%***	***40%***	***22%***	***31%***	***100%***



Error! Not a valid bookmark self-reference.. Graphic showing insets of the larger flood hazard map where photographs of high storm-tide events have been captured. Each letter on the map corresponds to the images on the right, with key features identified in each. Flooded areas captured by the images are areas identified by the SVTM as vulnerable. Images provided by Angela Johnson, November 2020.

4.4.3 Shoreline Change Analysis

The following subsections display and describe results from the community erosion and flooding vulnerability assessment. Results are coupled with infrastructure data layers to quantify the overall risk to the community's buildings and utilities, and project future risks with an assumption of linearity in shoreline change rates. A subsample of the plotted cross-shore elevation profiles from representative sections of the shoreline are presented and discussed; the complete dataset can be found in appendix ii.

Important Note: Projected shoreline positions have significant uncertainties brought about by the stochastic non-linear nature of coastal and environmental changes. Future shoreline positions have been determined by extrapolating rates of change based off past movements of the shoreline indicator. As such, projections do not account for accelerated change.

To quantify decadal shoreline change, the lateral position of shorelines along the Nelson Lagoon spit was delineated using orthorectified aerial imagery spanning approximately 40 years (**Table 7**). Net shoreline changes and weighted linear change rates were calculated using the USGS Digital Shoreline Analysis System (DSAS) by casting cross-shore virtual transects at 25 m (82 ft) intervals with 500 m (1600 ft) smoothing over the shorelines from a reference line. The vegetation line (vegline) was selected as the shoreline indicator because it is easily discernable on the ground and in aerial imagery, and there is no inherent error due to tidal fluctuations and/or swash action as is the case with other potential indicators.

The average *rate* of change of the area over the 40-year study period was quantified using the weighted linear regression rate-of-change statistic (WLR) computed at each transect along the shoreline. The WLR is supported with a 95% confidence interval (WCI) and R-squared value (WR^2). *Total* change was calculated using the net shoreline movement (NSM) statistic, which describes the distance between the oldest and most recent shoreline along each transect over the study period (Himmelstoss et al., 2018).

Table 7. Summary of aerial imagery used for shoreline delineation.

Year	Type	Source	Spectral Attributes	Resolution [m^2]
1983	Aerial	NASA AHAP	NIR Composite	2.2
2013	Aerial	Kodiak Mapping Inc.	RGB	0.61
2018	Aerial	UAF ACGL	RGB	0.15
2019	Aerial	UAF ACGL	RGB	0.15

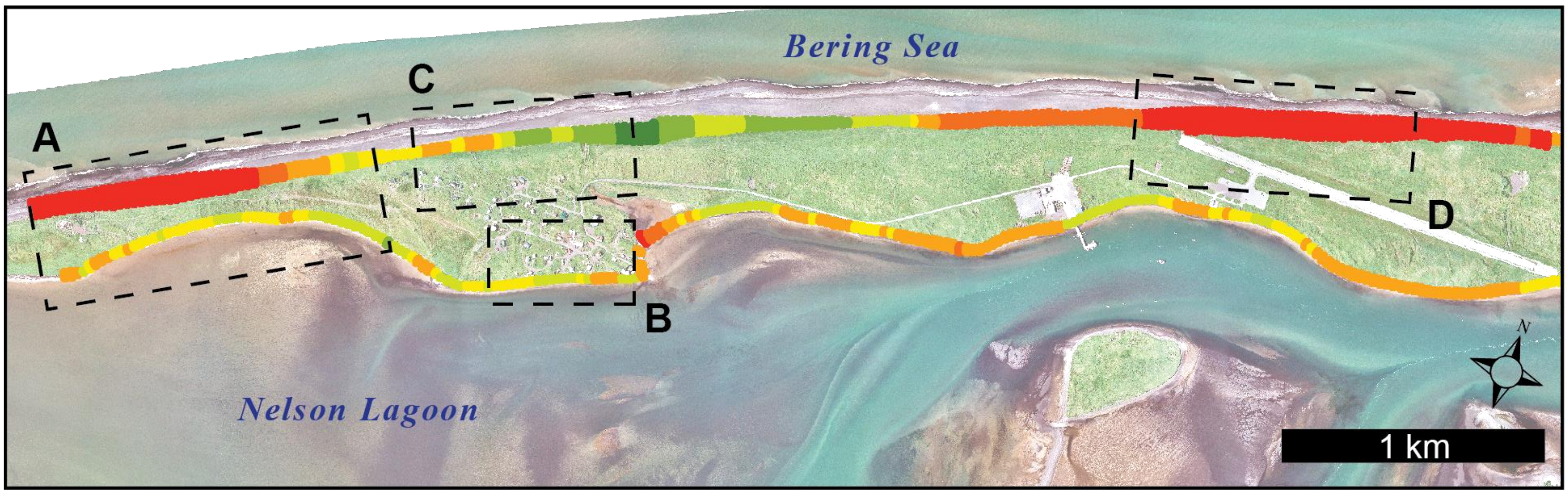


Figure 36. Shoreline Change analysis of Nelson Lagoon. Net Shoreline Movement (NSM) between 1983 and 2019 as computed by the historic shoreline change assessment. Boxes A-D represent areas of particular concern, which are described in more detail in section 5.

5. IDENTIFIED COASTAL HAZARD AREAS

The analysis revealed that the Nelson Lagoon spit narrowed between 1983 and 2019, with an average NSM of -16.9 m (-55 ft) (both sides, tip of the spit not included); however, this value showed variability above the average (σ = 21.9 m), and the lagoon and seaward sides of the spit exhibited different erosional regimes (**Figure 36**). The spit also elongated by more than 800 m (2600 ft) between 1983 and 2013. These findings render averaged shoreline changes extremely misleading; so, the results of the historic shoreline change analysis have been split up into four shoreline sections based on their proximity to infrastructure: A) the solid waste disposal site, B) the lagoon side of the community, C) the sea side of the community, and D) the airstrip (**Table 8**). This section documents the results of the erosion vulnerability assessment, with an emphasis placed on identifying infrastructure at risk of erosion over spatiotemporal scales relevant to community planning; the long term morphodynamic evolution of the entire spit is beyond the scope of this report.

Table 8. Average shoreline change analysis results by shoreline section. Net shoreline movement (NSM) and Weighted Linear Regression (WLR) rate is provided. Refer to figure 22 for the extent of each section; letters correspond to each inset map.

Section	NSM m (ft)	WLR m/yr (ft/yr)	WCI m/yr (ft/yr)	WR2
A – Solid Waste Disposal	-29.6 (-97.1)	-0.98 (-3.21)	2.72 (8.92)	0.71
B – Community (lagoon side)	-6.30 (-20.7)	-0.19 (-0.62)	1.25 (4.10)	0.76
C – Community (sea side)	2.31 (7.58)	-0.06 (-0.20)	3.01 (9.87)	0.18
D – Airstrip	-55.8 (-183)	-1.53 (-5.02)	2.52 (8.27)	0.98

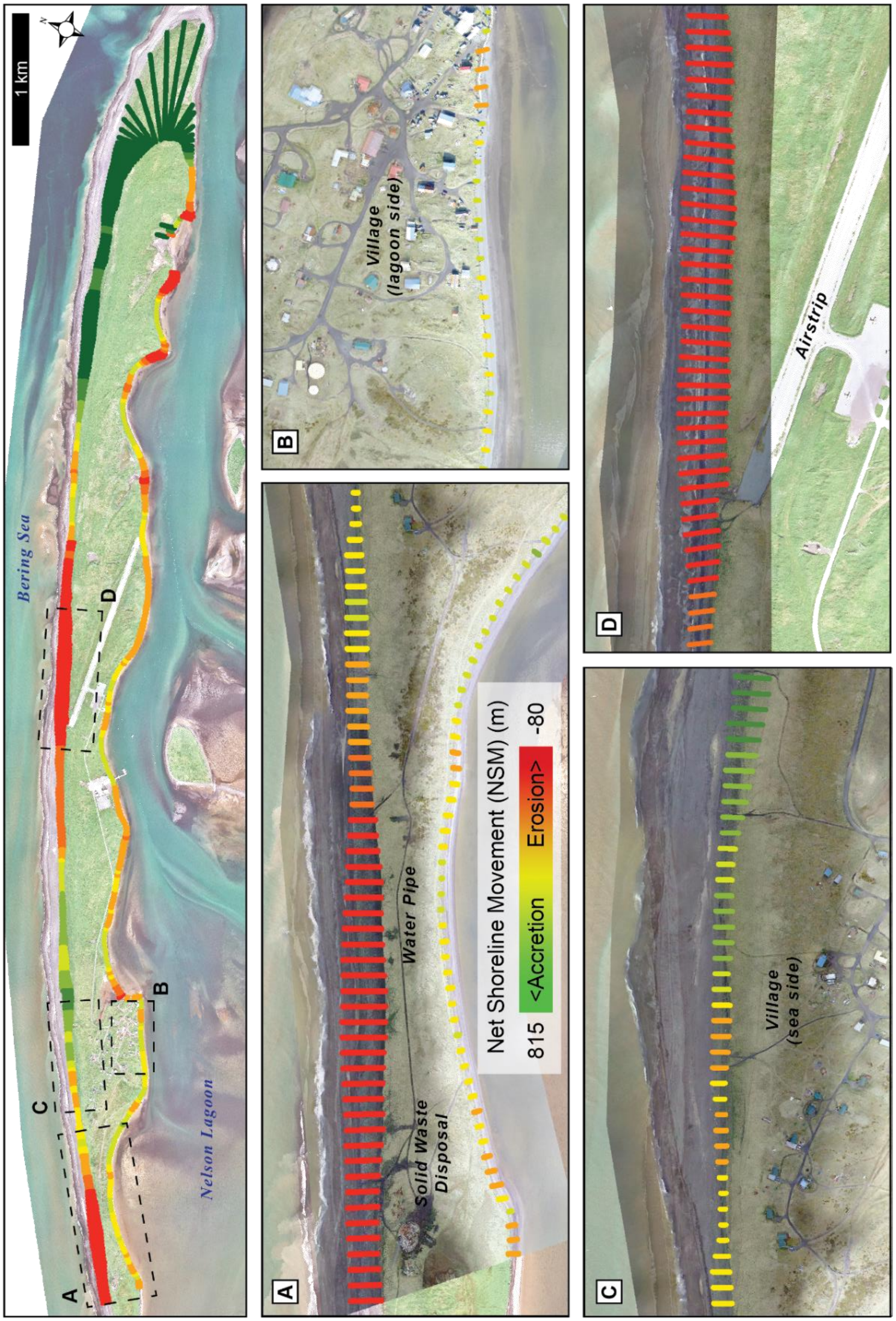


Figure 37. Shoreline Change analysis of Nelson Lagoon with hazard areas. Net Shoreline Movement (NSM) between 1983 and 2019 as computed by the historic shoreline change assessment. The top panel displays the entire spit; letters correspond to each inset map.

5.1 SOLID WASTE DISPOSAL

The shoreline fronting the solid waste disposal site showed among the highest average NSM across the spit, with a value of -29.6 m. The lagoon shoreline along this section observed significantly less change when compared to the seaward coastline (-7.6 m as opposed to -48.6 m avg. NSM). The average WLR across section A came out to -0.98 ± 0.36 m/yr (90% confidence; WR2 = 0.71). Using this rate to extrapolate the position of the shoreline shows that both the road and solid waste disposal site is at risk of erosion. Projected shoreline positions using the WLR rate shows that the solid waste disposal site will likely be eroded into the sea within the next three decades, depending on storm impact frequency and magnitude (**Figure 37**).

The solid waste disposal site has been flooded by storms from the seaward side multiple times in recent years (**Figure 40**). Of most concern is the main water line that runs across this portion of the spit, though its exact position is unknown (CE2, 2002). The foredune fronting the solid waste disposal site steepended considerably between 2018 and 2019 being eroded by waves during high storm-tide events (**Figure 41**).

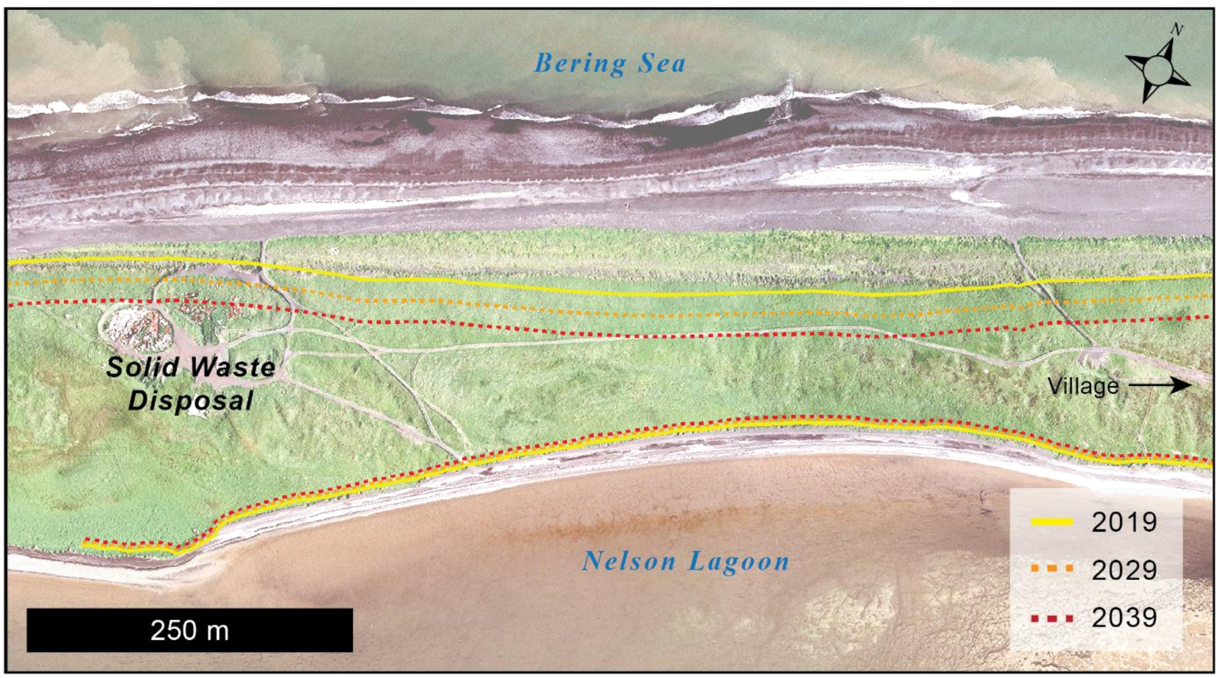


Figure 38. Map showing projected shoreline positions (2029 and 2039) at section A from the 2019 shoreline. Notice that the road and solid waste disposal site is at risk of erosion.

The cross-shore elevation profiles along this section were taken in 2018, 2019, and 2021 and reveal wave undercutting and slumping of the incipient dune face (**Figure 40**). The *slope* of the dune face steepened, coinciding with its landward retreat due to surge and wave action. This process was captured during a site visit in 2018.

Figure 39. Photograph showing remnants of an overwash and flooding event at the access road from the beach to the solid waste disposal site, which can be seen to the left. October 2018.

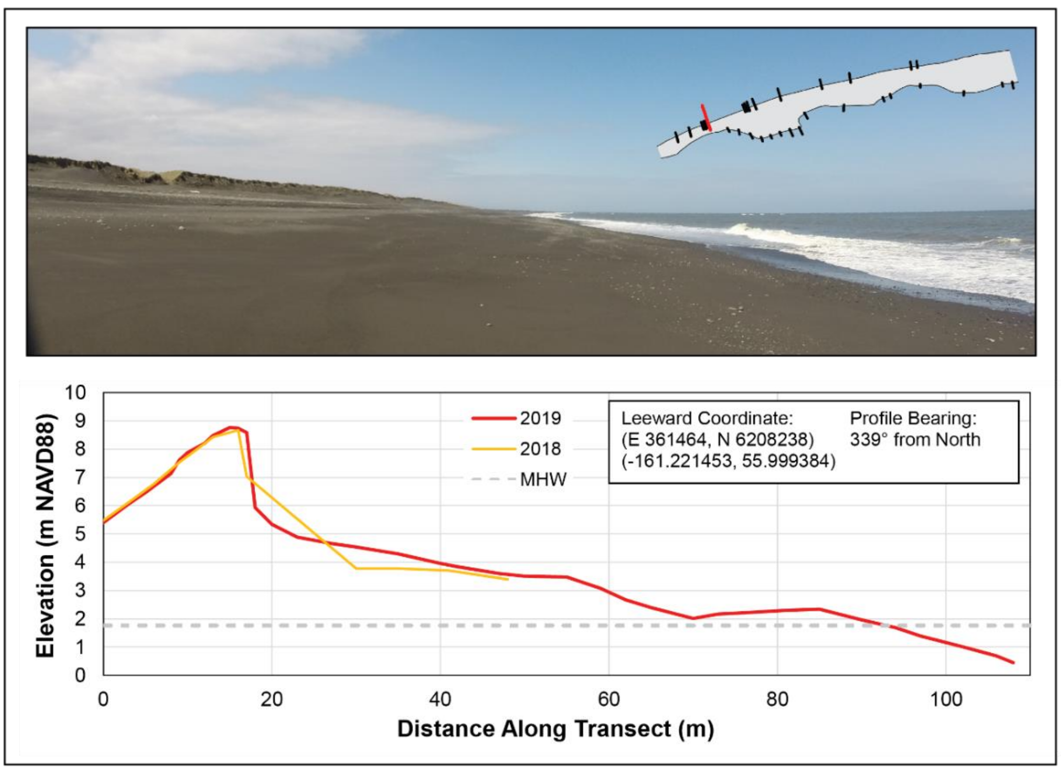


Figure 40. Cross-shore elevation profiles from 2018 and 2019 within section A. Notice the under-cutting of the dune face.

Figure 41. Photograph taken during a relatively minor storm event from the solid waste disposal site looking towards the community on the ocean side of the spit. As the bluff face erodes, sediment at or near the vegetation line is removed and there is an increase in the slope of the dune toe as it retreats landward. October 2018.

5.2 COMMUNITY (LAGOON SIDE)

The lagoon side of the community, which is the area of highest concern for residents, showed relatively smaller rates of change when compared to section A or D, but the proximity of the shoreline across section B is much closer to residential and commercial infrastructure (**Figure 42**). In fact, some buildings along this reach have already been undercut by wave action and abandoned. The average NSM was -6.30 m (-21.0 ft) between 1983 and 2019, with a WLR of -0.19 ± 0.10 m/yr (-0.62 ± 0.33 ft/yr; 90% confidence; WR2 = 0.76). Multiple buildings are intersected by the projected shoreline positions. The cross-shore elevation profiles along this section were taken in 2014, 2015, and 2019, and reveal the beach slope has decreased through time as the dune face retreats landward (**Figure 43**). Flooding impacts this stretch on a regular basis during high storm-tide events (**Figure 44**) and some buildings on the shore have already been undercut by wave action and abandoned.

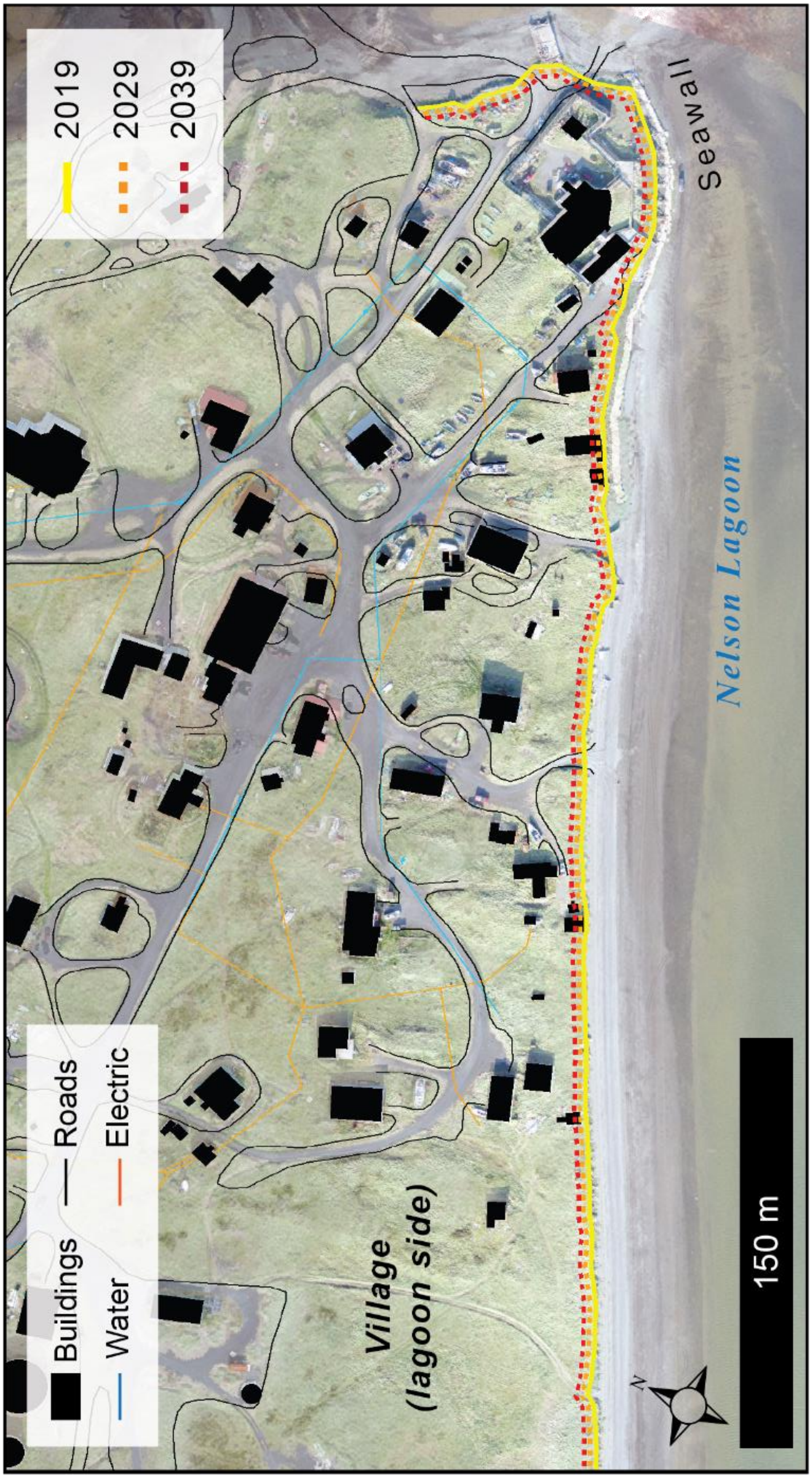


Figure 42. Map showing projected shoreline positions (2029 and 2039) at section B from the 2019 shoreline. Notice how the projected shorelines intersect multiple buildings along the coast.

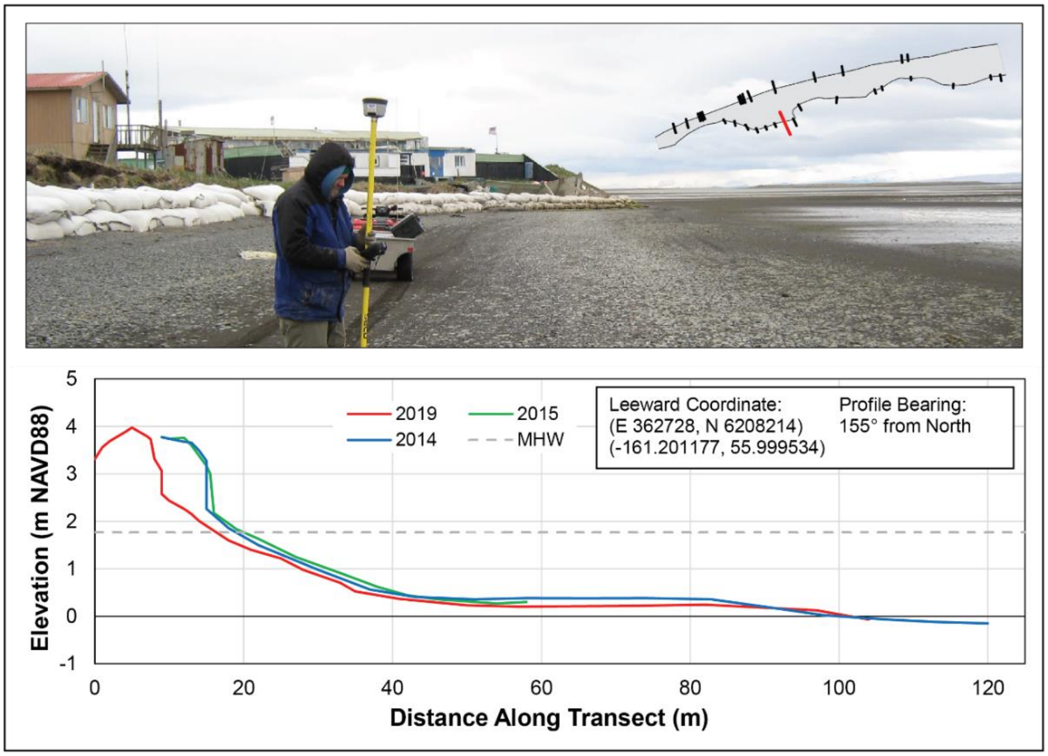


Figure 43. Cross-shore elevation profiles from 2014, 2015, 2018 & 2019 at section B. Notice how the slope of the beach face has decreased while the dune face has retreated landward.

Figure 44. A flooded road near the retaining wall on the east side of the community . This stretch of coastline floods regularly during high storm-tides. Image provided by Angela Johnson, November 2020.

5.3 COMMUNITY (SEA SIDE)

The shoreline fronting the sea side of the community is the only shoreline among the four sections that observed a positive average NSM between 1983 and 2019 (+2.31 m; +7.58 ft). Though, this section is abutted by highly erosional stretches of coastline. Given such a low WLR, the projected shoreline positions show minimal changes to the shoreline positions over the next few decades (**Figure 45**). The cross-shore elevation profiles along this section were taken in 2018 and 2019 and show that storm berms were deposited along this reach in 2019 (**Figure 46**). The differences between the two profiles appear to be seasonally driven, with the 2018 profile representing a typical winter beach configurarion and the 2019 profile being more representative of summer, although the position of the bluff face and crest did not migrate laterally between the two years.

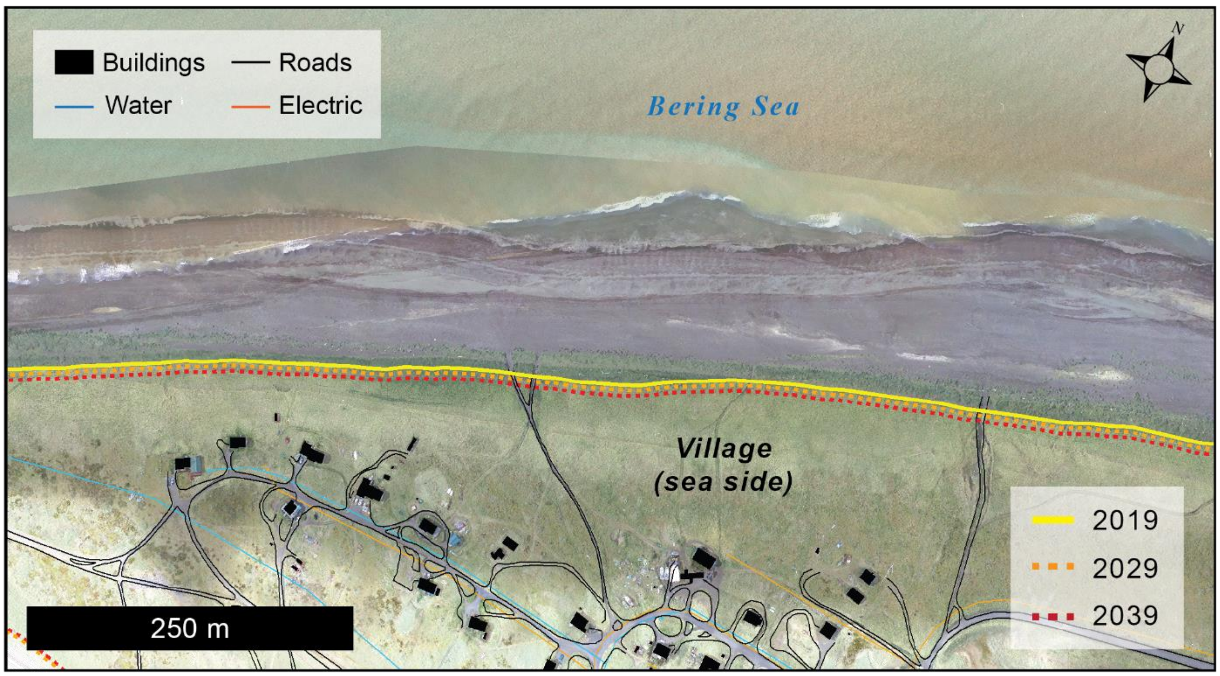


Figure 45. Map showing projected shoreline positions (2029 and 2039) at section C from the 2019 shoreline.

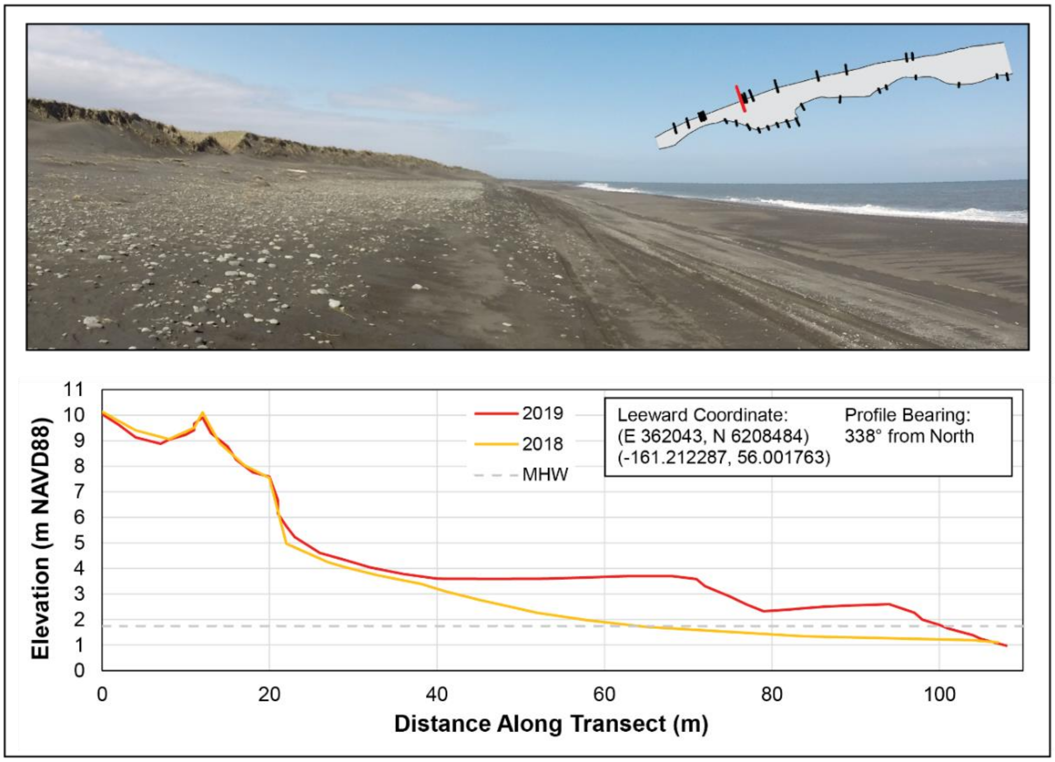


Figure 46. Cross-shore elevation profiles from 2018, and 2019 within section C. Notice the storm berms deposited in 2019.

5.4 AIRSTRIP

The shoreline fronting the airstrip exhibited the most pronounced erosion of all the survey units, with an average NSM of -55.8 m (-183 ft) and a WLR of -1.53 ± 0.36 m/yr (5.02 ± 1.18 ft/yr; 90% confidence; WR2 = 0.98). The projected shoreline positions show the northern tip of the airstrip to be the most at-risk section to erosion, with the airstrip apron just 15 m (50 ft) from the 2019 shoreline (**Figure 47**). This portion of the shoreline contains dune-blowouts – lowering the elevation threshold for flooding – making it particularly vulnerable to both erosion and flooding. This is discussed further in section 4.2.2. This extreme shoreline retreat is also captured by the cross-shore elevation profiles, which were collected in 2014, 2015, and 2019 at this location. Between 2014 and 2019, the swash zone moved more than 50 m (160 ft) landward and observed more than 2 m (7 ft) of vertical erosion (**Figure 48**). This change is indicative of a sediment budget deficit (stronger wave erosion), with the width of the foreshore decreasing substantially. Given the accretion observed just down drift from this section (the tip of the spit), the eroded sediment from section D has significantly contributed to the lengthening of the spit over the last few decades.

The projected shoreline positions show the northern tip of the airstrip as the most at-risk section to erosion, with the airstrip being just 15 m (50 ft) from the 2019 shoreline. Since our field work at Nelson Lagoon, a high storm-tide event in November 2020 breached the foredune fronting the airstrip, opening its gravel pad to further erosion and potential inundation during future storm events (**Figure 49**). It is highly likely that steps to mitigate erosion at this location will be needed if the airstrip is to stay operational during future extreme storm-tide events.

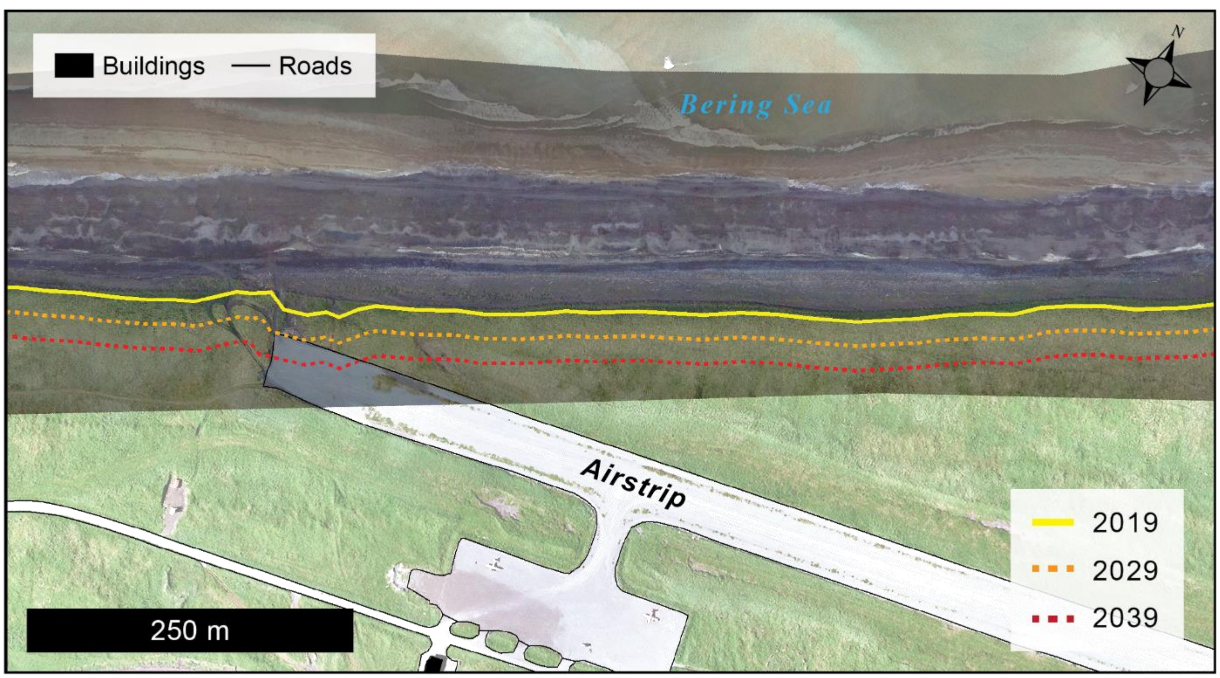


Figure 47. Map showing projected shoreline positions (2029 and 2039) at section D from the 2019 shoreline. Notice how the projected shorelines intersect the northernmost section of the airstrip, which is only 15 m (50 ft) from the position of the 2019 shoreline.

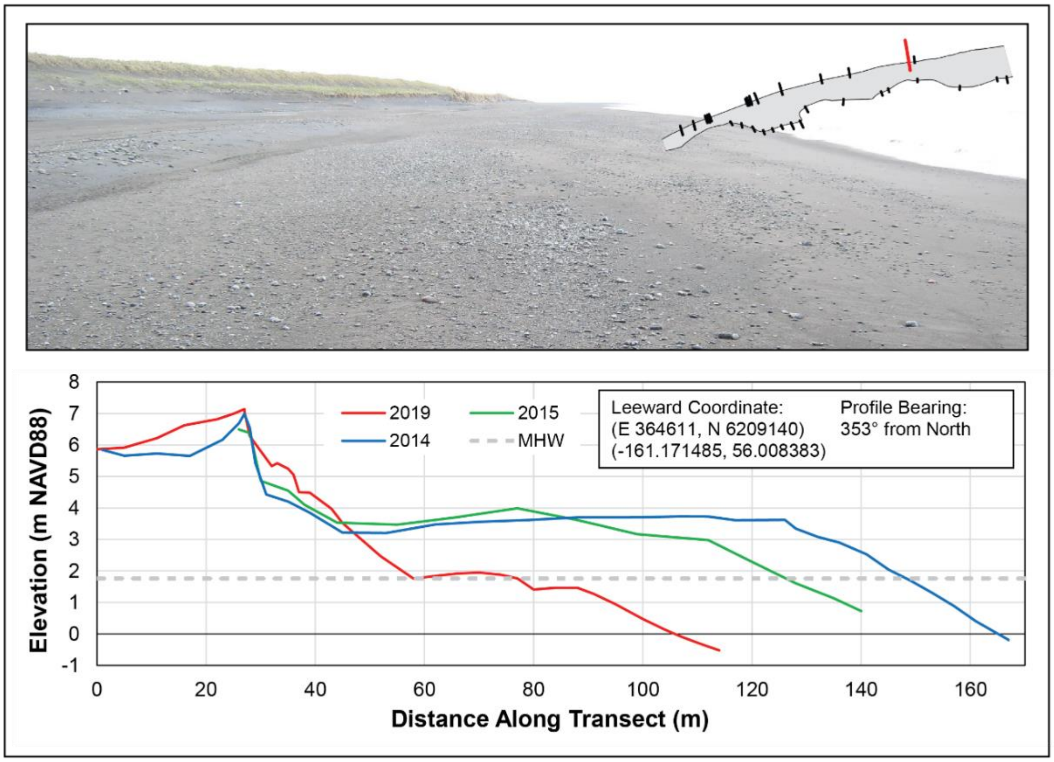


Figure 48. Cross-shore elevation profiles from 2014, 2015 2018 & 2019 at section D . Notice the swash zone moved more than 50 m (160 ft) landward and observed more than 2 m (7 ft) of vertical erosion.

Figure 49. Foredune breach along the ocean shoreline fronting community airstrip . Image generously provided by Angela Johnson, November 2020.

6. SUMMARY OF COMMUNITY THREATS AND RESILIENCY

6.1. SUMMARY OF THREATS

There are multiple areas, buildings, and utilities in Nelson Lagoon that are in immediate risk of erosion and flooding related geohazards:

- The main water line to the community runs along the entire length of the spit, which now includes regions where there is <100 m (<330 ft) of land between the lagoon and open ocean. This water line has been exposed before and will be exposed more frequently in the future since the spit is getting longer and narrower.
- The airstrip has been exposed to the open ocean side of the spit since this project identified it as an area of high concern due to erosion. It is inevitable the north portion of the airstrip will flood in the future.
- The current erosion mitigation structures along the lagoon side of the community have been successful at dampening rates of erosion of their operational lifetimes, but they are structurally failing. This is a particularly important point to address moving forward, given that buildings and utilities are mere meters away from the shoreline at this location. Regular flooding occurs here during high storm-tides. Engineering options and project cost assessments for this stretch have been carried out by HDR Alaska, Inc., though the community has very limited available construction funds.
- The solid waste disposal site to the west of the community is at risk of flooding and erosion from the ocean side. Portions of the site have already flooded within the last few years. It is likely that further erosion and flooding will occur and may eventually erode material into the ocean within a few decades if no action is taken.

6.2. COASTAL RESILIENCY

Nelson Lagoon faces many challenges related to coastal geohazards. The oceanographic setting means that any mitigation structures must withstand significant waves and currents, large tides, and ice. The geologic setting means that there are limited locally available construction materials and resources, which equates to most engineering solutions being expensive to undertake. The climatic setting means that there is a short (seasonal) construction window for any largescale projects. Also, the outdated and failing existing shoreline protection structures mean that there is limited time to procure funding and implement new or bolstered erosion defenses. However, the strongest defense against coastal geohazards at Nelson Lagoon has been and is its extremely proactive and hard-working people. An overwhelming majority of the residents of Nelson Lagoon have lived there most of their lives. The community has ongoing erosion monitoring efforts and numerous partnerships with state and private entities. Great strides have been made by the Nelson Lagoon Environmental Department in opening and maintaining funding channels for instrumentation and equipment to help address the community’s changing coastline.

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 Nelson Lagoon. Additionally, improving understanding of potential storm and flooding impacts is a major goal for mitigation efforts in Nelson Lagoon. 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 9. Summary of data gaps at Nelson Lagoon. Applications and expected acquisitions for each item is provided.

Item	Application(s)	Exp. Acquisition
Past Storm TWLs	Developing a historical index of past storm events; informing city planning and decision making	Summer 2021
First Floor Heights	Accurately assess flooding vulnerability; informing city planning and decision making	TBD

7.2. ACGL FUTURE WORK

Continued work is being carried out to improve the vulnerability assessment of Nelson Lagoon and another field work campaign is planned for Fall 2022. This will include repeat beach profiles and UAV 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.

8. CITATIONS

Citations of reports and assessments directly pertaining to Nelson Lagoon are bolded.

ADEC, Alaska Department of Environmental Conservation, 2004. Source water assessment, A hydrogeologic susceptibility and vulnerability assessment for Nelson Lagoon water system. Report PWSID#260804.001.

ADLWD, Alaska Department of Labor and Workforce Development., 2011. Alaska Local and Regional Information: Nelson Lagoon.

Agisoft, L.L.C. and St Petersburg, R., 2019. Agisoft Metashape User Manual: Professional Edition.

Agisoft, L.L.C. and St Petersburg, R., 2019. Agisoft Metashape User Manual: Professional Edition.

Antunes, N.S.M., 2000. The Importance of the tidal datum in the definition of maritime limits and boundaries. Ibru.

AOOS, Alaska Ocean Observing System, 2014. Data from: Historical Sea Ice Atlas: Alaska Sea Ice, Mid-1800s to the Present. Fairbanks: University of Alaska.

ASOS, Automated Surface Observing System Users Guide, 1998. National Weather Service ASOS Program Office, 74 pp.

Atkinson, D.E., 2005. Observed storminess patterns and trends in the circum-Arctic coastal regime. Geo-Marine Letters, 25(2-3), pp.98-109.

Bader, J., Mesquita, M.D., Hodges, K.I., Keenlyside, N., Østerhus, S. and Miles, M., 2011. A review on Northern Hemisphere sea-ice, storminess and the North Atlantic Oscillation: Observations and projected changes. Atmospheric Research, 101(4), pp.809-834.

Barnhart, K.R., Overeem, I. and Anderson, R.S., 2014. The effect of changing sea-ice on the physical vulnerability of Arctic coasts. The Cryosphere, 8(5), pp.1777-1799.

Bogardus, R., Maio, C., Mason, O., Buzard, R., Mahoney, A. and de Wit, C., 2020. Mid-Winter Breakout of Landfast Sea Ice and Major Storm Leads to Significant Ice Push Event Along Chukchi Sea Coastline. Frontiers in Earth Science, 8, p.344.

Brower Jr, W.A., Diaz, H.F., Prechtel, A.S., Searby, H.W. and Wise, J.L., 1977. Climatic Atlas of the Outer Continental Shelf Waters and Coastal Regions of Alaska. Volume II. Bering Sea. alaska univ anchorage arctic environmental information and data center.

Buzard, R.M., 2017. Spatiotemporal patterns of bluff erosion at Goodnews Bay, Alaska. University of Alaska Fairbanks. Master's thesis.

Buzard, R.M., Overbeck, J.R., and Maio, C.V., 2019a, Community-based methods for monitoring coastal erosion: Alaska Division of Geological & Geophysical Surveys Information Circular 84, 35 p. http://doi.org/10.14509/30182

Buzard, R.M., Overbeck, J.R., and Maio, C.V., 2019b. Baseline shoreline assessment using time-lapse photography and emery rods. Environmental Protection Agency Quality Assurance Project Plan. Approved 3/8/2017, updated and approved 4/11/2019.

Buzard, R., Maio, C.V., Kinsman, N., and Verbyla, D., 2020. Shoreline change analysis of Goodnews Bay, Alaska. Shore and Beach, 88(2), pp. 1-13.

Cacchione, D.A. and Drake, D.E., 1979. A new instrument system to investigate sediment dynamics on continental shelves. Marine Geology, 30(3-4), pp.299-312.

Cazenave, A., Meyssignac, B., Ablain, M., Balmaseda, M., Bamber, J., Barletta, V., Beckley, B., Benveniste, J., Berthier, E., Blazquez, A. and Boyer, T., 2018. Global sea-level budget 1993-present. Earth System Science Data, 10(3), pp.1551-1590.

CE2 Engineers, Inc., 2002. Water system improvement plan, Nelson Lagoon, Alaska. Prepared for Nelson Lagoon Council.

Cooper, A.K., Marlow, M.S. and Scholl, D.W., 1976. Mesozoic magnetic lineations in the Bering Sea marginal basin. Journal of Geophysical Research, 81(11), pp.1916-1934.

Davidson-Arnott, R., Bauer, B. and Houser, C., 2019. Introduction to coastal processes and geomorphology. Cambridge university press.

Davies, J., Sykes, L., House, L. and Jacob, K., 1981. Shumagin seismic gap, Alaska Peninsula: History of great earthquakes, tectonic setting, and evidence for high seismic potential. Journal of Geophysical Research: Solid Earth, 86(B5), pp.3821-3855.

Dean, B., Collins, I., Divoky, D., Hatheway, D. and Scheffner, C.N., 2005. FEMA Coastal Flood Hazard Analysis and Mapping Guidelines Focused Study Report.

Donnelly, C., Kraus, N. and Larson, M., 2006. State of knowledge on measurement and modeling of coastal overwash. Journal of coastal research, 22(4 (224)), pp.965-991.

Dygas, J.A. and Burrell, D.C., 1976. Wind and current patterns in an arctic coast Lagoon. Ocean Engineering, 3(5), pp.317-327.

Emery, K.O., 1961. A simple method of measuring beach profiles. Limnology and Oceanography, 6(1), pp.90-93.

Erikson, L.H., Espejo, A., Barnard, P.L., Serafin, K.A., Hegermiller, C.A., O'Neill, A., Ruggiero, P., Limber, P.W. and Mendez, F.J., 2018. Identification of storm events and contiguous coastal sections for deterministic modeling of extreme coastal flood events in response to climate change. Coastal Engineering, 140, pp.316-330.

Farquharson, L.M., Mann, D.H., Swanson, D.K., Jones, B.M., Buzard, R.M. and Jordan, J.W., 2018. Temporal and spatial variability in coastline response to declining sea-ice in northwest Alaska. Marine Geology, 404, pp.71-83.

Fok, H.S., 2012. Ocean tides modeling using satellite altimetry (Doctoral dissertation, The Ohio State University).

Forbes, D.L., 2011. State of the Arctic coast 2010: scientific review and outlook. Land-Ocean Interactions in the Coastal Zone, Institute of Coastal Research.

Francis, J.A., Chen, Y., Miller, J.R. and Russell, G., 2011, December. Projected regime shift in arctic feedbacks. In AGU Fall Meeting Abstracts (Vol. 2011, pp. A31D-0107).

Frey, K.E., Moore, G.W.K., Cooper, L.W. and Grebmeier, J.M., 2015. Divergent patterns of recent sea-ice cover across the Bering, Chukchi, and Beaufort seas of the Pacific Arctic Region. Progress in Oceanography, 136, pp.32-49.

Freymueller, J.T., 2013. Vertical Analytical Model for Vertical Crustal Deformation in Alaska.

Fu, L.L. and Pihos, G., 1994. Determining the response of sea level to atmospheric pressure forcing using TOPEX/POSEIDON data. Journal of Geophysical Research: Oceans, 99(C12), pp.24633-24642.

Gindraux, S., Boesch, R. and Farinotti, D., 2017. Accuracy assessment of digital surface models from unmanned aerial vehicles' imagery on glaciers. Remote Sensing, 9(2), p.186.

Glaeser, J.D., 1978. Global distribution of barrier islands in terms of tectonic setting. The Journal of Geology, 86(3), pp.283-297.

Gornitz, V., 1995. Sea-level rise: A review of recent past and near-future trends. Earth surface processes and landforms, 20(1), pp.7-20.

Grow, J.A. and Atwater, T., 1970. Mid-Tertiary tectonic transition in the Aleutian arc. Geological Society of America Bulletin, 81(12), pp.3715-3722.

HDR, 2011. Nelson Lagoon Hazard Impact Study, Prepared for the Aleutians East Borough.

HDR, 2014a. Nelson Lagoon Coastal Erosion Study Numerical Hydrodynamic Model Technical Memorandum, Prepared for the Aleutians East Borough.

HDR, 2014b. Nelson Lagoon Coastal Erosion Study Numerical Wave Model Technical Memorandum, Prepared for the Aleutians East Borough.

HDR, 2014c. Nelson Lagoon Coastal Erosion Study Historical Shoreline Map Report, Prepared for the Aleutians East Borough.

HDR, 2015. Nelson Lagoon Shoreline Protection 20% Preliminary Design. Project No. 213165. Prepared for the Aleutians East Borough.

Herring, S.C., Christidis, N., Hoell, A., Kossin, J.P., Schreck III, C.J. and Stott, P.A., 2018. Explaining extreme events of 2016 from a climate perspective. Bulletin of the American Meteorological Society, 99(1), pp. S1-S157.

Himmelstoss, E.A., Henderson, R.E., Kratzmann, M.G. and Farris, A.S., 2018. Digital Shoreline Analysis System (DSAS) version 5.0 user guide (No. 2018-1179). US Geological Survey.

Hoyt, J.H., 1967. Barrier island formation. Geological Society of America Bulletin, 78(9), pp.1125-1136.

Hubertz, J.M., 1992. A users guide to the WIS wave model, Version 2.0, WIS report 27, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Hume, J.D. and Schalk, M., 1967. Shoreline processes near Barrow, Alaska: a comparison of the normal and the catastrophic. Arctic, pp.86-103

Iowa State University. 2020 "ASOS-AWOS-Metar Data Download." Retrieved 10/20/2020 from https://mesonet.agron.iastate.edu/request/download.phtml?network=AK_ASOS

James, M.R., Robson, S. and Smith, M.W., 2017. 3-D uncertainty-based topographic change detection with structure-from-motion photogrammetry: precision maps for ground control and directly georeferenced surveys. Earth Surface Processes and Landforms, 42(12), pp.1769-1788.

Johnson, E.A., 1983. Textural and compositional sediment characteristics of the southeastern Bristol Bay continental shelf, Alaska (Doctoral dissertation, California State University, Northridge).

Jones, S.C., Harr, P.A., Abraham, J., Bosart, L.F., Bowyer, P.J., Evans, J.L., Hanley, D.E., Hanstrum, B.N., Hart, R.E., Lalaurette, F. and Sinclair, M.R., 2003. The extratropical transition of tropical cyclones: Forecast challenges, current understanding, and future directions. Weather and Forecasting, 18(6), pp.1052-1092.

Kinder, T.H. and Schumacher, J.D., 1981. Circulation Over the Continental Shelf. The eastern Bering Sea shelf: oceanography and resources, 1, p.53.

Kinsman, N.E. and DeRaps, M.R., 2012. Coastal hazard field investigations in response to the November 2011 Bering Sea storm, Norton Sound, Alaska. Report of Investigations, p.2.

Kinsman, N.E., DeRaps, M.R. and Smith, J.R., 2013. Preliminary Evaluation of Coastal Geomorphology and Geohazards on" Kigiqtam Iglua," an Island Northeast of Shishmaref, Alaska. Alaska: Alaska Department of Natural Resources, Division of Geological & Geophysical Surveys.

Kinsman, N.E. and Gould, A., 2014. Contemporary shoreline retreat rates at Meshik in Port Heiden, Alaska. State of Alaska, Department of Natural Resources, Division of Geological & Geophysical Surveys.

Laporte-Fauret, Q., Marieu, V., Castelle, B., Michalet, R., Bujan, S. and Rosebery, D., 2019. Low-cost UAV for high-resolution and large-scale coastal dune change monitoring using photogrammetry. Journal of Marine Science and Engineering, 7(3), p.63.

Mancini, F., Dubbini, M., Gattelli, M., Stecchi, F., Fabbri, S. and Gabbianelli, G., 2013. Using unmanned aerial vehicles (UAV) for high-resolution reconstruction of topography: The structure from motion approach on coastal environments. Remote sensing, 5(12), pp.6880-6898.

Mangor, K., Drønen, N., Kærgaard, K., Kristensen, S.,E., 2017: Shoreline Management Guidline, DHI, Danmark, 2017, DHI ebook, www.dhigroup.com, 466 pp.

Marlow, M.S., Scholl, D.W., Cooper, A.K. and Buffington, E.C., 1976. Structure and evolution of Bering Sea shelf south of St. Lawrence Island. AAPG Bulletin, 60(2), pp.161-183.

Mason, O.K., Salmon, D.K. and Ludwig, S.L., 1996. The periodicity of storm surges in the Bering Sea from 1898 to 1993, based on newspaper accounts. Climatic Change, 34(1), pp.109-123.

Mesquita, M.S., 2009. Characteristics and variability of storm tracks in the North Pacific, Bering Sea and Alaska (Doctoral dissertation).

Mesquita, M.S., Atkinson, D.E. and Hodges, K.I., 2010. Characteristics and variability of storm tracks in the North Pacific, Bering Sea, and Alaska. Journal of Climate, 23(2), pp.294-311.

Morton, R.A., Ward, G.H. and White, W.A., 2000. Rates of sediment supply and sea-level rise in a large coastal lagoon. Marine Geology, 167(3-4), pp.261-284.

Nelson Lagoon SECD, Strategic economic plan, 2001. Prepared for the Native Village of Nelson Lagoon by Stadium Group, pp. 1-56

NOAA, National Oceanic and Atmospheric Administration, 2020. Data from: Water Levels - NOAA Tides, and Currents. Silver Spring, MD: NOAA.

Overbeck, J., Buzard, R. and Maio, C., 2017, September. Storm impacts in western alaska documenting shoreline change and flooding through remote sensing and communitybased monitoring. In Oceans 2017-Anchorage (pp. 1-6). IEEE.

Overbeck, J.R., ed., 2018, Alaska coastal mapping gaps & priorities: Alaska Division of Geological & Geophysical Surveys Information Circular 72, 34 p.

Overbeck, J.R., Buzard, R.M., Turner, M.M., Miller, K.Y., and Glenn, R.J., 2020, Shoreline change at Alaska coastal communities: Alaska Division of Geological & Geophysical Surveys Report of Investigation 2020-10, 29 p., 47 sheets.

Overeem, I., Anderson, R.S., Wobus, C.W., Clow, G.D., Urban, F.E. and Matell, N., 2011. Sea-ice loss enhances wave action at the Arctic coast. Geophysical Research Letters, 38(17).

Overland, J.E. and Pease, C.H., 1982. Cyclone climatology of the Bering Sea and its relation to sea-ice extent. Monthly Weather Review, 110(1), pp.5-13.

Rachold, V., Are, F.E., Atkinson, D.E., Cherkashov, G. and Solomon, S.M., 2005. Arctic coastal dynamics (ACD): An introduction. Geo-Marine Letters, 25(2-3), pp.63-68.

Reimnitz, E., Dethleff, D. and Nürnberg, D., 1994. Contrasts in Arctic shelf sea-ice regimes and some implications: Beaufort Sea versus Laptev Sea. Marine Geology, 119(3-4), pp.215-225.

Rodionov, S.N., Bond, N.A. and Overland, J.E., 2007. The Aleutian Low, storm tracks, and winter climate variability in the Bering Sea. Deep Sea Research Part II: Topical Studies in Oceanography, 54(23-26), pp.2560-2577.

Ruggiero, P., Komar, P.D., McDougal, W.G., Marra, J.J. and Beach, R.A., 2001. Wave run-up, extreme water levels and the erosion of properties backing beaches. Journal of coastal research, pp.407-419.

Ruggiero, P., Holman, R.A. and Beach, R.A., 2004. Wave run-up on a high-energy dissipative beach. Journal of Geophysical Research: Oceans, 109(C6). 90

Sallenger Jr, A.H., Howard, P.C., Fletcher III, C.H. and Howd, P.A., 1983. A system for measuring bottom profile, waves and currents in the high-energy nearshore environment. Marine Geology, 51(1-2), pp.63-76.

Sallenger Jr, A.H., 2000. Storm impact scale for barrier islands. Journal of Coastal Research, pp.890-895.

Sepp, M. and Jaagus, J., 2011. Changes in the activity and tracks of Arctic cyclones. Climatic Change, 105(3), pp.577-595.

Sorteberg, A. and Walsh, J.E., 2008. Seasonal cyclone variability at 70 N and its impact on moisture transport into the Arctic. Tellus A: Dynamic Meteorology and Oceanography, 60(3), pp.570-586.

Spargo, E., Hess, K., Myers, E., Yang, Z. and Wong, A., 2006. Tidal datum modeling in support of NOAA's vertical datum transformation tool. In Estuarine and Coastal Modeling (2005) (pp. 523-536).

Stabeno, P.J., Farley Jr, E.V., Kachel, N.B., Moore, S., Mordy, C.W., Napp, J.M., Overland, J.E., Pinchuk, A.I. and Sigler, M.F., 2012. A comparison of the physics of the northern and southern shelves of the eastern Bering Sea and some implications for the ecosystem. Deep Sea Research Part II: Topical Studies in Oceanography, 65, pp.14-30.

Suleimani, E.N., Nicolsky, D.J., and Salisbury, J.B., 2020, Regional tsunami hazard assessment for communities of Bristol Bay and the Pribilof Islands, Alaska:

Alaska Division of Geological & Geophysical Surveys Report of Investigation 2020-1, 32 p., 6 sheets.

Thoman, R.L., Bhatt, U.S., Bieniek, P.A., Brettschneider, B.R., Brubaker, M., Danielson, S., Labe, Z., Lader, R., Meier, W.N., Sheffield, G. and Walsh, J.E., 2020. The record low Bering sea-ice extent in 2018: context, impacts, and an assessment of the role of anthropogenic climate change.

Thomson, J. and Rogers, W.E., 2014. Swell and sea in the emerging Arctic Ocean. Geophysical Research Letters, 41(9), pp.3136-3140.

Thomson, J., Fan, Y., Stammerjohn, S., Stopa, J., Rogers, W.E., Girard-Ardhuin, F., Ardhuin, F., Shen, H., Perrie, W., Shen, H. and Ackley, S., 2016. Emerging trends in the sea state of the Beaufort and Chukchi seas. Ocean Modelling, 105, pp.1-12.

Tschetter, T., Kinsman, N.E. and Fish, A., 2014. Color-indexed elevation maps for flood-vulnerable coastal communities in western Alaska. State of Alaska, Department of Natural Resources, Division of Geological & Geophysical Surveys.

USACE, United States Army Corps of Engineers., 2007. Alaska baseline erosion assessment, erosion information paper – Nelson Lagoon, Alaska.

Vaught, Douglas. 2016. “Nelson Lagoon, Alaska Wind and Solar Resource Assessment Report.” *V3 Energy LLC.* https://www.v3energy.com/wp-content/uploads/2017/04/Nelson-Lagoon-Wind-and-Solar-Resource-Assessment-Report.pdf

Vessey, A.F., Hodges, K.I., Shaffrey, L.C. and Day, J.J., 2020. An inter-comparison of Arctic synoptic scale storms between four global reanalysis datasets. Climate Dynamics, 54(5), pp.2777-2795.

Watanabe, Y. and Kawahara, Y., 2016. UAV photogrammetry for monitoring changes in river topography and vegetation. Procedia Engineering, 154, pp.317-325.

WEAR, Waste Erosion Assessment and Review., 2015. Detailed action plan Nelson Lagoon landfill, 6 p.

Weaver, R.J., 2008. Storm surge: influence of bathymetric fluctuations and barrier islands on coastal water levels. University of Florida.

Wesson, R.L., Boyd, O.S., Mueller, C.S., Bufe, C.G., Frankel, A.D. and Petersen, M.D., 2007. Revision of time-independent probabilistic seismic hazard maps for Alaska. US Geological Survey Open-File Report, 1043(2007), p.33.

Wilson, F.H., Hults, C.P., Mull, C.G, and Karl, S.M, comps., 2015, Geologic map of Alaska: U.S. Geological Survey Scientific Investigations Map 3340, pamphlet 196 p., 2 sheets, scale 1:1,584,000, http://dx.doi.org/10.3133/sim3340.

WMO, World Meteorological Organization. Commission for Maritime Meteorology, 1970. The Beaufort Scale of Wind Force: (technical and operational Aspects) (No. 3).

Wuebbles, D.J., Fahey, D.W., Hibbard, K.A., Arnold, J.R., DeAngelo, B., Doherty, S., Easterling, D.R., Edmonds, J., Edmonds, T., Hall, T. and Hayhoe, K., 2017. Climate science special report: Fourth national climate assessment (NCA4), Volume I.

Yin, J.H., 2005. A consistent poleward shift of the storm tracks in simulations of 21st century climate. Geophysical Research Letters, 32(18).

Goodwin, I.D., Ribó, M. and Mortlock, T., 2020. Coastal sediment compartments, wave climate and centennial-scale sediment budget. In Sandy Beach Morphodynamics (pp. 615-640). Elsevier.

APPENDIX

APPENDIX A. WAVE ROSES

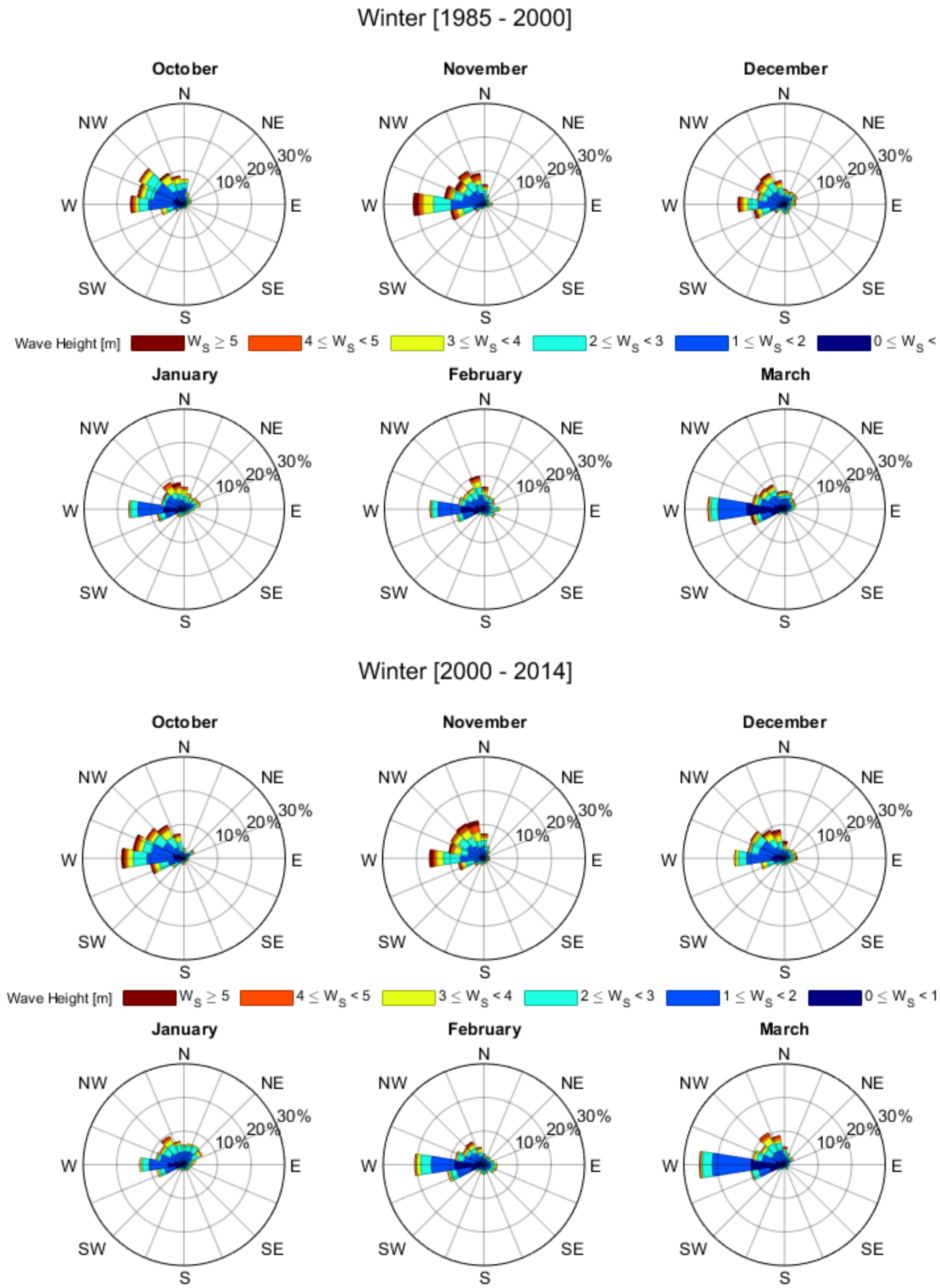


Figure A1. Wave roses of annual wave height and direction for the winter months from WIS Station 82289. Spokes in each rose point in the compass direction from which the waves travel. Colors within each spoke denote wave height bins and the length of the spokes denote the frequency of occurrence.

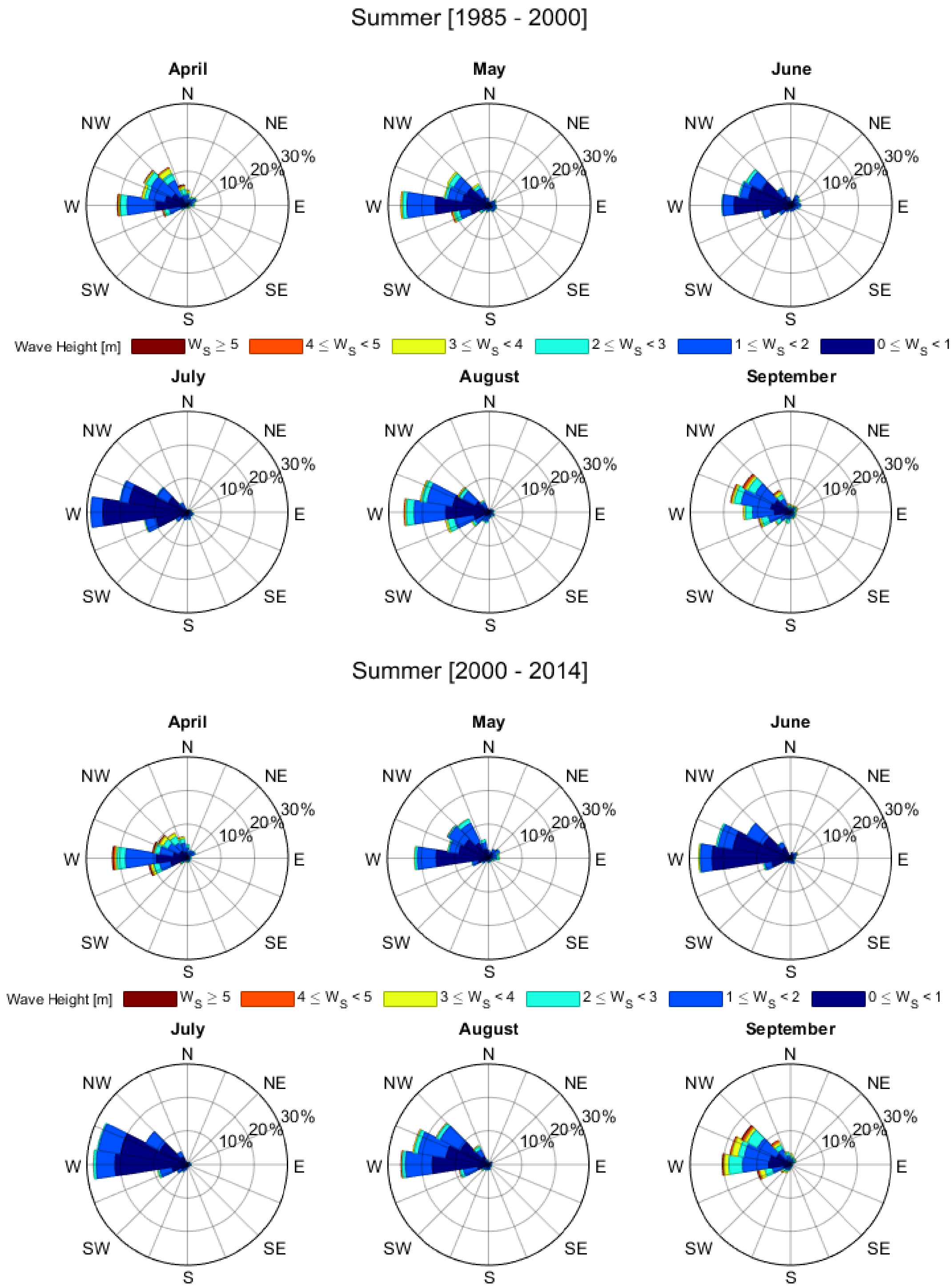
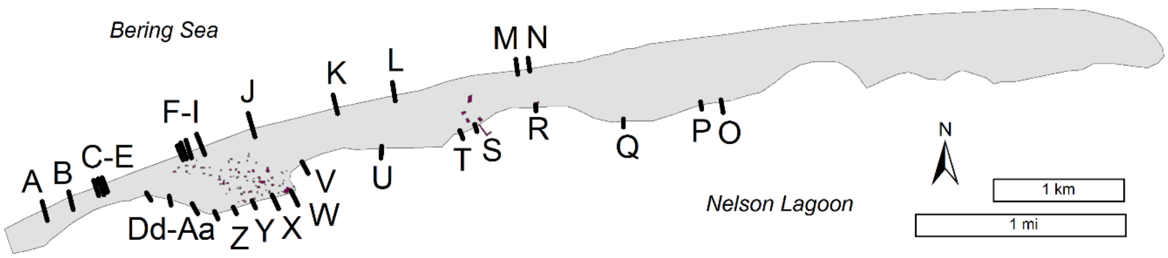


Figure A2. Wave roses of annual wave height and direction for the summer months from WIS Station 82289. Spokes in each rose point in the compass direction from which the waves travel. Colors within each spoke denote wave height bins and the length of the spokes denote the frequency of occurrence.

APPENDIX B. CROSS SHORE PROFILE PLOTS



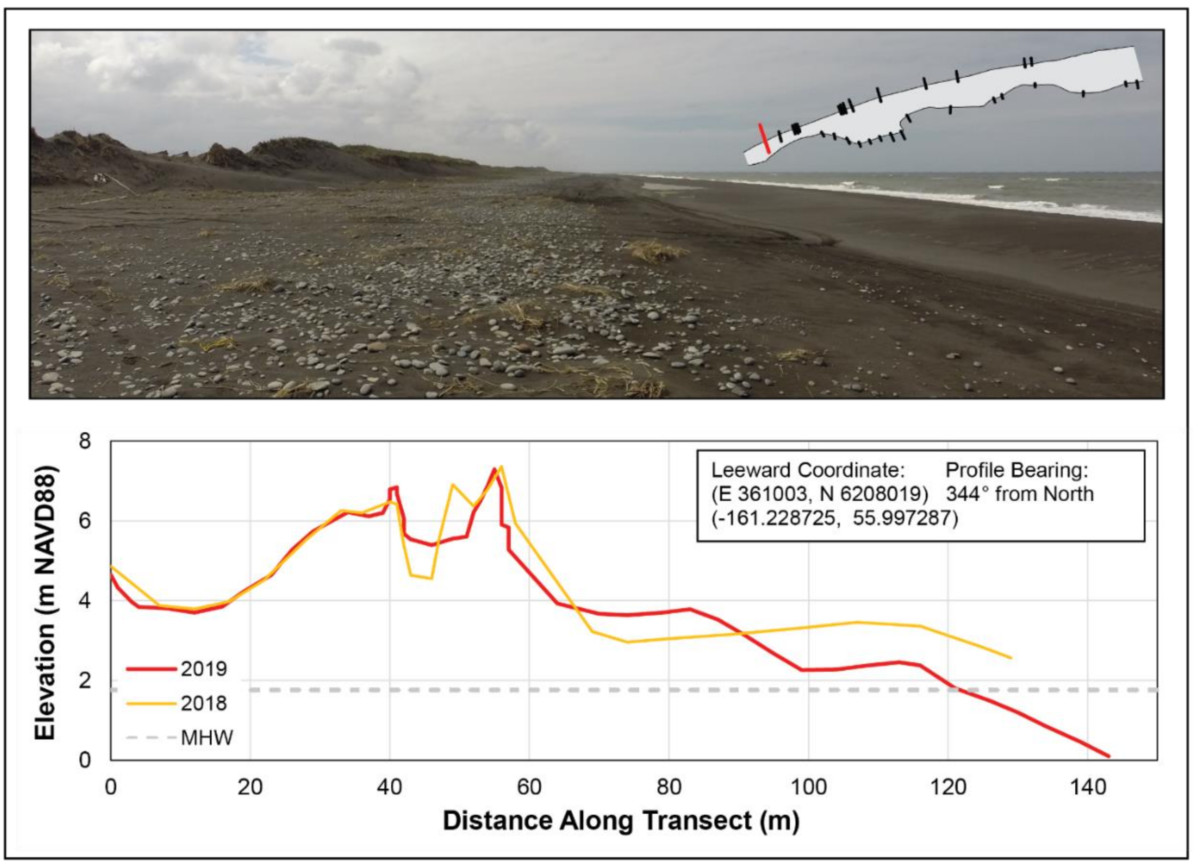


Figure A3. Cross shore elevation profile A measured in 2019 (red) and 2018 (yellow). Notice up to 0.5 m (2 ft) of vertical and horizontal thinning of the bluff face, approximately 1 m (3 ft) of deposition along the base of the bluff, and more than 1 m (3 ft) of vertical erosion of the swash zone at this western sea-side profile.

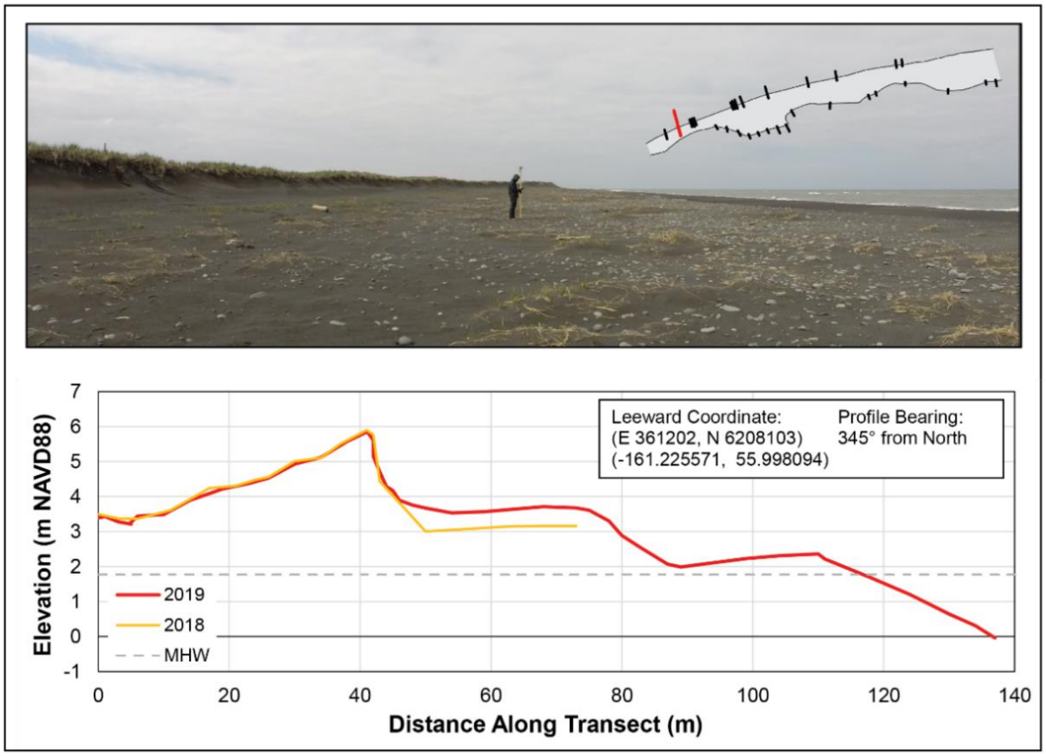


Figure A4. Cross shore elevation profile B measured in 2019 (red) and 2018 (yellow). Notice approximately 0.5 m (2 ft) of deposition beneath the bluff face located 45-75 m along the transect at this western sea-side profile.

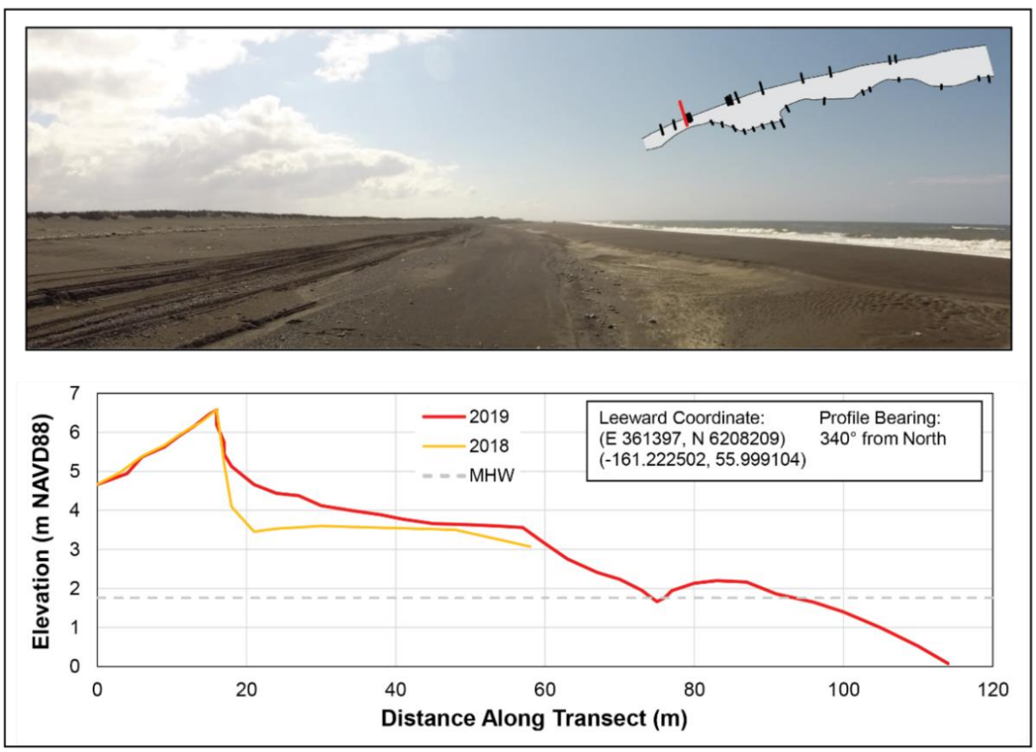


Figure A5. Cross shore elevation profile C. Notice up to 1 m (3 ft) of deposition along the base of the bluff face located 18-40 m along the transect at this western sea-side profile.

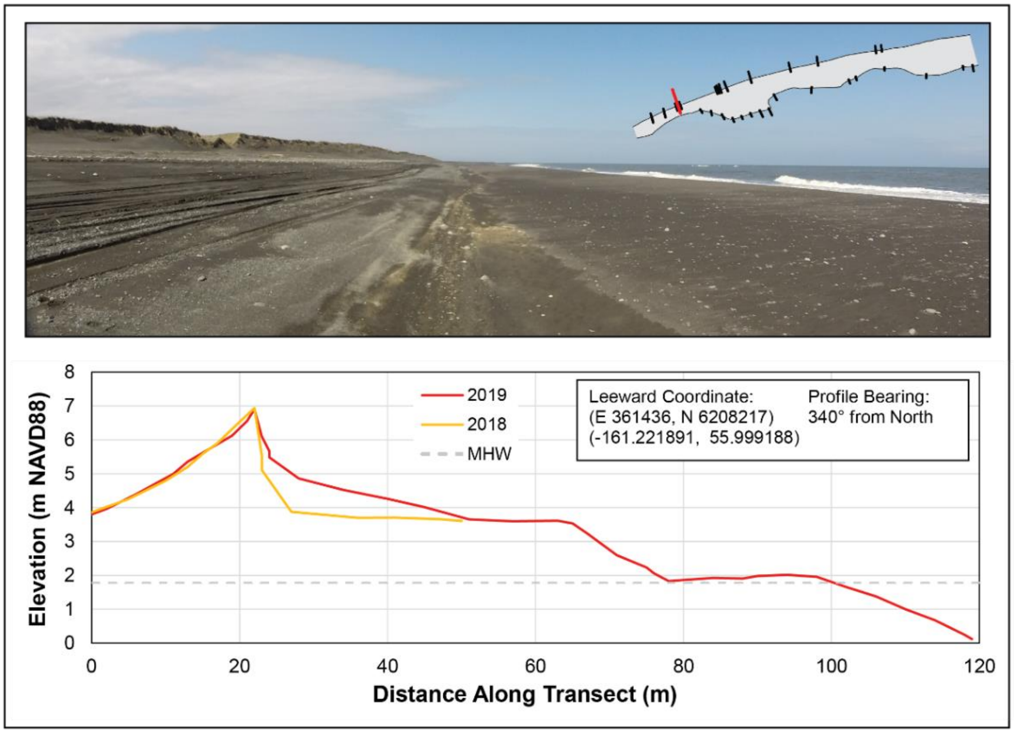


Figure A6. Cross shore elevation profile D measured in 2019 (red) and 2018 (yellow). Notice up to 1 m (3 ft) of deposition along the base of the bluff face located 22-50 m along the transect at this western sea-side profile.

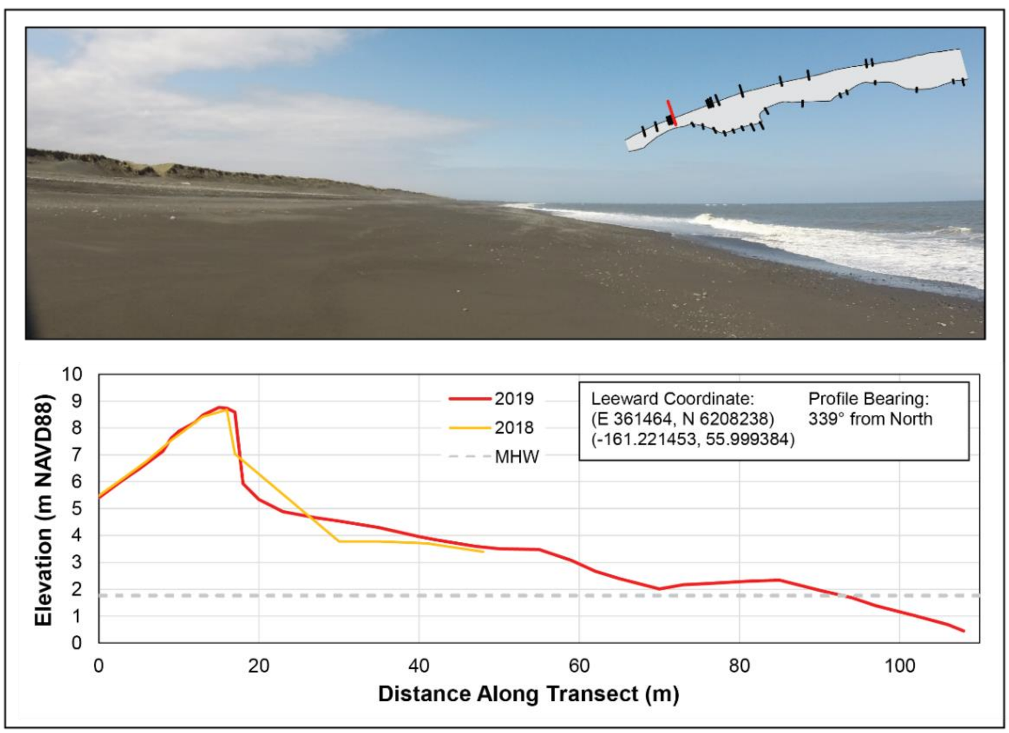


Figure A7. Cross shore elevation profile E measured in 2019 (red) and 2018 (yellow). Notice vertical erosion at the base of bluff face located 18-25 m along the transect and deposition along the foreshore located 25-40 m at this western sea-side profile.

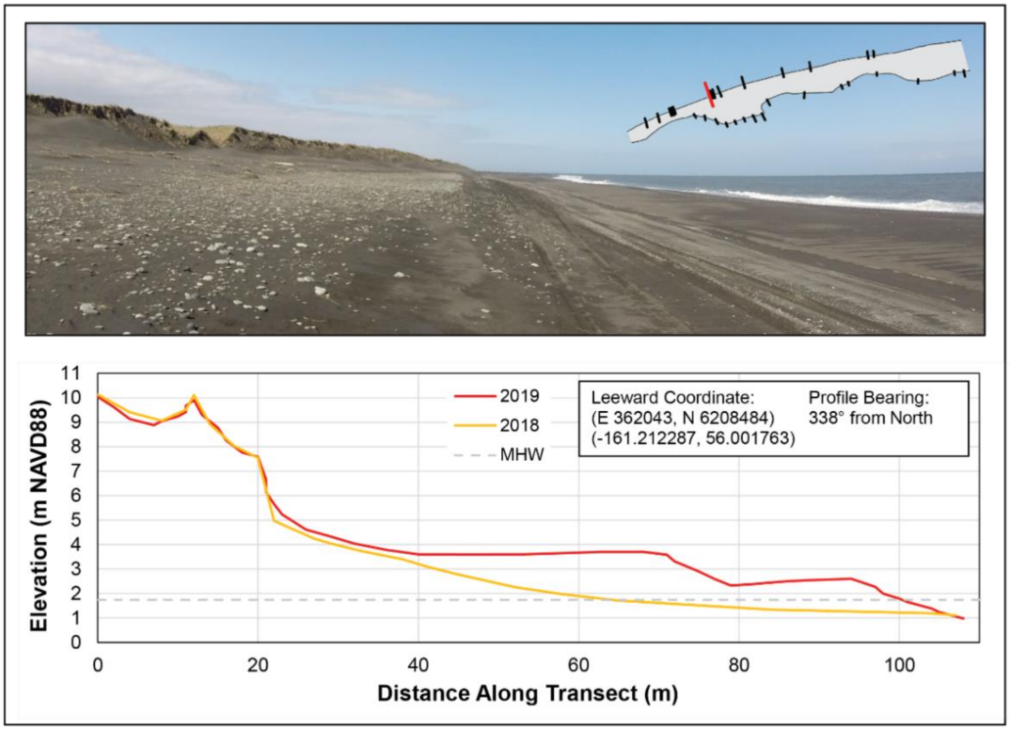


Figure A8. Cross shore elevation profile F measured in 2019 (red) and 2018 (yellow). Notice approximately 1 m (3 ft) of vertical deposition along the backshore located 35-110 m along the transect at this sea-side profile.

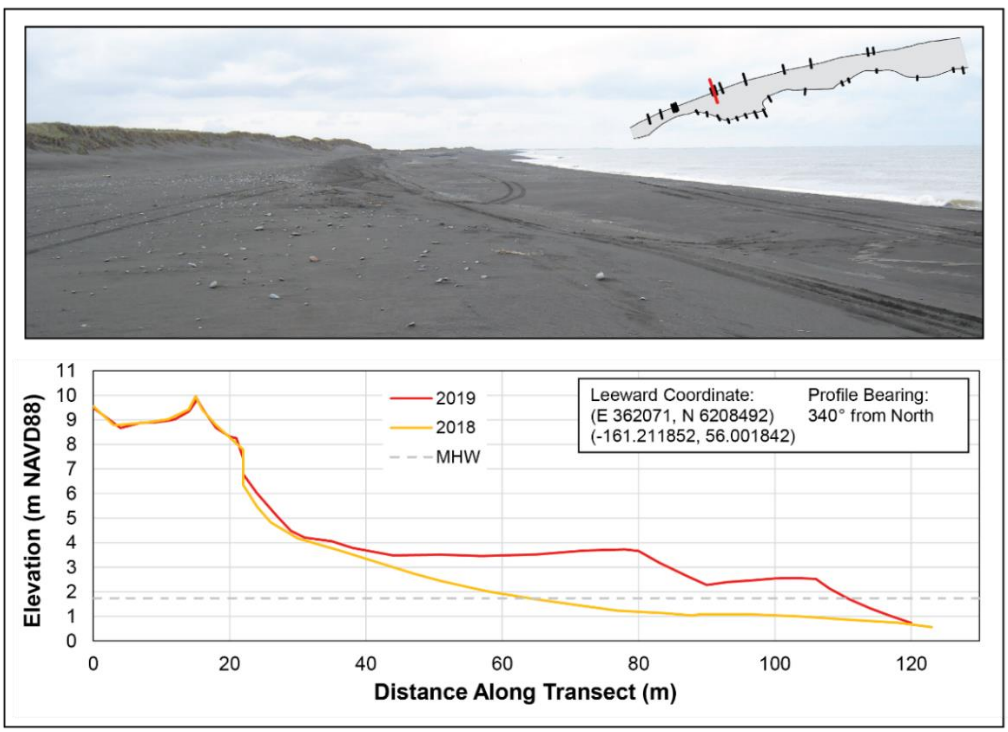


Figure A9. Cross shore elevation profile G measured in 2019 (red) and 2018 (yellow). Notice up to 2 m (7 ft) of vertical deposition along the backshore located 35-120 m along the transect at this sea-side profile.

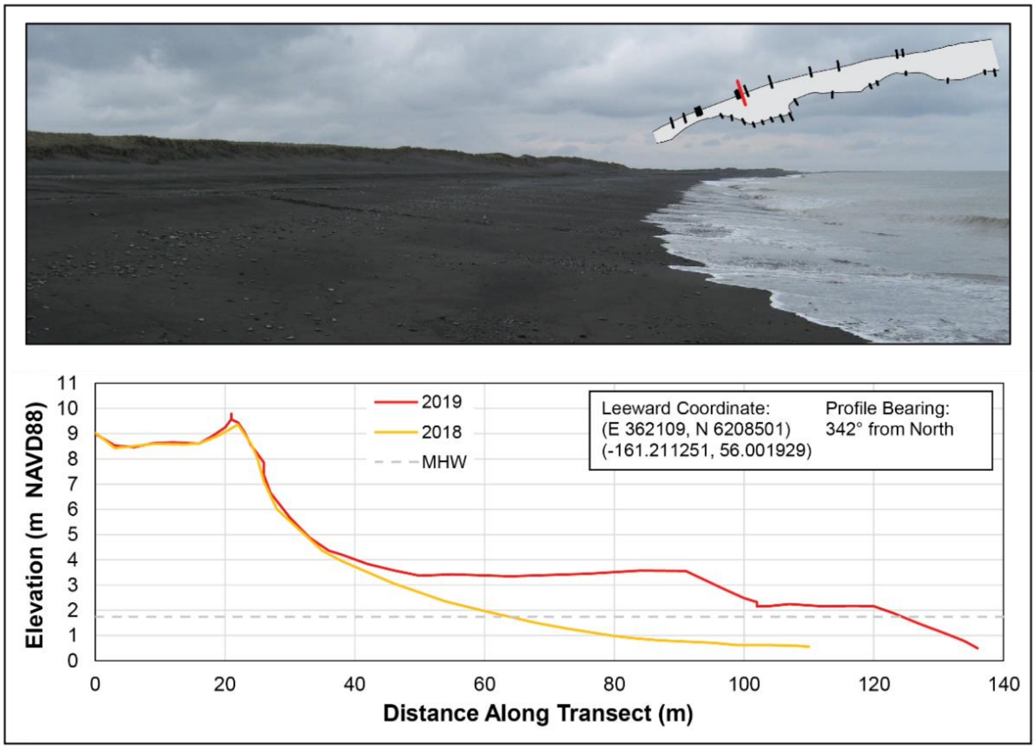


Figure A9. Cross shore elevation profile H measured in 2019 (red) and 2018 (yellow). Notice up to 2.5 m (8 ft) of vertical deposition along the swash zone located 40-110 m along the transect at this sea-side profile.

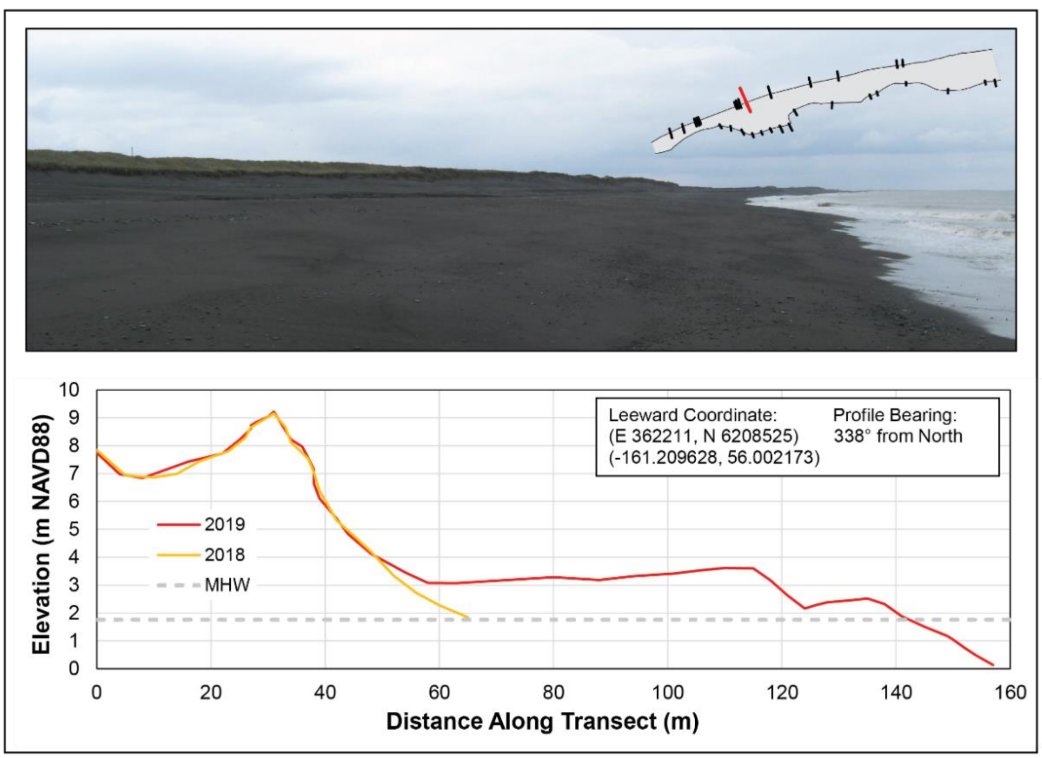


Figure A10. Cross shore elevation profile I measured in 2019 (red) and 2018 (yellow). Notice minimal change of the bluff profile.

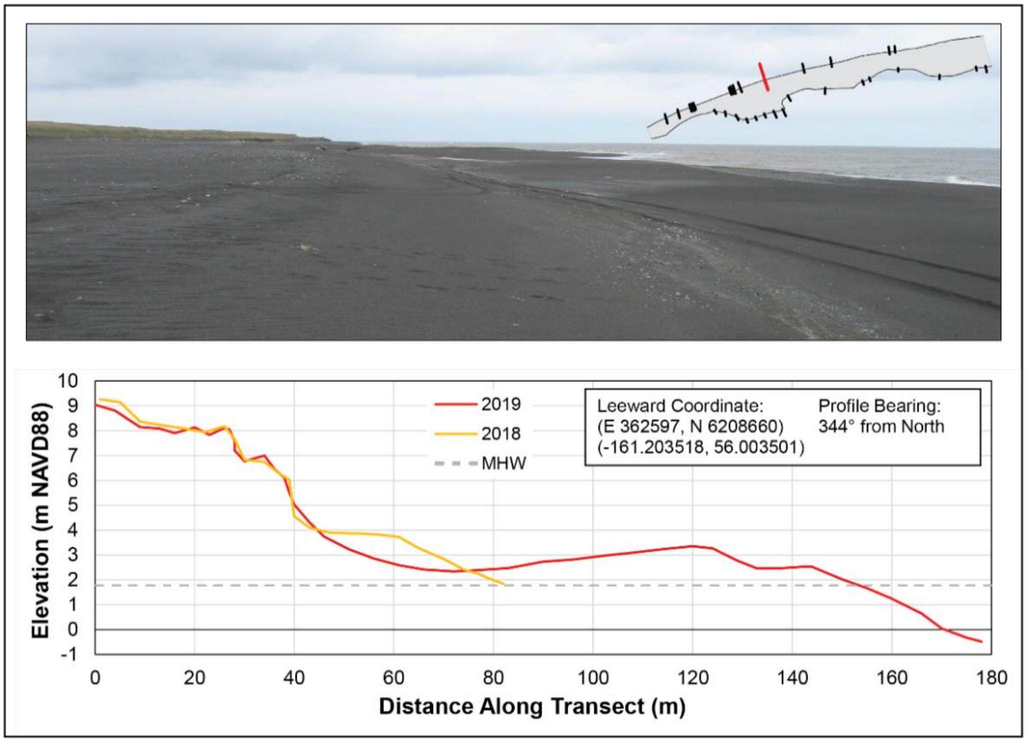


Figure A11. Cross shore elevation profile J measured in 2019 (red) and 2018 (yellow). Notice up to 1 m (3 ft) of vertical erosion beneath the bluff located 45-75 m along the transect at this sea-side profile.

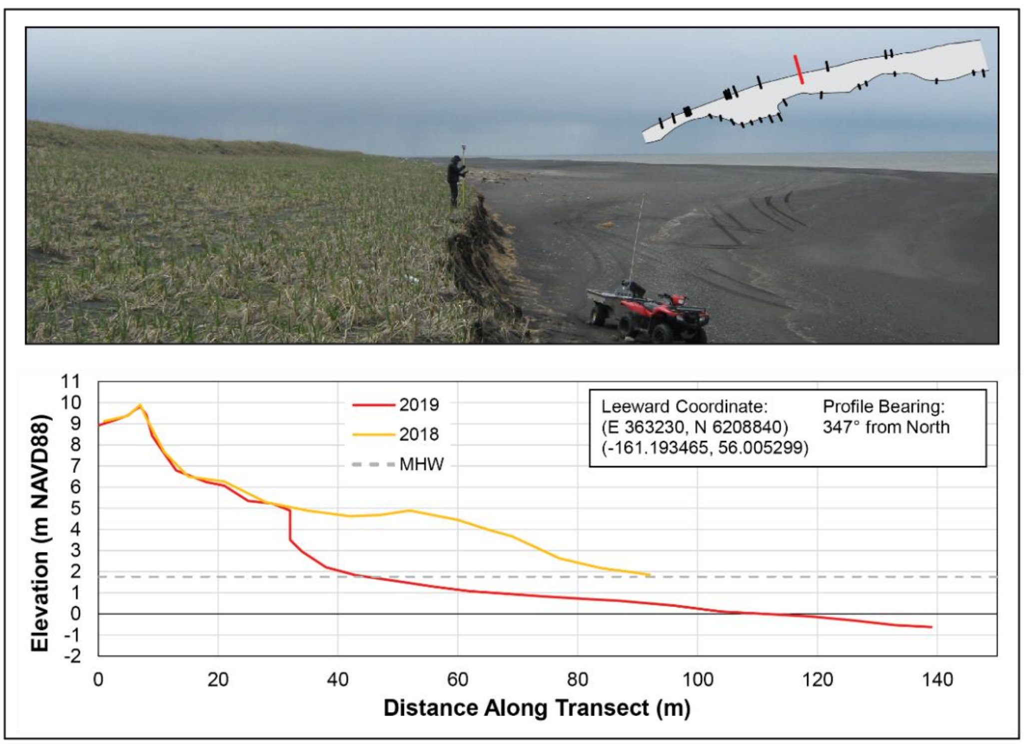


Figure A12. Cross shore elevation profile K measured in 2019 (red) and 2018 (yellow). Notice up to 3 m (10 ft) of vertical erosion of the bluff located 30-90 m along the transect at this sea-side profile.

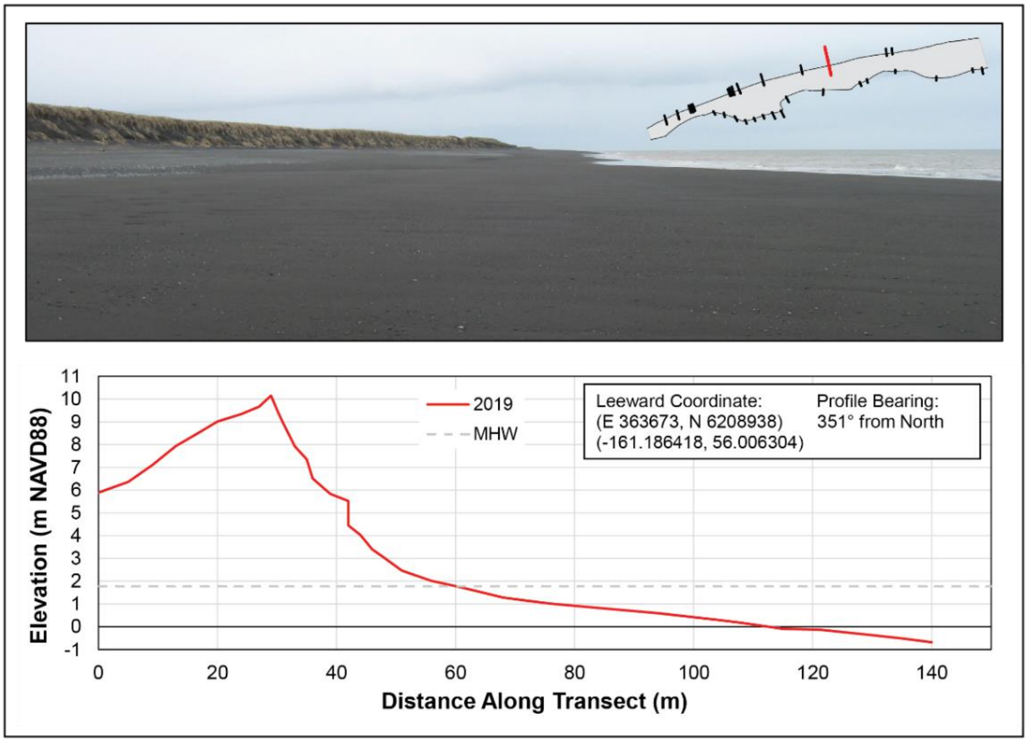


Figure A13. Cross shore elevation profile L measured in 2019 (red). This profile will serve as a baseline in monitoring coastal change at this sea-side location.

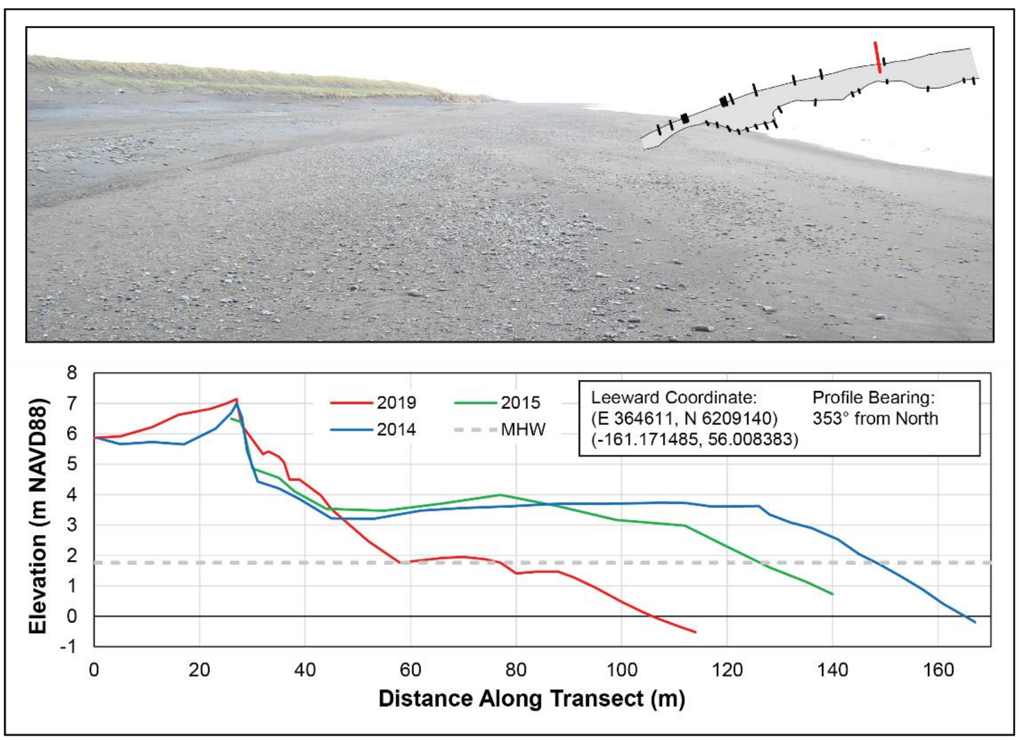


Figure A14. Cross shore elevation profile M measured in 2019 (red), 2015 (green) and 2014 (blue). Notice up to 5 m (16 ft) of vertical erosion along the backshore located 45-120 m along the transect and upwards of 1 m (3 ft) of deposition along the bank of the bluff located 30-45 m along the transect at this eastern sea-side location.

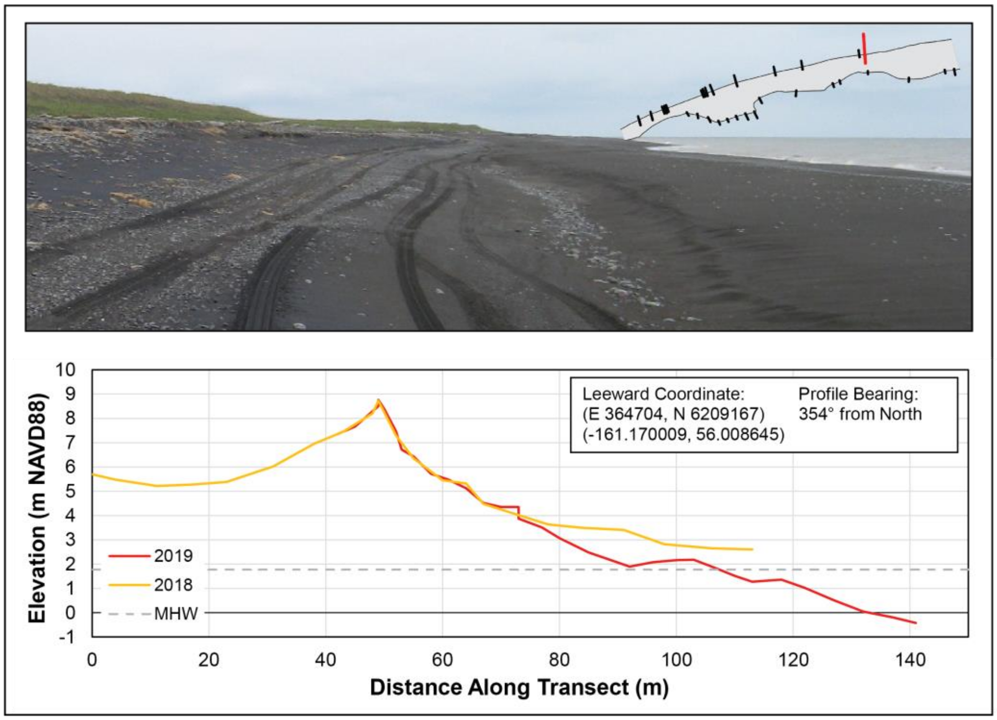


Figure A15. Cross shore elevation profile N measured in 2019 (red) and 2018 (yellow). Notice upwards of 1 m (3 ft) of vertical erosion along the backshore located 75-115 m along the transect and minimal elevation change of the bluff at this easternmost sea-side profile.

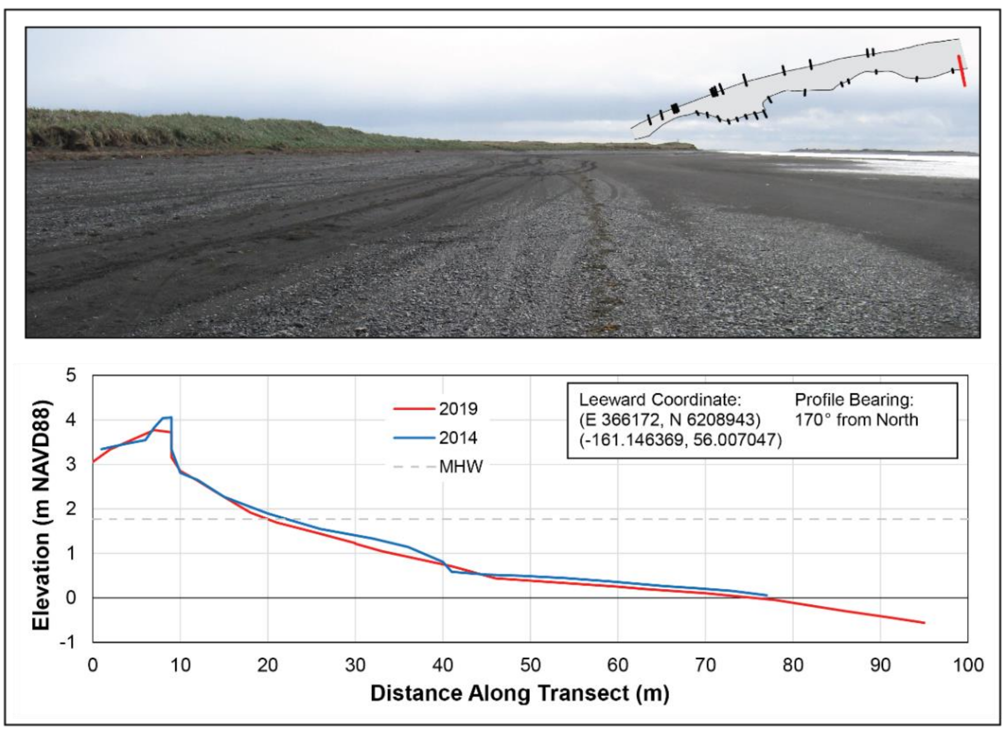


Figure A16. Cross shore elevation profile O measured in 2019 (red) and 2014 (blue). Notice up to 0.3 m (1 ft) of vertical erosion occurred over a duration of 5 years at this eastern lagoon-side profile.

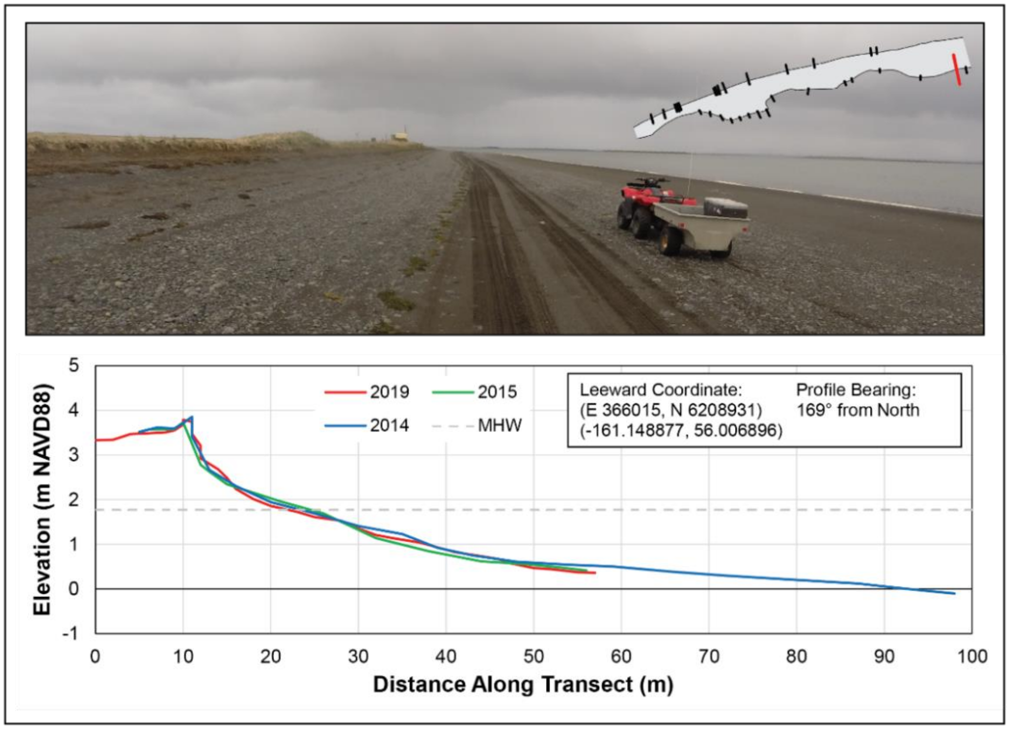


Figure A17. Cross shore elevation profile P measured in 2019 (red), 2015 (green) and 2014 (blue). Notice minimal elevation change occurred over a span of five years indicating stability of the shoreline at this eastern lagoon-side profile.

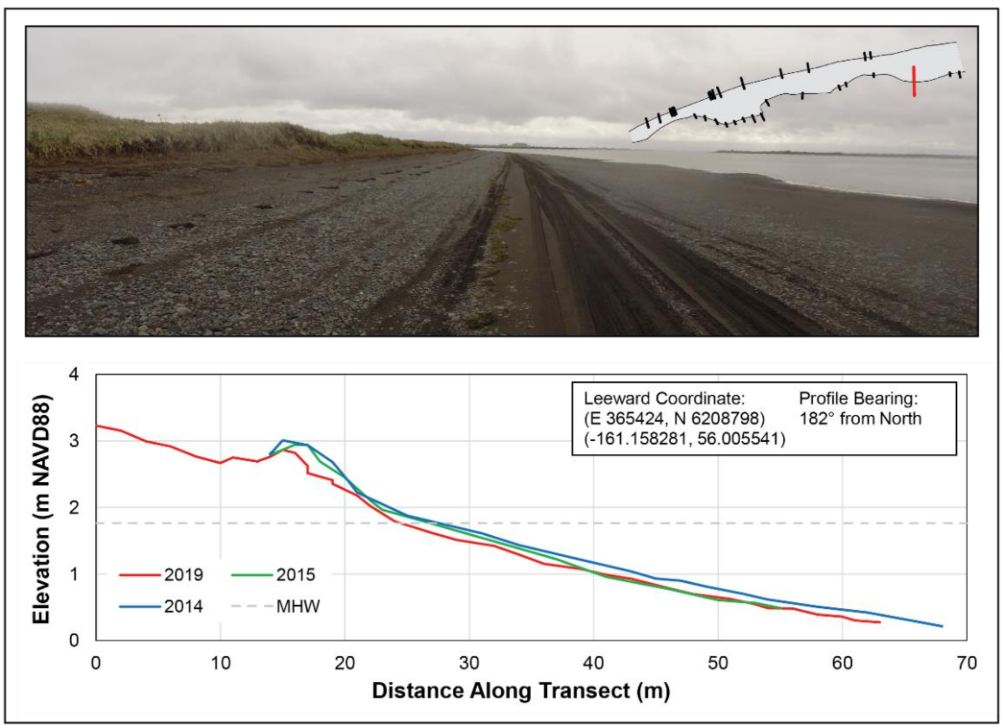


Figure A18. Cross shore elevation profile Q measured in 2019 (red), 2015 (green) and 2014 (blue). Notice up to approximately 0.4 m (1 ft) of vertical erosion and more than 5 m (16 ft) of landward retreat of the backshore located 15-20 m along the transect at this lagoon-side profile.

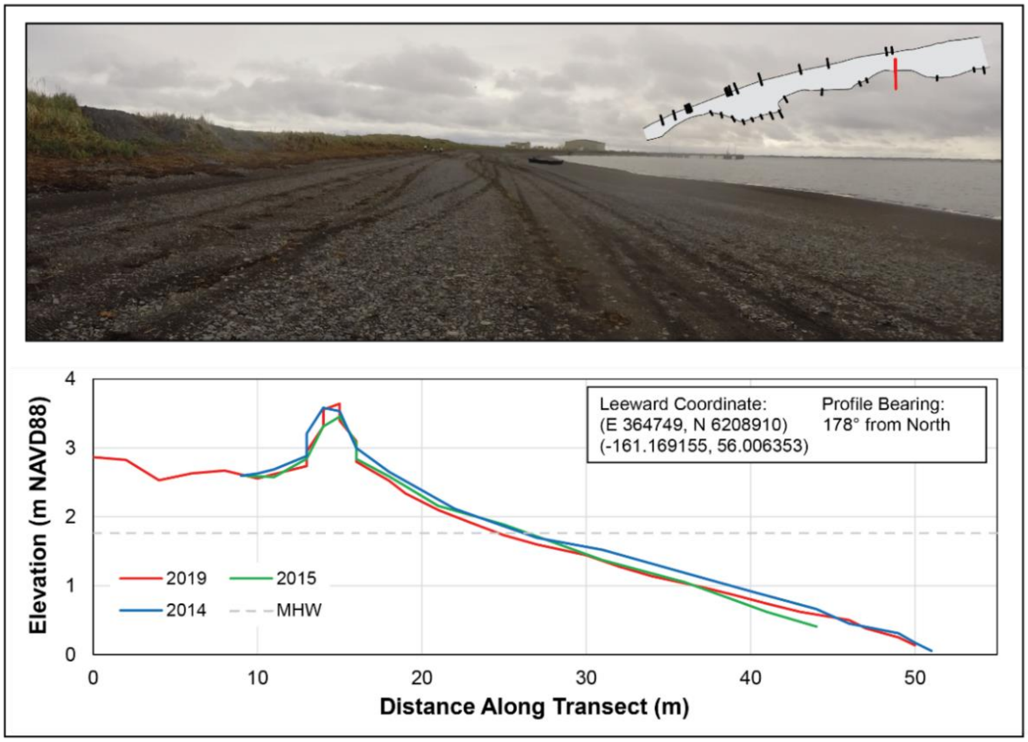


Figure A19. Cross shore elevation profile R measured in 2019 (red), 2015 (green) and 2014 (blue). Notice more than 0.1 m (0.3 ft) of vertical erosion along most of the transect at this lagoon-side profile.

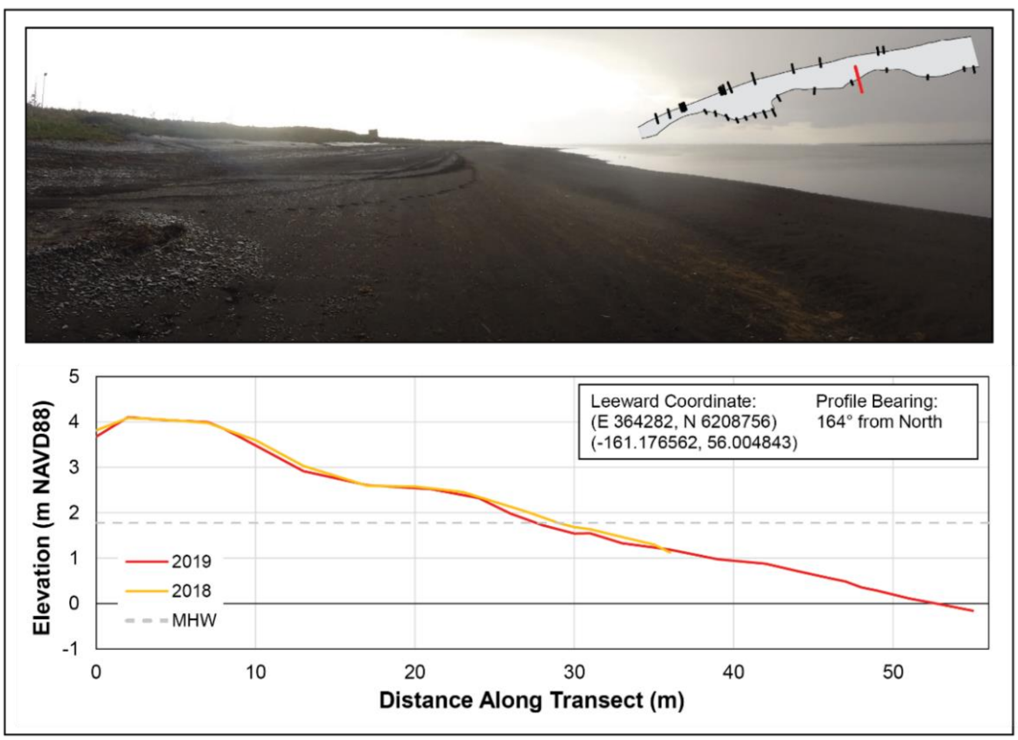


Figure A20. Cross shore elevation profile S measured in 2019 (red) and 2018 (yellow). Notice up to 0.2 m (0.7 ft) of vertical erosion of the backshore and swash zone at this lagoon-side profile.

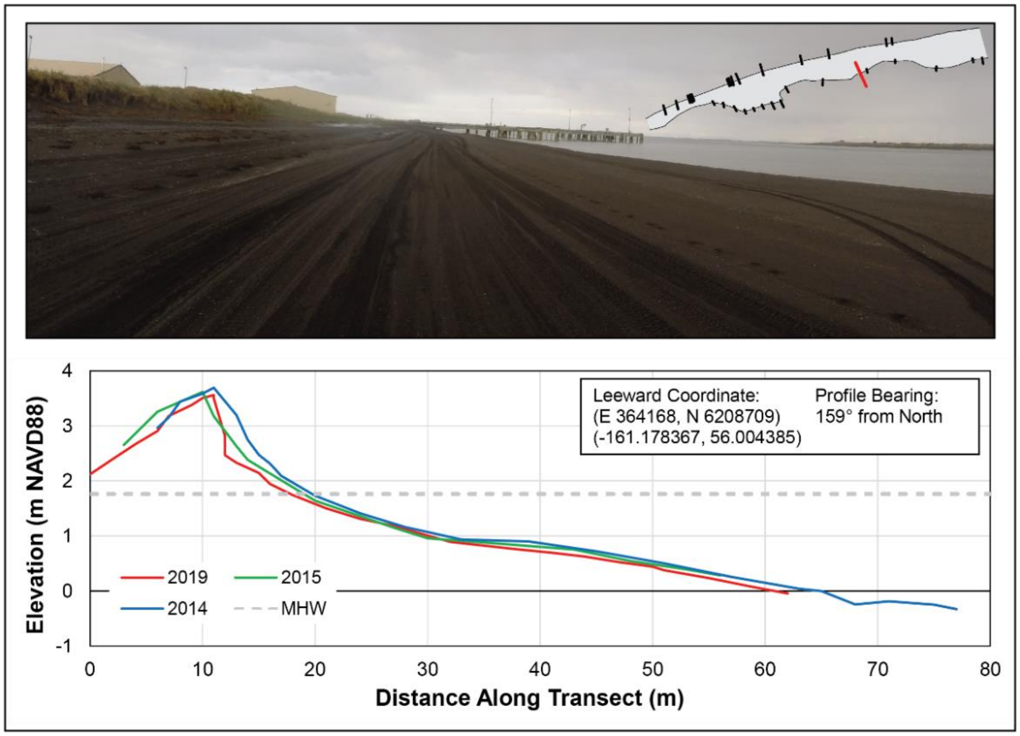


Figure A21. Cross shore elevation profile T measured in 2019 (red), 2015 (green) and 2014 (blue). Notice up to 0.6 m (2 ft) of vertical erosion and more than 5 m (16 ft) of landward retreat of the bluff face located 12-17 m along the transect at this lagoon-side profile.

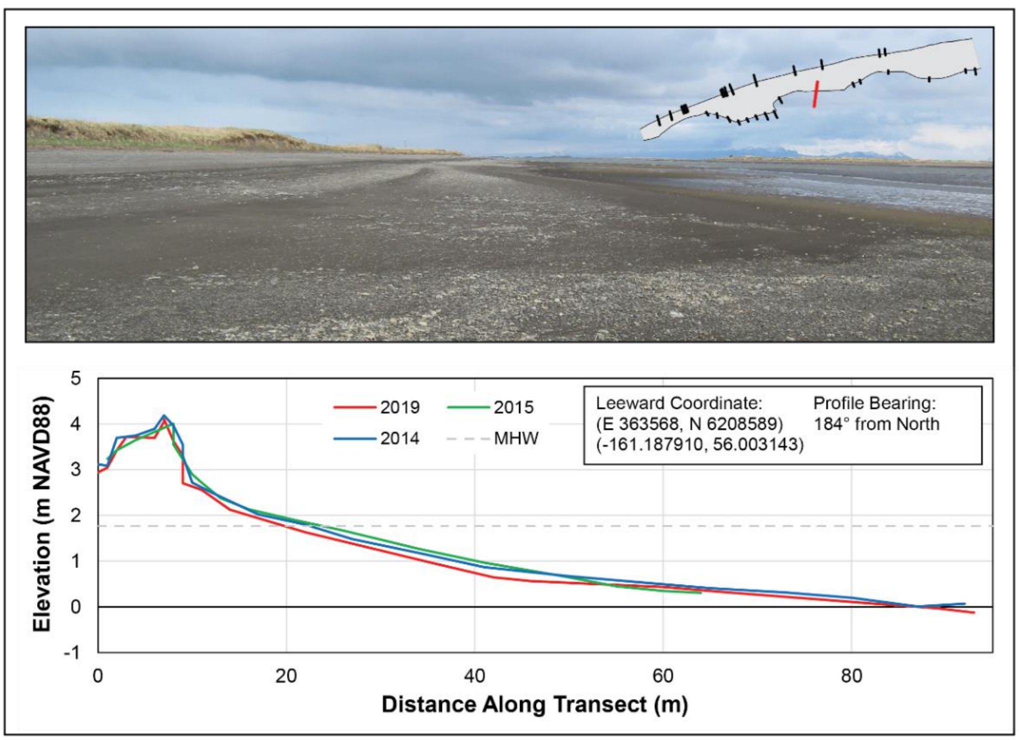


Figure A22. Cross shore elevation profile U measured in 2019 (red), 2015 (green) and 2014 (blue). Notice up to 0.2 m (0.7 ft) of vertical erosion along the shore zone and bluff face at this lagoon-side profile.

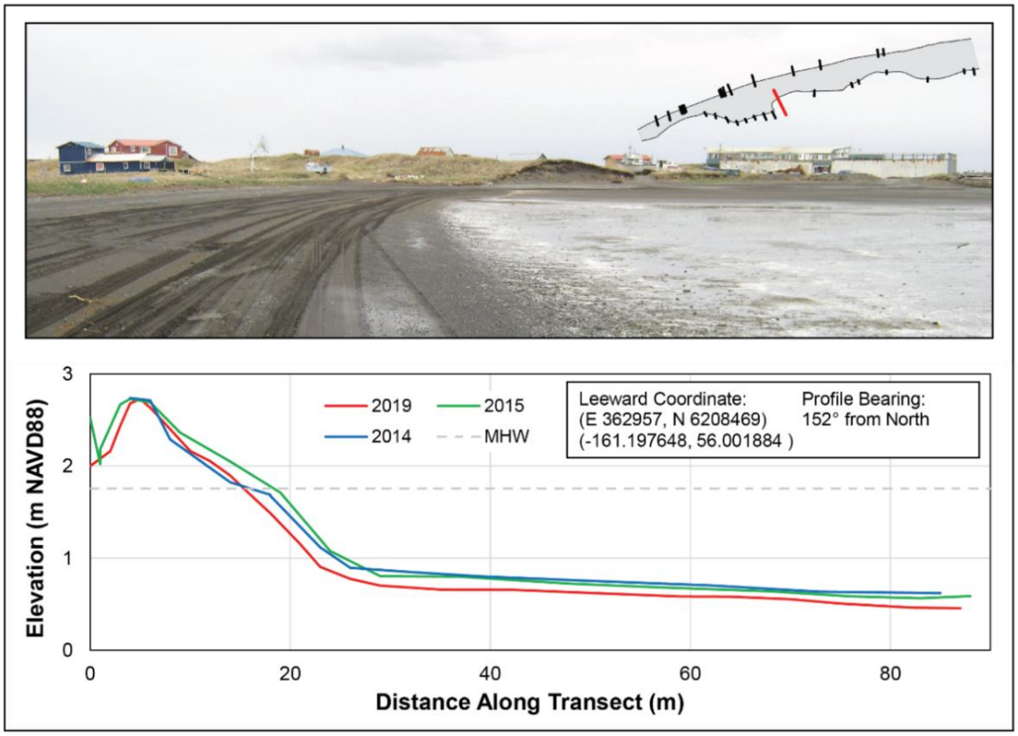


Figure A23. Cross shore elevation profile V measured in 2019 (red), 2015 (green) and 2014 (blue). Notice up to 0.6 m (2 ft) of vertical erosion along the bluff face and shore zone at this lagoon-side profile.

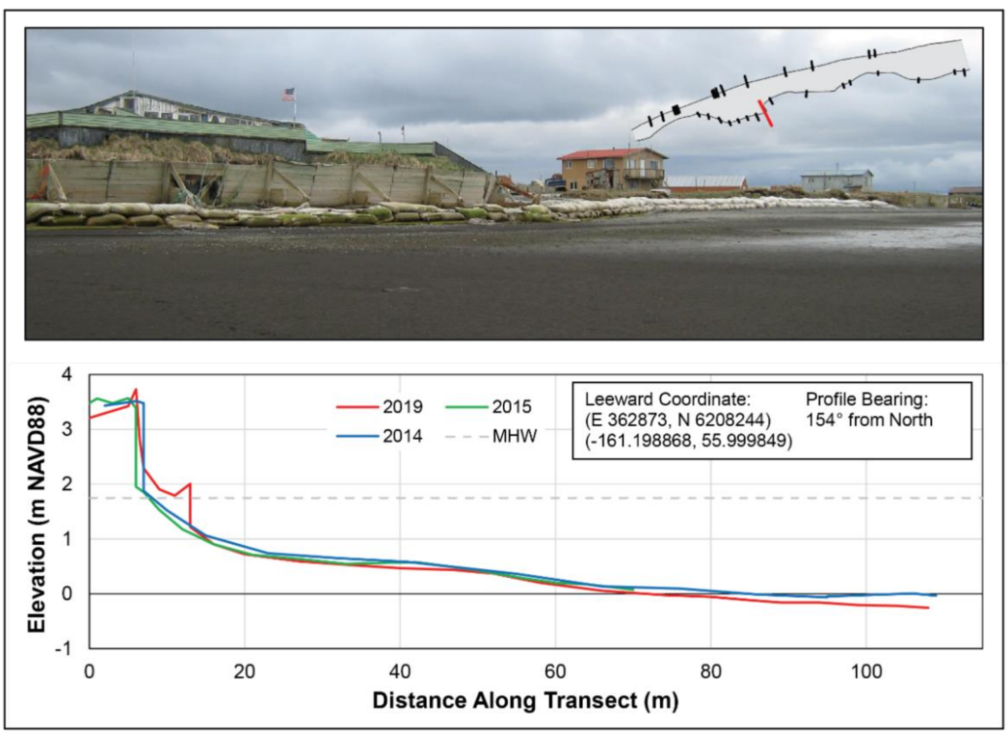


Figure A24. Cross shore elevation profile W measured in 2019 (red), 2015 (green) and 2014 (blue). Notice deposition along the bank of the bluff and approximately 0.2 m (0.7 ft) of vertical erosion along the nearshore at this lagoon-side profile.

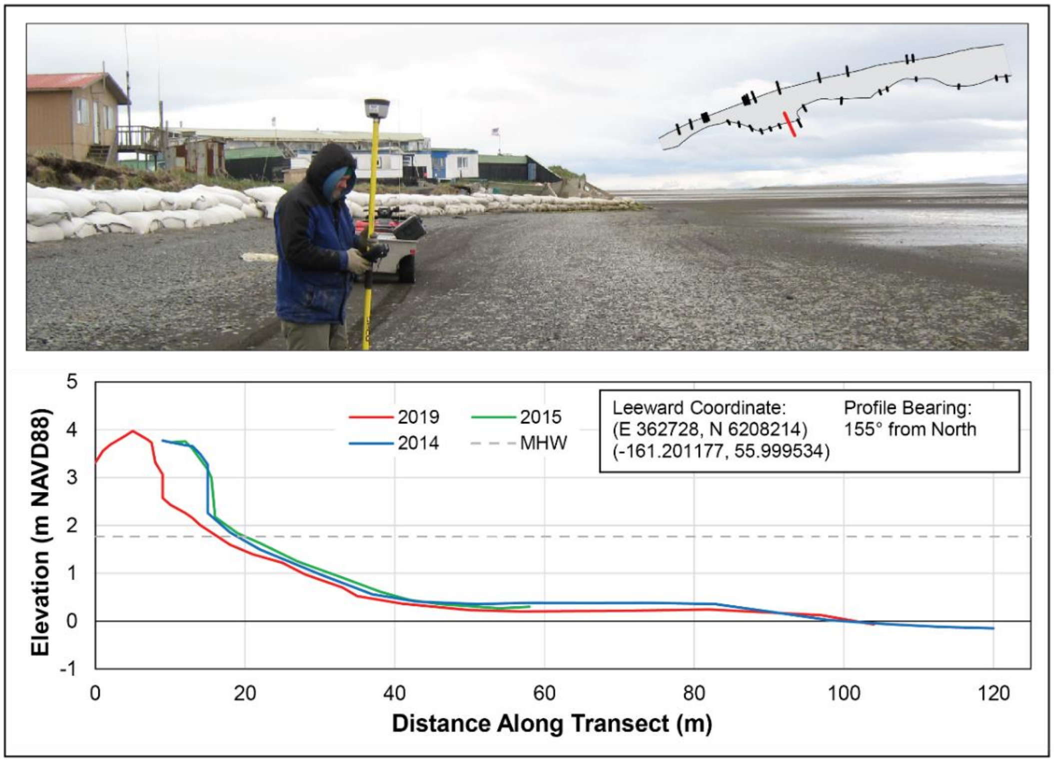


Figure A25. Cross shore elevation profile X. Notice more than 5 m (16 ft) of landward retreat of the bluff at this lagoon-side profile.

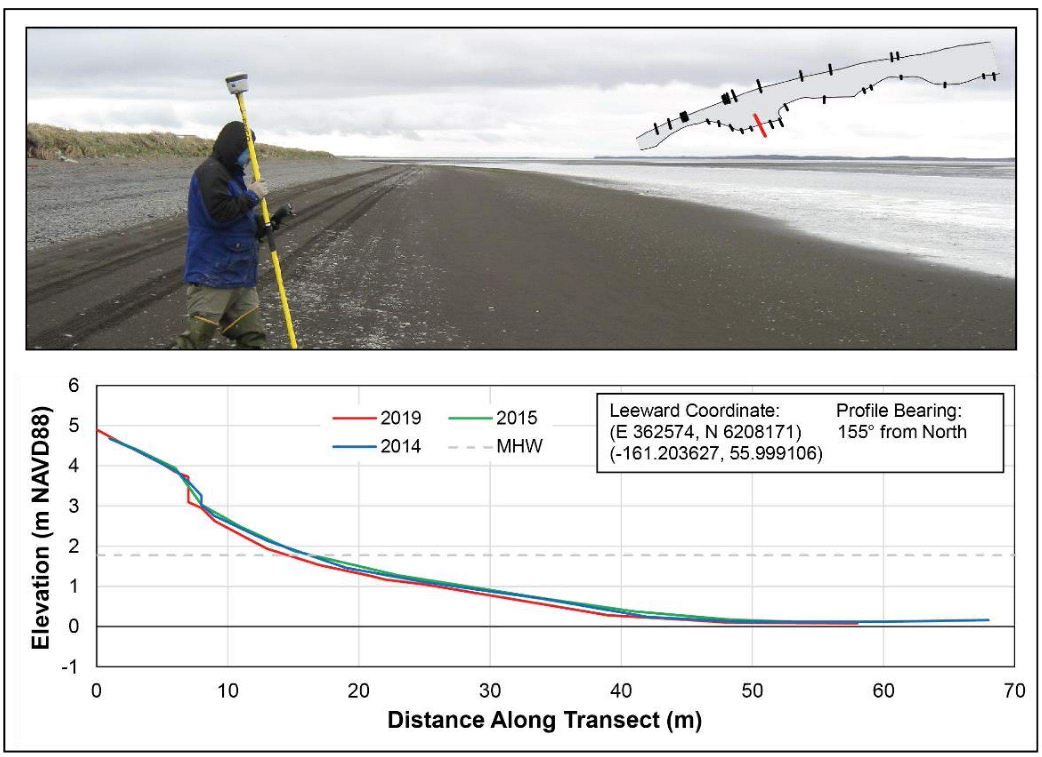


Figure A26. Cross shore elevation profile Y measured in 2019 (red), 2015 (green) and 2014 (blue). Notice more than 0.1 m (0.3 ft) of vertical erosion along the nearshore at this lagoon-side profile.

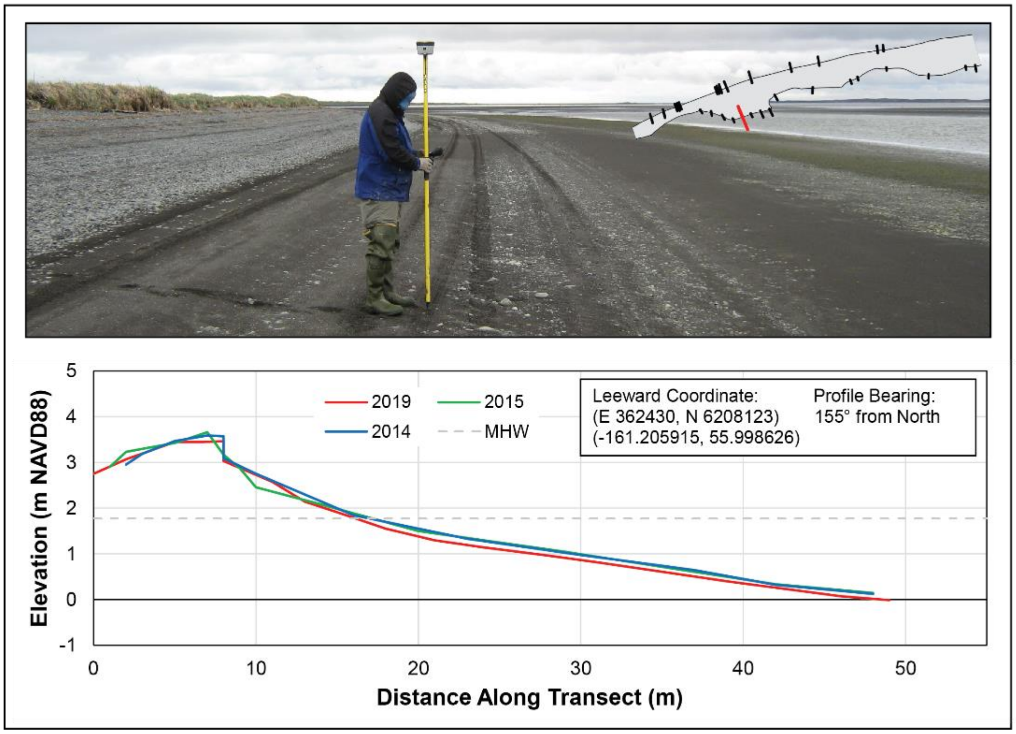


Figure A27. Cross shore elevation profile Z measured in 2019 (red), 2015 (green) and 2014 (blue). Notice approximately 0.2 m (0.7 ft) of vertical erosion along the nearshore at this lagoon-side profile.

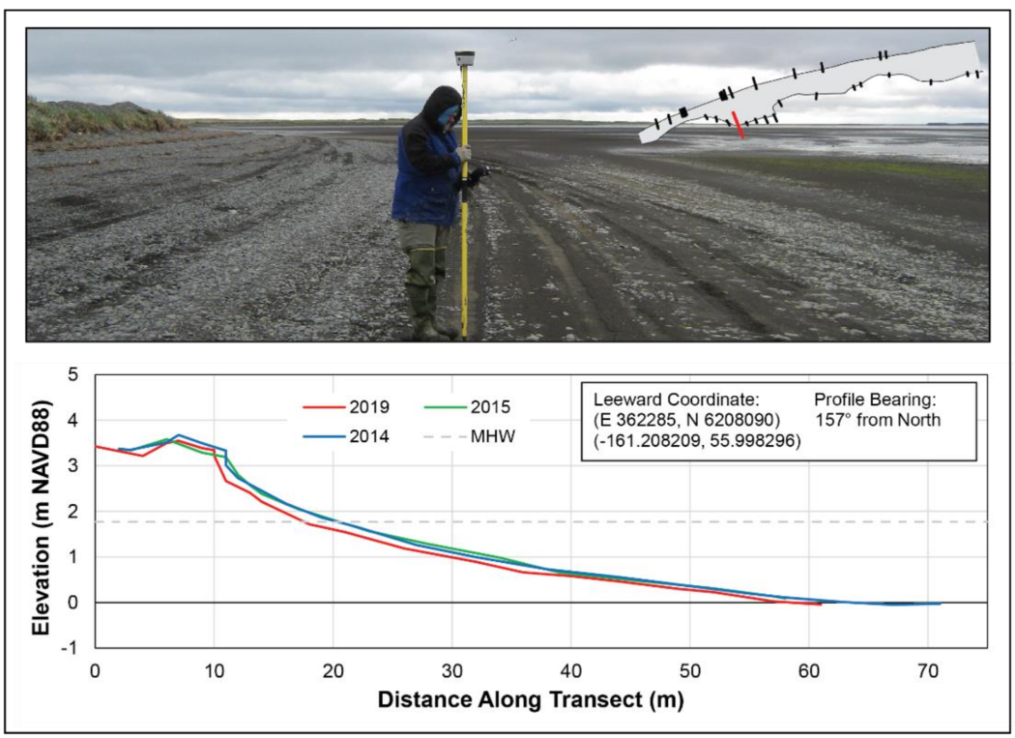


Figure A28. Cross shore elevation profile Aa measured in 2019 (red), 2015 (green) and 2014 (blue). Notice up to 0.3 m (1 ft) of vertical erosion along the shore zone and more than 1 m (3 ft) of landward bluff retreat at this lagoon-side profile.

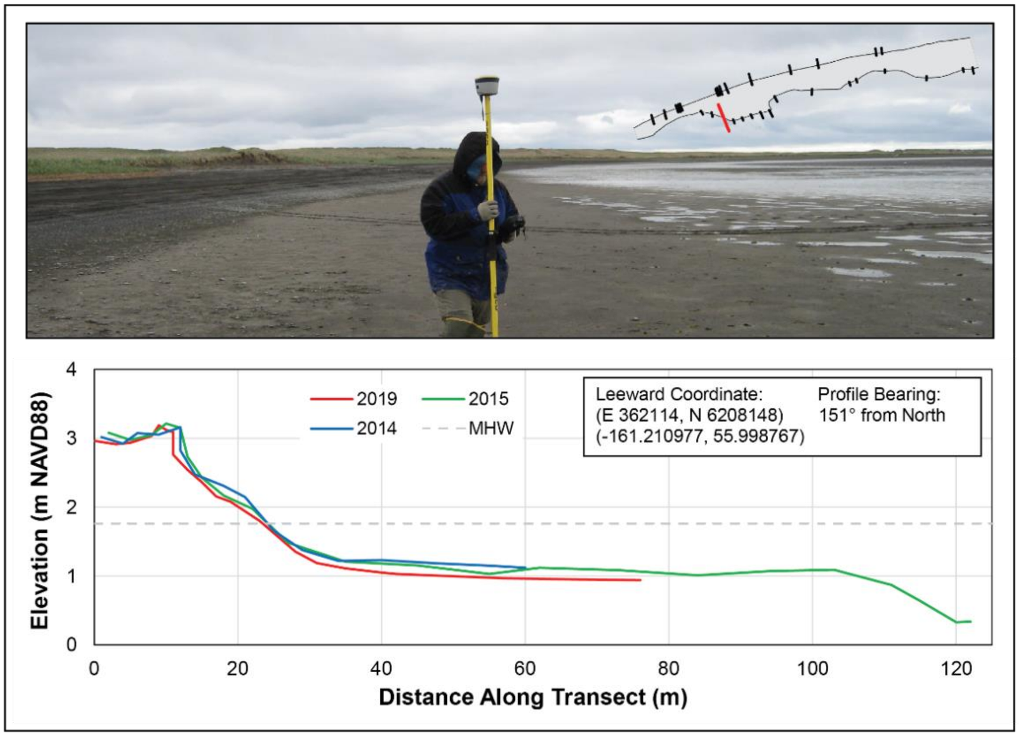


Figure A29. Cross shore elevation profile Bb measured in 2019 (red), 2015 (green) and 2014 (blue). Notice more than 0.1 m (0.3 ft) of vertical erosion along the nearshore and more than 1 m of landward retreat of the bluff at this western lagoon-side profile.

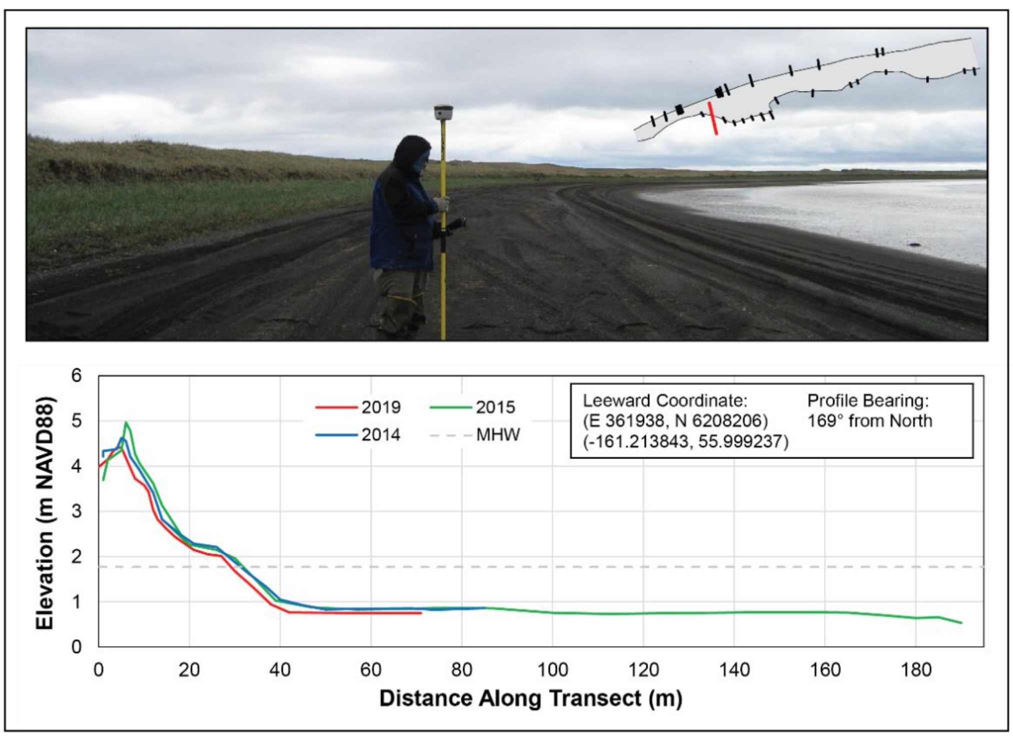


Figure A30. Cross shore elevation profile Cc measured in 2019 (red), 2015 (green) and 2014 (blue). Notice more than 0.1 m (0.3 ft) of vertical erosion along the nearshore and bluff face at this western lagoon-side profile.

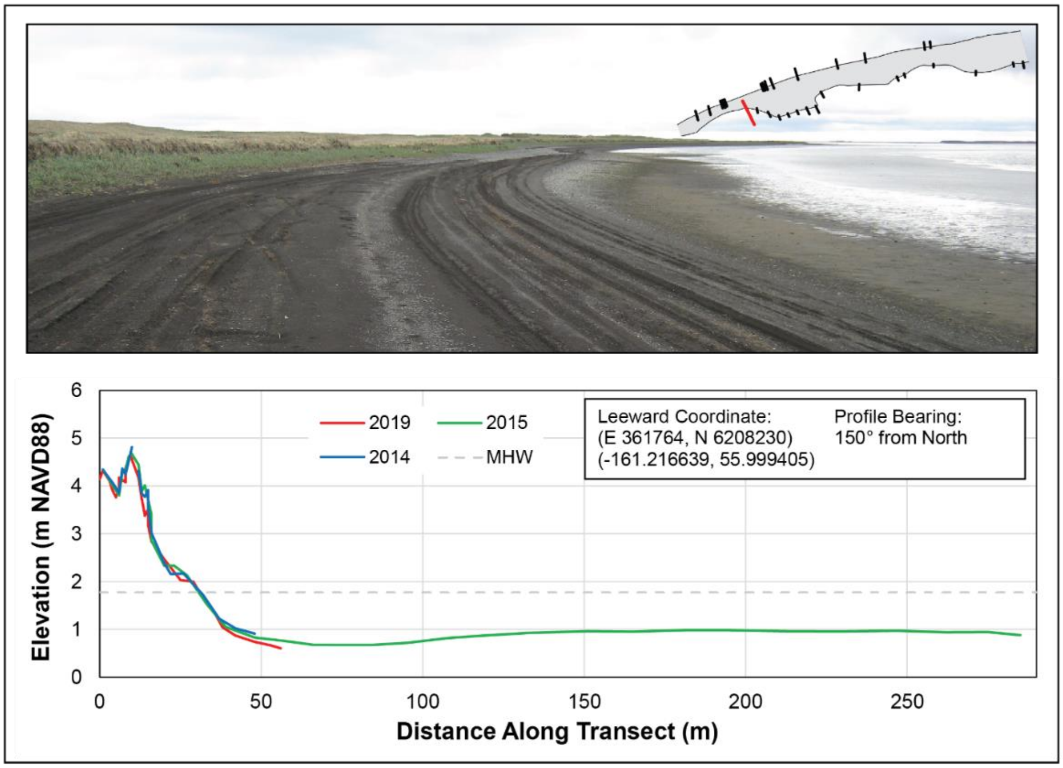


Figure A31. Cross shore elevation profile Dd measured in 2019 (red), 2015 (green) and 2014 (blue). Notice minimal horizontal change and up to 0.1 m (0.3 ft) of vertical erosion of the nearshore at this westernmost lagoon-side profile.