COASTAL HAZARD ASSESSMENT AND CLIMATE ADAPTATION USING HYBRID SHORELINE EVOLUTION MODELS FOR REMOTE COMMUNITIES IN ALASKA

Dr. Ashwin Gadgil[1], Dr. Kathryn De Rego Semiao[1], Dr. Phil Osborne[2], and Keyvan Mahlujy[1]

Remote communities at northern latitudes are most vulnerable to climate change driven impacts. Communities, specifically in Alaska, that are severely impacted by climate change have to make the decision to relocate or adapt in place. Hybrid numerical models that rely on a combination of hydrodynamics, morphodynamics, statistics, and are informed by Indigenous knowledge are developed to guide the decisions surrounding relocation vs adaptation. These tools are used to support two different communities in Alaska, one of which is planning to relocate and the other is preparing to adapt. Numerically modelled environmental forces are correlated with the observed rate of retreat of shoreline to support the relocation planning at Napakiak. A statistical correlation between the simulated environmental forces and the shoreline retreat is established. Indigenous knowledge is used to develop the theoretical basis of the forcing mechanism underlying the statistical correlation. This correlation is used with projected future environmental conditions to forecast likely shoreline positions in the years 2030, 2040, and 2050. The projected shoreline positions will be used by the community to update their managed relocation plan. Similarly, numerically simulated berm responses to incident storms are used to evaluate the feasibility of the different nature-based berm optimization concepts and hybrid design options for improving berm resilience at Shaktoolik. These numerical models are also used to study the sensitivity of berm responses to various forcing elements and underlying conditions, which provides insight regarding the lifecycle effectiveness of sediment-based and hybrid nature-based options in an open coast context. The application of these models in the respective communities has provided projections of shoreline change, evaluation of protection berm concepts, and recommendations for future steps towards the communities' climate change adaptation strategies.

Keywords: Shoreline evolution; hybrid numerical model; berm design; climate adaptation

INTRODUCTION

Climate change is threatening coastal communities globally. The effects are especially acute at northern latitudes where a large number of coastal communities face erosion, flooding, and loss of sea ice or permafrost degradation caused by more intense/frequent storms, higher water levels, and warmer temperatures. Many at-risk northern coastal communities face difficult decisions regarding the need to relocate versus remaining in place with adaptation. The remote setting and geologic context often mean there are limited locally available construction materials and resources, and a short seasonal construction window. Relocation comes with a significant cost burden, social environmental and technical challenges. Parameters governing the communities' decision to relocate, or adapt-in-place include metocean conditions, climate projections, historical shoreline trends, availability of construction materials, feasibility of proposed solutions, funding, ability of First Nations to sustain traditional subsistence practices and cost-benefit comparison. The present work outlines development and application of hybrid numerical models combined with Indigenous knowledge to guide the decision of relocation vs adaptation at two remote communities in Alaska.

RELOCATION AT NAPAKIAK

Background

The Village of Napakiak, Alaska (Napakiak) is located on an island on the north bank of the Kuskokwim River estuary (see Fig. 1). The site is approximately 55 miles upriver from the river mouth on the Bering Sea and approximately 10 miles downriver from Bethel, Alaska. Napakiak has been experiencing persistent bank erosion (shoreline retreat) along its riverbank, which has been an ongoing threat to village infrastructure. Shoreline retreat at Napakiak ranks among the most severe in Alaska (Overbeck et al. 2020), and the Division of Geological and Geophysical Surveys (DGGS) estimates that the village may incur over $76 million in infrastructure replacement costs over the next several decades resulting from erosion (Buzard et al. 2021).

---

[1] WSP Canada Inc., Canada.

[2] Northwest Hydraulic Consultants, Canada.

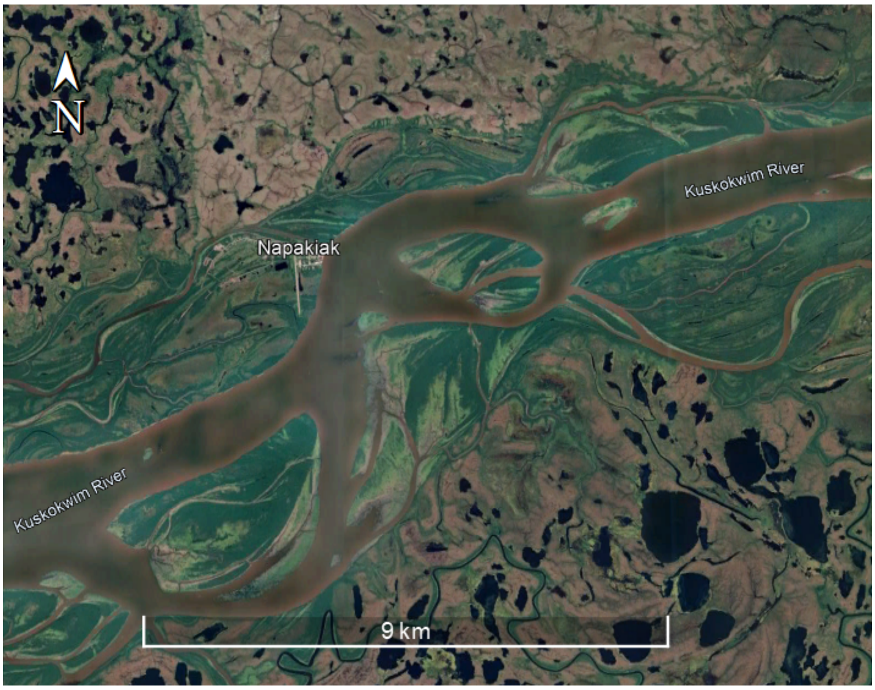

Figure 1. Community of Napakiak.

As a response to the continuing bank erosion risk, Napakiak has developed a Managed Retreat Plan to provide a framework for community relocation (Summit 2020). There are two timelines for relocation: near-term goals to mitigate immediate erosion risks, and long-term goals to eliminate the risk of bank erosion to community infrastructure. Options for long-term mitigation include (1) retreating directly to the bluff to the west of Napakiak, (2) retreating first to a western location on the island further away from the eroding shoreline in the medium-term, then moving to the bluff in the long term, and (3) retreating to a western location on the island further away from the eroding shoreline and remaining there. Reliable projections of future Kuskokwim River shoreline locations are key tools for evaluating the most feasible retreat option. Shoreline projections into the mid-late 21st century are available, however considerable uncertainty about the trajectory of bank retreat remains; of particular concern is the impact of climate change on rates of erosion. The primary objective of the present work is to forecast future shoreline locations over the next 30 years. The forecast will account for projected changes in the rate of bank erosion as a result of climate change. The findings and conclusions from this work will be used by the community and other key stakeholders as they evaluate the long-term adaptation and relocation options for the village as outlined in the Managed Retreat Plan.

Physical Processes

Napakiak is located in southwestern Alaska, along the outer edge of a meander bend on the north bank of the Kuskokwim River. The Kuskokwim River is snowmelt dominated with tidal influence. The Kuskokwim River has an anastomosing planform, which is characterized by a multi-threaded channel with stable islands and side channels. Channel change is primarily expressed as bank erosion along the outer margins of the dominant flow conveyance route. Upstream of Napakiak, bank erosion typically occurs at the outer banks of meander bends where river flow is most powerful. Downstream of the village, channel change is dominated by wave energy, and bank retreat is concentrated on south and southeast facing channel margins which are exposed to waves during high-wind events driven by Bering Sea cyclones. Napakiak is situated at the transition between these river-dominated and marine-dominated sections of the delta, and its position on the outer edge of a meander bend combined with its southeast aspect makes its banks vulnerable to both fluvial and wave generated energy (Golder 2020a). Historically, the rate of bank retreat at Napakiak appears to have been largely constant since the 1960s (Buzzard et al. 2021). However, bank retreat has accelerated, especially in the past decade and there is considerable uncertainty regarding future rates of bank retreat due to climate change-driven alterations to flow, ice cover, and storm regimes.

It was hypothesized that the riverbank can be divided into two parts: The upper bank, characterized by a scarp and shoreline that is within the range of wave energy, and the bank toe that is typically submerged and below the influence of wave energy. Based on the anecdotal information gathered from the indigenous community it appeared that the erosion events typically occur during southerly or southeasterly storm events and may involve one or more of the following steps (see Fig. 2):

1. The bank toe is eroded due to the shear stress exerted along the banks by the flow exceeding the gravitational and frictional forces holding it in place. This may occur during high tidal flood flows caused by storm surges or during high flow events such as at freshet or following a large rainfall event.
2. As the bank toe is eroded, it may become undercut, making the bank susceptible to collapse.
3. Southerly and southeasterly winds produce waves that erode the upper bank as the tide is rising. Storm surge may exacerbate water pileup on the shore and increase the exposure to wave attack. If the toe is undercut, the wave energy at the upper bank may trigger bank collapse.
4. As the tide falls and during successive tidal cycles, the collapsed sediment is transported onto the new bank toe.

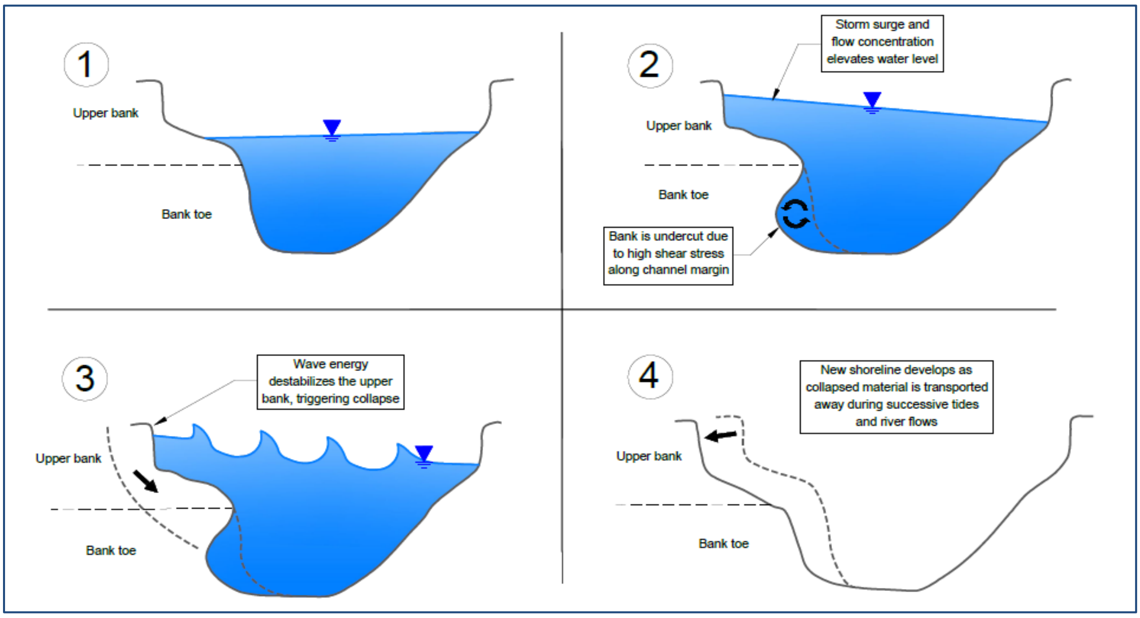

Figure 2. Schematic of the theorized erosion processes at Napakiak.

Hybrid River Morphology Model

Overview

Bank erosion is a function of environmental forcing and resistance along the bank. The resistance is a result of passive environmental factors such as vegetation coverage, sediment type and properties, orientation of the bank and channel morphology. The forcing is a result of active environmental drivers such as river discharge, tides, and storm waves. Hydrodynamic and morphodynamic modelling of a site with these many interacting environmental factors requires extensive morphological and environmental data. At Napakiak, such data do not currently exist and would require an extensive and long term data collection effort. Therefore, a hybrid river morphology model is developed that combines simulated forcing conditions, such as the typical storm and flow conditions, and observed shoreline retreat rates to characterize future bank erosion risks and predict shoreline locations in the years 2030, 2040, and 2050. A series of hindcast numerical simulations, run on an adjusted digital elevation model (DEM) bathymetry representative of each historic interval, are used to quantify the magnitude of the primary drivers of shoreline position change and correlated with the observed change in the shoreline at a series of locations along the riverbank at the village. This correlation is then extrapolated to predict future shoreline changes.

Numerical Model

Numerical simulations are developed using the 2D Delft3D FM (DFM) model which used a fully unstructured flexible mesh grid. The DFM model extents (see Fig. 3) are chosen based on a balance between coverage of study area, locations of gauges used to establish boundary conditions, and practical run-times. The DFM model has an open boundary at Lomavik. Time series of tides are used to force water level boundary conditions at this open boundary. Winds from the sectors of interest (East and South) are used to calculate the most likely duration and most likely wind speeds during a windstorm event from that sector. The DFM model has an upstream discharge boundary at Bethel and another one at Johnson Slough, approximately 5 km west of Napakiak. Wave conditions are not specified at any open boundary. Wave generation and propagation is limited to storm condition simulations and based purely on the wind action along the dominant fetches and the flow-wave interactions within the model domain.

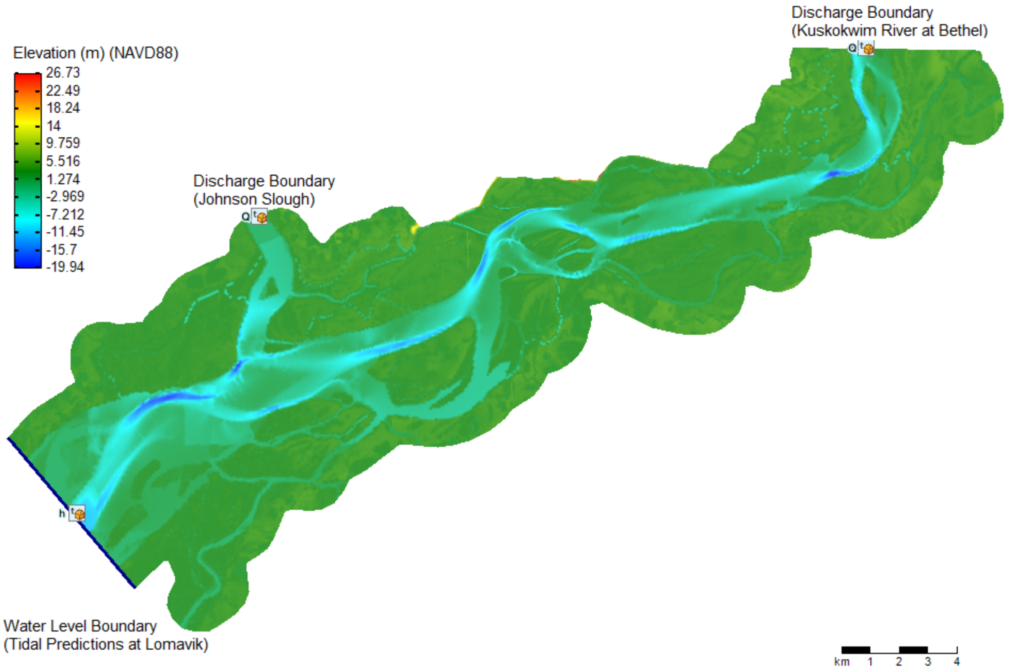

Figure 3: Numerical Model Extents, Elevations, and Boundaries

Hindcast

Two environmental drivers, storm waves and river flow currents (typical and extreme), are selected to represent all environmental forcing that may affect the shoreline. A representative sediment grain size is assumed based on the observations onsite and a corresponding critical bedshear is calculated to estimate the threshold of sediment motion. Three (3) sets of hindcast simulations (see Table 1) are used to analyze the bank retreat patterns and correlate them with the modelled environmental forcing. Hindcast analysis is done in 2-year time intervals 2014-15, 2016-17, and 2018-19. These time intervals are chosen based on data availability. They represent a time period over which wind speed and bank erosion are both higher than the long-term average (Golder 2020a). Each set of hindcast simulations consists of one (1) 6-monthly daily average flow condition, one (1) extreme flow condition corresponding to a 2-year return period flow event, and two (2) typical windstorms (1 Southerly and 1 Easterly) with one downstream water level boundary and two river discharge boundaries. The daily average flow condition is only limited to 6 months between the annual ice break-up and freeze-up dates in the region. The 2-year return period is used to represent the peak flow conditions because it corresponds to a 50% chance of exceedance in any given year and could therefore be used as a reasonable representation of an annual extreme event without overestimating the magnitude of the same. Typical windstorms are modelled along the two dominant fetches near the community and are based on the average duration and wind speed calculated from the historical wind records during the hindcast time intervals being modelled. Excess bed shear values and wave energy from each set of simulations are used to establish a statistical correlation between these factors and the rate of shoreline retreat.

Table 1. Hindcast Simulations

Years Spanned	Type	Primary Environmental Forcing	Model Inputs	Model Outputs
2014-2015 2016-2017 2018-2019	Hindcast	6-Monthly Daily Mean Flows	● DEM (2014, 2016, 2018) ● Mean daily river discharge at Bethel and Johnson Slough ● Tidal elevation predictions at Lomavik (2014, 2016, 2018)	● Mean bed shear ● Flow velocity
2014-2015 2016-2017 2018-2019	Hindcast	2-Year Return Period Extreme Flow	● DEM (2014, 2016, 2018) ● Extreme river discharge corresponding to a 2-year return period at Bethel and Johnson Slough ● Tidal elevation predictions at Lomavik (2014, 2016, 2018)	● Mean bed shear ● Flow velocity
2014-2015 2016-2017 2018-2019	Hindcast	Typical Windstorm (Southerly and Easterly)	● DEM (2014, 2016, 2018) ● Mean freshet river discharge at Bethel and Johnson Slough ● MSL predictions at Lomavik ● Mean wind speed and duration of Southerly and Easterly storms based on wind data at Napakiak airport (2014-15, 2016-17, 2018-19)	● Significant wave height ● Peak period

Statistical Correlation

Annualized rates of bank retreat are estimated for three periods: 2013-2016, 2016-2018, and 2018-2020. These periods approximately align with a series of hindcast model simulations, which are run for the years 2014-2015, 2016-2017, and 2018-2019. Shorelines for 2013, 2016, 2018 and 2020 are digitized from aerial and satellite imagery (see Table 2). A total of 35 approximately shore perpendicular transects are established at 50-meter intervals along the shoreline and centered on the village using the U.S. Geological Survey Digital Shoreline Analysis System (DSAS). The distance between digitized shorelines is measured along the transect for each interval, and the annualized erosion rates are calculated by dividing the distance between shorelines by the time elapsed between images.

Table 2. Imagery used in bank erosion analysis (Golder, 2020a)

Date	Type	Resolution	Source
2013-Jul-12	Orthophoto	15 m (49 ft)	USGS (Landsat 8)
2016-Apr-28	Orthophoto	10 m (33 ft)	USGS (Sentinel-2)
2018-Jun-14	Orthophoto	0.50 m (1.6 ft)	WV02 Imagery, World imagery from ESRI
2020-May-14	Orthophoto	10 m (33 ft)	USGS (Sentinel-2)

Two metrics of erosive energy, total excess shear stress and wave energy over a typical storm event, are selected based on understanding of the processes driving erosion at Napakiak and from spatial patterns of hydrodynamics and erosion near the village. These metrics are summarized in Table 3.

Table 3. Hydrodynamic metrics for erosive energy

Metric	Method of calculation	Rationale
Total excess shear stress (τ_{TOT}) for 6-month normal and peak flow model scenarios	Total cumulative excess shear stress for the model simulation is calculated for each model output point based on flow velocity driven bed shear, and a critical Shields' parameter threshold calculated using an assumed uniform particle size of 0.100 mm. The total cumulative excess shear stress for the 6-month normal and peak flow model scenarios are summed.	Excess shear stress is typically correlated with sediment transport. At Napakiak, sediment transport by river flow carries eroded sediment away from the bank, allowing the thalweg of the river to migrate in step with the shoreline. At Napakiak, the spatial pattern of shear stress makes it an ideal candidate for the statistical relation. Shear stress is highest in the deepest portions of the channel where the channel is more confined, and is negatively correlated with rates of bank erosion because the highest bank erosion rates are located in less confined areas with larger fetch for wave development.
Energy generated by typical storm (E_s) for southerly and easterly storm model scenarios	Wave energy generated during a typical storm is calculated as a product of the energy of a single wave in a random wave spectrum and the estimated number of waves during a typical storm. These calculations are based on the modeled wave heights, wave periods, and estimated storm durations. The wave energy from typical southerly and easterly storms is summed.	At Napakiak, bank retreat is largely driven by wave erosion, with river erosion playing a secondary role. The areas experiencing the highest rates of erosion near Napakiak are adjacent to the village itself, in a relatively open portion of the channel where fetch is high and the largest waves can develop. Wave energy is positively correlated to bank erosion.

A relationship between total excess shear stress (τ_{TOT}), wave energy over a typical storm event (E_s), and bank erosion rate (e) is derived by multiple linear regression using a least-squares approach:

$$e = -7.5\text{x}10^{(-3)}\tau_{TOT} + 2.0\text{x}10^{(-5)}E_s \qquad (1)$$

where e is the bank erosion rate in m/yr, τ_{TOT} represents annual total excess shear stress in Pascals, and E_s represents the sum of wave energies over typical southerly and easterly storm events, in Joules. τ_{TOT} and E_s are determined at each transect for the three hindcast time periods (see Fig. 4). It should be emphasized that this relation is based on site-specific spatial patterns of flow, wave and bank dynamics at Napakiak as well as physics-based relationships between wave energy and erosion. It is not applicable at other locations within the Kuskokwim River or elsewhere. Uncertainty of +/- 5 m/yr is assumed for e based on the amount of scatter in the statistical relation. This uncertainty accounts for error derived from the statistical relation. It does not take into account error associated with model uncertainty or the climate projections, nor does it explicitly account for historical image digitization error. Therefore, the uncertainty should be interpreted as a minimum estimate.

The wave energy results along the shoreline show a direct correlation between wave energy and shoreline retreat along the community, which is consistent with local observations that large waves have caused the most erosion along the shorelines in recent years (Golder 2020a). Depth-averaged flows and associated mean bedshear values show an inverse correlation with the rate of shoreline retreat. Mean bedshear increases in areas upstream and downstream of the community where the thalweg is deeper, which results in a more concentrated flow and faster current speeds. Alongside the community the thalweg is shallower, and the river is wider, which distributes the flow and associated bedshear over a wider area and effectively lowers the bedshear magnitude. However, factors such as variation in vegetation cover and local sediment properties, which also affect bank erosion are unaccounted for in this study due to a lack of availability of relevant vegetation and sediment data in the area. Accounting for impacts of these passive factors may help explain the inverse statistical correlation obtained between the bedshear values and the rate of shoreline retreat.

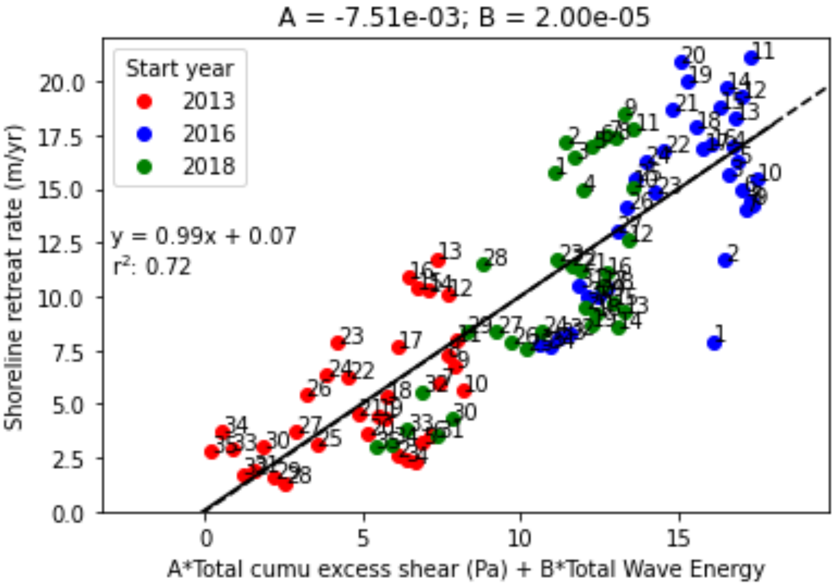

Figure 4: Regression between excess shear stress, wave energy, and bank erosion rate

Forecast

The same two primary drivers are modelled for the future condition using modified river flows, wind, and water level conditions. A similar approach of using an adjusted DEM is used to represent bathymetry at the start of each future interval for the hydrodynamic simulations. The results from these numerical simulations are used along with the previously established statistical correlations derived from the hindcast data to estimate the position of the shoreline in 10-year forecast intervals. This process is repeated with 10-year forecast intervals up to the year 2050. The compounded uncertainties associated with the various forcing factors, simulations and underlying assumptions become too large to make reliable projections beyond this point in time.

This statistical correlation is used to project the shoreline positions for three (3) sets of forecast simulations spanning 2020-29, 2030-39, and 2040-49 (see Table 4). Forecast simulations use the 2020 shoreline as the present-day shoreline position and simulate one (1) 6 monthly daily average flow condition, one (1) extreme flow condition corresponding to a 2-year return period flow event, and two (2) typical windstorms (1 Southerly and 1 Easterly) with one downstream water level boundary and two river discharge boundaries. Climate change driven effects on all the environmental forcings are accounted for in the forecast simulations by adjusting the environmental inputs to reflect the same. The outputs from these simulations are used along with the previously established statistical correlation to project the shoreline positions in the future. This process is repeated for the years 2030-39 and 2040-49.

Table 4. Forecast simulations

Simulation Years	Type	Primary Environmental Forcing	Model Inputs	Model Outputs
2020-2029 2030-2039 2040-2049	Forecast	6-Monthly Daily Mean Flows	● DEM (2020, 2030, 2040) ● Mean daily river discharge at Bethel and Johnson Slough ● Tidal elevation predictions at Lomavik (2020, 2030, 2040) ● Climate projections for sea level rise (Intermediate-high)	● Mean bed shear ● Flow velocity
2020-2029 2030-2039 2040-2049	Forecast	2-Year Return Period Extreme Flow	● DEM (2020, 2030, 2040) ● Extreme river discharge corresponding to a 2-year return period at Bethel and Johnson Slough ● Tidal elevation predictions at Lomavik (2020, 2030, 2040) ● Climate projections for sea level rise (Intermediate-high)	● Mean bed shear ● Flow velocity
2020-2029 2030-2039 2040-2049	Forecast	Typical Windstorm (Southerly and Easterly)	● DEM (2020, 2030, 2040) ● Mean freshet river discharge at Bethel and Johnson Slough ● MSL predictions at Lomavik and climate projections for sea level rise (Intermediate-high) ● Mean wind speed and duration of Southerly and Easterly storms based on wind data at Napakiak airport (2014-2021) ● Climate projections for changes in wind speeds under the RCP8.5 emissions scenario	● Significant wave height ● Peak period

Projected Shoreline Evolution

The predicted rate of retreat at two community locations—the northeast corner of the school and the southeast corner of the airport runway—are presented in Figure 4. Linear shoreline retreat projections made by the DGGS (Buzard et al. 2021) are shown for comparison. Bank retreat at Napakiak has progressed at an approximately linear rate in the past (Buzard et al. 2021), however projections from the present work suggests that the retreat rate could accelerate in the future.

This rate of retreat is approximately twice that predicted by DGGS (Buzard et al. 2021) and is also significantly higher than that of the USACE (USACE, 2009). The reasons for this are twofold:

1. Present study uses a more recent time period (2013-2020) to establish the baseline erosion rate than the DGGS (1952-2019) and USACE (up to 2004). Storm intensity and erosion rates are of greater magnitude during this period than the historical average (Golder 2020a).
2. The present prediction rests on the assumption that bank erosion is currently predominantly driven by wave erosion, and that this relationship will persist into the future. Since wave energy is expected to increase in the future as a result of increasing windspeed, it follows that the erosion rate will accelerate in step.

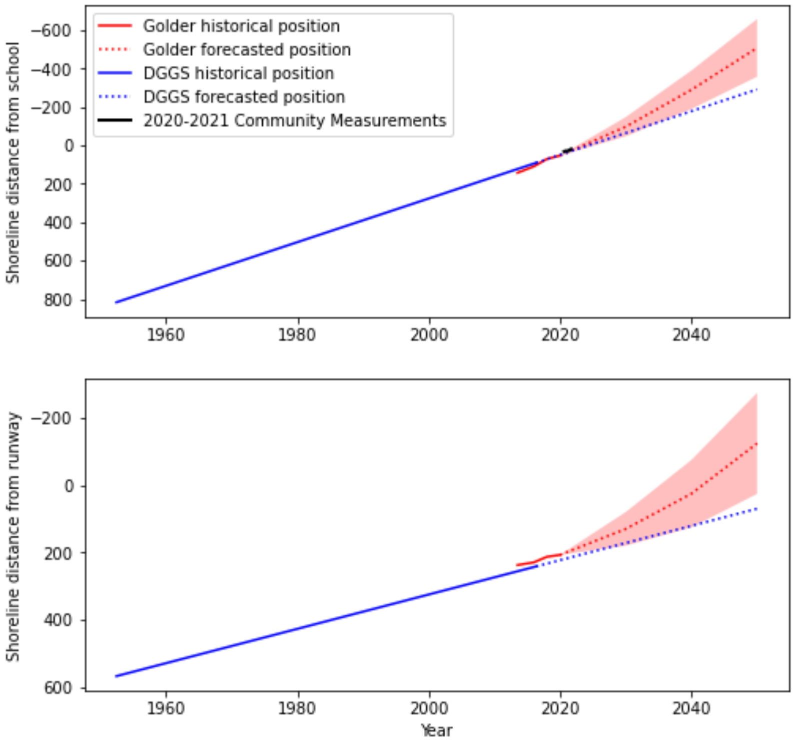

Figure 4: Historical and future projections of distance from shoreline to NE corner of school (top figure) and SE corner of runway (bottom figure).

Based on the forecast banklines for 2030, 2040, and 2050 (see Fig. 5), it is expected that the shoreline will reach the general store and community center by 2030. Much of the eastern end of the village, including the airport, could be at risk by 2040-2050. After that time, it is increasingly difficult to predict the trajectory of shoreline retreat because of the uncertainty in the trajectory of climate change and the increasing likelihood of significant channel morphological change. As the shape of the shoreline at Napakiak continues to evolve, it is possible that the channel thalweg will move to a new position within the Kuskokwim River channel. In addition, erosion and deposition within shoals and bars upstream and downstream of Napakiak may alter channel position in ways that are currently unpredictable.

The bank erosion analysis and shoreline projection presented here is one of several studies conducted at Napakiak. As with the other studies, the results must be viewed within the context of the underlying assumptions of the analysis and the limitations of the methodology. Key points for consideration are:

1. The bank erosion model assumes that erosion at Napakiak is driven primarily by wave energy and that the most recent period of erosion record is relevant to forecasts in the short to medium term. The bank projections are conservative and likely represent a ‘worst case scenario’ that can be expected if rates of bank erosion accelerate beyond those experienced over the past decade.
2. Available morphological, morphodynamic and hydrodynamic data at Napakiak is extremely limited, and the uncertainty associated with parameters in the hybrid morphological model is high. An extensive and long term data collection effort would be necessary to provide a physical basis for morphological modelling and reduce uncertainty in the model simulations.
3. The model does not predict river morphologic change, which may drive a shift in erosion patterns in the future.

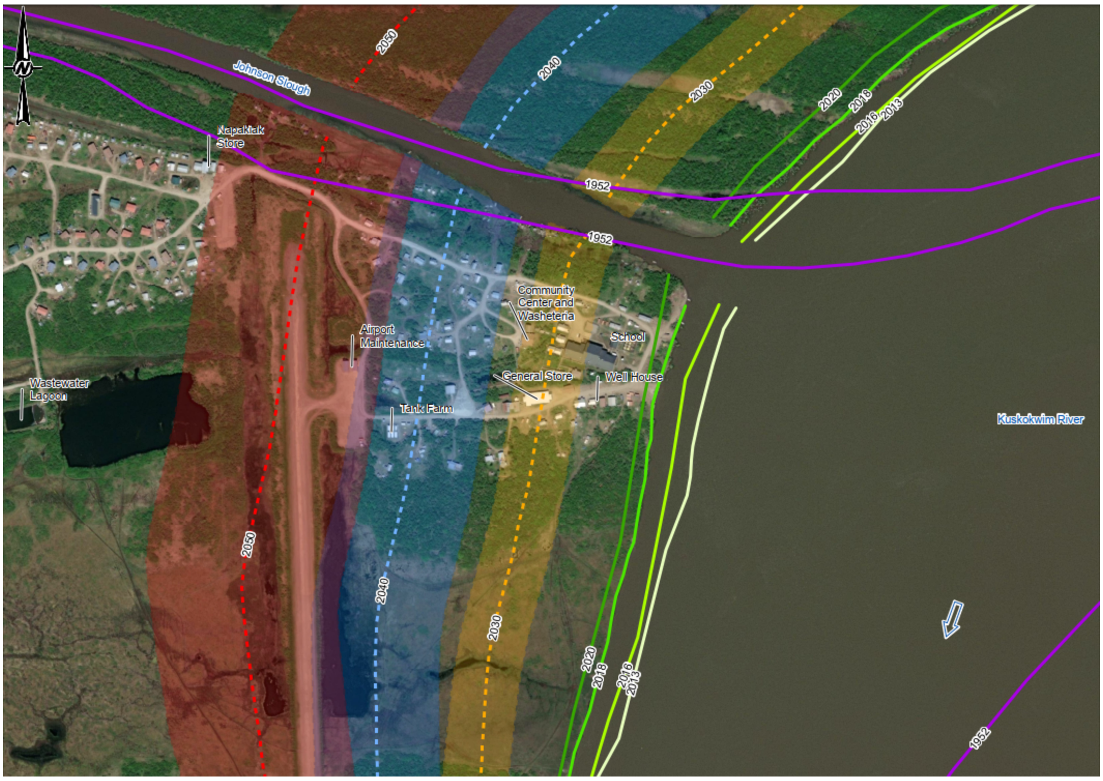

Figure 5: Forecast and hindcast bank lines at Napakiak. Uncertainty bands are shown alongside respective forecast shoreline positions.

ADAPTATION AT SHAKTOOLIK

Background

The village of Shaktoolik is located approximately 125 air miles east of Nome, Alaska on a narrow barrier spit composed of sand and gravel. The barrier spit is bounded by Norton Sound to the west and the Tagoomenik River and Shaktoolik Bay to the east. Shaktoolik Bay is an estuary formed where the Tagoomenik River and Shaktoolik River meet Norton Sound (see Fig. 6).

Historically, the Native Village of Shaktoolik (Community) has been, and continues to be, vulnerable to coastal flooding from both the open coast to the west and the river and estuary behind the barrier spit to the east. Coastal storm surge and wave action is a leading cause of both flooding and erosion in the Norton Sound region of Alaska, and the potential negative consequences of storms may be increasing with changing climatic trends, including the timing and extent of arctic sea ice cover (Douglas, 2010). Coastal erosion and the dynamics of the barrier spit contribute to vulnerability of the Community. Presently, buildings in the Shaktoolik Community are protected by a manmade sand berm on the seaward side of the barrier spit constructed using sand excavated from the distal end of the spit. A recent study (Golder, 2020b) found that the existing sand berm, constructed to provide erosion and flood protection to the Community, is presently vulnerable to erosion during storm events. Significant reshaping of this berm during storms can render the Community vulnerable to flooding from the seaside. It is understood that maintenance occurs regularly after large storm events and the analysis in this study shows that this will be an ongoing effort. Climate Change will cause the storm events resulting in berm erosion to become more frequent and result in increasing maintenance requirements for the berm (Golder, 2020b).

The present study is mainly focused on assessing the performance of various berm upgrade concepts in different extreme events (storms) to evaluate how revised berm geometry and composition might lead to improvements in life cycle performance. This study outlines and summarizes the various berm upgrade concepts and the numerical models that are used to evaluate the resilience of these concepts. The findings from this study will be used by the Community and other stakeholders to select a preferred concept and future progress the design/planning of the upgrades to the protection berm to improve its resilience.

Figure 6: Community of Shaktoolik.

Berm Evolution Model

This study uses the XBeach 2D model for wave propagation, long waves and mean flow, sediment transport and morphological change simulations. The XBeach model couples the flow, wave, sediment, and morphology modules, which enables modelling the wave-current interactions, wave transformations, sediment transport, and resulting morphological changes. The morphodynamic processes include bed load and suspended sediment transport, dune face avalanching, bed level update and breaching. The XBeach numerical model domain extends approximately 0.6 mile (mi) cross shore, 2.2 mi alongshore and covers approximately 1.35 mi^2 of nearshore areas on the seaward side of Shaktoolik.

Qualitative Calibration

The XBeach model is qualitatively calibrated by utilizing information available before and after the extreme weather event that occurred in September 2022 (Typhoon Merbok). Typhoon Merbok significantly reshaped the berm adjoining the Community and caused significant flooding due to storm surge. This event occurred almost immediately following the 2022 seasonal restoration of the berm by the Community. In the absence of site-specific surveyed berm profiles, visual observation data obtained from the Community combined with an understanding of the pre-storm condition from our prior reconnaissance have been used to evaluate the berm response caused by Typhoon Merbok.

The approximate Summer 2022 constructed berm profile is estimated using the topography scans from September 2021 (see Fig. 8), presuming the design profile used for the annual berm reconstruction in both years is the same. Visual examination of post-Merbok photographs of the protection berm and anecdotal information from the Community are used to approximate the post-Merbok berm profile (see Fig. 8).

Wave conditions and water levels during Typhoon Merbok are obtained and applied to the offshore boundary of the XBeach domain. Several simulations with likely combination of factors governing bottom friction, wave skewness, and wave asymmetry are conducted to generate a best estimate of the post-Merbok berm profile in Xbeach (see Fig. 8) such that it aligns with the visual approximation.

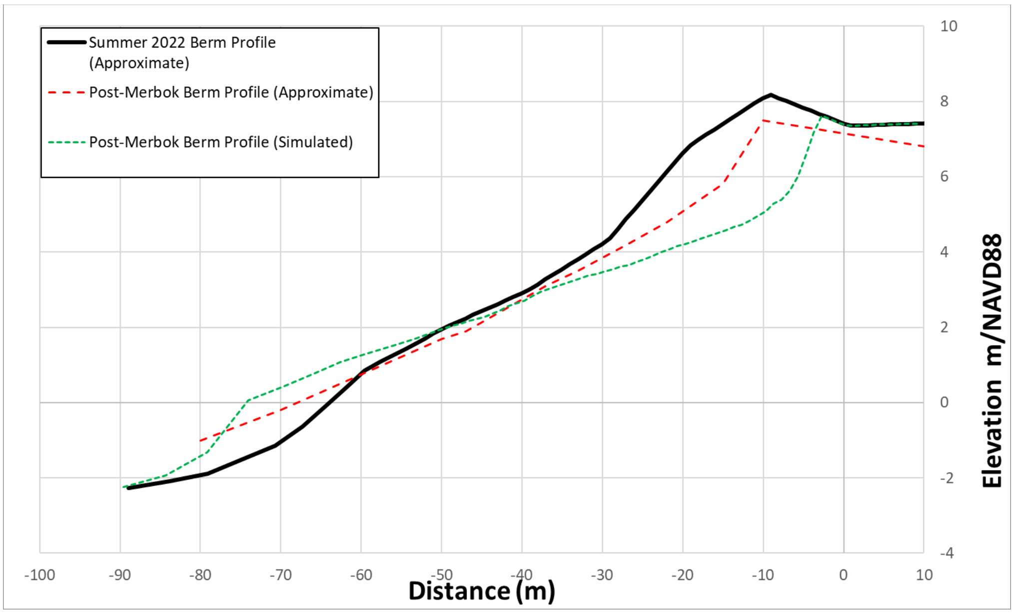

Figure 8: Approximate berm profile from Summer 2022 (Black); Approximate post-Merbok berm profile (Red dashed); Simulated post-Merbok berm profile (Green dashed)

Slopes of the numerically simulated and approximated post-Merbok profiles agree satisfactorily but the simulated profile indicates higher erosion (near the crest) and deposition (near the toe) than the approximated profile.

Berm Concept Evaluation

XBeach and XBeach-G are used to evaluate the responses of the native sand berm and gravel berms constructed with different sediment sizes, respectively. The gravel berm concepts are assumed to have the same profile shape as the existing berm. The environmental conditions at the offshore boundary of the XBeach-G model are given in Table 5.

Table 5. Simulated Nearshore Environmental Conditions

Scenario	Sig. Wave Height [m]	Peak Wave Period (sec)	Return Period of Sig. Wave Height (Yrs)	Water Level [m] NAVD88	Return Period of Water Level (Years)
A	2.7	8	20	2.0	Annual
B	2.8	7	Annual	3.0	Annual+1m Storm Surge
C	3.7	8	20	5.0	15
D	4.4	9	100	6.5	100

Figures 9 to 12 show the responses of native sand (D50 = 0.5-mm) and gravel (D50 = 5-mm, 50-mm, and 75-mm) berms in Scenarios A to D respectively. Larger gravel/cobble sizes (50-mm and 75-mm) show more resilience in all scenarios compared to smaller particle sizes (5-mm) and native sand (0.5-mm). The native sand berm is expected to significantly reshape in Scenarios A and B, and is expected to be completely leveled in Scenarios C and D. Scenarios A and B have lower water levels, which intersect the berm at a gentle slope. Therefore, relative differences in performance of the different gravel sizes are less apparent due to all gravel sizes having steeper equilibrium slopes than the initial berm profile. The 75-mm gravel berm is expected to buildup in Scenarios A and B due to its steep equilibrium slope thereby providing the most resilience out of all the options. The 5-mm gravel berm reshapes significantly in Scenario C, whereas the 50-mm and 75-mm gravel show minor reshaping. The 75-mm gravel berm demonstrates the best resilience in this scenario as well, however the relative difference in performance of the 50-mm berm and the 75-mm berm is not pronounced. The berm profile is expected to be overtopped in Scenario D. This scenario levels the 5-mm berm crest and significantly reshapes the 50-mm and 75-mm berms. The 50-mm and 75-mm berms show some accretion on the landward side of the berm crest, however most of the eroded material is swept away either further back on the profile due to overtopping or by longshore transport.

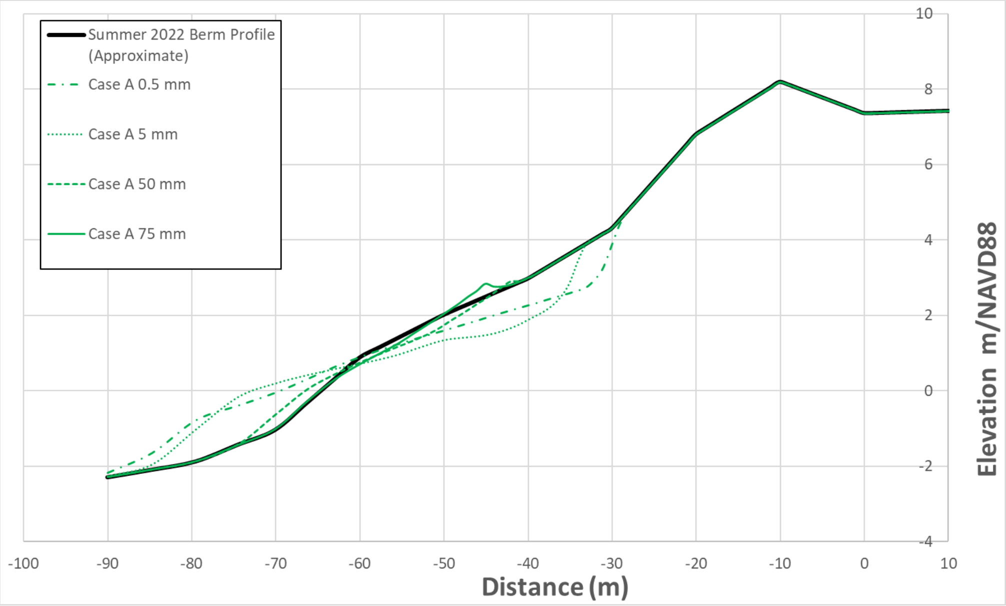

Figure 9: Berm response to scenario A.

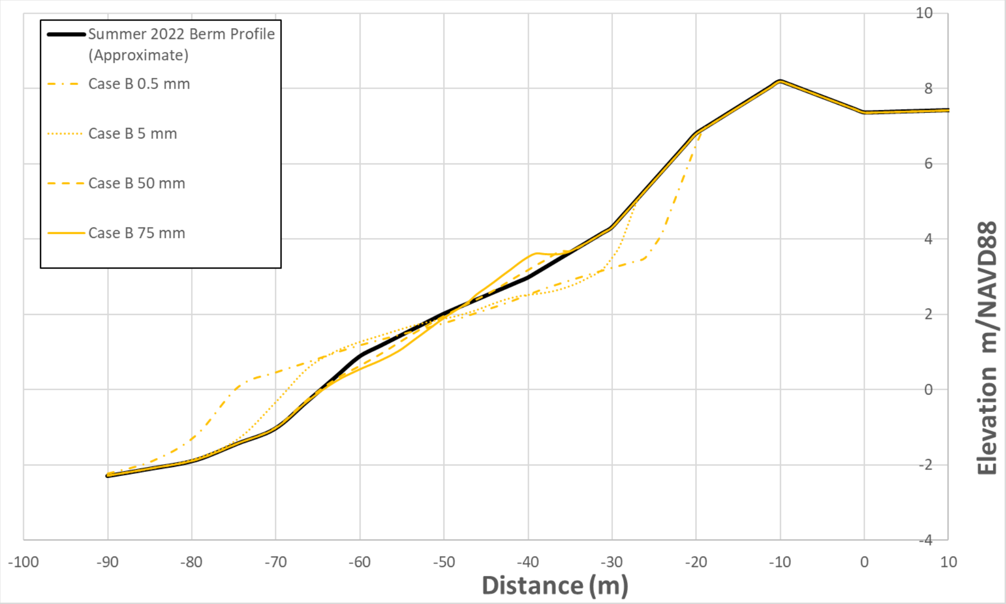

Figure 10: Berm response to scenario B.

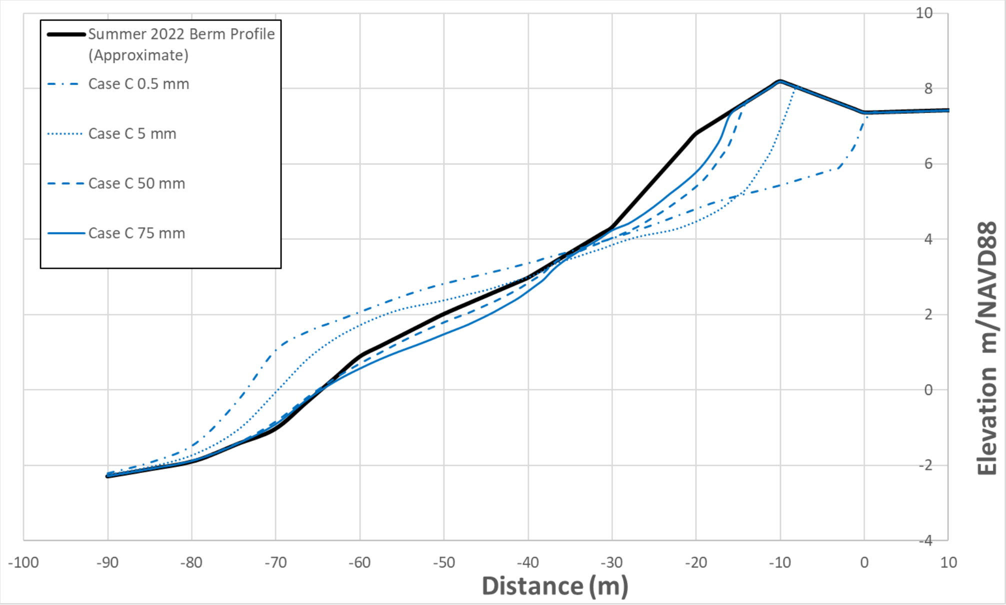

Figure 11: Berm response to scenario C.

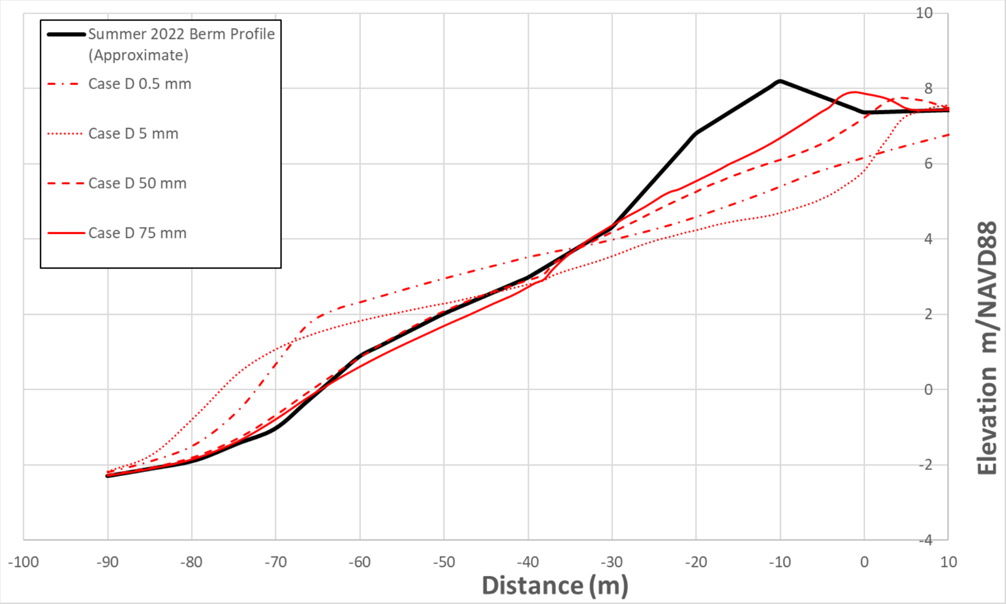

Figure 12: Berm response to scenario D.

A proposed reshaping gravel berm concept (see Fig. 13) is developed based on the results presented above. It is expected that the berm will be gradually reshaped by wave action to an equilibrium/stable profile protecting lower slope.

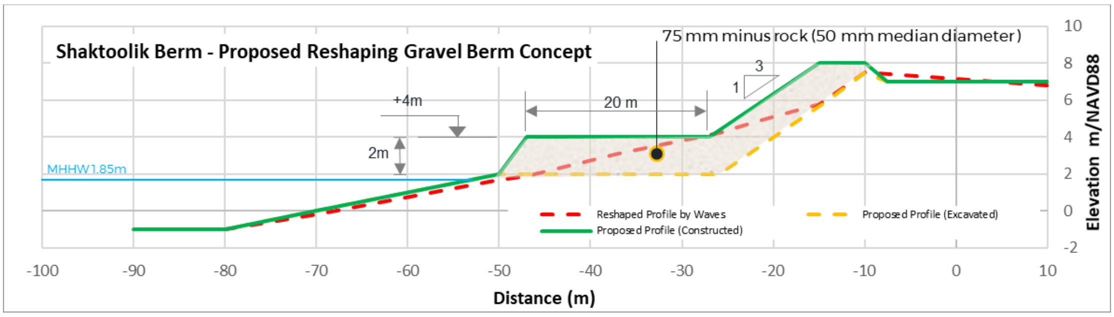

Figure 13: Proposed reshaping gravel berm concept.

SUMMARY

Hybrid numerical models that rely on a combination of hydrodynamics, morphodynamics, statistics, and are informed by Indigenous knowledge are developed to guide the decisions surrounding relocation vs adaptation for remote communities in Alaska. This approach bridges traditional scientific methods and local expertise, enhancing decision-making frameworks for adaptation and relocation.

In Napakiak, the hybrid river morphology model effectively predicted shoreline retreat under future scenarios. Hindcast simulations combined with observed erosion patterns provided a foundation for forecasting shoreline positions for 2030, 2040, and 2050. Findings indicate accelerated bank retreat rates driven by increased wave energy from climate change-induced storm intensification. These insights support updates to the Managed Retreat Plan, offering a transparent methodology adaptable to other regions.

At Shaktoolik, the XBeach modeling framework evaluated berm designs under escalating storm conditions. Analysis highlighted the superior resilience of coarser-grained materials, particularly in extreme scenarios, emphasizing the need for berm compositions that balance efficacy and maintenance. The model's qualitative calibration, incorporating community-derived data, further demonstrated the value of localized engagement.

This work shows that integrating Indigenous knowledge and community participation is essential for contextual relevance and solution acceptance. The hybrid modeling approach exemplifies how multidisciplinary methods can address complex environmental challenges.

REFERENCES

Buzard RM, Turner MM, Miller KY, Antrobus DC, Overbeck JR. 2021. Erosion Exposure Assessment of Infrastructure in Alaska Coastal Communities: Alaska Division of Geological & Geophysical Surveys Report of Investigation 2021-3.https://doi.org/10.14509/30672.

Douglas, D.C., 2010, Arctic sea ice decline—Projected changes in timing and extent of sea ice in the Bering and Chukchi seas: U.S. Geological Survey Open-File Report 2010-1176, 32 p., http://pubs.usgs.gov/of/2010/1176/

Golder Associates, Inc. 2020a. Napakiak Managed Retreat Project, Phase 1—Kuskokwim River Morphology Study. Report submitted to Summit Consulting Services, Inc. 18 December 2020. Report No. 20141907-001-R-Rev0.

Golder, 2020b, Climate Change Vulnerability and Risk Assessment Report for Shaktoolik. Reference No. 19115518-001-R-Rev1

Overbeck JR, Buzard RM, Turner MM, Miller KY, Glenn RJ. 2020. Shoreline change at Alaska coastal communities: Alaska Division of Geological & Geophysical Surveys Report of Investigation 2020-10, 29 p., 47 sheets.

Summit Consulting Services, Inc. 2020. Napakiak Managed Retreat Plan. Report submitted to the City of Napakiak, 25 September 2020.

U.S. Army Corps of Engineers (USACE). 2009. Alaska Baseline Erosion Assessment, Study Findings and Technical Report, Elmendorf Air Force Base, Alaska.