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Alaska Climate Trend Vulnerability Study

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16. Abstract

This report presents the findings of a study that examined three transportation projects in Alaska for potential vulnerability to climate change and extreme weather events. The study was initiated jointly by the Alaska Department of Transportation and Public Facilities (AKDOT&PF) and the United States Federal Land Management Agencies (FLMAs) through a grant provided by the Federal Highway Administration (FHWA). The focus of the study was to better understand changing climate conditions in Alaska and how this understanding could potentially lead to more informed decisions on transportation asset investments, both capital investment and operation/maintenance decisions. The three case studies included an examination of roadway exposure to permafrost thaw, airport runway exposure to sea level rise and changing wind and sea ice patterns, and slope instability related to permafrost thaw and more intense precipitation. An eleven-step process developed by FHWA for engineering vulnerability assessment was used to develop the findings for each case study.

The study found that future efforts to incorporate changing climate conditions into engineering decision-making will require a coordinated effort among federal agencies, state agencies, and academic or research institutions that focus on climate forecasts. The data produced by these agencies is often not specific to a project site and thus some effort is needed to translate the more aggregate forecasts to site-specific data. In particular, defining longer term climate change exposure in Alaska would benefit from more data on transportation assets including information on surrounding environmental conditions (e.g. permafrost measurement), site conditions (e.g. elevations), construction assumptions/methods, and any noted maintenance records that focus on environment-related problems. The application of the eleven-step process is outside of normal engineering practice and requires significant commitment and coordination for successful application as it is a new process requiring the development of information not currently prepared for other engineering projects. Shifting to a more risk-based decision-making framework will help facilitate this process moving forward. The case studies also showed that relatively low cost options can be viable strategies for dealing with climate change-related vulnerabilities. Importantly, the process of developing input data requires significant coordination between climate scientists and engineers.

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Alaska Climate Trend Vulnerability Study

Alaska Department of Transportation and Public Facilities
United States Bureau of Land Management
National Park Service
United States Fish and Wildlife Service
United States Forest Service

July, 2016

This report was developed by the FHWA-Western Federal Lands Division, through close coordination with the Alaska Department of Transportation and Public Facilities and the US Federal Lands Management Agencies. This effort also included input from participants at the University of Alaska at Fairbanks. The statements, findings, conclusions and recommendations are those of the author(s) and do not necessarily reflect the views of FHWA or the U.S. Department of Transportation.

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EXECUTIVE SUMMARY

The Alaska Vulnerability Assessment Pilot project was initiated jointly by the Alaska Department of Transportation and Public Facilities (AKDOT&PF) and United States Federal Land Management Agencies (FLMAs) through a grant provided by the Federal Highway Administration (FHWA). The project was a part of a larger national initiative of 19 pilot projects sponsored by the Federal Highway Administration (FHWA) to conduct climate change and extreme weather vulnerability assessments of transportation infrastructure and to analyze options for adapting and improving resiliency. The focus of the Alaska project was to better understand changing climate conditions in Alaska and how this understanding could potentially lead to more informed decisions on transportation asset investments (capital and operation/maintenance).

The challenge for Alaska transportation officials is to define possible future scenarios of climate change, determine the relative magnitude of a change that will affect the design and operations of infrastructure, and determine how today's decisions on design could have longer term implications on damage and maintenance costs over the lifetime of an asset. The changing nature of Alaska's climate might also accelerate in coming decades, thus reinforcing the need to examine and apply appropriate strategies to reduce risk to the transportation system. This is the focus of the study—how to make design and maintenance/operations decisions given observed uncertainties and/or expected changes in the future due to warming conditions statewide.

Historical records suggest that Alaska is already facing dramatically changing climatic conditions. The state has warmed twice as fast as the rest of the nation. This has resulted in sea ice receding, thawing glaciers and permafrost, and increased wildfire occurrence. Over the past 30 years, Alaska has experienced a reduction in snow-cover extent and duration, shorter river- and lake-ice seasons, melting of mountain glaciers, sea-ice retreat and thinning, and permafrost thaw. Over the past 50 years, average precipitation levels in the state have increased 10%, with the greatest increases occurring in the winter in western, southern, and southeastern Alaska. However, the Arctic regions and far southeast Alaska saw significant decreases in precipitation, and summer precipitation has decreased or remained near long-term averages in most of the state. Extreme precipitation (the heaviest one percent of three-day precipitation totals for each calendar season) experienced a statistically significant decrease in the Arctic in all seasons except for fall; all other regions saw an increase in extreme precipitation during summer months.

Climate projections for Alaska indicate that many of the challenges the state is facing now will only become worse in the future. This is especially true with the melting of the permafrost, which impacts the foundation conditions of roads and bridges, in particular. Along the coasts, transportation infrastructure that is located in areas subject to large storm surge due to more extreme weather events will also be particularly vulnerable.

An eleven-step process, developed by the U.S. Department of Transportation (USDOT) to consider climate change at the project level, was used to assess the vulnerability of three transportation projects. The first case study examines the potential impacts of thawing permafrost on paving decisions on the Dalton Highway, a major north-south highway in Alaska. The second case study looks at the increased risk of storm damage at an airport in the Native Alaska village of Kivalina due to diminishing sea ice. The third case study assesses the landslide risk along Denali Park Road in Denali National Park at a site of a recent slide and the potential for increased risk associated with thawing permafrost and increased precipitation in the area. These case studies were chosen because they represent the types of challenges facing infrastructure agencies in Alaska as climate changes.

Roadway Exposure to Permafrost Thaw, Dalton Highway's (Alaska 11) "Nine Mile Hill" (Mileposts Nine to Eleven)

The 414-mile long Dalton Highway (Alaska State Route 11) is a critical lifeline connecting Alaska's North Slope oil fields to the rest of the state. Miles 9 through 11 of the highway, the focus in this case study, are located on the southern portion of the highway. Most of the soils in the project area are extremely ice rich and would be expected to have excessive settlement upon thawing. There are also significant ice wedges interspersed within the general permafrost matrix. This case study was originally intended to develop and implement a methodology to determine the long-term effects of climate change on the Dalton Highway by quantifying the amount of settlement to be expected from thawing permafrost. The case study was modified when it was decided to conduct a more specific assessment of potential changes using permafrost thaw modeling. This change recognized that many factors impact thawing, which might not be captured with more generalized assessment methods. Given that this project has been included in a FHWA-sponsored Transportation Engineering Approaches to Climate Resiliency (TEACR) study, it was decided to rely on the FHWA project to produce specific conclusions on roadway exposure to permafrost thaw.

Airport Runway Exposure to Sea Level Rise and Changing Wind and Sea Ice Patterns—Kivalina Airport

Coastal shore protection is an important and sometimes underappreciated component of adjacent highways, airports, ports, etc., infrastructure that can be highly sensitive to climate change based on its proximity to the coastline and associated floodplain. The coastal airport of Kivalina Airport located in northern Alaska on the Chukchi Sea was used as a case study to determine whether projected changes in wind, sea ice, and sea level rise associated with climate change will pose a shoreline erosion risk to the facility and, if so, to develop and evaluate a representative adaptation option for managing that risk. Erosion impacts to the airport under climate change were modeled using a cross-shore sediment transport model, which calculated the erosion distance and volume of material lost under storm conditions. Various other analysis tools were used to model wind, sea level rise and storm surge. A benefit cost analysis was conducted that examined various options of protecting the airport runways from inundation. The most cost-effective alternative, under a single storm event, is to pursue the baseline option of periodic beach repairs.

Slope Instability Related to Permafrost Thaw and More Intense Precipitation—The Igloo Creek Landslide

This case study assessed the cost effectiveness of adaptation strategies to deal with possible future ground movements in the vicinity of a past landslide near Igloo Creek; ground movements that could be exacerbated by climate change induced permafrost thaw and precipitation intensification. The landslide site is located within the foothills north of the Alaska Mountains in Denali National Park, and is part of the sub-arctic continental (Interior) climactic zone. The case study developed several plausible scenarios that bound the range of likely future slide movements. Plausible landslide events ranged in size from minor raveling and shallow sloughs (10 cubic yards of earth movement) to an event of 50,000 cubic yards of earth movement, nearly twice the size of the past event. Four adaptation strategies ranging from revegetating the slope to building a hardened structure were considered in a benefit cost analysis. The only adaptation strategy that produced a positive net present value and consistently high benefit-cost ratios was the revegetation option.

Three major categories of lessons learned are provided in the conclusions section—data application, case study approach, and policy decisions.

Data Application

- The database used for downscaled climate data, the Scenarios Network for Alaska + Arctic Planning (SNAP), was a valuable data source for use in engineering applications that incorporate future climate trends or changes. The development of a data agreement between SNAP and AKDOT&PF and FLMA agencies would be appropriate for future efforts.

- Future efforts to incorporate changing climate conditions into engineering decision-making will require a coordinated effort between federal agencies, state agencies, and academic or research institutions that focus on climate forecasts. The data generated by these institutions is often not specific to a project site and thus some effort will be needed to translate the more aggregate forecasts to site-specific data.

- The process of developing input data requires significant coordination between climate scientists and engineers. A defined and refined process for projects that require such coordination should be developed to keep future projects from becoming extensive research efforts.

- The effort to define longer term climate change exposure in Alaska would benefit from more data on transportation assets including information on surrounding environmental conditions (e.g. permafrost measurement), site conditions (e.g. elevations), construction assumptions/ methods, and any noted maintenance records that focus on environment-related problems.

Case Study Approach

- The engineering approach applied in the case studies takes into account the dynamic changes to conditions currently observed and projected into the future. The analysis of costs and benefits over time helps facilitate the selection of the best solution. This approach, while based on a number of assumptions, is a method that could be employed to assess planning and design projects and allows for information to be presented to stakeholders or interested parties interested in understanding how final policy decisions are determined.

- The eleven-step process is outside of normal engineering practice and requires significant commitment and coordination for successful application. It is a new process requiring the development of information not currently used in other engineering projects.

- Engineering practitioners who traditionally base their decisions on statistically derived historic data are often hesitant to move away from such data. Shifting to a more risk-based decision-making framework will help facilitate this process moving forward.

Policy Decisions

- Because Alaska is so sparsely populated, the benefits of adapting transportation infrastructure to future climate change-related risks, which are primarily measures of movement (people and freight), will not be a large part of the calculation. Traditional benefit-cost assessments may need to consider broader factors of concern to reflect appropriate response measures.

- The case studies yielded recommendations that were relatively low cost, contrary to most perceptions about incorporating future change into project decision-making. It has been an instructive exercise in assessing the range of costs and other implications of a warming climate on project decision processes.

- The state of Alaska has developed a long range transportation plan that identifies the need to incorporate changing climate conditions as a part of its investment strategy. While FLMA agencies have also completed a multi-agency long range transportation plan that includes climate change as a goal, a similar policy regarding investment strategies should be considered for the FLMA plan. The risk-based engineering approach defined and applied in this study could be carried forward as agency policy on future project efforts statewide.

1. Project Introduction

Introduction

The Alaska Vulnerability Assessment Pilot project was initiated jointly by the Alaska Department of Transportation and Public Facilities (AKDOT&PF) and United States Federal Land Management Agencies (FLMAs)[1] through a grant provided by the Federal Highway Administration (FHWA). The project was a part of a larger national initiative of 19 pilot projects sponsored by the Federal Highway Administration (FHWA), "to pilot approaches to conduct climate change and extreme weather vulnerability assessments of transportation infrastructure and to analyze options for adapting and improving resiliency."[2] The focus of the Alaska project was to better understand changing climate conditions in Alaska and how this understanding could potentially lead to more informed decisions on transportation asset investments (capital and operation/maintenance). The project was managed by the Western Federal Lands Division of the FHWA (WFL), with management input provided by representatives from the University of Alaska at Fairbanks (UAF), AKDOT&PF, and FLMAs at major project milestones.

The project was originally conceived as a system-wide vulnerability study to determine those assets that might be at higher risk given climate trends. However, the expansiveness of the state and the relative lack of information on both environmental hazards and asset data specific led to a change in focus of the approach. The other contributing factor to changing the approach was the fairly extensive anecdotal information from various agency leaders on the conditions being faced and associated impacts. These included changing precipitation patterns, permafrost[3] thaw, sea ice melting, and other conditions associated with warming that were impacting infrastructure throughout the state. In some cases, conditions were already changing rapidly, resulting in unforeseen impacts and necessitating climate-informed decision-making.

Alaska is one of the first states affected by a changing climate, mostly from warming seas and melting permafrost. The agencies charged with building and maintaining infrastructure systems have developed processes that recognize this reality. For example, Dalton Highway in northern Alaska, a gravel and dirt highway connecting Fairbanks and Prudhoe Bay, is the primary freight connection serving the North Slope. Maintenance crews work year round to keep the road clear of snow and ice during the winter months, to repair the damage caused by water flow during spring thaw, and to keep the surface relatively smooth in summer months. The maintenance required in summer months is partially an effect of impacts from heavy truck usage combined with shifting soils from thawing permafrost, which is the foundation for much of the roadway. The maintenance response to these conditions is to have teams constantly responding to the problems caused by changing environmental conditions.

Changing conditions and associated decision-making is not an unknown in Alaska; Alaska officials accept a perspective that change and managing the response to that change is a part of their regular activities.

Alaska thus has a head start in the type of thinking needed to address the implications of changing climate conditions.

The challenge for Alaska transportation officials is to define possible future scenarios of climate change, determine the relative magnitude of a change that will affect the design and operations of infrastructure, and determine how today's decisions on design could have longer term implications on damage and maintenance costs over the lifetime of an asset. The changing nature of Alaska's climate might also accelerate

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[1] The FLMAs are comprised of the United States Forest Service, the United States Fish and Wildlife Service, the Bureau of Land Management, and the National Park Service

[2] FHWA 2015

[3] Permafrost is defined as soil that is below 32 degrees Fahrenheit for at least two years

in coming decades, thus reinforcing the need to examine and apply appropriate strategies to reduce risk to the transportation system. This is the focus of the project—how to make design and maintenance/operations decisions given observed uncertainties and/or expected changes in the future due to warming conditions statewide.

The report starts by describing Alaska's transportation system followed by a discussion of the changing climate conditions over the past few decades and forecasts of future conditions. The report then presents three case studies that are representative of the challenges facing Alaska infrastructure agencies as they consider changing climate conditions in transportation system decision-making. The case studies include:

- An analysis of the potential impacts of thawing permafrost along Dalton Highway and how this thawing could affect decisions on paving the roadway
- An analysis of the increased risk of storm damage at an airport in the Native Alaskan village of Kivalina due to diminishing sea ice, which has historically protected the coastline when autumn coastal storms are present in the Chukchi Sea north of the Bering Strait
- An analysis of the landslide risk along Denali Park Road in Denali National Park at a site of a recent slide and the potential for increased risk associated with thawing permafrost and increased precipitation in the area

Each of these case studies presents a methodology for applying climate data derived from a range of sources, combined with academic or other agency research, to identify potential future scenarios of climate-related stressors that may affect the facilities in coming decades. These studies are thus forward-focused in how they approach project decisions, combining research and engineering best practices to determine an engineering response to challenges faced today while considering potential future events to ensure that those decisions reflect likely future conditions. The case studies apply engineering design approaches to the target asset; however, this effort is hypothetical in a sense that there is no commitment to actually build the project. The design approach is offered as something to consider for future engineering efforts on similar projects across the state. In particular, the approach for developing projections of future climate provides lessons for similar projects in the future.

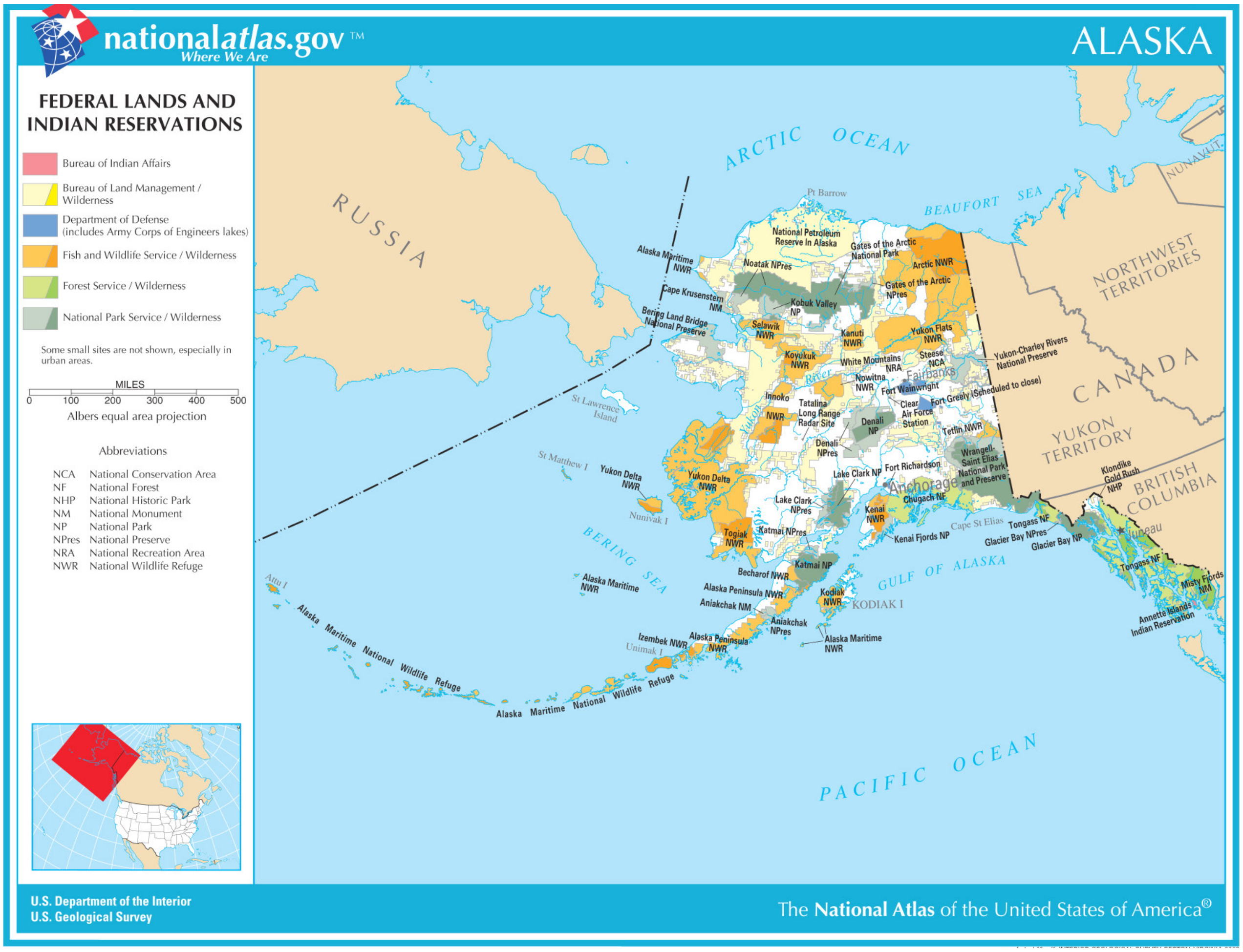
Special note needs to be given to the Dalton Highway case study. The study was originally intended to develop and implement a methodology to determine the long-term effects of climate change on Dalton Highway by quantifying the amount of settlement to be expected from thawing permafrost. Several approaches were used to conduct this assessment but it was decided that an on-going Federal Highway Administration (FHWA) study on risk-based design processes that was also examining Dalton Highway was better able to conduct the assessment given expanded project resources available to complete the permafrost thaw / settlement assessment. Efforts on this study should be considered preliminary at best as the complexity of defining changing conditions underground, in a very remote area, and with limited available data and large potential uncertainties identified primarily that additional work needed to be done to draw conclusions. Thus, the case study description in this report describes the steps taken to reach a point where the FHWA study could continue the analysis.

The 11-step process used on this project was originally developed by FHWA. The process is described later in the report, but it is important to recognize that FHWA identified a need for a design approach that incorporated combined practices with the uncertainty of future climate projections. This process was identified as a step-by-step guide on how to consider future vulnerabilities as part of engineering design.

Project Context

Alaska is a large state of great beauty. It attracts people from all over the world to its famous national parks and other natural scenic vistas. Three urban areas and a series of smaller communities are connected by a transportation network comprised of roadways, railroads, airports, and port facilities. The state is approximately 570,000 square miles in size and has a population estimated at around 738,000, or 1.3 people per square mile.[4] For comparison, the US average density is 87.4 people per square mile, highlighting the remoteness of much of the state. Alaska is also the state with the highest amount of federally owned land, with 62% managed by FLMA agencies or the Department of Defense.[5] Figure 1 identifies federal land ownership in Alaska.

Figure 1: Federal Land Ownership in Alaska[6]



Alaska's transportation network is focused on serving its urbanized areas and providing access to the state's abundant natural resources. The city of Anchorage, on the southern coast, has a population estimated at around 300,000 people, with Juneau and Fairbanks having populations of around 35,000.[7] A large number of smaller cities and towns make up the other half of the state's population. Many of the smaller towns are accessible by road, while others are accessible only by air. Figure 2 shows major communities in the state

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[4] USCB 2016a

[5] Vincent, Hanson, and Bjelopera 2014

[6] Image source: United States Geological Survey, National Atlas

[7] USCB 2016b

and the connectivity provided by the highway system which is primarily focused on connecting Anchorage and Fairbanks to Prudhoe Bay and with Canada to the east. Outside of the main urban areas, there is little to no redundancy in the highway network and any disruption to this network often requires long detours. There are also many communities that rely solely on their airports to provide materials needed for daily commerce, access to medical services, and supplies.

The state transportation system serves different user markets—serving commute travel in urban areas, providing for freight movement throughout the state, connecting remote villages to one another and to subsistence areas, and supporting access to FLMA lands for tourism. As noted above, the transportation system provides lifelines to many remote communities. To meet these needs, AKDOT&PF and FLMA agencies work to ensure that various transportation needs are met, safely and effectively. AKDOT&PF is committed to maintaining transportation access to every community in the state, including having the responsibility of ensuring remote airfields remain viable, while the FLMAs are committed to maintaining appropriate access to and through federally managed public lands.

Figure 2: Statewide Map of Alaska[8]

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[8] Image source: Nations Online Project

2. Current and Future Climate

Current and Future Climate

Alaska covers a vast land area with a wide range of climates. This chapter begins by providing an overview of Alaska's current climate. It then discusses some of the changes observed in recent years and projections for the future.

Alaska's Diverse Climate Regions

As noted by Shulski and Wendler, Alaska can be classified into five general climate regions (see Figure 3).

Figure 3: Alaska's Climate Regions[9]

- *Maritime*—the southeast, south coast and southwestern islands experience a maritime climate with high precipitation and moderate temperatures, including the State's highest annual average temperature and highest precipitation amounts (Western Maritime and Eastern Maritime Regions, respectively).

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[9] Image source: Alaska Humanities Forum

- *West Coast*—seasonal distribution of sea ice (typically in place along the coast by late fall and in place until late spring) plays a major role in the regional climate of west-central Alaska, which experiences a maritime influence until sea ice forms; this leaves the West Coast with a more continental-like climate.

- *South Central*—this area is a transitional zone between maritime and continental climates; although largely isolated from maritime influence by mountain ranges, this area experiences moderate temperatures in comparison to the continental interior climate.

- *Interior*—bordered by the Brooks and Alaska Ranges this area experiences a truly continental climate with large annual variability in temperature, low humidity, and relatively light precipitation; summers are warm and sunny whereas winters are long and cold with regular low-level temperature inversions, which are caused by radiational cooling at the surface.

- *Arctic*—the area north of the Brooks Range and bordered by the Arctic Sea experiences the lowest annual average temperatures; coastal regions are impacted by the moderating effect of sea ice. Along the coast summers are cool and cloudy while inland temperatures are more continental (warmer summers and cooler winters). In the winter blizzard conditions are common. Precipitation is relatively light but frequently underreported."[10]

The climate regions shown in Figure 3 have a strong influence on permafrost coverage. Figure 4, shows current permafrost coverage throughout the state: a pattern strongly related to temperatures.

Recent Trends

Alaska has been experiencing changes in climate in the recent past. According to the United States Global Change Research Program's (USGCRP) National Climate Assessment, some of the key changes include:[11]

- The state has warmed twice as fast as the rest of the nation. This has resulted in sea ice receding, thawing glaciers and permafrost, and increased wildfire occurrence. Indeed, many other studies have confirmed that Alaska is one of the first states in the nation to experience the impacts of several different climate stressors.[12]

- Sea levels are rising in some locations, but relative sea level is falling in others due to tectonic plate movements and glacial rebound as glaciers melt (and weight is removed) from the land surface.

- Over the past 30 years, Alaska has experienced a reduction in snow-cover extent and duration, shorter river- and lake-ice seasons, melting of mountain glaciers, sea-ice retreat and thinning, and permafrost thaw;

- Over the past 50 years, average precipitation levels in the state have increased 10%, with the greatest increases occurring in the winter in western, southern, and southeastern Alaska. However, the Arctic regions and far southeast Alaska saw significant decreases in precipitation, and summer precipitation has decreased or remained near long-term averages in most of the state.

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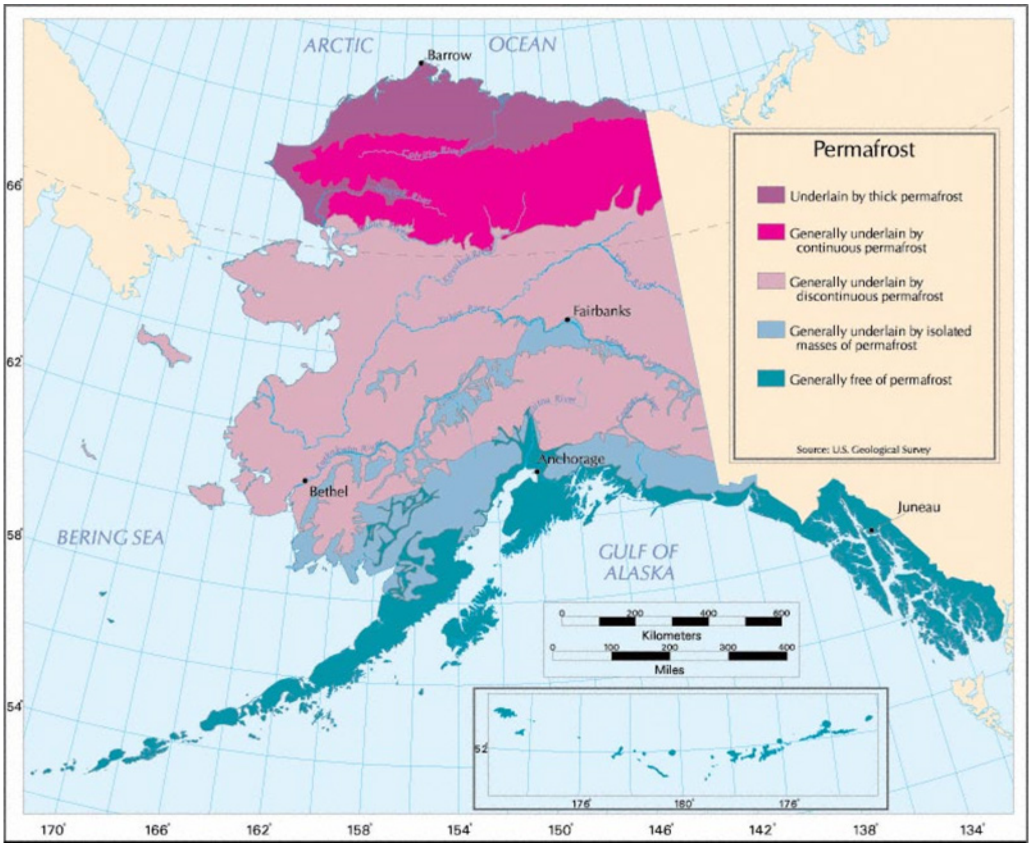
[10] Shulski and Wendler 2009

[11] USGCRP 2014

[12] Bliss, Hock, and Radić 2014; Karl, Melillo, and Peterson 2009; Lee, MacArthur, Mote, Ideker, and Figliozzi 2012; Markon, Trainor and Chapin 2012; Shulski and Wendler 2007; Smith and Carter 2011.; Stafford, Wendler, and Curtis 2000; and Stewart 2011

- Extreme precipitation (the heaviest one percent of three-day precipitation totals for each calendar season) experienced a statistically significant decrease in the Arctic in all seasons except for fall; all other regions saw an increase in extreme precipitation during summer months.

Figure 4: Alaska's Permafrost Regions[13]



Climate Projections

Climate projections have been made for Alaska by many different research groups. In each case, the studies have used an ensemble of general circulation models (GCMs). These models are used to simulate the atmospheric, oceanic, and land processes (and their interrelationships) that affect climate across the globe. Multiple models have been developed by different research groups and are guided by Intergovernmental Panel on Climate Change (IPCC)-specified parameters. GCMs divide the world into grid boxes that can be dozens of miles across. At each simulated point in time in each grid box, estimated levels of temperature, precipitation, and other climate variables are calculated based on the IPCC greenhouse gas emission scenarios that are assumed. Climate projections will therefore be influenced by the specific GCMs that are used for the forecasts and the selected IPCC emission scenarios. It should be noted that the most recent IPCC Fifth Assessment Report, published in 2014, is based on a set of scenarios called "Representative Concentration Pathways" (RCPs). The RCPs lay out different rates of greenhouse gas emissions over time. The scenarios used for the case studies in this report include RCP 4.5, RCP 6.0 and RCP 8.5 (listed in order of increasing greenhouse gas emissions).

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[13] Image source: National Snow & Ice Data Center

The Scenarios Network for Alaska Planning (SNAP) at the University of Alaska Fairbanks has developed regional climate projections by downscaling (to 1.2 mile resolution) five global climate models from the

IPCC (using the RCP scenarios). SNAP climate models relied on data from models that performed most accurately in Alaska and the Arctic based on historic climate data. Downscaled projections are provided for each of the five models selected, and for the average of the five models. SNAP climate projection summaries can be provided by regions within the state through 2099. Except where otherwise noted, the following information is provided from the SNAP program.

TEMPERATURE

Over the past 60 years, Alaska has warmed more than twice as rapidly as the rest of the United States, with state-wide average annual air temperature increasing by three degrees Fahrenheit and average winter temperature by six degrees Fahrenheit, with substantial year-to-year and regional variability.[14] The general effect of this overall warming has been more extremely hot days and fewer extremely cold days. According to the U.S. National Climate Assessment, "average annual temperatures in Alaska are projected to rise by an additional two to four degrees Fahrenheit by 2050 [Coupled Model Intercomparison Project Three [CMIP3], Scenario B1[15]]. If global emissions continue to increase during this century, temperatures can be expected to rise ten to twelve degrees Fahrenheit in the north, eight to ten degrees Fahrenheit in the interior, and six to eight degrees Fahrenheit in the rest of the state [by 2100, CMIP 3, Scenarios A2 and B1]. Even with substantial emissions reductions, Alaska is projected to warm by six to eight degrees Fahrenheit in the north and four to six degrees Fahrenheit in the rest of the state by the end of the century [CMIP 3, Scenarios A2 and B1]."[16] Figure 5 shows the projected number of days above freezing for the month of January in four Alaska cities (chosen because they are in different climate regions as shown Figure 3). As can be seen, the number of "warmer" days in all four cities in the middle of winter is projected to increase dramatically over the next several decades.

The implications for infrastructure of this significant warming trend are primarily in the melting of permafrost. Permafrost near the Alaskan Arctic coast has warmed four to five degrees Fahrenheit at 65 foot depths since the late 1970s and six to eight degrees Fahrenheit at 3.3 foot depths since the mid-1980s. In Alaska, 80% of land is underlain by permafrost, and of this, more than 70% is vulnerable to subsidence upon thawing because of ice content that is either variable, moderate, or high.17 Not only does this create challenges in providing a firm foundation for roads and bridges, but it also increases the risk of landslides.

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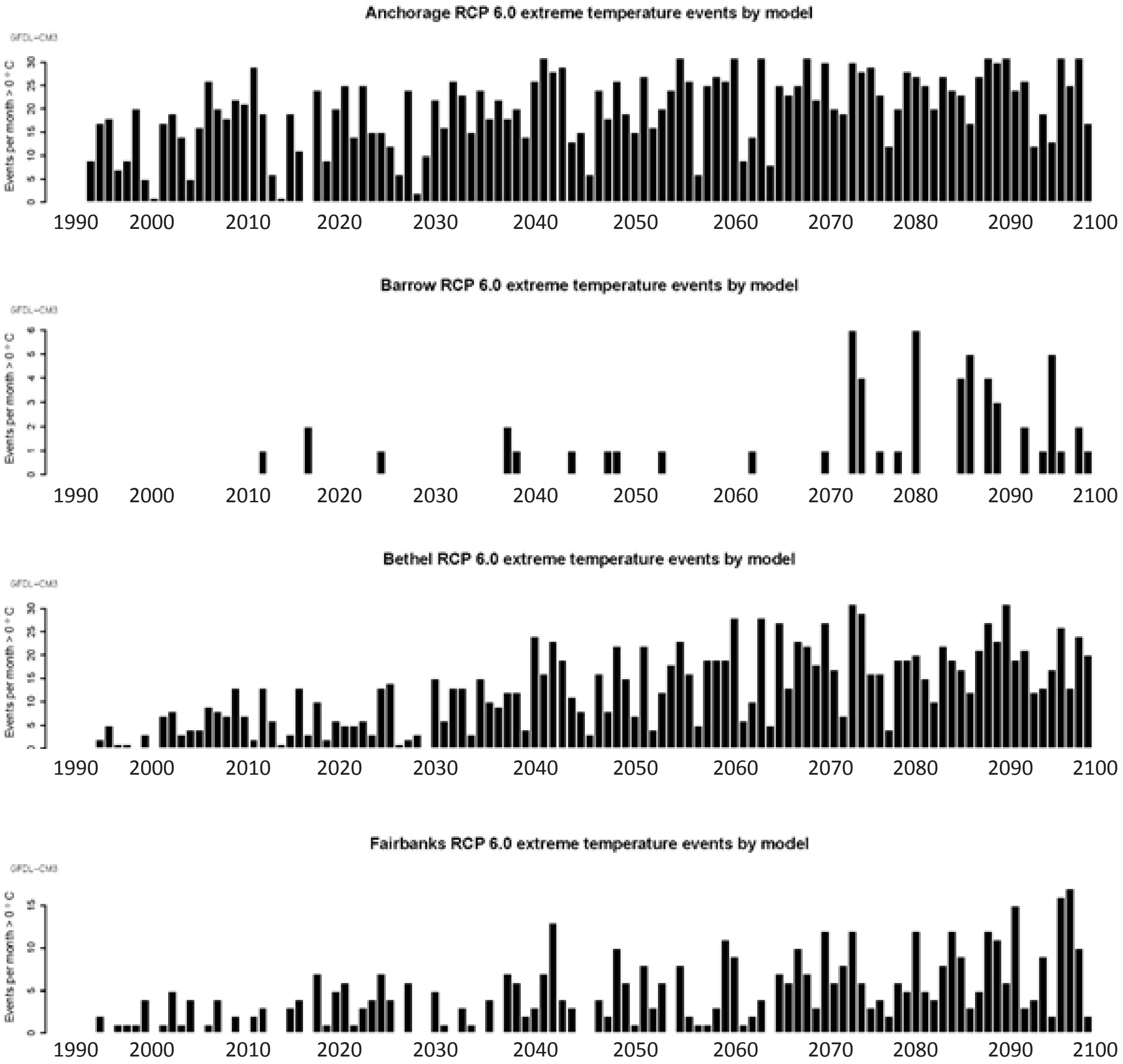
[14] USGCRP 2014

[15] Scenario B1 was one of the greenhouse gas emissions scenarios developed for CMIP3 which informed the IPCC's Fourth Assessment Report. The CMIP3 scenarios are forerunners to the RCP emissions scenarios used in the case studies. In some cases, the National Climate Assessment made use of these earlier emissions scenarios and they are cited here to provide a general context for projected conditions in the state. The RCPs can be thought of as complementing the CMIP3 scenarios, not superseding them.

[16] USGCRP 2014

[17] USGCRP 2014

Figure 5: Number of Days in January above Freezing, 1990—2100, Anchorage, Barrow, Bethel, and Fairbanks, GFDL-CM3 Model, RCP 6.0[18]



To date, there are few documented failures of permafrost slopes along the road systems in Alaska.[19,20] In one example along the Dalton Highway corridor, a major north-south highway, several frozen debris lobes (slow-moving landslides in permafrost) are advancing downhill towards the highway. Preliminary investigations indicate that these frozen features are composed of soil, rocks, trees, and brush, and that they move through a combination of basal sliding[21] and internal flow.[22] Rates of movement of these features vary; the fastest lobe has moved up to 150 feet per year, while the closest to the road moves consistently at about 15 feet per year. The closest frozen debris lobe was less than 150 feet from the Dalton Highway embankment as of June 2014.

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[18] Image source: SNAP

[19] Berg and Smith 1976

[20] Mageau and Rooney 1984

[21] Basal sliding is characterized by underground meltwater acting as a lubricant that exacerbates ground movement

[22] Daanen et al. 2012

Another possible implication of higher temperatures, mostly during summer months, is the danger of forest fires which could become worse given more extreme temperatures. Since 2000, interior Alaska has experienced four large fire years (years in which more than one percent of the landscape burned): in all, these fires have burned 17 percent of the landscape.[23] By 2100, the area burned is expected to triple in Alaska (assuming climate scenario B1), or quadruple (assuming an A2 emissions scenario).[24] Fires can thaw the permafrost and, in hilly terrain, that combined with the loss of vegetation can result in enhanced chances of landslides.

PRECIPITATION

Annual precipitation is projected to increase, especially in northwestern Alaska. The National Climate Assessment estimates that annual precipitation increases of about 15% to 30% are projected for Alaska by late century if global emissions continue to increase. Figure 6 shows projected increases in precipitation in four cities from the different climate regions highlighted in Figure 3.[25] As shown, the average amount of precipitation per month is expected to increase in all four cities in the second half of the century.

Extreme precipitation events are also expected to increase and would enhance the risk of flooding and the possible impact on culverts and bridge supports and foundations. There are also implications for the design and maintenance of drainage systems that provide channels to remove water from the road or bridge structures. Finally, as in temperature, high levels of precipitation can destabilize soil conditions and contribute to permafrost melting, raising the potential for landslides.

SEA LEVEL RISE AND EXTREME **COASTAL STORMS**

The potential effect of sea level rise is different from one Alaska coast to another. In the southern coastal areas, the coastline is slowly rising due to tectonic forces and isostatic rebound (the springing back of land after the weight of ice during the last ice age). A study of the effects of sea level rise on coastal marshes concluded that the net effect of projected sea level rise in these areas is minimal.[26] The primary reason for the relatively low vulnerability among these habitats was that significant land uplift in the region was predicted over the next century, which counteracts the regional impact of sea-level rise.

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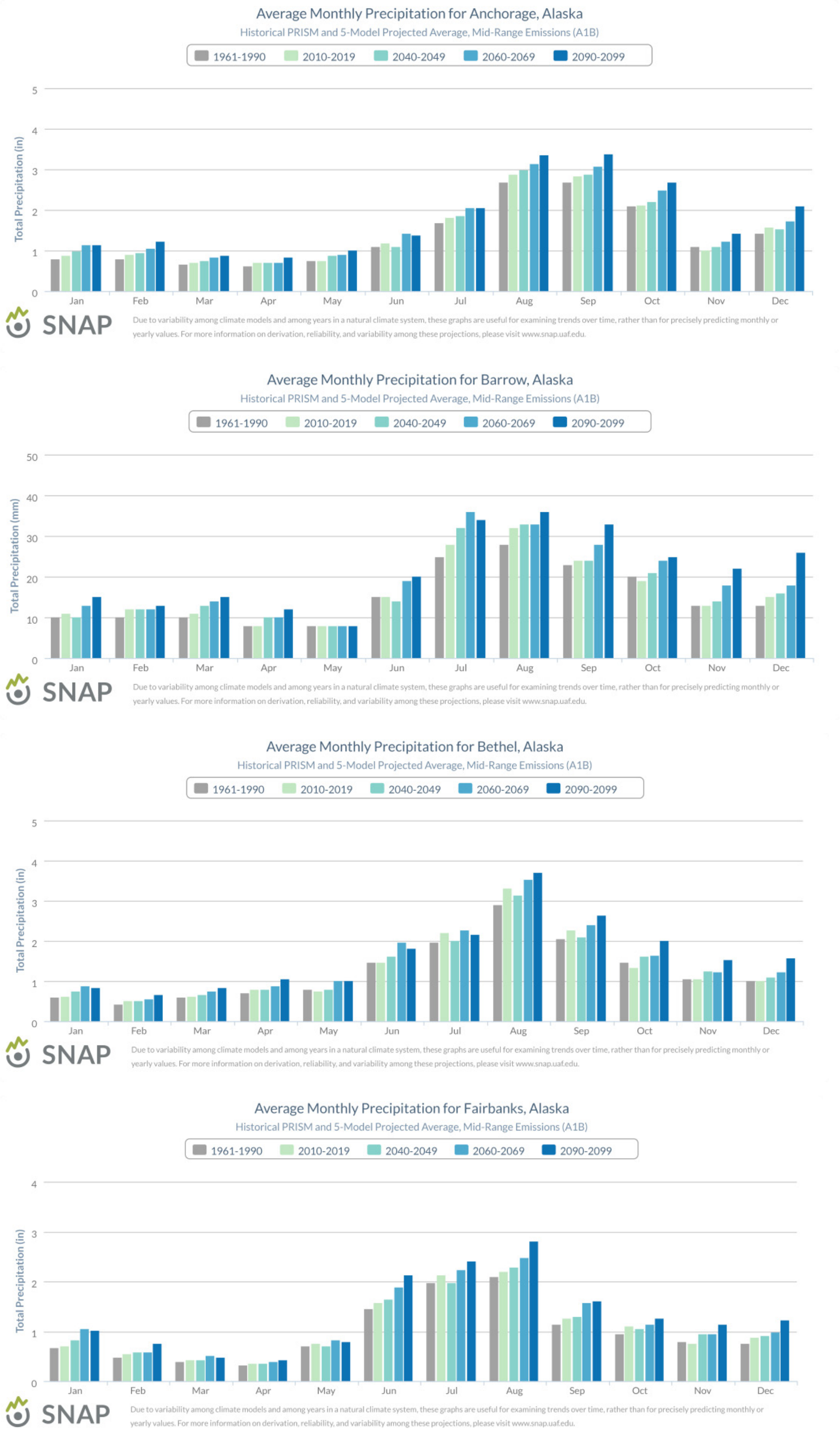
[23] Kasischke et al. 2010.

[24] Markon, Trainor and Chapin 2012; Balshi et al. 2009; Trainor et al. 2009

[25] Note: These figures are based on the CMIP3 scenarios for the Fourth Assessment Report as the RCP scenarios were not available from SNAP for precipitation at the time of publication

[26] Glick, Clough, and Nunley 2010

Figure 6: Average Monthly Precipitation, 1961—2099, Anchorage, Barrow, Bethel, and Fairbanks, Historical PRISM and 5-Model Projected Average, Mid-Range Emissions (A1B)[27]



Average Monthly Precipitation for Anchorage, Alaska

Historical PRISM and 5-Model Projected Average, Mid-Range Emissions (A1B)

Due to variability among climate models and among years in a natural climate system, these graphs are useful for examining trends over time, rather than for precisely predicting monthly or yearly values. For more information on derivation, reliability, and variability among these projections, please visit www.snap.uaf.edu.

Average Monthly Precipitation for Barrow, Alaska

Historical PRISM and 5-Model Projected Average, Mid-Range Emissions (A1B)

Due to variability among climate models and among years in a natural climate system, these graphs are useful for examining trends over time, rather than for precisely predicting monthly or yearly values. For more information on derivation, reliability, and variability among these projections, please visit www.snap.uaf.edu.

Average Monthly Precipitation for Bethel, Alaska

Historical PRISM and 5-Model Projected Average, Mid-Range Emissions (A1B)

Due to variability among climate models and among years in a natural climate system, these graphs are useful for examining trends over time, rather than for precisely predicting monthly or yearly values. For more information on derivation, reliability, and variability among these projections, please visit www.snap.uaf.edu.

Average Monthly Precipitation for Fairbanks, Alaska

Historical PRISM and 5-Model Projected Average, Mid-Range Emissions (A1B)

Due to variability among climate models and among years in a natural climate system, these graphs are useful for examining trends over time, rather than for precisely predicting monthly or yearly values. For more information on derivation, reliability, and variability among these projections, please visit www.snap.uaf.edu.

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[27] Image source: SNAP

The most important coastal threat in much of Alaska is likely to be storm surge. On the Bering Sea coast and in the Arctic, large storm surges (extreme high water events caused by high winds and low atmospheric pressure) have already been occurring over recent years. The National Oceanic and Atmospheric Administration (NOAA) predicts storm surges of ten feet or more for many western Alaska coastal communities during the next 50 years, and some parts of the western Alaska coast could experience surges as high as 13 feet.[28]

The potential impacts of storm surge are exacerbated by a declining extent and thickness of sea ice. Arctic sea ice extent and thickness have declined substantially, especially in late summer (September), where studies have shown there is now only about half as much sea ice as at the beginning of the satellite record in 1979. Models that best match historical trends project northern waters that are virtually ice-free by late summer in the 2030s.[29] Decline of sea ice increases ocean fetch (the distance waves travel uninterrupted), which increases wave height. Decline of shore-fast ice leaves the coast unprotected from waves and more vulnerable to wave action, and as ice coverage decreases so does the damping effect it has on wave action. Figure 7 shows projected thickness of sea ice along the Bering Sea and Chukchi Sea coasts. As shown, the decline in sea ice thickness is dramatic, especially for the Chukchi coast. Furthermore, changing climate may cause a change in storm pathways, bringing more frequent or intense storms to some parts of Alaska.

The loss of sea ice combined with more extreme storm surge, on top of a net increase in sea level rise where occurring, creates potentially significant challenges to infrastructure in coastal areas. This is particularly true for airport runways that have been constructed along the coast in many communities.

In summary, climate projections for Alaska indicate that many of the challenges the state is facing now will only become worse in the future. This is especially true with the melting of the permafrost, which impacts the foundation conditions of roads and bridges, in particular. Along the coasts, transportation infrastructure that is located in areas subject to large storm surge due to more extreme weather events will also be particularly vulnerable.

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[28] Alaska Sea Grant Marine Advisory Program 2015

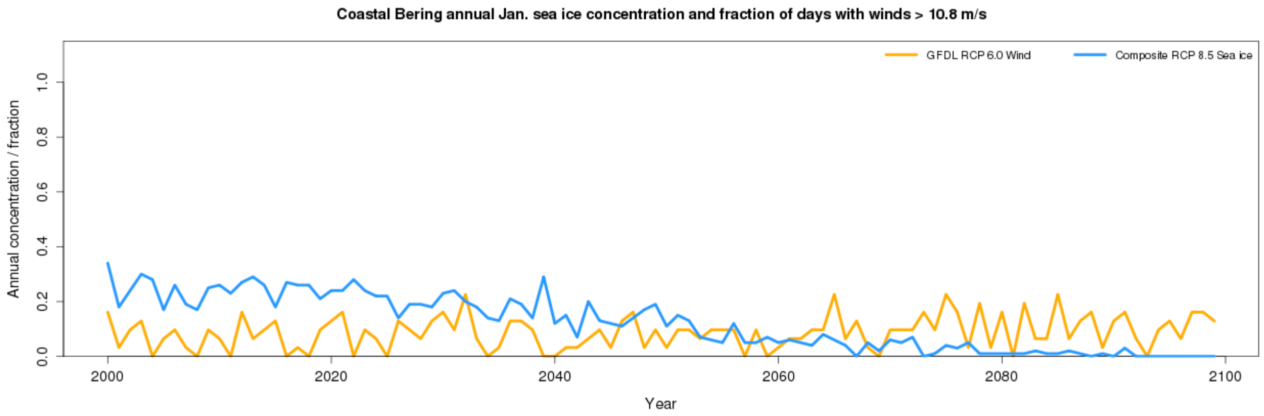
[29] Alaska Sea Grant Marine Advisory Program 2015

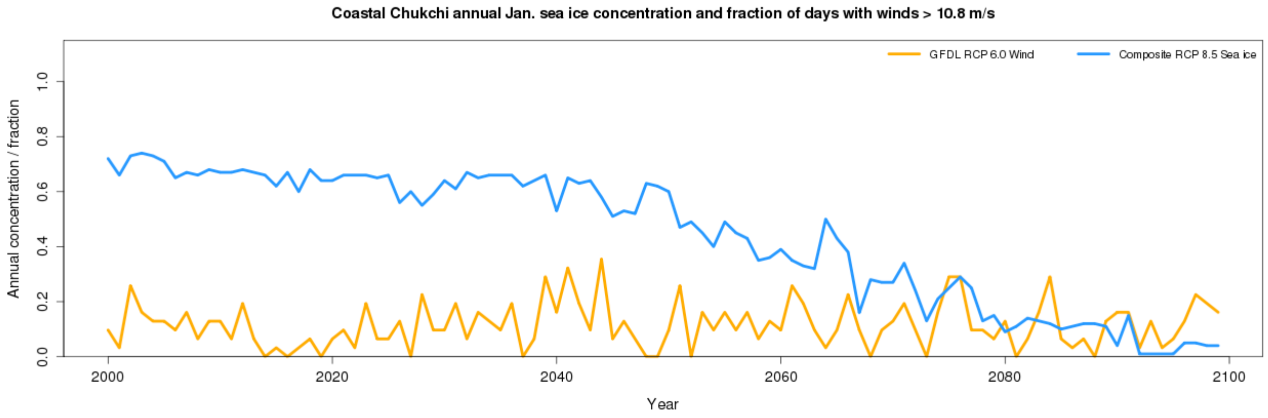
3. Methodology

Methodology

In order to consider possible climate changes and the uncertainties associated with them, the U.S. Department of Transportation (USDOT) developed a General Process for Transportation Facility Adaptation Assessments (the Process). The Process was developed for the USDOT's Gulf Coast Study, Phase 2 and distributed to adaptation pilot project grant recipients for use on the pilot projects. The description of the Process that follows has been excerpted from the Gulf Coast 2 Study's Task 3.2 Report[30] with the permission of USDOT. Some modifications to the text have been made to shorten the length of the description to better fit this document.

Figure 7: Sea Ice Concentrations and Wind Events, 2000s—2090s, Bering and Chukchi Seas, GFDL-CM3 Model, RCP 6.0, Wind Threshold 24.2 miles per hour[31]


Coastal Bering annual Jan. sea ice concentration and fraction of days with winds > 10.8 m/s


Coastal Chukchi annual Jan. sea ice concentration and fraction of days with winds > 10.8 m/s

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[30] USDOT 2014

[31] Image source: SNAP

The Process provides an 11-step framework to consider climate change and identify the best methods for decision-making at the project level. The steps are generally as follows:

1. Describe the Site Context
2. Describe the Existing/Proposed Facility
3. Identify Climate Stressors that May Impact Infrastructure Components
4. Decide on Climate Scenarios and Determine the Magnitude of Changes
5. Assess Performance of the Existing/Proposed Facility
6. Identify Adaptation Option(s)
7. Assess Performance of the Adaptation Option(s)
8. Conduct an Economic Analysis
9. Evaluate Additional Decision-Making Considerations
10. Select a Course of Action
11. Plan and Conduct Ongoing Activities

Each of these steps is described in more detail below.

Importantly, the Process does not change specific current approaches to design. What it potentially does change, however, are, (1) the climate-related inputs used in the design methodology, (2) the number and type of design options one develops, and (3) how the final option is chosen to provide a cost-effective and resilient improvement to the transportation network.

STEP 1—DESCRIBE THE SITE CONTEXT

The first step involves developing and defining a thorough understanding of the site context. The site's context is key to determining the appropriateness of various adaptation options considered in subsequent steps. Some of the important issues to be identified in this step include:

- Characteristics of the surrounding land uses, population, economic activities and significant environmental or community resources
- Existing performance of the facility including information such as volumes/ridership, fleet mix, and role in network continuity
- Characteristics of the surrounding topography and hydrography
- The function that the facility will serve within the broader transportation network, both in the near term and in the future (e.g., evacuation route or critical network link)

STEP 2—DESCRIBE THE EXISTING/PROPOSED FACILITY

This step develops detailed knowledge on the existing or proposed facility. This knowledge is critical for developing appropriate and effective adaptation options in subsequent steps. Key information that should be gathered includes: location, functional purpose, design type, dimensions, elevations, proposed/remaining design life, age/condition, and design criteria.

STEP 3—IDENTIFY CLIMATE STRESSORS THAT MAY IMPACT INFRASTRUCTURE COMPONENTS

This step documents the climate-related variables typically considered in the planning and design of the type of facility being investigated. The design standards associated with these variables, if applicable, should also be noted (e.g., a policy that all bridges and their approaches must be designed to pass the 50-year storm without overtopping). For many facilities, there could be multiple climate stressors relevant to designers that should be considered.

STEP 4—DECIDE ON CLIMATE SCENARIOS AND DETERMINE THE MAGNITUDE OF CHANGES

After the climate-related variables affecting the facility have been identified, the next step is to use climate model projections (or proxies if unavailable) to determine whether and how much each of the variables of concern may change in the future. The information gathered for each variable should, if possible, relate to the design standards identified in Step 3. Recognizing the uncertainty inherent in climate projections, a scenario-based approach is recommended, involving generating a variety of climate scenarios to capture the range of possible future values of each climate variable.

After gathering the climate projections and considering the full range of potential climate changes, it might be determined that none of the climate variables are expected to change significantly or in a way that would potentially threaten the facility. If this is the case, then the assessment is complete and no further climate adaptation analysis is required at this time.

STEP 5—ASSESS PERFORMANCE OF THE EXISTING/PROPOSED FACILITY

This step ascertains whether the facility is currently operating effectively and if it would be expected to do so under each of the possible future climate scenarios selected in Step 4. The standards by which performance is assessed can vary depending on the asset being studied. Whenever possible, however, performance should be assessed against the design standards tied to the climate variables of interest noted in Step 3. For example, if a bridge and its approaches were required not to overtop during the 50-year storm, one would test each scenario's 50-year storm to determine if it overtops the facility.

At the conclusion of Step 5, it is possible that the facility is found to perform adequately under the full range of potential climate changes that it could experience throughout its intended design life: if this is the case, no further analysis is necessary at this time and the assessment is complete.

STEP 6—IDENTIFY ADAPTATION OPTION(S)

Adaptation options should be identified for each scenario that does not meet design expectations as determined in Step 5. The adaptation options could be planning or design-oriented; in many cases, the best adaptation may be to avoid a hazardous area altogether rather than to design an engineered solution.

In general, at least one adaptation option should be identified for each climate scenario. These options then become the basis for analyzing performance and decision-making. Adaptation options could consist of either one action (raising a bridge) or a package of actions that address a climate stressor or set of climate stressors (e.g. raising a bridge and armoring the approach embankments). Each option should be developed so that applicable design standards are met under the given scenario realizing that, as is the case with such standards generally, some exceptions may be necessary based on unique site constraints.

Note that there are likely to be multiple possible ways to achieve design standards under any given scenario (e.g., to accommodate higher flows through a culvert, one could add additional culvert cells or convert the culvert to a bridge): it is up to the project team to decide on how many options to develop and test. Whatever approach is chosen, a high-level cost estimate to construct and maintain each adaptation option should be developed. This will be used in the economic analysis in Step 8.

STEP 7—ASSESS PERFORMANCE OF THE ADAPTATION OPTION(S)

This step assesses the performance of each adaptation option under each potential climate change scenario selected in Step 4. This analysis is similar to Step 5 except that it is performed on the adaptation options as opposed to the existing facility or, in the case of new facilities, the standard design without adaptations. The key determination is whether each adapted facility satisfies its mandated performance standard (e.g., a 50-year design storm for a culvert) under each scenario.

STEP 8—CONDUCT AN ECONOMIC ANALYSIS

Economic analysis enables one to determine how the benefits of undertaking a given adaptation option, defined as the costs avoided with adaptation, compare to its incremental costs under each of the possible future scenarios developed in Step 4. The basic technique involves estimating the expected impact costs from climate or weather events over the life of the facility and discounting them to determine the present value of these expected costs. This is done for the base case of the existing facility or standard new design and repeated for each adaptation option under each climate change scenario selected in Step 4. The (lower) costs with the adaptation options in place can then be compared to the base case costs to determine the cost savings expected as a result of adaptation. The net present value and/or the benefit-cost ratio of each adaptation option can then be computed and compared amongst the adaptation options. The results can be presented in tables showing each adaptation option's cost-effectiveness under each scenario.

Decision-makers can then look for (1) adaptation options that have benefit-cost ratios greater than one and (2) the adaptation option that performs best across the full range of scenarios tested (the robust option). It should be noted that the economic analysis does not in and of itself always provide an answer as to whether an adaptation option makes financial sense. There is no guarantee that an adaptation option that performs cost-effectively under each scenario will exist: an option may be cost-effective under one scenario but not another. Likewise, there may be no single adaptation option that is the most robust economic performer across all scenarios. In every case, but in these cases especially, trade-offs will have to be made and the community's and/or facility owner's risk tolerance evaluated to help choose the "best" option from a financial standpoint. Ultimately, because of the uncertainty involved in knowing what climate scenario will actually occur, determining the "best" option financially is often subjective and based on the decision-maker's appetite for risk.

STEP 9—EVALUATE ADDITIONAL DECISION-MAKING CONSIDERATIONS

As in other areas of transportation decision-making, the cost-effectiveness of adaptation options is not the only factor important to making wise investment decisions. Other factors that can be difficult to monetize (for benefit/cost analysis) should also be considered before a final decision is reached. These may include: broader project sustainability, project feasibility and practicality, ongoing maintenance needs, capital funds availability, and stakeholders' tolerance for risk of service interruption and associated costs of all types.

STEP 10—SELECT A COURSE OF ACTION

Once as much information as possible has been gathered on both economic and non-economic factors, decision-makers should weigh the information presented and decide on a course of action. Those involved should keep in mind that adaptation does not always make sense from a financial feasibility or community acceptance standpoint and a decision to take no action may be justified in some cases.

STEP 11—PLAN AND CONDUCT ONGOING ACTIVITIES

Once a decision has been made on a course of action, a management plan for the facility should be developed. At a minimum, the management plan should contain an element of monitoring to determine if the facility is performing as expected over time. If an adaptation option was used, estimates of the costs saved from implementing the adaptation could be developed so that the benefits of the adaptation are documented and compared to its costs. This information could prove beneficial in future years as the community continues to make decisions on which adaptations, if any, make sense in various situations.

4. Case Studies

Case Studies

The next sections present the analysis and findings from the three case studies. The first case study examines the potential impacts of thawing permafrost on paving decisions on the Dalton Highway, a major north-south highway in Alaska. The second case study looks at the increased risk of storm damage at an airport in the Native Alaska village of Kivalina due to diminishing sea ice. The third case study assesses the landslide risk along Denali Park Road in Denali National Park at a site of a recent slide and the potential for increased risk associated with thawing permafrost and increased precipitation in the area. These case studies were chosen because they represent the types of challenges facing infrastructure agencies in Alaska as climate changes.

The case study descriptions are organized around the steps in the Process illustrating how it can be applied in practice. However, the case studies are simply illustrative of the type of thinking that engineers need to consider for future engineering efforts on similar projects across the state.

Roadway Exposure to Permafrost Thaw, Dalton Highway's (Alaska 11)"Nine Mile Hill" (Mileposts Nine To Eleven)

INTRODUCTION

As noted in the introductory section, the ground in the northern areas of Alaska is similar to ground in other near-Artic climates around the world in that there are soils below the surface that remain frozen (below the freezing point for water) throughout much or all of the year. These areas of permafrost provide a foundation for structures and infrastructure throughout the state, including along Dalton Highway, the road originally constructed to provide access along the Alaska pipeline and to the Prudhoe Bay and North Slope oil extraction areas. Dalton Highway, originally termed the "Haul Road," now serves as the only roadway connection for freight shipments, worker transportation, and tourism between the City of Fairbanks and Prudhoe Bay.

This case study is somewhat different than the two that follow in that this study developed thaw and settlement rates for the highway that were then refined in a follow-on study conducted by the FHWA, Washington DC office as a part of the ongoing Transportation Engineering Approaches to Climate Resiliency (TEACR) Study. The TEACR study is examining different types of transportation assets throughout the United States for various asset-stressor combinations to define engineering approaches that incorporate climate change adaptation strategies into project decision making.

This case study was originally intended to develop and implement a methodology to determine the long-term effects of climate change on the Dalton Highway by quantifying the amount of settlement to be expected from thawing permafrost. The original assessment was focused on determining whether paving the road to provide a more reliable surface for highway users was appropriate for the corridor given the travel benefits of such a surface over the existing gravel surface of the facility. A generalized permafrost thaw function (Stephan's Equation) was used to determine the impacts of thawing for various climatic conditions. This original effort was modified when it was decided to conduct a more specific assessment of potential changes using permafrost thaw modeling. This change recognized that many factors could impact thawing, which might not be captured with more generalized assessment methods.

The study included an assessment of various methods to determine potential thaw rates for permafrost in areas of warming climate conditions. The original study effort, along with the follow-up TEACR project, has resulted in an ongoing and continuous effort to refine the understanding of thawing permafrost in the study area. This had been done by revisiting the various data inputs required of thermal modeling and by identifying a resulting settlement rate that can be used to conduct the analysis. As of the writing of this report, the TEACR project analysis remains ongoing as the consulting team and the Alaska DOT&PF (AKDOT&PF) work cooperatively to determine thaw values acceptable for use in engineering adaptation efforts. The conclusions for this case study were to be held until that project's outcomes could be included. However, the delays in producing a result from the TEACR project analysis have been such that this case study can no longer wait for results.

This report identifies the work that was conducted for the case study and then recommends further research on permafrost thaw and its consideration in engineering decision making on projects in the artic regions of Alaska. The reader is encouraged to visit the TEACR site and review the material, which includes more detailed analysis of permafrost thaw, and assesses the viability of an insulating measure as a means of reducing thaw and associated settlement.

Currently, large portions of Dalton Highway are gravel (305 of the 414 mile length), including the case study section. The highway undergoes fairly constant maintenance, with maintenance teams keeping the road fully operational given heavy freight traffic, weather stresses, and resulting foundation settlement. The cost of maintaining the roadway is carried by the state and, given that these maintenance costs may increase over time as a result of changing climate conditions, state DOT officials are interested in strategies to reduce such costs. Once the costs of required maintenance are estimated for this and similar projects, the benefits and effectiveness of design strategies to reduce subsidence could be used in a benefit-cost assessment. This effort, like the effort underway on the TEACR project, could then determine the cost effectiveness of measures to limit thaw and reduce settlement rates and longer term maintenance costs for the highway. Two major cost factors considered in this study include impacts of ground movement (due to climate change) on potential maintenance and repair costs, as well as associated travel delays for road users due to maintenance operations.

This study, as well as the related work in the TEACR study, represent what is arguably one of the most complex assessments for understanding the impact of climate change on transportation infrastructure. This is due in large part to the complexity of modeling permafrost thaw and in knowing the underground conditions of the road foundation at any particular point along the Dalton Highway.

The uncertainties in this type of analysis are therefore considerable, and include:

- The climate model outputs (and all of the uncertainties behind the assumptions therein)
- The temperature inputs to the thaw analysis, given an uncertain definition of which model outputs to apply for which climate scenario
- Limited data points along a two-mile corridor with which to assess thawing and settlement
- The effects of thawing on areas adjacent to the highway and its impact on the road foundation

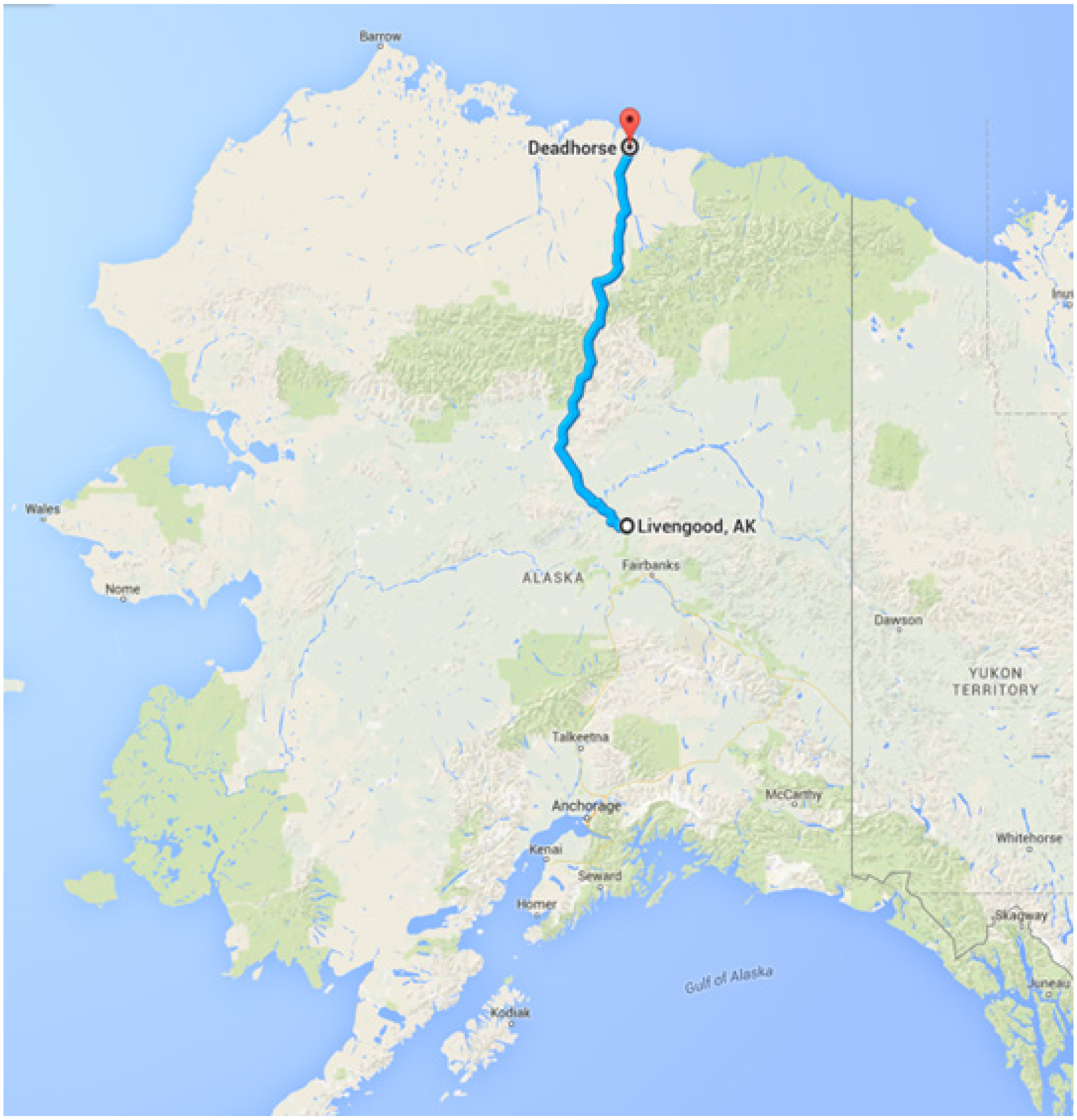
Given the subsurface nature of the investigated impact, there are also the unknowns and uncertainties that accompany any geotechnical investigation of subsurface effects. In particular, most such investigations rely on samples of subsurface conditions with inferences drawn on conditions between the sample sites. The analysis had to rely on the data that existed from such geotechnical investigations.

STEP 1—DESCRIBE THE SITE CONTEXT

The 414-mile long Dalton Highway (Alaska State Route 11) is a critical lifeline connecting Alaska's North Slope oil fields in Deadhorse to the rest of the state (see Figure 41). Miles 9 through 11 of the highway, the focus in this case study, are located on the southern portion of the highway in hilly terrain (see Figure 4 2). The road, which traverses sparsely settled wilderness for its entire length, is primarily used by trucks hauling supplies from Fairbanks and points south to the oilfields and camps of the North Slope. Disruption at any point along the highway could result in access disruptions for important highway users. Fewer than 100 full-time residents live along the highway, so keeping the highway open and operational presents some significant challenges to the AKDOT&PF.

The case study road segment is characterized by steep grades and moderately sharp curves. In late 2013, AKDOT&PF completed a reconstruction of this segment of the highway. The project rehabilitated the existing gravel roadway and provided some limited curvature improvements. The project involved a detailed assessment of permafrost in the study area to limit the potential that ice wedges or other ice rich permafrost thawing could result in rapid settlement on the roadway and become a safety concern for roadway users. The intent was to inform the corridor design decisions on how the roadway would be constructed. This section of the roadway is located near a borrow pile, used by maintenance crews to obtain material to keep the roadway surface even when deemed necessary.

Figure 4-1. Dalton Highway Location



OVERVIEW OF PERMAFROST CONDITIONS

In 2008, extensive geotechnical investigations were conducted by AKDOT&PF and the University of Alaska-Fairbanks to study the feasibility of a re-alignment of Dalton Highway between mileposts 8 and 12 This study provided the most detailed geotechnical data available for the Nine Mile Hill case study.[32] The investigation showed that most of the soils in the project area are extremely ice rich and would be expected to have excessive settlement upon thawing. There are also significant ice wedges interspersed within the general permafrost matrix. Two of the four segments that were investigated were extremely ice rich. Wedge ice occurrence in the other two segments was less significant; however, thaw settlement was still considered an important issue for the entire study area.

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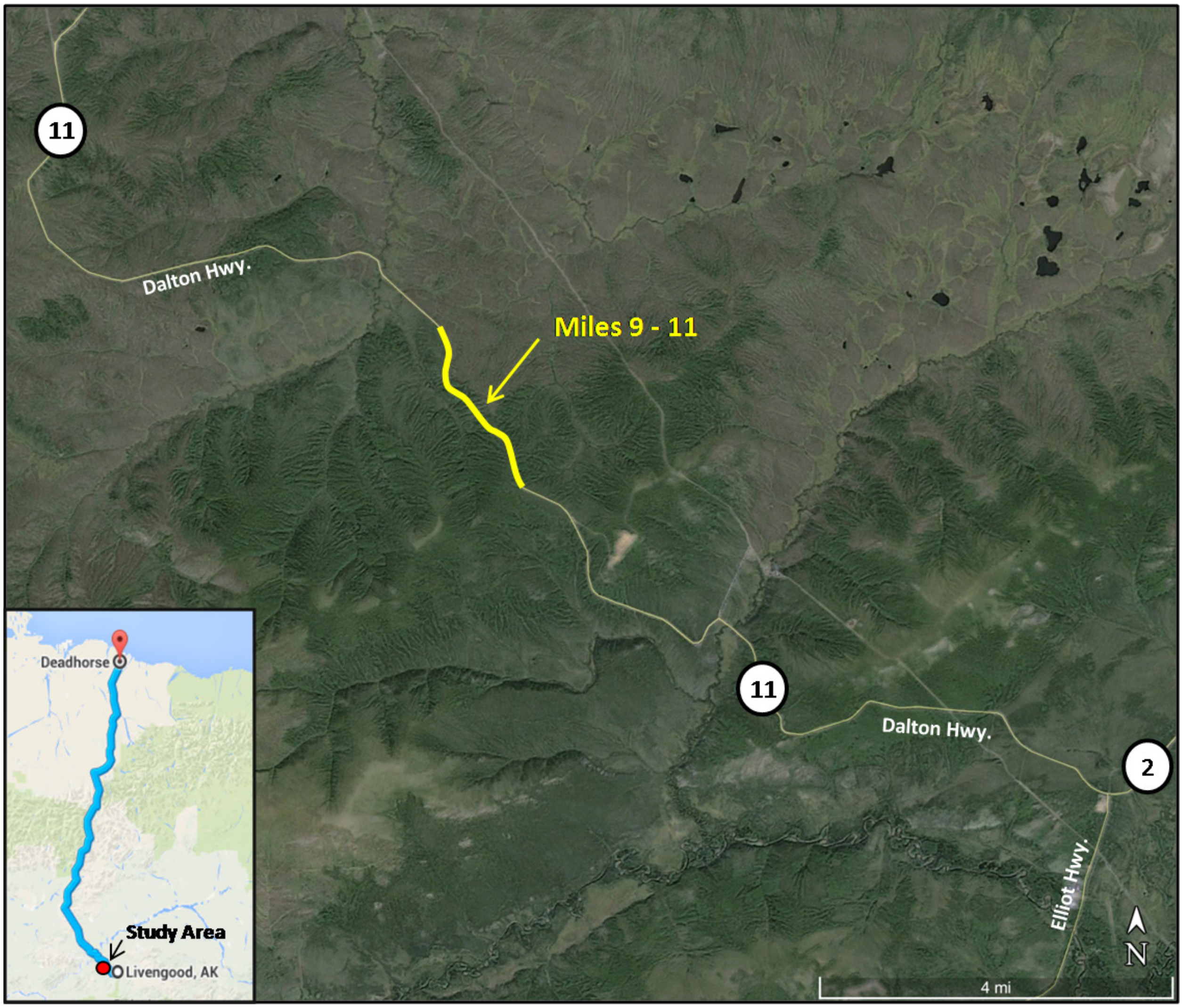
[32] Shur, Kanevskiy, Dillon, et. al. February 2010. "Geotechnical Investigations for the Dalton Highway Innovation Project as a Case Study of the Ice Rich Syngenetic Permafrost" by Alaska DOT&PF and Alaska University Transportation Center

Figure 4-2. Study Area Location



Furthermore, the corridor shows variation in the depth and extent of the silt, gravel, gravelly silt, sand, and bedrock. The presence of these elements can result in varying thaw rates and settlement rates for the roadway, meaning settlement would not advance uniformly over time, but instead would occur inconsistently, increasing the need for a proactive maintenance program to address these potential issues. The deepest boring taken during the geotechnical investigations, 85 feet, showed frozen ground down to that point in some areas.[33] However, it is unclear how deep the permafrost extends beyond this point.[34] The permafrost thaw models developed and applied in this study used as inputs the soils, depths, and temperatures noted in these borings to assess the potential impact of temperature change on thawing in the case study site.

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[33] Ibid

[34] Shur, Kanevskiy, Dillon, et. al., February 2010. "Geotechnical Investigations for the Dalton Highway Innovation Project as a Case Study of the Ice Rich Syngenetic Permafrost" by Alaska DOT&PF and Alaska University Transportation Center

STEP 2—DESCRIBE THE EXISTING /PROPOSED FACILITY

AKDOT&PF's Northern Region Materials Section (NRMS) conducted three separate geotechnical investigations as part of a location study in 1990, 1996, and 2004 for 9 Mile Hill.[35] Evaluating data from the 45 boreholes from these investigations yields varying depths of organics, silt, colluvium, and ice layers before encountering the chert bedrock. The depth to bedrock is an important factor, as once the thaw reaches this level, in essence, the depth of impact has been established.

Existing Gravel Roadway

The segment from milepost 9 to milepost 11 on Dalton Highway currently consists of a two-lane, 36-foot total roadway width. Figure 43 provides a typical section for the road; Figure 44 shows a recent image of the road taken near the study area. The existing roadway surfacing is gravel (aggregate surfacing) with calcium chloride added to reduce roadway dust. Roadway ditches are provided in cut areas to process rain water. The facility has a 50 mile per hour design speed.

Figure 4-3. Typical Section, Current Roadway Design

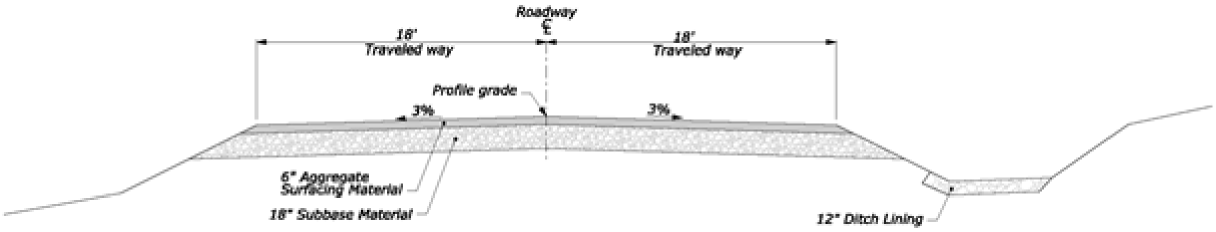

Figure 4-4. Existing Dalton Roadway (2014)

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35 The five models used were CCSM4, GFDL-CM3, GISS-E2-R, IPSL-CM5A-LR, and MRI-CGCM3. These models were selected by SNAP as they were determined to represent Alaska's climate well.

STEP 3—IDENTIFY CLIMATE STRESSORS THAT MAY IMPACT INFRASTRUCTURE COMPONENTS

As described above, the road segment from milepost 9 through milepost 11 is underlain by ice-rich permafrost. Permafrost is susceptible to thawing due to both climatic changes and man-made impacts such as construction equipment cutting into the permafrost layer and directly exposing the permafrost to (periodically warmer) open air and altering the thermal regime by removing vegetation. The specific climate variables that influence permafrost thaw include:

- Ambient air temperature: The number of days at or below freezing is vital to permafrost formation and keeping the ground frozen. As the surrounding air temperature increases, the ground is more susceptible to thawing.
- Rainfall: Precipitation on frozen soil acts to thaw permafrost.
- Amount of snowfall: Snow acts as a natural insulator between the ambient air and the ground.
- Other effects: Roadway surface, traffic movement, etc.

Due to study scope limitations, only ambient air temperature, the primary driver of permafrost thaw, was considered for this assessment.

The thawing of the permafrost layer and ice wedges results in voids where the ice used to be and leads to soil consolidation and ground movement that can damage roadways. The more ice that is originally in the permafrost, the larger the voids left after thawing, and the more ground movement and damage that are possible. Particular challenges occur where the ice content of the soil varies horizontally over short distances, as is often the case, leading to differential settling and a wavy pattern of ground movement. In addition, ponding in roadside ditches can help accelerate thawing because water can retain heat that contributes to thawing and prevents re-freezing.

Given the characteristics of permafrost thawing, the Nine Mile Hill study area is likely to incur the following risks:

- Significant differential settlement along the corridor
- Potential for abrupt settlement in areas where ice wedges thaw
- Cut slope instability due to the retreating (thawing) permafrost
- Introduction of sediment into surface water (due to thawing of ice-rich silts at the slopes)

All of these impacts have a direct effect on the level (frequency and extent) of maintenance required to maintain a passable roadway, with the expectation that these effects would increase over time as a result of changing climate conditions, warming temperatures, and the resulting thawing of the permafrost layer.

STEP 4—SELECT CLIMATE SCENARIOS AND DETERMINE THE MAGNITUDE OF CHANGES

Projections of future temperatures based on three atmospheric greenhouse gas concentration scenarios (RCP 4.5 [lower emissions], RCP 6.0 [moderate emissions], and RCP 8.5 [higher emissions]) were used to develop estimates of future permafrost thaw and ground movement in the study area between now and the 2030s. A few techniques currently exist for determining the amount of thaw and ground movement associated with warming temperatures: (1) finite element analysis, (2) the Modified Berggren Equation, (3) the Stefan Equation, and (4) the more detailed thermal modeling. Finite element analysis involves more detailed analysis of ground settlement. While it produces relatively more accurate, site-specific results, it is also significantly more costly to conduct, requires significant data to implement, and is therefore limited in use. The Modified Berggren Equation can be challenging to apply to large data sets due to significant limitations inherent to the software, which will not run on newer computing platforms. The Stefan Equation is a simpler method that considers ground settlement or depth of thaw in a uniform soil, but can over-generalize impacts for thaw/settlement and assumes an undisturbed surface layer which is not found on this section of the Dalton Highway.

The study was initially scoped to assess thawing by applying Stephan's Equation to define thaw potential. The focus was shifted instead to a thermal modeling approach given available inventory data resources and the ability to develop the thermal model assumptions in cooperation with the TEACR study. The modeling effort was also conducted to better understand the implications of thawing on the roadway given specific conditions present within each section given that the results for each section may be dependent on very localized conditions and could potentially vary from one to the next. The analysis then would provide an opportunity to assess thawing along the corridor in a way that recognized the variations between sections, and would enable a cost assessment that would be developed recognizing these differing effects.

SNAP downscaled daily temperature projections from five global climate models[36] to a grid with a cell resolution of 2,530 feet. Data from the cells covering the study area were applied by feeding the daily temperature values directly into the thermal model developed for the study. In recognition of limited resources and the level of effort required to complete the thermal modeling effort, only one model output was analyzed.

The climate models provide daily temperature outputs which, while containing uncertainties, were recognized as a potential data source that could be fed directly into the thermal modeling software program. This input could then be used by the analysis to quantify the potential impacts of daily temperatures predicted by the models on permafrost thawing the region. A comparison of climate model outputs was conducted by reviewing the outputs of each at the daily scale to determine their relative contributions to the freeze and thaw cycles. Figures 4-5 and 4-6 highlight the predicted daily temperatures in summer 2010 and again in 2040 to show the differences and trends in the data.

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[36] The five models used were CCSM4, GFDL-CM3, GISS-E2-R, IPSL-CM5A-LR, and MRI-CGCM3. These models were selected by SNAP as they were determined to represent Alaska's climate well.

Figure 4-5. Predicted Daily Temperatures, Various Climate Models, 2010

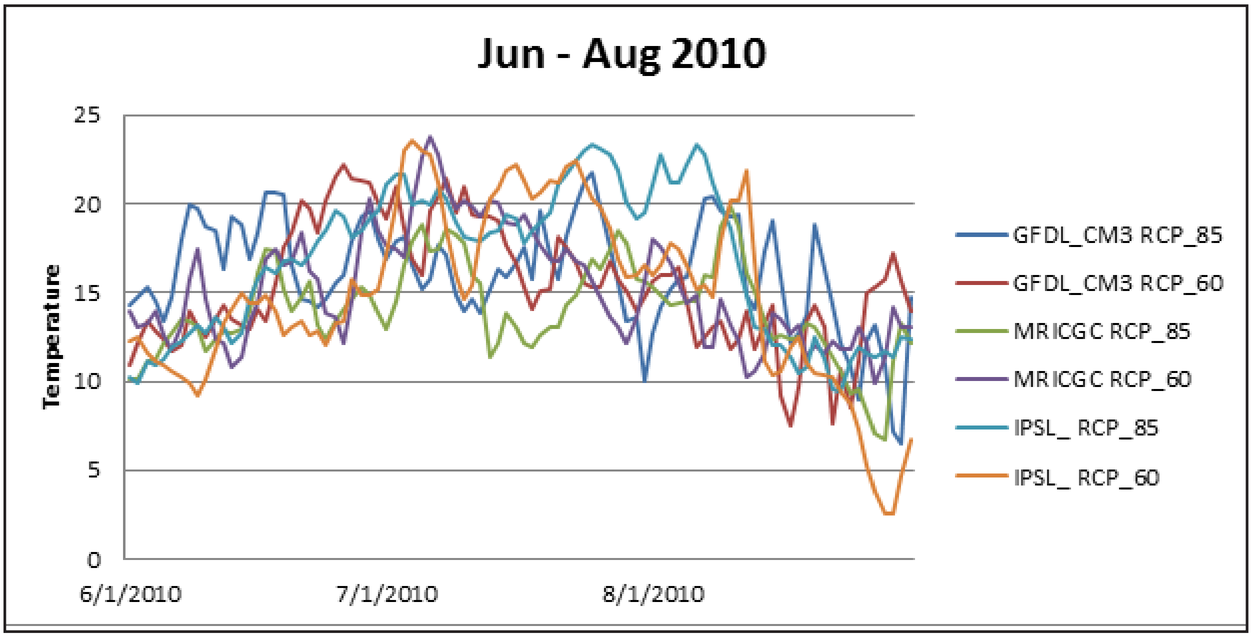
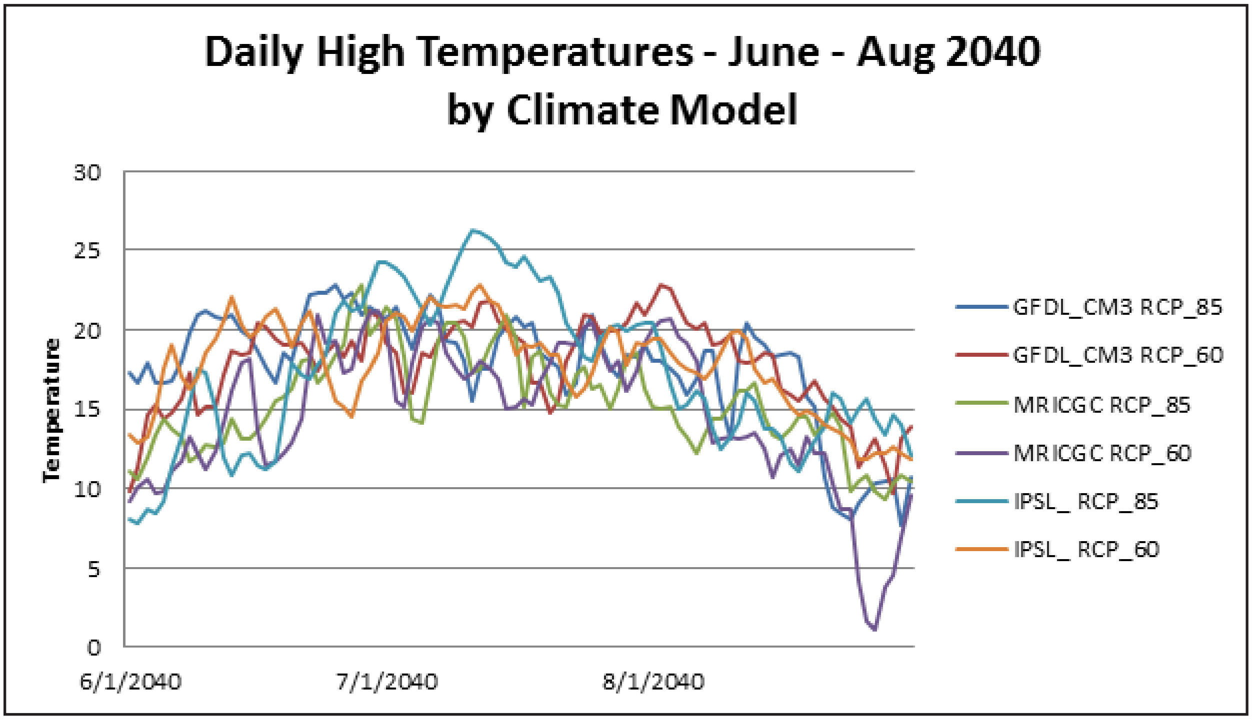
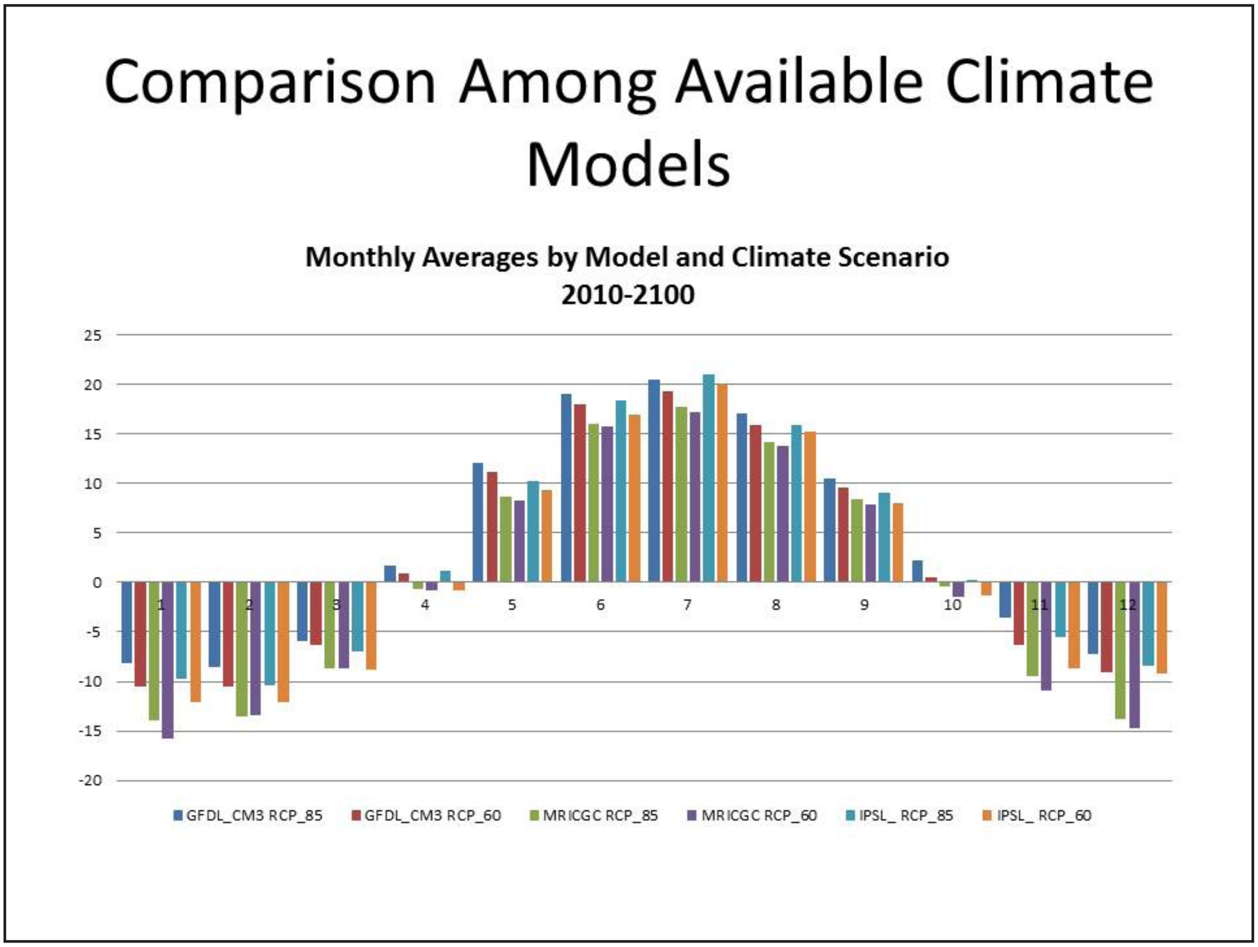


Figure 4-6. Predicted Daily Temperatures, Various Climate Models, 2040



A general trend of warming across the models can be noted when comparing the two graphs and the data represented therein. However, there are global weather influences and other factors included in global models so direct comparison across a specified timeframe like this are not necessarily the best method for understanding the potential effects of temperature change. It is necessary to understand the overall trends for warming based on the assumptions behind each climate model. Figure 4-7 highlights the differences in modeled temperatures by showing average temperatures by month across a year for the climate models available for this study. The trends across the models are better defined in this graphic and the differences over the next century in terms of differences in predicted temperature are noted. The differences, while minor when compared in an assessment of any one time period, are more significant when assessed across a longer time frame.

Figure 4-7. Differences in Monthly Average Temperatures, Various Climate Models, 2010 to 2100



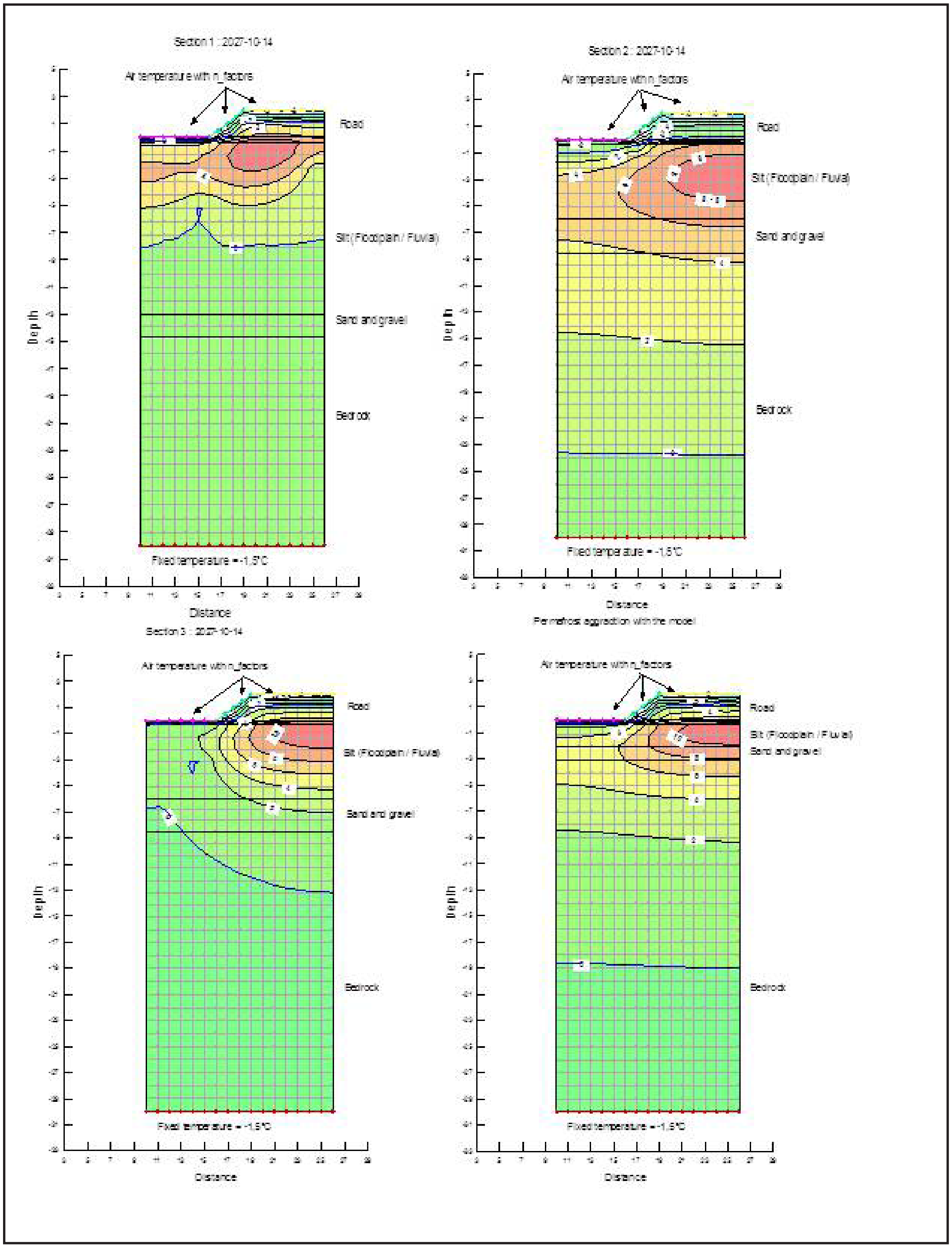
The data in Figure 4-7 are presented as the average above and below 0° Fahrenheit as that is the important point for permafrost, with temperatures above that contributing to thawing while temperatures below that contribute to freezing. This data shows that generally the climate models for higher emissions scenarios are warmer across the year, with higher temperatures in freezing months, above freezing temperatures in April and October and also warmer temperatures in the summer months, when thawing would be expected to occur. The model selected for the case study analysis was the Geophysical Fluid Dynamics (GFDL) Model maintained by NOAA, for the Relative Concentration Pathway (RCP) 8.5 . The selection of this model for this study enabled the analysis team to assess the highest expected thawing potential as a means of analyzing the potential maintenance costs that could be expected given changing climate conditions.

The data collected from SNAP for this climate scenario was used in combination with a thermal model to develop expected thawing and settlement rates for the corridor. The thermal model applied - GEO-SLOPE TEMP/W – is a model applied for engineering design purposes in areas of permafrost and is applied by both the WSP | Parsons Brinckerhoff team and the AKDOT&PF engineering teams on projects in artic regions. This model includes multi-variable analysis assessments to determine the effect of temperature on the thaw rates for permafrost in the area.

The analysis originally completed for this study includes an assessment of the effects of temperature increases on permafrost thawing and land settlement in the area. The model effort to determine the potential settlement rates and depths for four different roadway condition types noted the potential variances in conditions along the corridor and how those differences may affect final thawing and settlement rates. Figure 4-8 presents the four generalized conditions noted along the mile 9-11 section of Dalton Highway and how that information was input into the thermal model to generate the understanding of thawing over the project assessment period.

The sections are notable in that they have different depths of soils, including silt (floodplain/fluvial), sand, and gravel at varying depths and include a range of depth to bedrock from approximately 25 feet to an unknown depth.

Figure 4-8. Thermal Modeling Input Conditions for Case Study Sections



The study analysis team and AKDOT & PF staff have gone through a series of iterations on model development and refinement – a process that is ongoing still. The TEACR study is now assessing potential methods to further refine the models to develop a final accepted analysis technique that can be applied in the area to better represent the potential conditions in the corridor. This method will include assumptions on how climate change may impact permafrost thawing in the 9-11 section, the mile 0-9 section and along other sections of Dalton Highway.

STEP 5—ASSESS PERFORMANCE OF THE EXISTING / PROPOSED FACILITY

The study did not, in the end, contain enough resources to conduct a full project-level assessment and therefore the development of methods by which to assess the current facility and/or assess the potential benefits of improving the facility did not occur.

STEP 6—DEVELOP ADAPTATION OPTIONS

This analysis was set up to assess the maintenance costs associated with various climate change scenarios. No adaptation measures were included in this assessment. Later project efforts should assess the economic benefits of any measure to limit thawing and settlement, with the expectation that the ability to control thaw and settlement would be limited solely to the road bed. The natural permafrost thawing brought on by impacts to the broader corridor environment will not be controlled with road design treatments and would therefore not be included in the analysis.

STEP 7—ASSESS PERFORMANCE OF THE ADAPTATION OPTION(S)

Since no adaptation measures were included in this assessment, this step is not applicable to this study.

STEP 8—CONDUCT AN ECONOMIC ANALYSIS

The study economics team developed approaches that can be used for assessing the benefits and costs of agency strategies. They are presented here as context for how similar efforts can be conducted but a full economic assessment was not completed.

Calculation of Costs

Total maintenance costs of the gravel option were calculated in 2015 dollars assuming a real growth rate of 3.35% per year in the future costs. This value represents the assumed real escalation rate used in the analysis, which corresponds to the average construction cost inflation from 2000 to 2014, as calculated from the Engineering News-Record construction cost index.[37]

The estimation of values to be applied for travel time savings was calculated by projecting the average annual daily traffic (AADT) on Dalton highway over the course of the analysis length. A base year estimate of an average 180 trips per day was provided by AKDOT&PF. This amount was increased by one percent per year from 2016 to 2039 and annualized by multiplying by a factor of 365 for autos and 252 for trucks (assuming truck volumes are less on weekends and holidays). The composition of trucks and autos was determined by taking an average of the most recent estimate of truck volumes on Dalton highway, as provided by AKDOT&PF. In accordance with U.S. Department of Transportation guidance, the value of time for trucks was assumed to be $27.30 per hour and $16 per hour for autos.[38] (Note - Feedback from the DOT is that this value may be low based for trucks and/or high for cars on costs for an area like central Alaska, a point to be refined as later similar assessments are conducted.) Finally, the vehicle occupancy ratio was assumed to be 1.0. Table 41 below summarizes the parameters used in the analysis.

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[37] Engineering News-Record 2014

[38] US DOT "Revised Departmental Guidance on Valuation of Travel Time in Economic Analysis" published Sept. 28, 2011.

Table 41. Parameters of the Analysis of Travel Time Savings Estimation

Parameter	Value	Units
AADT	180	Trips per day
Truck %	68%	Percent
Auto %	32%	Percent
Value of Travel Time (truck)	$27.3	$2015 undiscounted
Value of Travel Time (auto)	$16	$2015 undiscounted

The estimation of vehicle operating cost savings was calculated by taking the projections for AADT and the segment length of 2.46 miles to calculate the total vehicle miles traveled each year. The yearly estimates for VMT were later multiplied by the truck and auto percentages to divide the miles by vehicles type. Table 4-2 below summaries the parameters used in this analysis.

Table 42. Parameters of the Analysis of Vehicle Operating Costs Savings Estimation

Parameter	Value	Units	Source	Notes
Truck costs per mile gravel	$0.79	$2015 undiscounted	University of Kentucky	
Auto costs per mile gravel	$0.31	$2015 undiscounted	University of Kentucky	

For the purposes of this study, these estimates were escalated to 2015 values using the Bureau of Labor Statistics' Consumer Price Index for All Urban Consumers (CPI-U).

STEP 9—EVALUATE ADDITIONAL DECISION-MAKING CONSIDERATIONS

No additional design decision-making considerations were discussed as no design recommendations were included with this study.

STEP 10—SELECT A COURSE OF ACTION

The conclusions of this study are, as noted, that further research and development is needed to apply a thermal model that fully integrates the lessons learned on this study, and the TEACR study, to define more fully the implications of warming temperatures on permafrost in Alaska.

STEP 11—PLAN AND CONDUCT ONGOING ACTIVITIES

Actively monitoring settlement in the corridor to help inform the level of maintenance needed and providing sufficient maintenance funding to fully maintain the roadway, ditches, culverts and side slopes will help avoid roadway closures for major repairs. Close monitoring and timely maintenance will be increasingly important as temperatures continue to warm.

Airport Runway Exposure to Sea Level Rise and Changing Wind and Sea Ice Patterns—Kivalina Airport

Introduction

Coastal shore protection is an important and sometimes underappreciated component of adjacent highways, airports, ports, etc., infrastructure that can be highly sensitive to climate change based on its proximity to the coastline and associated floodplain. This section of the report illustrates how the *Process* can be applied to coastal airport runways by examining the Kivalina Airport located in northern Alaska on the Chukchi Sea.

The goals of this assessment are to (1) determine whether projected changes in wind, sea ice, and sea level rise associated with climate change will pose a shoreline erosion risk to the facility and, if so, (2) to develop and evaluate a representative adaptation option for managing that risk. This case study does not go into all the details of the shoreline erosion process, but rather focuses on two particular design considerations that are affected by climate change; wave conditions and storm surge and their potential impact on coastal erosion. The case study is organized around the 11 steps in the Process.

STEP 1—DESCRIBE THE SITE CONTEXT

The town of Kivalina is located in northwest Alaska on the coast of the Chukchi Sea (see Figure 8). Kivalina Airport is located on the coastline immediately northwest of the town as shown in Figure 9. The town and the airport are located on a narrow spit of land bounded to the south by an inlet to Kivalina Lagoon. The spit continues to the northwest and has one inlet approximately five miles from Kivalina and connects to land approximately nine miles from the town.

Figure 8: Location of Kivalina and Surrounding Points of Interest[39]

Travel to/from Kivalina is primarily by plane or, in some cases, boat or barge in the summer and fall. Transportation across the ice in winter and spring is also possible; however, the remote location of Kivalina essentially limits this form of travel. Due to the limited overwater access that is only possible on a seasonal basis, the airport plays a critical role for Kivalina as it provides the only year-round option for transporting supplies and passengers. It is also a lifeline to regional health facilities in Kotzebue.

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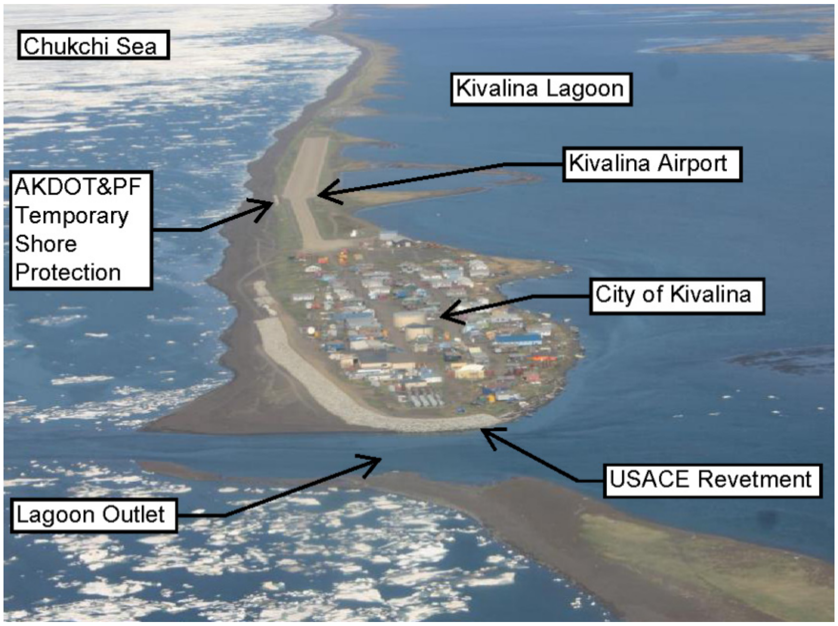
[39] Image source: Google Earth (as modified)

Figure 9: Aerial photo of Kivalina and its Airport[40]



History of Coastal Hazards and Response Strategies at Kivalina

A brief history of Kivalina[41] and coastal hazards, provided in a recent study by the Alaska Native Tribal Health Consortium (ANTHC), is summarized here. Prior to 1900, Kivalina was used as a temporary or seasonal camp but soon became a year round settlement due to the ease of barge shipments. A school was built about 1905 and already by 1911 concerns regarding Kivalina's vulnerability to flooding and discussion among the residents of moving were documented in a letter by school teacher Clinton Replogle. A post office was constructed in 1940 followed by an airstrip in 1960. A storm occurred in 1970 when a 13.5 foot surge inundated the streets with sea water. This was followed by another storm in 1976 that flooded 20% to 30% of the town. Despite this, Kivalina continued to develop with new housing, a high school, and electrical system. Nearby development of the Teck Cominco Alaska, Inc. open pit lead and zinc mine provided the impetus to establish the Northwest Arctic Borough to manage the development. The mine brought job growth and development to the region along with concerns regarding the risk of pollution and other potential impacts.

By the 1990s, erosion in Kivalina was becoming critical with residents considering re-location; an idea that was assessed in the U.S. Army Corps of Engineer's (USACE's) Relocation Planning Project Master Plan.[42] In October 2002 and 2004 storms battered Kivalina with the 2004 storm resulting in the loss of 39 feet of shoreline. Additional storms occurred in September and October 2005 all of which led to state disaster declarations. Residents applied temporary shore protection but the erosion still caused a loss of 69 feet of shore. In the summer of 2006, shore protection was installed consisting of three foot square metal baskets filled with sand and connected, similar to gabions, to serve as a protective wall. Shortly after completion of this wall a storm damaged the wall again leaving the community exposed. In 2007 the seawall was reinforced using sand filled sacks provided by USACE as shown in Figure 10. On September 12,

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[40] Image source: AKDOT&PF (as modified)

[41] ANTHC 2011

[42] USACE 2006

2007 another storm prompted the evacuation of the community. Revetment[43] protection was installed in 2007 and subsequent storms shortly thereafter caused damage of this protection. An example of the erosion is shown in Figure 11. The residents of the community understand relocation is inevitable but there are challenges with funding and achieving consensus on where to relocate. Estimates of the cost of relocation to several alternative locations, including an alternative to remain at Kivalina and associated improvements, have been placed between 100 and 250 million dollars.[44,45]

Figure 10: Kivalina's 2007 Revetment[46]

Recent shore protection efforts include a rock revetment consisting of 400 feet of protection constructed in 2008; Phase I of a larger project.[47] An additional 1,200 feet of revetment was constructed in 2009 at a cost of $12.5 million as shown in Figure 12. These revetments were designed for a life of 15 years, provided regular maintenance is performed. The crest elevation of the revetment is at 14 feet above mean lower low water[48] (MLLW) to protect against storm surge and waves.

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[43] A revetment is an overlay of stone or other materials used to provide protection to an embankment

[44] USACE 2006

[45] Glen Gray and Associates 2010

[46] Image source: USACE

[47] Glen Gray and Associates 2010

[48] Mean Lower Low Water is a low water datum calculated as the average tidal height of lower low water for a location with a diurnal tide (i.e. two high tides and two low tides per day). Thus, in a tidal cycle consisting of two high tides and two low tides per day the lowest of the low tides is used in the calculation.

Figure 11: Erosion along the Chukchi shoreline[49]

Figure 12: Kivalina's Rock Revetment[50]

Although there are plans to move the town, one of the Kivalina re-location feasibility study alternatives analyzed by USACE[51] involved significant yet costly improvements to the shoreline protection around Kivalina allowing it to remain at its current location. Although it is highly unlikely the town would remain in place through the end of the century, use of Kivalina Airport as a case study was selected in collaboration with AKDOT&PF as being representative of other similar erosion related issues at other villages. Thus, the study is used to illustrate the application of the 11-Step Process to a typical infrastructure asset, namely an airport, with significant vulnerability due to climate change.

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[49] Image source: USACE

[50] Image source: USACE

[51] USACE 2006

Environmental Context

As discussed above, Kivalina is located on a barrier island separating Kivalina Lagoon from the Chukchi Sea (see Figure 9). The width of the barrier island varies along its length but, based on an aerial photo in Google Earth dated June 20, 2009, generally ranges from a minimum width of about 330 feet along some areas at the airport to a maximum width of about 920 feet near the north end of the town. The sea in the vicinity of Kivalina has historically been ice free from early July through late October but recently the ice departs earlier and arrives later.[52,53]

A study of winds in the Arctic and Chukchi Seas[54] indicates a strong seasonality in wind speeds with minimum average winds in May and maximum average monthly winds in October. Both the mean wind speeds and 95th percentile wind speeds follow this same seasonal trend. In addition, over the course of the study from 1979 through 2009, wind speeds are increasing, including both the mean and 95th percentile winds. Extreme events in October show an eight percent increase over those in 1979. These results agree with shoreline erosion experience at Kivalina[55] where the more intense storms impacting the coast tend to occur in the fall while in the spring and summer milder conditions coupled with beach accretion occur. These two factors, increasing wind speed and reduced sea ice in the fall, can both contribute to more frequent and larger wave conditions in the area.

Erosion in the vicinity of Kivalina, including net longshore sediment transport[56] and episodic storm related events,[57] is summarized below. Longshore transport is documented to be from north to south at the Red Dog Dock several miles south of Kivalina based on field experience since construction of the facility. Longshore transport well to the north of Kivalina at Point Hope (see Figure 8) has been reported to be from south to north. At Kivalina, the transport of gravel has been reported to be from north to south[58] due to large storms from the northwest that overpower the relatively steady, but weaker, northward flows and cause net transport to the south. Because of this southward transport, local borrow sites for sediment for Kivalina shoreline repair are recommended at locations south of the lagoon entrance.[59] Use of sand from the beaches fronting Kivalina and the airport have been implicated in exacerbated erosion related problems.[60] In recognition of this, sources of sediment for any future costal protection efforts sources should be obtained from locations other than the beaches adjacent to Kivalina or the airport on either side of the barrier island. Episodic erosion events attributable to particular storms[61] include a storm in 2004 that eroded 39 feet of beach near the school principal's residence in Kivalina. In 2005 a storm eroded 69 feet of beach near the school and to within 13 feet of the airport.

Long term accretion and erosion trends in the vicinity of Kivalina were developed using aerial photo

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[52] Glen Gray and Associates 2010
[53] Wang 2012
[54] Stegall 2012
[55] Carter and Smith 2015
[56] Longshore sediment transport is primarily generated by waves approaching the shoreline at an oblique angle resulting in the development of a wave induced current parallel with the shoreline which, when combined with the wave induced agitation, can mobilize and transport significant quantities of sediment along the beach
[57] Glen Gray and Associates 2010
[58] USACE 2007
[59] Glen Gray and Associates 2010
[60] Stegall 2012
[61] Stegall 2012

analysis from 1952 to 2003.[62] The study area included approximately 21 miles of shoreline centered on Kivalina. The results show both areas of erosion and accretion in the vicinity of Kivalina. Overall, along the entire study shoreline area, the maximum shoreline erosion is approximately 200 linear feet and the maximum shoreline accretion is approximately 100 linear feet. Seaward erosion was 76 acres and seaward accretion was 49 acres with average seaward linear erosion reported to be 10 to 35 feet. Thus, the overall trend on the seaward side is erosion which appears to be consistent with erosion trends and associated damage at Kivalina over the past 10 years. On the lagoon side of the study area, 11 acres of accretion and three acres of erosion occurred for a net reported accretion of eight acres.

Tides are available at the NOAA gauge located at Red Dog Dock (see location in Figure 8).[63] The dock is located approximately 16 miles southeast of Kivalina at the Delong Mountain Terminal which serves the Red Dog Mine. As shown in Table 1, tides are relatively small with a diurnal range (mean higher high water [MHHW][64] to MLLW) of 0.9 feet. The period of record for the gauge is August 2003 through the present. However, within this relatively short time span the maximum measured water level reached 6.9 feet above mean sea level (MSL).

Table 1: NOAA Tidal Datums for Red Dog Dock[65]

Tidal Datums	MSL (ft)
MHHW	0.44
MHW	0.34
MSL	0.00
MLW	-0.32
MLLW	-0.44
NAVD88	-3.0[66]
Highest (2011-02-25)	6.97
Lowest (2005-11-09)	-6.22

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[62] NOAA 2014a

[63] NOAA 2014b

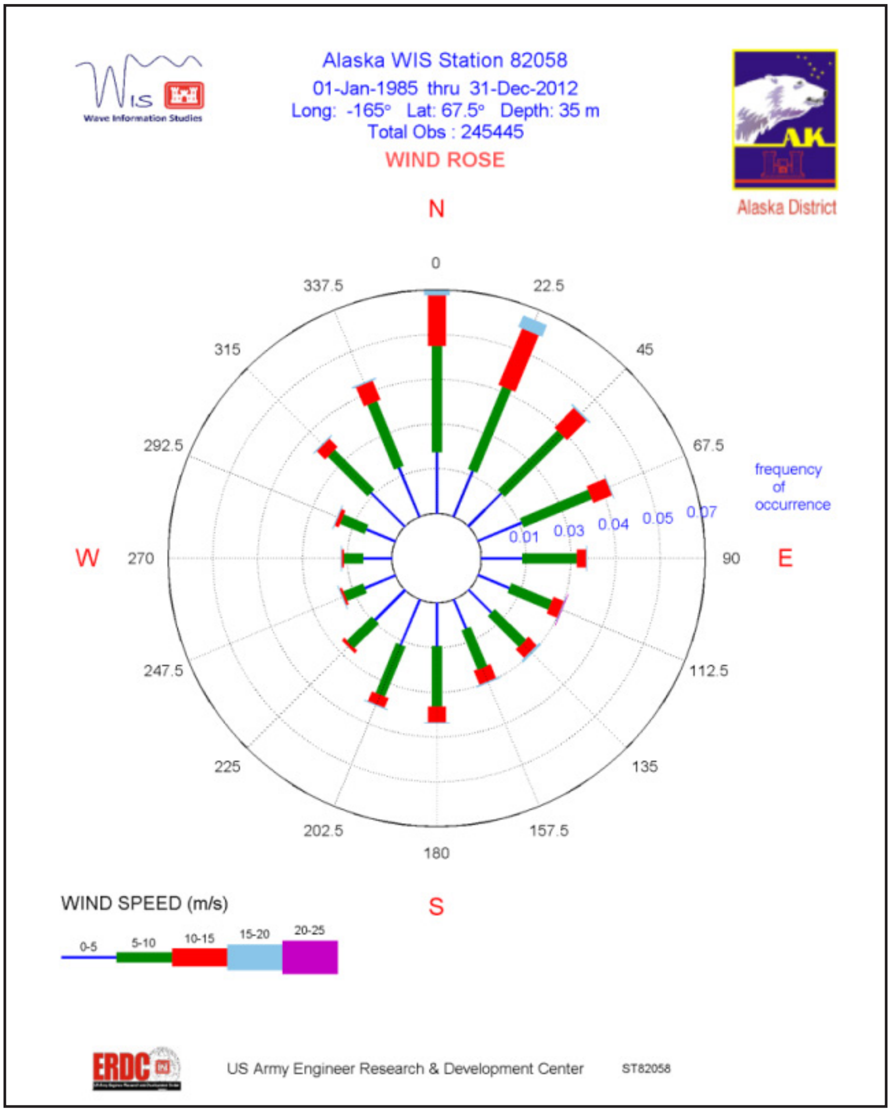
[64] Mean Higher High Water is a high water datum calculated as the average tidal height of higher high water for a location with a diurnal tide (i.e. two high tides and two low tides per day). Thus, in a tidal cycle consisting of two high tides and two low tides per day the highest of the high tides is used in the calculation.

[65] Station number 9491094

[66] Information relating MSL to NAVD88 for Kivalina obtained from Tschetter 2014

Wind measurements in the area are available from the meteorological station at the Red Dog Dock and provided through NOAA. Historical winds are available at the offshore USACE Wave Information Study (WIS) stations. This wind information is developed using historical observations for use in the WIS wave hindcast.[67] A wind rose from WIS station number 82058 is provided below in Figure 13.

Figure 13: Wind Rose from USACE WIS Station 82058



Offshore waves measurements were not available for this study. Instead, the USACE WIS hindcast waves from Station 82058 were used. A wave rose from this station is provided below in Figure 14. The influence of the longest fetch distances from the site to the southwest and northwest are evident in the wave rose as compared to the wind rose.

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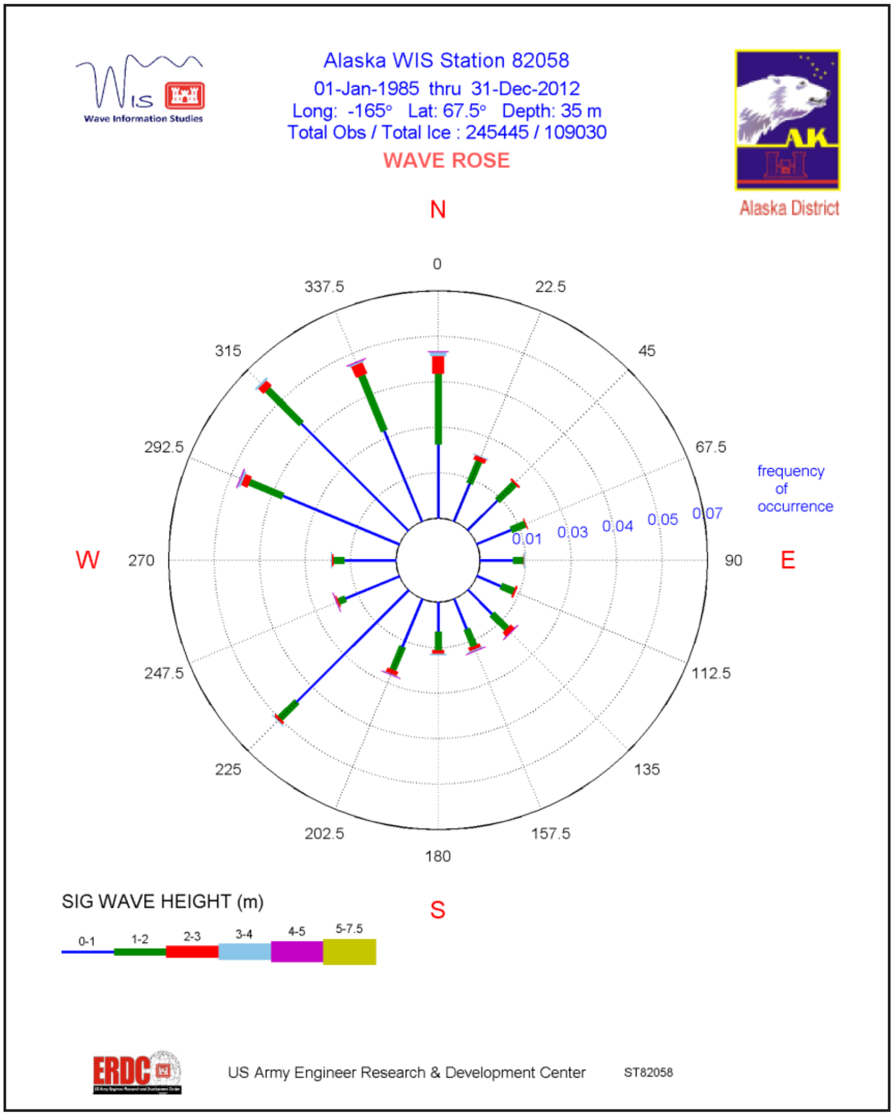
[67] Wave hindcasting refers to the use of a numerical wave model with the historical winds to calculate waves which would have occurred at that time.

Figure 14: Wave Rose based on USACE WIS Hindcast from Station 82058



A recent storm surge study[68] includes Average Recurrence Interval (ARI) surge levels for Kivalina: these are summarized below in Table 2. This study includes the primary storm surge components such as atmospheric pressure, wind, and current effects. The analysis does not include wave effects such as wave setup or runup.

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[68] Chapman, Kim, and Mark 2009

Table 2: Kivalina Storm Surge Frequencies[69]

ARI (Years)	Surge (Ft., MLLW)	Standard Deviation (Ft.)
5	3.67	0.33
10	4.58	0.36
15	5.17	0.56
20	5.67	0.69
25	5.96	0.69
50	6.91	0.89
100	7.77	1.08

STEP 2—DESCRIBE THE EXISTING FACILITY

The Kivalina Airport was constructed in 1960. The airport lies northwest of the town on the spit and is bounded on the southwest by the Chukchi Sea and on the northeast by Kivalina Lagoon (see Figure 9). The airport is owned and maintained by AKDOT&PF. The airport property fronts approximately 6,500 feet of beach. It consists of a 60 foot by 3,000 foot gravel runway, a 45 foot by 1,600 foot gravel taxiway, an apron, and ancillary structures such as lighting, an electrical equipment enclosure, fuel tanks, a snow removal equipment building (SREB), and a storage building (see Figure 15).[70] Reported runway elevations[71] vary from 16.1 feet[72] at the northwest end of the runway up to a high point of 18.4 feet then down to an elevation of 17.8 feet at the southeast end of the runway. In comparison, the homes in Kivalina are located between 10.4 feet and 13.4 feet above NAVD88.[73,74]

Geotechnical information gathered from the site[75] indicates gravel to fine sand on the alignment of the runway below grade at elevations consistent with the beach in the shoreline and extending into the surf zone. This material underlying the airport is anticipated to be similar to that comprising the beach.

Evidence of erosion is visible along the southern part of the runway in Figure 9 and is highlighted below in Figure 16. Both figures show the emergency protections constructed in 2005 which still remain as of April 2015. In addition, the USACE recently installed an armored revetment around the town of Kivalina beginning at the inlet to Kivalina Lagoon and extending to the northwest along the shoreline.

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[69] Chapman, Kim, and Mark 2009

[70] AKDOT&PF. 2014.

[71] FAA 2015

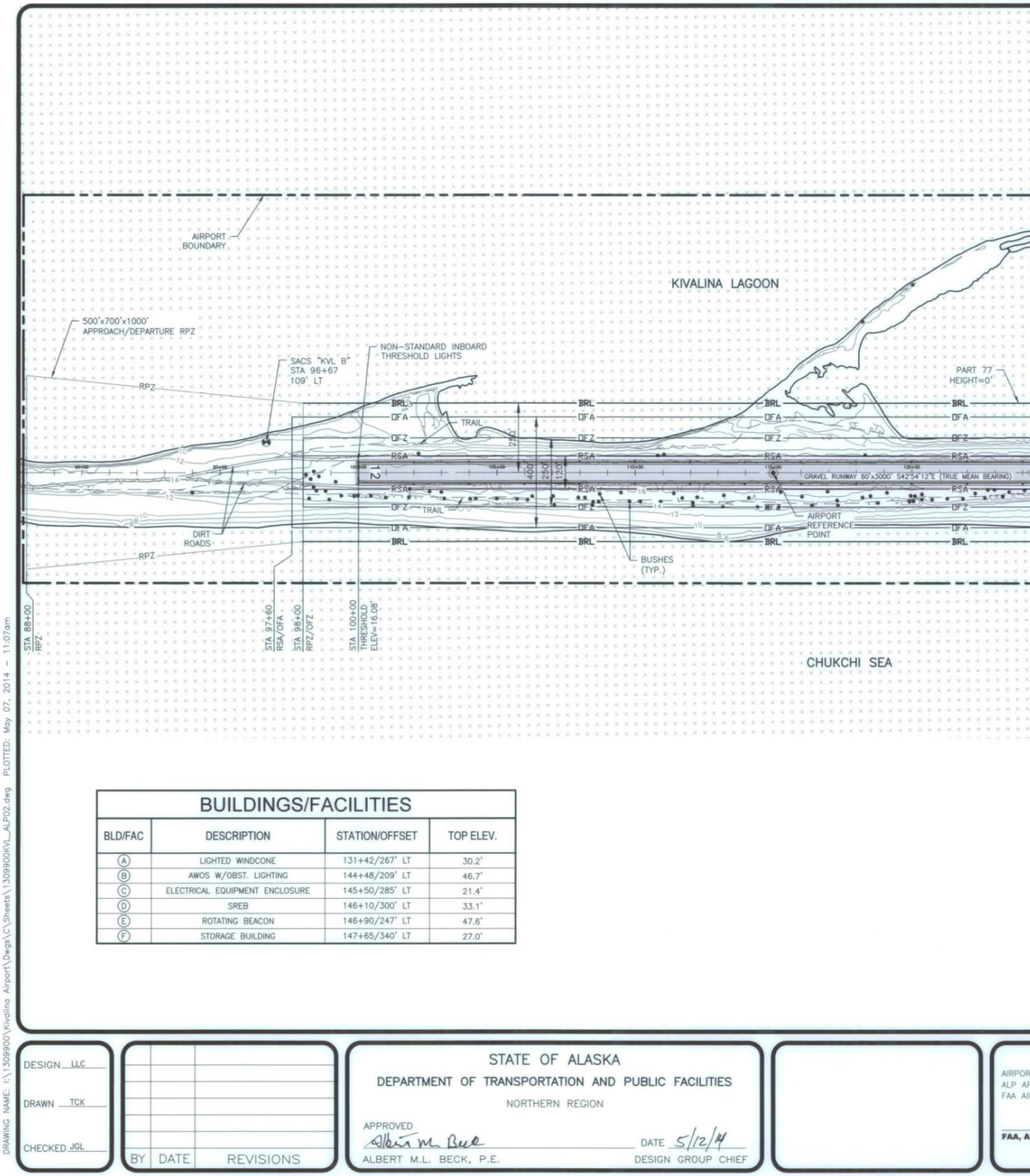
[72] Note: All airport elevation measures are expressed in the North American Vertical Datum of 1988 (NAVD88)

[73] NOAA 2014a

[74] Glen Gray and Associates 2010

[75] Shannon & Wilson 1982

Figure 15: Kivalina Airport Plan[76]



DRAWING NAME: I:\1309900\Kivalina Airport\Dwgs\C\Sheets\1309900KVL_ALP02.dwg PLOTTED: May 07, 2014 - 11:07am

BUILDINGS/FACILITIES

BLD/FAC	DESCRIPTION	STATION/OFFSET	TOP ELEV.
Ⓐ	LIGHTED WINDCONE	131+42/267' LT	30.2'
Ⓑ	AWOS W/OBST. LIGHTING	144+48/209' LT	46.7'
Ⓒ	ELECTRICAL EQUIPMENT ENCLOSURE	145+50/285' LT	21.4'
Ⓓ	SREB	146+10/300' LT	33.1'
Ⓔ	ROTATING BEACON	146+90/247' LT	47.6'
Ⓕ	STORAGE BUILDING	147+65/340' LT	27.0'

DESIGN LLC
DRAWN TCK
CHECKED JGL

BY | DATE | REVISIONS

STATE OF ALASKA
DEPARTMENT OF TRANSPORTATION AND PUBLIC FACILITIES
NORTHERN REGION
APPROVED Albert M. Beck
DATE 5/12/14
ALBERT M.L. BECK, P.E.
DESIGN GROUP CHIEF

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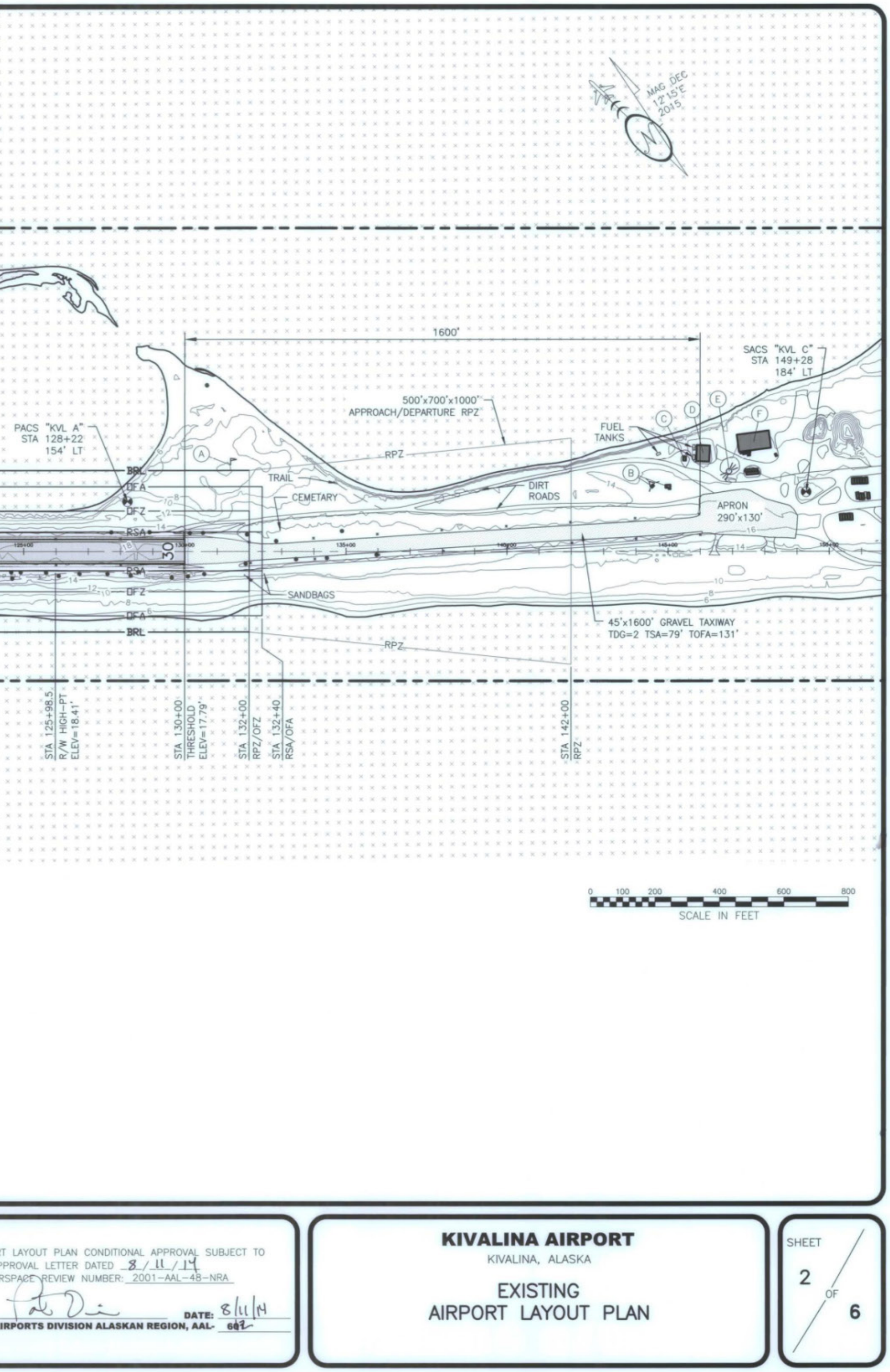
76 Image source: AKDOT&PF 2014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PPROVAL LETTER DATED 8 / 11 / 14
RSPACE REVIEW NUMBER: 2001-AAL-48-NRA
DATE: 8/11/14
IRPORTS DIVISION ALASKAN REGION, AAL- 602
KIVALINA AIRPORT
KIVALINA, ALASKA
EXISTING
AIRPORT LAYOUT PLAN
SHEET
2
OF
6

Figure 16: Aerial photo of Kivalina Airport Showing Emergency Repairs Constructed in 2005[77]

STEP 3—IDENTIFY CLIMATE STRESSORS THAT MAY IMPACT INFRASTRUCTURE COMPONENTS

Wind, sea ice extent, and sea level rise are the primary environmental factors affecting water levels and erosion at the airport; each of these factors is expected to be affected by climate change. Wind affects storm surge as well as wind wave development. Sea ice extent can limit wind wave development and reductions in sea ice, as currently documented,[78] can lead to larger and more frequent waves for a given wind. Sea level rise can cause increased erosion and revetment damage due to reduced freeboard and larger depth limited waves in the vicinity of the shoreline or toe of the revetment. Sedimentation, including sediment supplies, sinks, longshore and cross shore transport,[79] are all additional factors that will have a significant impact on the long term stability of the Kivalina shoreline. However, there is little information or field data at this time from which to assess and analyze such effects: these should be considered in future more detailed studies for the airport. For this study, the data sources for wind, sea ice, and sea level rise will be used to assess climate change related impacts to the shoreline.

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[77] Image source: Google Earth (as modified)

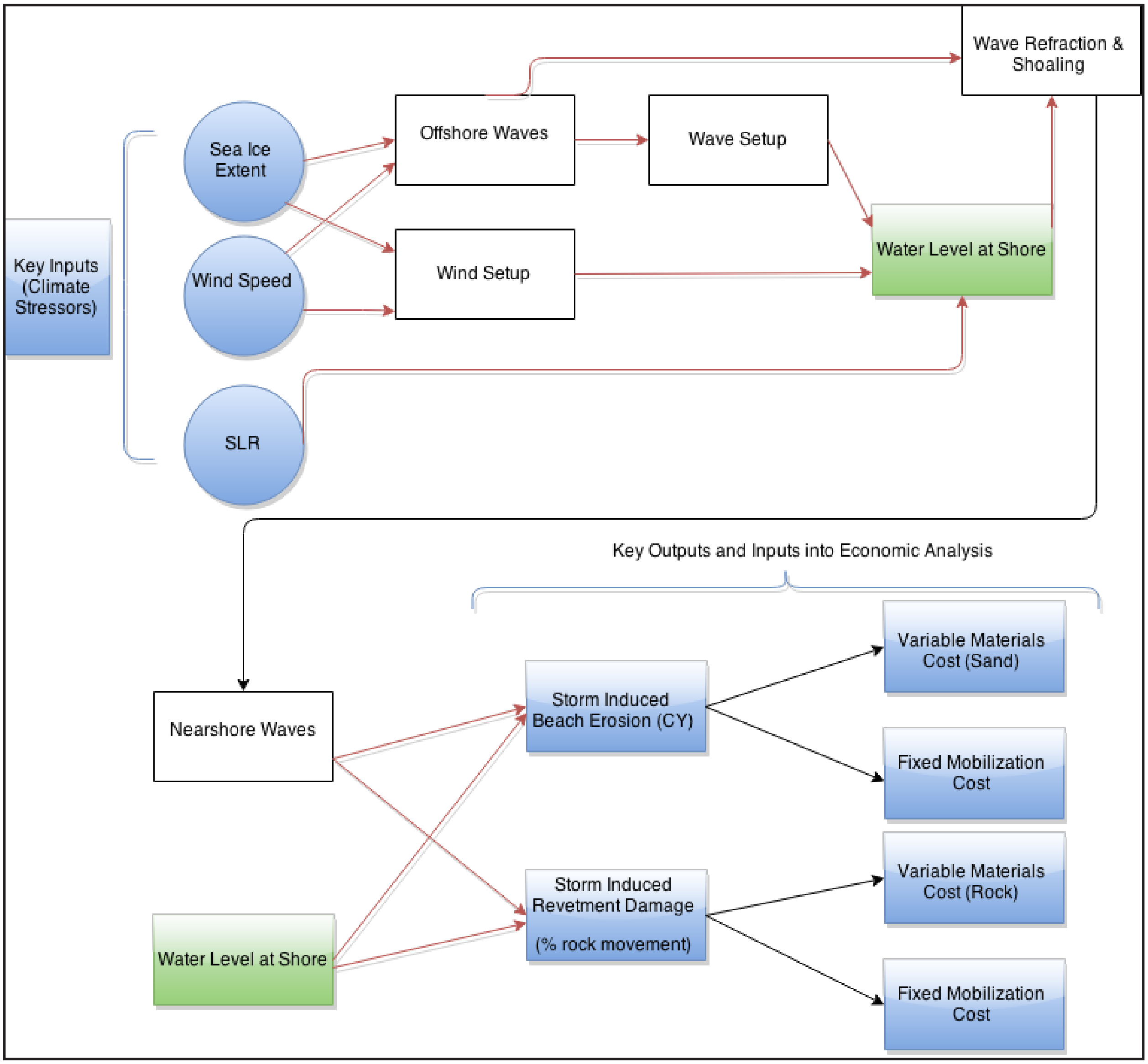
[78] Overeem et al. 2011

[79] Cross shore transport of sediment is primarily dependent on water level and wave conditions and tends to result in offshore transport during storm conditions and onshore transport during mild wave activity

STEP 4—DECIDE ON CLIMATE SCENARIOS AND DETERMINE THE MAGNITUDE OF CHANGES

The approach used to model erosion impacts to the airport under climate change consisted of a cross-shore sediment transport model which calculated the erosion distance and volume of material lost under storm conditions. The model incorporates inputs on high water levels and wave action associated with storms. The overall approach is illustrated in the flow chart shown in Figure 17 for both the existing beach and a revetment adaptation option (discussed further in Step 6). The remainder of this section describes the development of the climate change-influenced storm surge and wave projections used in the modeling effort. Step 5 then describes how this storm information is used to estimate erosion and damage to the airport.

Figure 17: Flow Chart Illustrating the Steps used in the Beach Erosion and Revetment Damage Model



Development of Climate Stressor Projections

Greenhouse Gas Emissions Scenario Utilized

As discussed in Chapter 2, the latest International Panel on Climate Change (IPCC) report[80] utilizes various scenarios, called Representative Concentration Pathways (RCPs), to capture possible greenhouse gas (GHG) emissions trajectories throughout the 21st century. The emission scenario time series that are developed using the RCPs are then analyzed in GCMs resulting in climate change projections for temperature, precipitation, sea ice extent, and sea level rise among others. The four RCPs used in the IPCC report include RCP 2.6 (low GHG emission scenario), RCP 4.5 and 6.0 (intermediate scenarios), and RCP 8.5 (highest greenhouse gas emission scenario). The numerical values associated with each RCP represent values of radiative forcing (a measure of the degree of warming caused by the greenhouse gases) at the end of the century (2100) in watts per square meter.

Based on the scope of this study and limited ice extent data availability, only one climate change scenario, RCP 8.5, was analyzed for this project. This is intended to serve as a demonstration of how an assessment could be performed for a single future climate scenario; the same approach used here could then be repeated for other scenarios. For an actual detailed assessment of the airport that will inform future investment decisions, analysis of a wider range of climate scenarios is recommended to capture the full range of uncertainty regarding future climate and to better inform decision-making. Note that this would require procurement and analysis of additional ice data beyond that currently available through the Scenarios Network for Alaska Planning (SNAP) web site.

Climate Models Utilized

For purposes of this assessment, ice extent was obtained from the ACCESS model data set posted on the SNAP web site. The ACCESS model provides sea ice data from 2006 through 2100. Daily averaged directional winds were obtained from the GFDL model data set posted on the SNAP web site with projections available from 2006 through 2100. Additional sea ice and wind models are available and should be used for a full assessment of the site. Multiple models should be used since each model provides different patterns of outputs (given the same inputs) based on different assumptions of how the Earth's climate system works. Multiple models were not included in this assessment due to scope limitations. Incorporation of different model outputs, within a given climate scenario, can be accomplished for this type of analysis through either testing the various discreet combinations of sea ice and wind models independently (a technique that can quickly become laborious given the number of possible combinations) or by first deriving grids of the median (or some other percentile output) sea ice and wind outputs from across the models cell-by-cell and then analyzing a single combination of the median sea ice and median wind outputs to get future surge and wave conditions. Examples of efforts to include climate change in a comprehensive coastal vulnerability assessment include the recently completed North Atlantic Comprehensive Coast Study for the United States East Coast[81] and modeling work on climate change related impacts to coastal erosion in northern Alaska.[82]

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[80] IPCC 2013

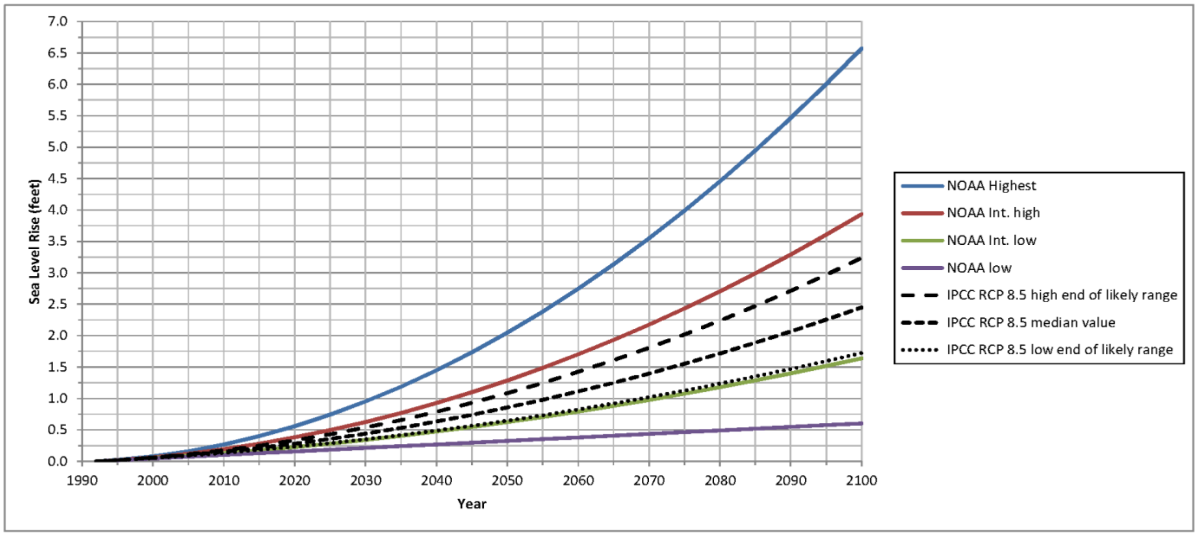
[81] USACE 2015b

[82] Ericksen 2015

Sea Level Rise Projections

Sea level rise projections based on the global mean from NOAA and the IPCC are shown in Figure 18. The high, mean, and low end of the RCP 8.5 scenario falls between the NOAA intermediate high and intermediate low projections. Unfortunately, there are no long term sea level measurements in the vicinity of Kivalina from which to assess the current local trends in sea level rise. Thus, sea level rise trends for this study were based on global average trends which are in reasonable agreement with long term trends measured at gauges located in Russia on its Chukchi Sea coast and Arctic coast.[83]

Figure 18: Global Average Sea Level Rise Projections from 1992 through 2100[84,85]



The projected sea level rise is based on a quadratic formula,[86] as used by NOAA, including a linear term equivalent to the current linear trend in sea level rise and a quadratic term based on the applicable climate change scenario. The IPCC reports sea level rise, for the climate change scenarios, at various times in the future. For this study, the quadratic term in the formula was fitted to match the reported sea level projections provided by the IPCC as shown in Figure 18. The curve for the IPCC RCP 8.5 median value, shown in Figure 18, was used in this study for sea level rise. For a more detailed study, multiple climate change scenarios and the range of results for a given scenario should be considered in developing the approach. Due to scope limitations for this study, only one projection of sea level rise is used.

Land subsidence and uplift information,[87] an important factor in determining relative sea level rise for a location, is shown below in Figure 19 indicating near zero values for the Kivalina area. Thus, the land is assumed to remain at a constant elevation through 2100 and no adjustments are made to sea level rise based on land movement.

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[83] Proshutinsky et al. 2004

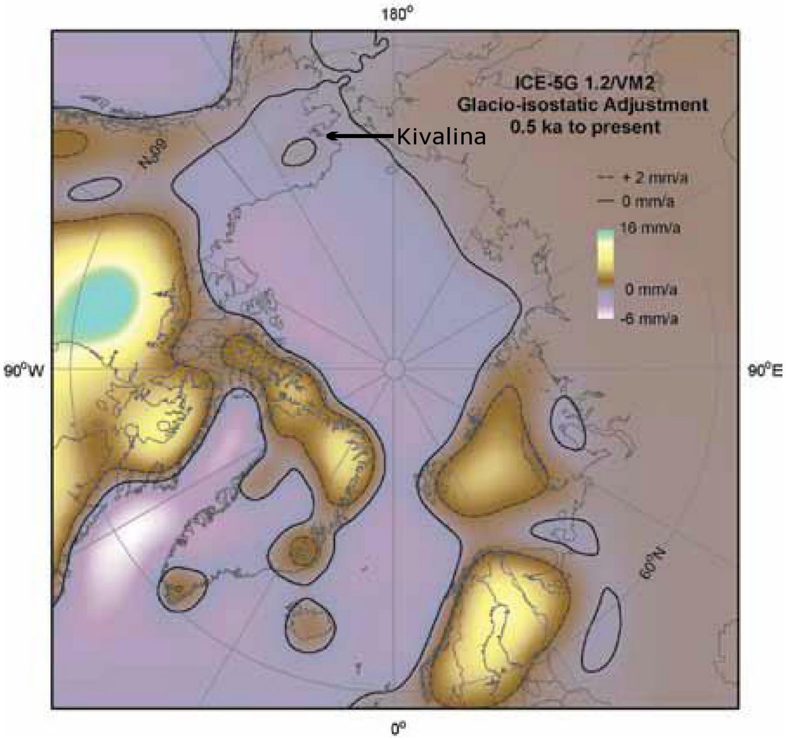
[84] NOAA 2012

[85] IPCC 2013

[86] NOAA 2012

[87] Forbes 2011

Figure 19: Land uplift and subsidence rates[88]



Sea Ice Projections

As discussed earlier, sea ice extent on a seasonal basis is decreasing.[89,90] Illustrations of the trends in ice coverage from 1960 through 2100 are shown in Figure 20 through Figure 24. These figures are based on historical data from 1960 through 2005 and the RCP 8.5 scenario for 2006 through 2100.[91] The historic data is obtained from the sea ice atlas available on the SNAP web site and is derived from 13 sources of information including the earliest records consisting of observations dating back to 1860 from whaling ships to the most recent information consisting of microwave sensor data. The ice data is reported each month of each year on a grid with the monthly averaged percentage of ice cover. For each of the following figures the monthly ice coverage was averaged over the number of years indicated. Each circle is a location where the ice cover projection data was queried for this study. These locations were selected since they lie along the fetch directions used in the wave analysis for this study. Three background colors inside the circles are used to indicate the percentage of ice cover. Dark blue indicates ice concentration of 15% or less, light gray indicates ice concentration between 15% and 50%, and white indicates ice concentrations above 50%.

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88 Forbes. 2011.

89 Glen Gray and Associates 2010

90 Wang 2012

91 SNAP 2015

Figure 20: Average Ice Coverage in January (1960—2005)

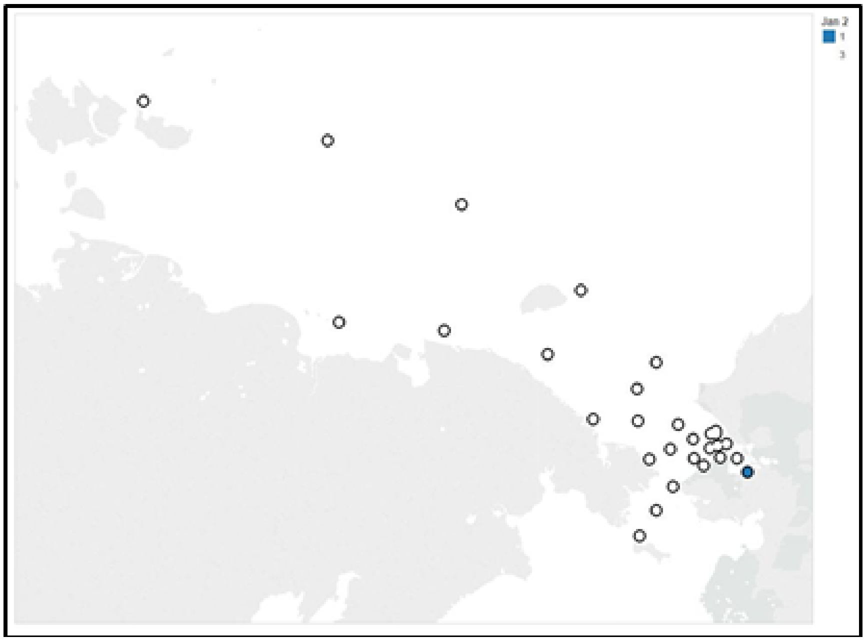
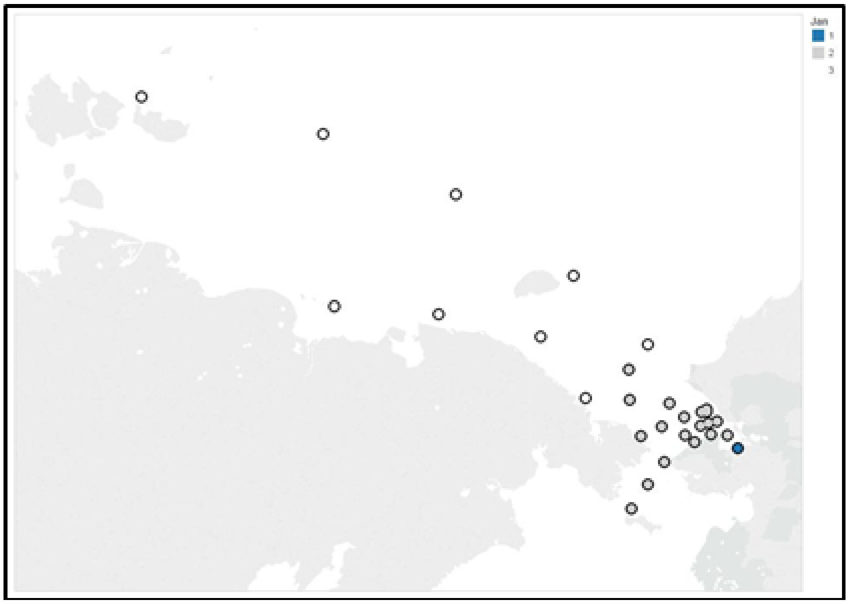


Figure 21: Average Ice Coverage in January (2006—2035)



Case Studies

Figure 22: Average Ice Coverage in January (2036—2065)

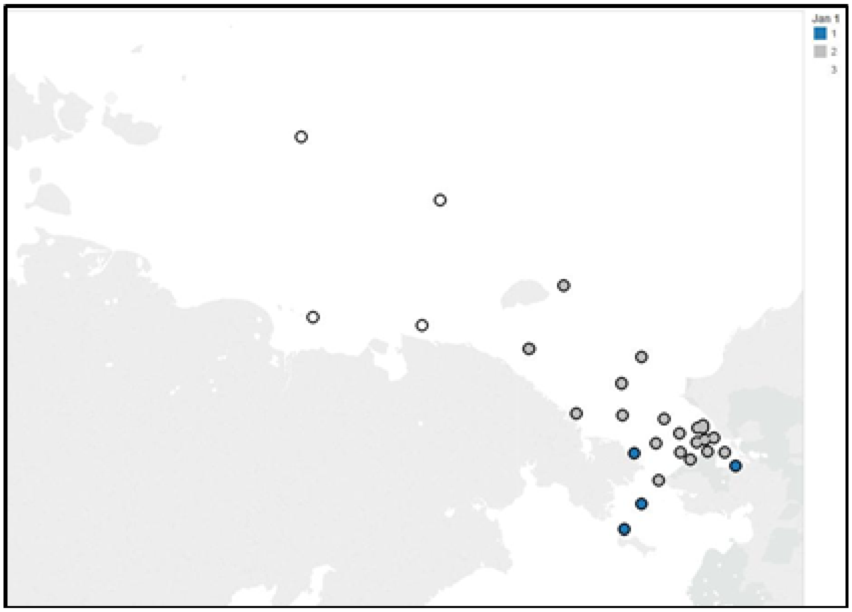


Figure 23: Average Ice Coverage in January (2066—2096)

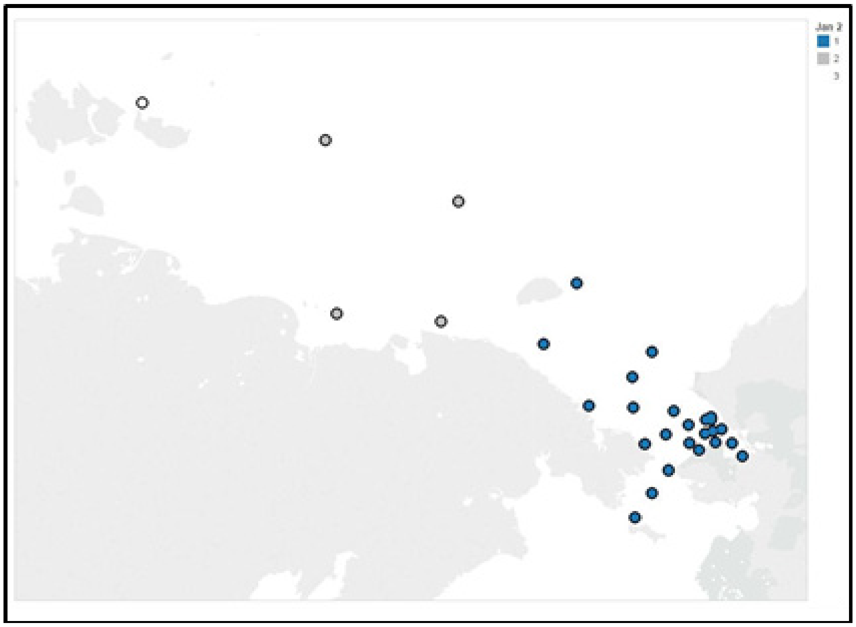
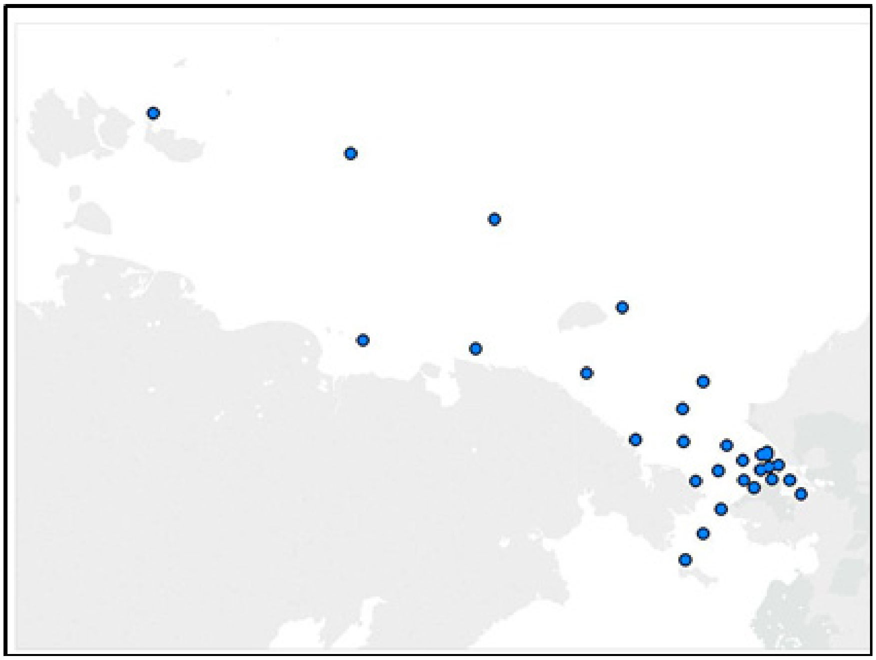


Figure 24: Average Ice Coverage in January (2097—2100)



In Figure 20 all locations have ice concentrations above 50% except the location nearest Kotzebue. In Figure 21 all the nodes in the Bearing Strait and most in the Chukchi Sea have ice concentrations less than 50%. By the end of the century, Figure 24 shows all nodes having average ice concentrations in January below 15%.

Wind Projections

Projected winds used for the study[92] include daily average winds on a directional basis. The winds are reported as daily averages in two principal directions, namely north and south. These were converted to a magnitude and compass direction for use in the study. The winds were separated into three thirty-year periods over the remaining 90 years of this century. The frequency and cumulative frequency of the winds are shown in Figure 25. The plot illustrates the rather modest increases in wind speed through the century. Projected increases in wind speed between the first and last period include an increase of seven percent for the 50th percentile winds and nine percent for both the 90th and 99.9th percentile winds.

Storm Surge and Wave Modeling

Offshore Wave Modeling

The USACE WIS[93] hindcast from Station 82058 was used to calibrate the wind wave model results. This WIS station is located about 20 miles southwest of Kivalina as shown in Figure 8. Fetch lengths for open water distances across which wind can generate wind waves were calculated. This was done across open water to the nearest land with the origin of each fetch length originating from WIS Station No. 82058 as shown in Figure 26 and Figure 27. The fetches were measured for increments of 10 degrees. For selected directions, the ice data was queried at several locations along each of the chosen fetches. These

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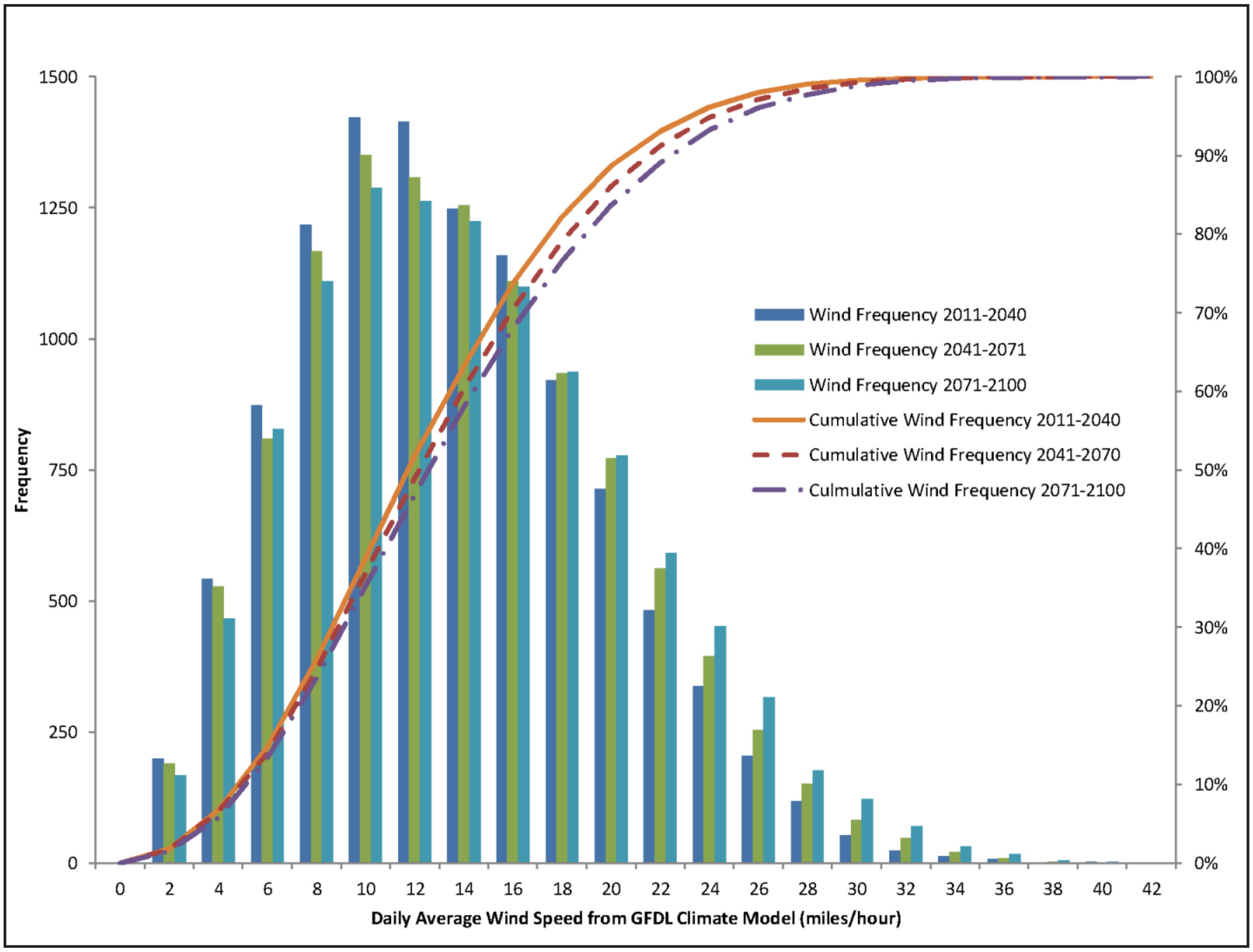
[92] SNAP 2015

[93] USACE 2015a

locations where the ice data was queried are shown as light blue dots in Figure 26 and Figure 27. The fetch available for wind wave generation was limited by the open water distance until a location is reached where the ice concentration exceeds 15% following recent work in the Arctic Sea on the effects of loss of sea ice on wind waves.[94] [95] For the remainder of the fetch length beyond this location, wave generation is assumed to be zero. The effect is an ice limited fetch distance that is used in the wave generation model.

Figure 25: Projected Changes in Wind Frequencies through 2100, GFDL Model, RCP 8.5



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94 Overeem et al. 2011

95 Glen Gray and Associates 2010

Figure 26: Locations (Light Blue Dots) where Ice Data was Queried to Identify Limitation of Fetch Length for Wind Wave Generation along Southeasterly to Southwesterly Fetches[96]

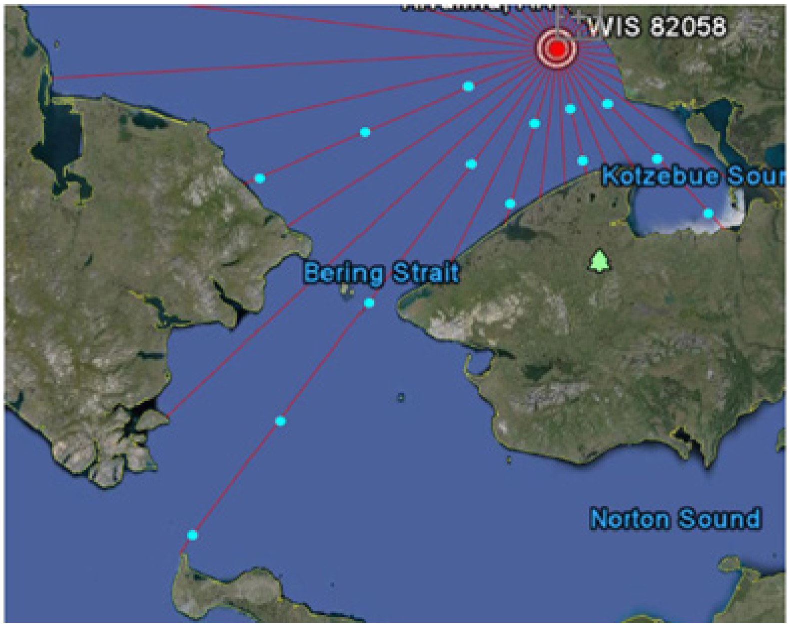
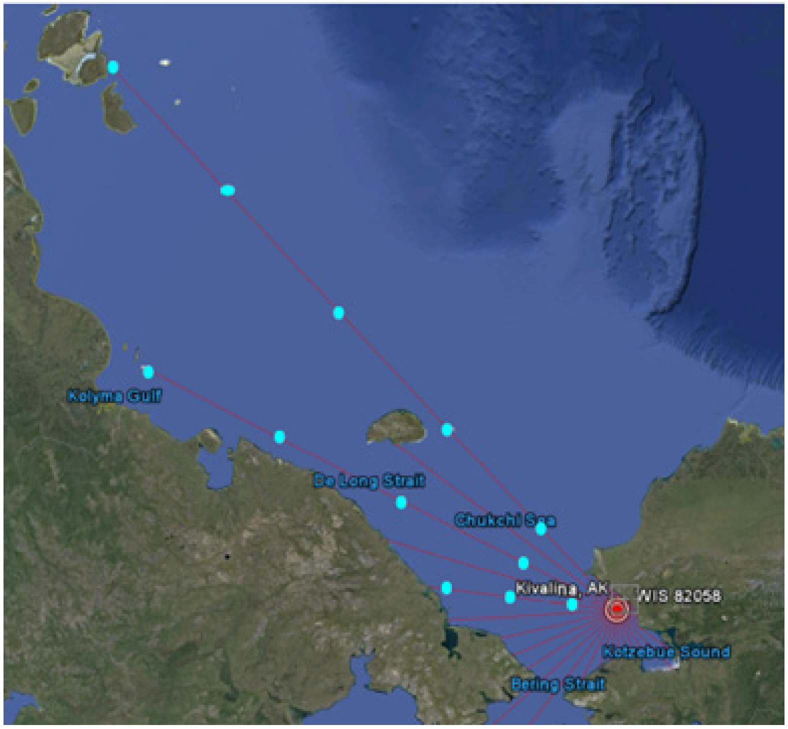


Figure 27: Locations (Light Blue Dots) where Ice Data was Queried to Identify Limitation of Fetch Length for Wind Wave Generation along Westerly and Northwesterly Fetches[97]



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[96] Image source: Google (as modified)

[97] Image source: Google (as modified)

The winds were converted from daily averaged components on an easting/northing basis to a magnitude and direction. The Sverdrup, Munk, and Bretschneider (SMB) wave model[98] was used to calculate waves at the WIS station using the ice restricted fetch lengths shown in Figure 26 and Figure 27 and the projected winds. The model includes adjustment of the wind duration based on the fetch length to identify the wind speed that produces the maximum wave height for a given fetch length. The SMB is a well-known empirical model for ocean wave generation given a fetch length, duration of wind, and wind speed. Other recent studies of wind waves in the Arctic Sea and Chukchi Sea have used similar empirical methods to calculate waves.[99,100]

Numerical modeling of wind wave development in the ocean as well as nearshore wave transformation to account for nearshore bathymetry is also commonly used, including recent work in the Chukchi Sea,[101] but was beyond the scope of this study. Such nearshore modeling efforts benefit from field data collection to document the bathymetry which is not available for this study. Ongoing work by the United States Geologic Survey (USGS) is underway in the northern areas of the Chukchi Sea and the North Slope but does not include the Kivalina area.[102] This work includes large scale ocean wave modeling, nearshore wave modeling, and storm surge modeling as part of a study that is motivated by ongoing coastal erosion in small local communities similar to Kivalina. As part of this work there are plans to collect LIDAR data in the Chukchi Sea including the Kivalina area but the data is not likely to be available until around 2017.

The SMB wave results were first calculated at the WIS station using the historic ice cover and wind data. The wave heights calculated using the SMB method were compared with the hourly maximum wave condition obtained from the USACE WIS station hindcast. The maximum events on an annual basis were then individually ranked according to wave height and plotted against each other. The data, including the hindcast and modeled waves, were individually ranked highest to lowest because the historic wind data from the SNAP dataset did not necessarily correlate with the winds reported from the hindcast on a given day. This difference, most likely due to the different data sources used for the wind, is reflected in a comparison of the wind from the SNAP data and from the hindcast. Although both wind sources are based on historic data, the methods used to develop the winds on a grid and other processing methods used to yield the time series result in some differences including the correlation on a day-to-day basis. The ranked wave data were plotted against each other as shown in Figure 28 along with a linear fit that provides an excellent calibration as illustrated by the correlation coefficient. After using the linear fit to calibrate the SMB model results, representing an increase in wave height of about 22%, the data is plotted using a histogram and cumulative frequency distribution as shown in Figure 29. Since in the future there is little concern whether a major event falls on a particular day, there is no loss of relevant detail in decoupling the timing of the data before calibrating it in this manner.

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[98] CIRIA, CUR, and CETMEF 2007

[99] Wang 2012

[100] Thomson and Rogers 2014

[101] Ericksen et al. 2011

[102] Ericksen 2015

Figure 28: Calibration Plot of Modeled Ocean Wave Heights using the SMB Method and the USACE WIS Hindcast

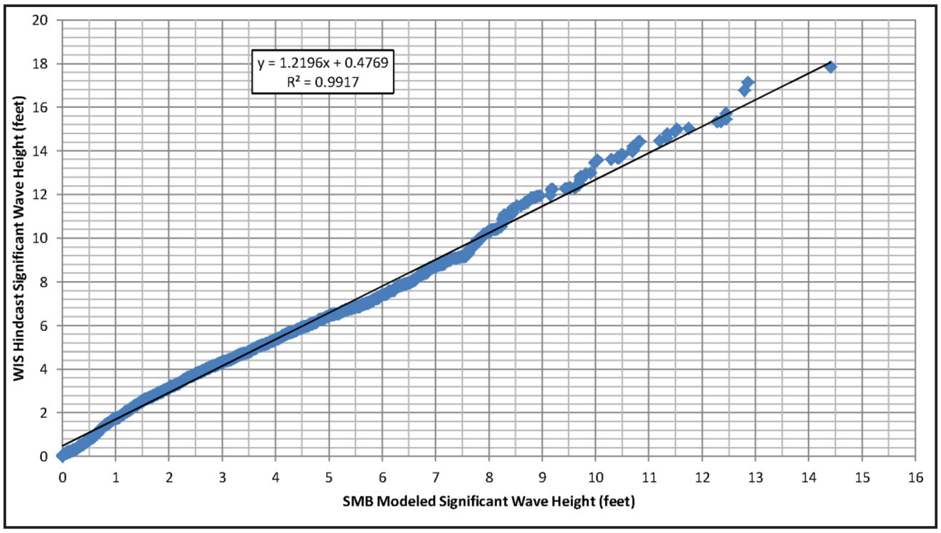
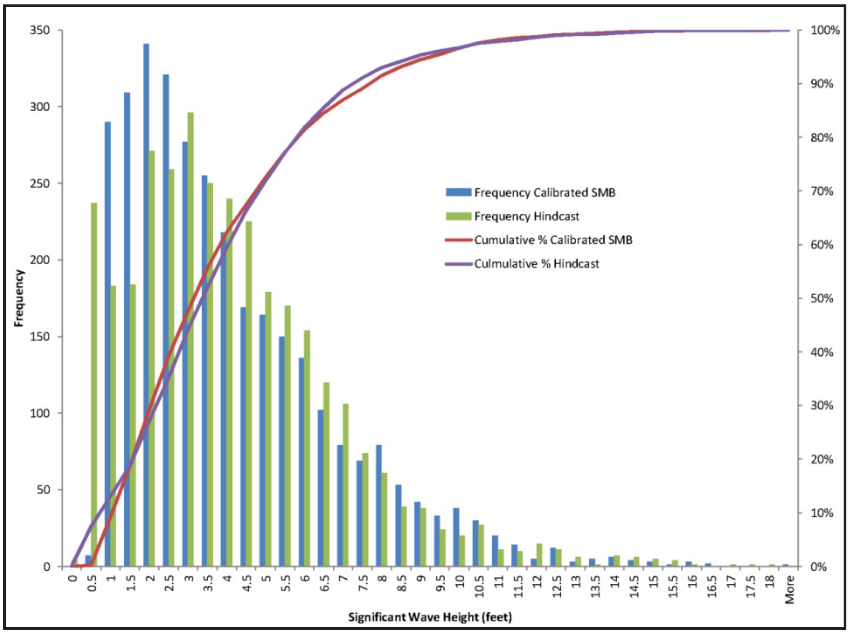


Figure 29: Histogram and Cumulative Frequency Plot of Calibrated SMB Wave Model Results versus the USACE WIS Hindcast Data



Storm Surge Modeling

The storm surge at the coast is calculated using a simplified procedure based on the wave setup. The Red Dog Dock tide gauge was used as the measured water surface for purposes of calibrating the storm surge. The significant wave height[103] at the WIS station calculated using the SMB method is multiplied by 17% following empirical relationships reported in the literature for wave setup at shorelines. This value of the wave setup was used in a calibration process with the Red Dog Dock tide measurements to identify a linear fit between the wave setup and the measured surge at the coastline.

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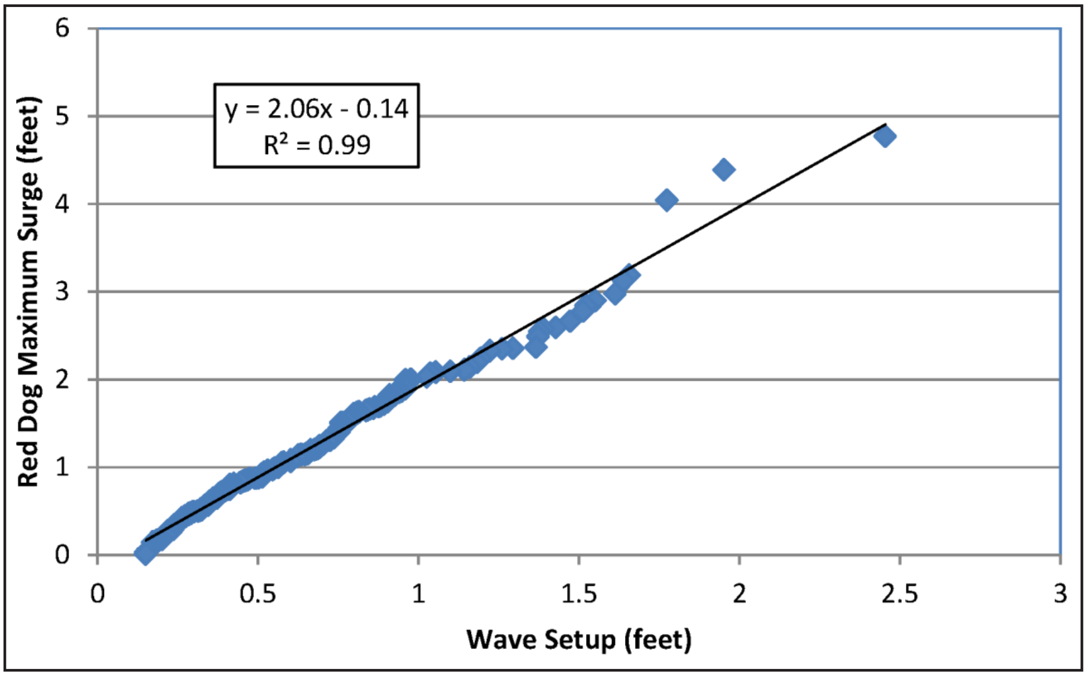
[103] The significant wave height can be calculated as the mean of the highest one third of waves in a random system of waves such as wind waves observed in the ocean. The significant wave is close to what an experienced observer would say the wave height is if asked to estimate it (Kinsman 1984).

The Red Dog Dock tide measurements were available from 2004 through 2012. The predicted tides were subtracted from the measured water levels and the resulting storm surges from this residual were used in the calibration process along with the wave setup. The SNAP wind directions were separated into 30 degree bands and only the bands involving along shore and onshore winds were used to calibrate the water levels.[104] The calibration plots showing the data and linear fits are shown in Figure 30 through Figure 36. The resulting correlation coefficients fall within the range of 0.86 to 0.99 with all but one direction at 0.93 or above. Although this is an extremely simplified method of estimating storm surge, it is judged to be adequate for this level of planning study. More intensive modeling of wind fields and associated hydrodynamics of storm surge[105] in the Chukchi Sea was well beyond the scope of this study but should be completed for an actual project.

Figure 30: Storm Surge Calibration Plot for Winds from 112.5 to 142.5 Degrees



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[104] For offshore winds, the storm induced water level effect would be a set down in water levels and this does not contribute to either revetment erosion or beach erosion in a way that would trigger damage or repairs

[105] Ericksen 2015

Figure 31: Storm Surge Calibration Plot for Winds from 142.5 to 172.5 Degrees

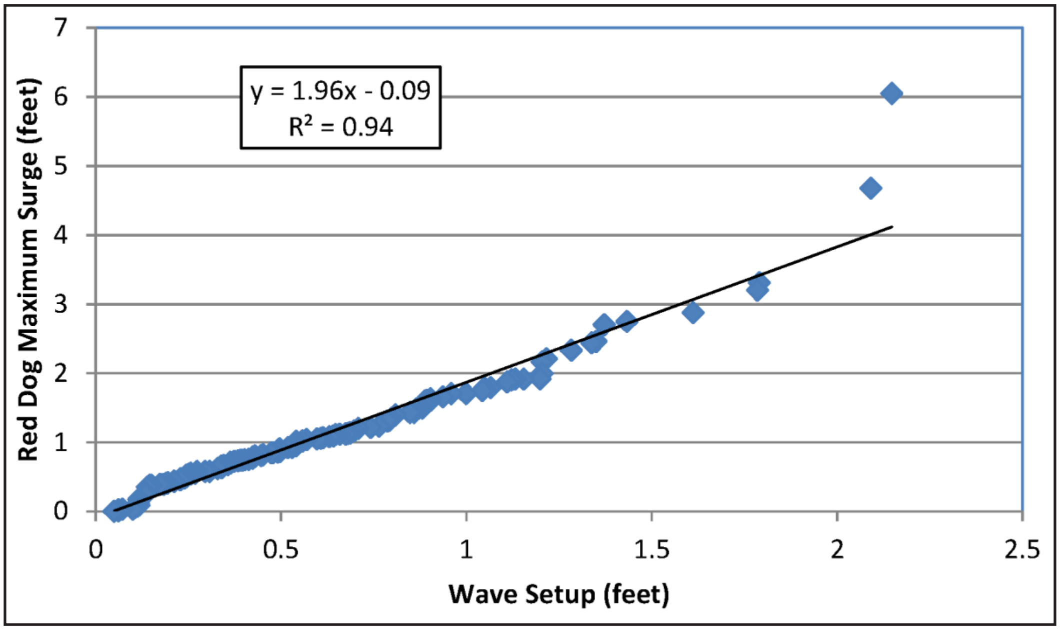


Figure 32: Storm Surge Calibration Plot for Winds from 172.5 to 202.5 Degrees

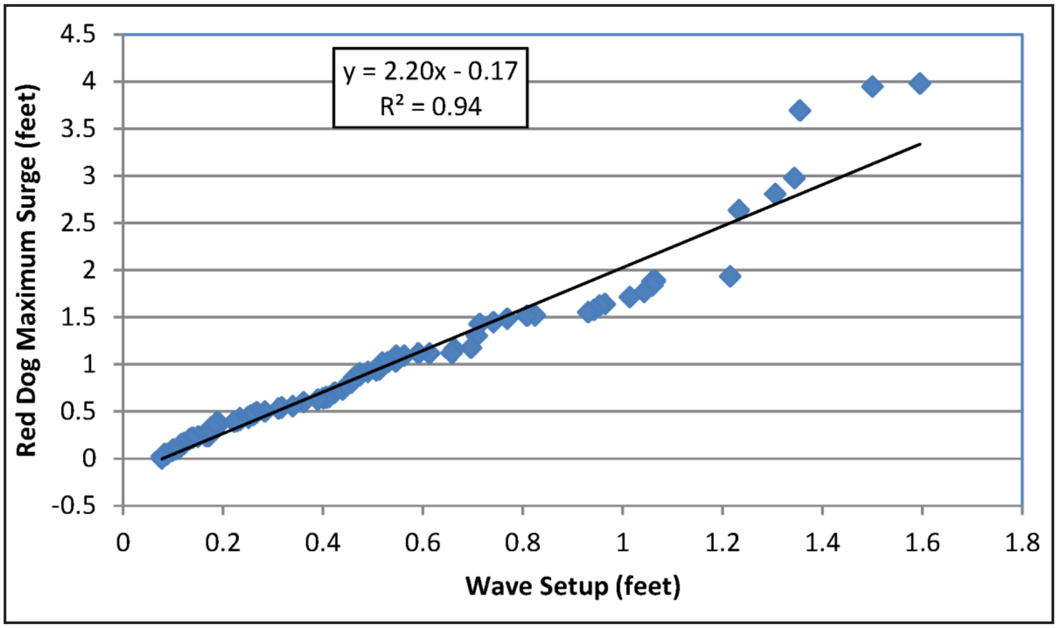


Figure 33: Storm Surge Calibration Plot for Winds from 202.5 to 232.5 Degrees

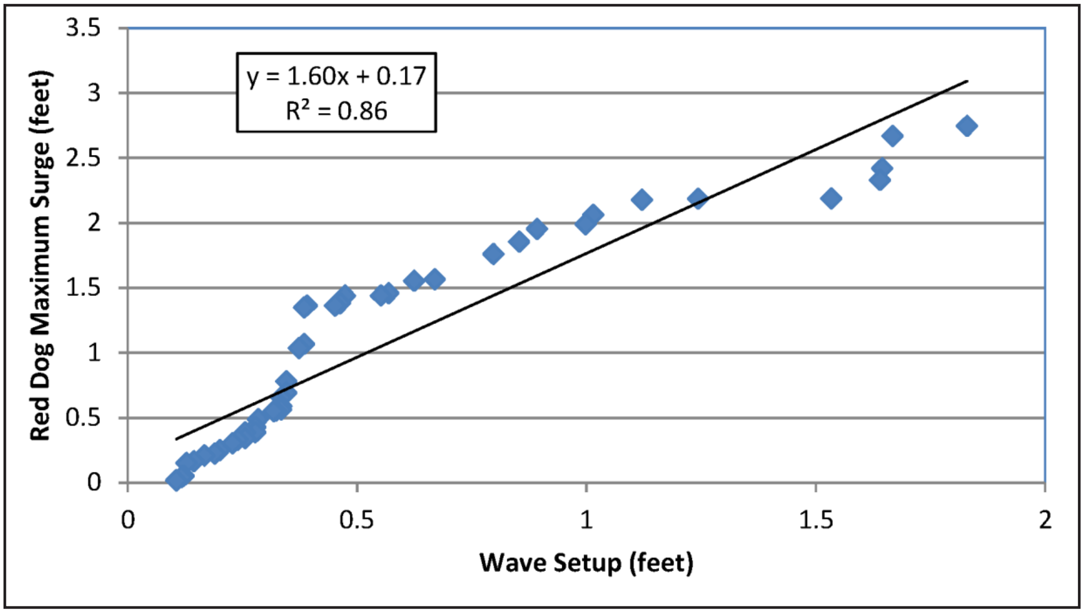


Figure 34: Storm Surge Calibration Plot for Winds from 232.5 to 262.5 Degrees

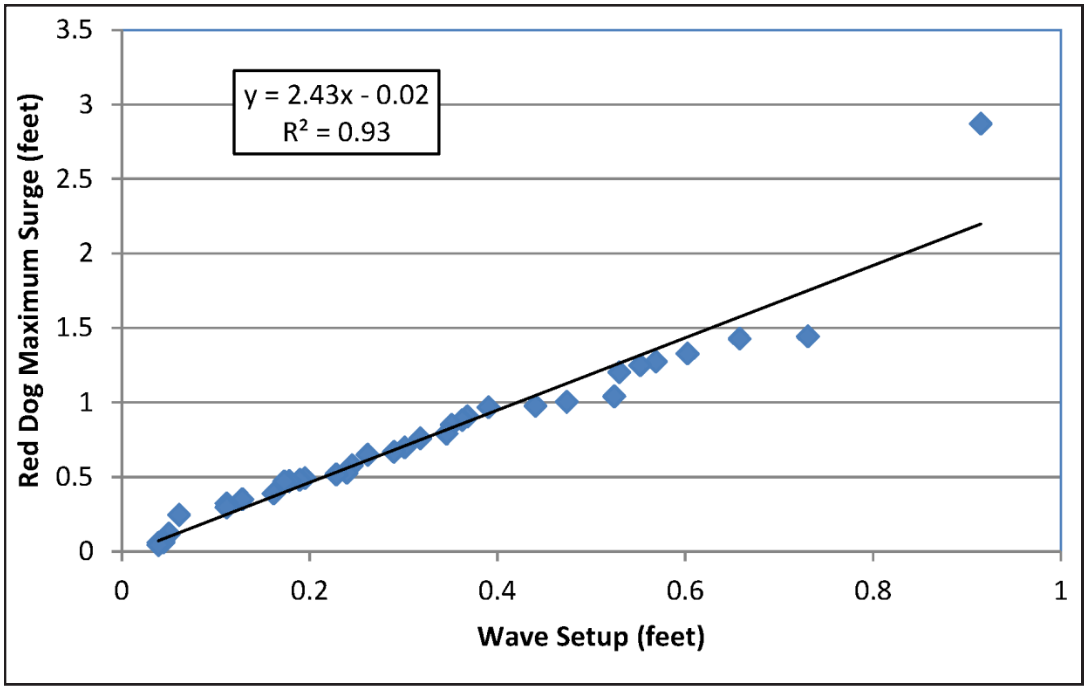


Figure 35: Storm Surge Calibration Plot for Winds from 262.5 to 292.5 Degrees

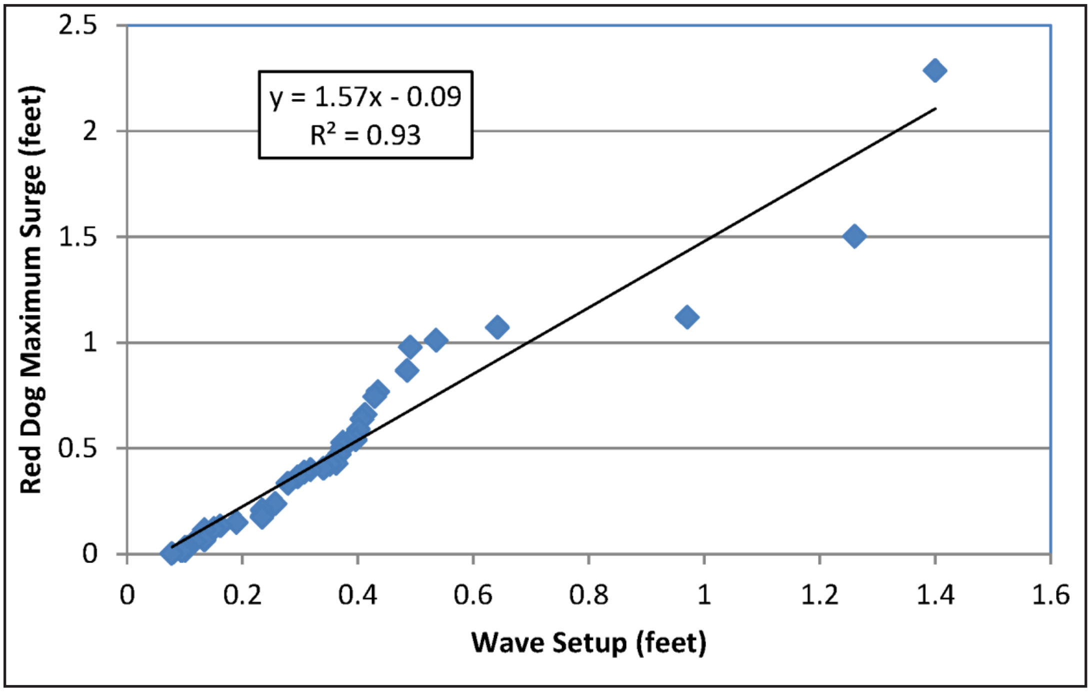
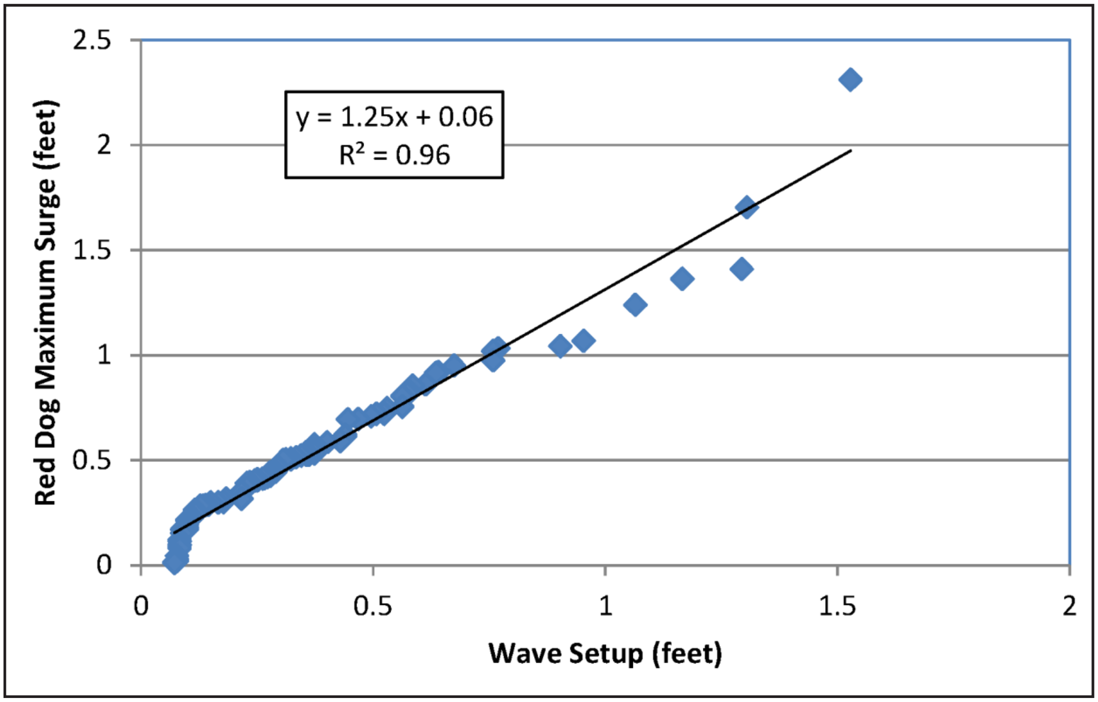
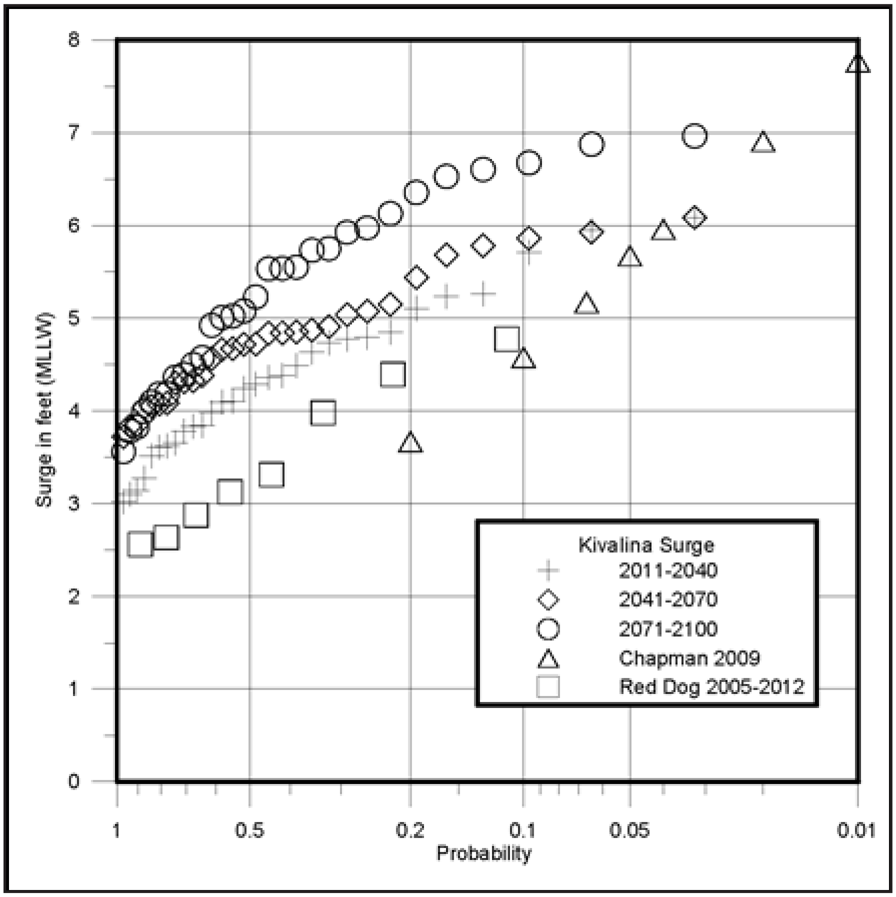


Figure 36: Storm Surge Calibration Plot for Winds from 292.5 to 322.5 Degrees



The surges were calculated over the century by using the SMB model to calculate the waves and the calibration formulas shown in Figure 30 to Figure 36 to calculate the surge. The results were separated into 30 year bins and the annual maximum surge was ranked and then plotted using the Weibull plotting position to assign a probability to each of the 30 values. The results are shown in Figure 37. Note that this plot only shows the effects of wind and sea ice extent. It does not include the effect of sea level rise. The results from the USACE storm surge study as well as the measured storm surge from the Red Dog tide gauge are included for reference and comparison. The model for storm surge used here produces surges that are significantly larger than the values reported by the USACE[106] for the lower probability events. However, the differences form the Red Dog Gauge results are not as large. This is most likely an artifact of the method using the wave setup as a signature for the storm surge. At a probability of 0.1 (10 year average annual return interval [ARI]), the results from the first period (2011-2040) are about 30 percent above the USACE results while at a probability of 0.33 (30 year ARI) the agreement is very close.

Figure 37: Annual Maximum Surges due to Projected Changes in Wind and Sea Ice Extent (Not Inclusive of Sea Level Rise) Ranked and Plotted using the Weibull Plotting Position



As shown in Figure 37, for the smaller surges with probabilities above 0.5 (two year ARI), the change in surge values is about 0.7 feet from the 2011-2040 period to the 2071-2100 period whereas for the more extreme events with probabilities of 0.1 and less (ten year and greater ARI) the difference from the first two periods to the 2071-2100 period is an increase in storm surge of about one foot. If sea level rise

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106 Chapman, Kim, and Mark 2009

is added to the surge, it will on average add, based on the mid-point of the 2011-2040 and 2071-2100 periods, an increase of about 1.4 feet. Therefore the effect of sea level rise over the sixty year period from the middle of the first period to the middle of the third period is only about 40 percent higher than the effect on the surge due to winds and sea ice extent.

Nearshore Wave Transformation

Using the calibrated wave heights based on the SMB method, a simplified approach was used to calculate the depth limited breaking wave height at the shoreline assuming the offshore bathymetric contours are straight and parallel. Waves are propagated to the beach accounting for refraction and shoaling per the implicit relationship presented in the Coastal Engineering Manual (CEM)[107] using Equation III-2-16. There are some bathymetric features offshore of Kivalina but to resolve the effect of these on wave propagation will require numerical wave modeling which is beyond the scope of this study. Such work, however, should be conducted for an actual project. The results of the simplified process applied here provide the wave height through the nearshore zone accounting for wave refraction and wave shoaling.

STEP 5—ASSESS PERFORMANCE OF THE EXISTING FACILITY

An assessment of the performance of the airport's beach to resist erosion can be conducted using detailed beach morphologic and coastal hydraulic related studies of the area. The morphologic changes can be used to assess beach response to changes in sediment supply and hydraulic stresses. Unfortunately, for this location, there is extremely limited information on beach morphology, primarily limited to historic aerial photos as discussed above. In addition, there is no information on the sediment supply or budgets along this shoreline. For a more detailed study, collection of this type of sediment transport related information should be considered including the possible effects of climate change on sediment supply.

Given data limitations, this analysis will focus on the hydraulic related stresses and their increasing propensity to cause erosion under projected climate change. As discussed in Step 4, sea level rise, reductions in sea ice extent, and changes in wind patterns lead to increased water levels (including those during storm surge) as well as more frequent and larger offshore wave conditions. In the nearshore area, sea level rise results in larger water depths and associated depth limited breaking wave heights at the toe of the protective structures (whether they be the existing beach along most of the airport or manmade shore protection such as the sand filled bags along approximately 430 feet of shore at the airport or the revetment along the town's shoreline). These wind and associated hydraulic related stresses due to water levels and waves can be analyzed to assess beach erosion for the existing condition or damage to manmade structures such as the revetments.

With this in mind, the depth limited breaking wave, beach profile, and beach sediment size were used with an empirical beach erosion model[108] to determine erosion at the airport's beach during storm events. This model and an example application are illustrated in the USACE Coastal Engineering Manual.[109] The model can be used to calculate the beach erosion (expressed as distance of retreat at the top of bank) and erosion volume for a given storm event. This model was used to calculate the beach erosion distance and volume for all storms.

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[107] USACE 2002

[108] Kriebel and Dean 1993

[109] USACE 2002

Information gathered from the site[110] indicates gravel to fine sand on the alignment of the runway. This information was used to guide the choice of beach material to be used in the model. A beach slope of 10% for the nearshore area was used based on a topographic survey of the area along the airport shown in Figure 15. The sediment size used in the beach erosion model was 0.01 inches: this is in the lower range of the grain size distribution reported for airport borings taken on the runway alignment.[111] Sand size versus beach slope data has been gathered from many locations including the Atlantic Coast of the United States which has similar (low energy) wave statistics as the hindcast data from the WIS station offshore of Kivalina used in this study.[112] A beach slope of 1:10 and grain size of 0.01 inches falls in the middle of the field data envelope on a plot of beach slope versus grain size for the United States Atlantic Coast. Thus, use of the sediment size of 0.01 inches for the 1:10 beach is consistent with field data at other similar low energy beaches. That said, this location is subject to ice whereas the Atlantic Coast of the United States is not. Although the beach profile shown in Figure 15 varies, it is about 1:10 in many locations and thus appears, in combination with the 0.01 inch sediment size, to be consistent with the United States Atlantic Coast beaches even though it's subject to ice cover in the Chukchi Sea many months of each year.

Some approximate beach erosion distances are reported[113] from actual storm events that can aid in assessing the accuracy of the erosion model. These include a loss of 40 feet of shoreline in 2004 and a loss of 70 feet in 2005. The reported erosion distances are likely maximum values relative to the overall shoreline erosion as these local maxima in the vicinity of Kivalina would be the most noticeable. Use of the 1:10 beach slope with the 0.01 inch sand assumptions in the erosion model yields predicted erosion distances from the 2004 and 2005 storms of 17 feet and 53 feet, respectively. These values are approximately 43% and 76% of the reported erosion distances noted above in 2004 and 2005, respectively. The erosion model yields values smaller than the reported values, which is reasonable, due to the maximum erosion values the reported distances likely represent. In addition, both values are within about a factor of two relative to the reported values. For a more definitive calibration more data would need to be collected along the coast after a storm so the "average erosion distance" representative of the model output can be compared against an average erosion distance calculated from the field data. This is an example of a data gap for the analysis consisting of beach profile data

on an annual, seasonal, and storm duration basis which could be used for calibration of the sediment transport model.

As illustrated in Figure 17, the process utilized to model the storm induced coastal erosion begins with the climate change projection data. The monthly averaged ice cover data is queried for any limitations on the fetch distance. For several months the sea in the vicinity of Kivalina is frozen and therefore in this case we assume incoming waves from outside the Kivalina area are dissipated by the ice cover and do not reach Kivalina. For times when Kivalina is not iced in, the fetch length, as affected by offshore ice, is determined and used, in combination with the wind data to calculate the wave conditions. The wave setup is calculated and then, using the wave setup to storm surge correlation shown in Figure 30 through Figure 36, the storm surge is calculated provided the wind is not in an offshore direction. With the storm surge and offshore wave conditions the information can be used to calculate the beach erosion using the model adopted for

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[110] Shannon & Wilson 1982

[111] Ericksen 2015

[112] Komar. 1998.

[113] Glen Gray and Associates 2010

this study as described below.

For a more detailed analysis, the approach should include information available from multiple climate models and climate change scenarios. A single climate model run for a given climate change scenario will yield a single time series of events. The actual sequence of events in the future cannot be predicted and will certainly have a different sequence and possible severity of storm events than that predicted by the model. The implication of this uncertainty includes the timing and magnitude of beach repairs and associated cost in the future. In order to account for this uncertainty one realization of the climate model output could be analyzed to determine its probability distribution and then this could be used in a Monte Carlo simulation to yield multiple realizations associated with the model and climate scenario. If automated with a time series approach for calculation of storm induced beach damage and repair cost, statistics of repair timing and costs could be generated. In this way, the statistical information, such as mean values and associated confidence intervals, can be used to address the uncertainty over the severity and timing of future storms. A single time series was used here for illustration purposes, due to scope limitations, but an actual analysis should use multiple sequences generated through Monte Carlo analysis. The analysis could utilize multiple climate change stressors such as sea level rise, wind, and sea ice extent for a situation such as Kivalina. In addition, there are multiple climate change models and multiple climate change scenarios. Thus, if utilizing all of these variables hundreds if not thousands of realizations could be produced using the Monte Carlo methods.

An alternative to the Monte Carlo approach of storm modeling involves development of a set storms predicted by the climate change models and an expansion of this storm set by development of synthetic storms based on likely variations in the modeled storms to more effectively cover the range of likely future storms. This set of predicted and synthetic future storms can then be simulated using wind, hydrodynamic, and wave models to simulate the resulting impacts such as waves and water levels at locations of interest. Once all the storms are simulated, the probabilities of those events can be used to identify the average annual return periods associated with various model outputs of interest such as winds, surge, and wave conditions. This approach is similar to that used in the recent USACE study for the North Atlantic coastline.[114]

The beach degradation model was used to calculate the beach erosion for a given event. At the end of the calendar year the largest event was used to incur damage that leads to a repair event provided the event exceeds an assumed minimum threshold. The threshold is set to result in needed repairs on average about once every ten years. For the storm sequence tested, the resulting damage thresholds selected resulted in nine repair events over the 85 year period of the analysis from 2016 through 2100. This approach effectively triggers a repair due to an event that is approximately a one in ten year event. Of course the events that trigger a repair will not come in ten year increments as illustrated in the analysis results. The threshold for beach repair was set at 39.4 feet (note: this value is derived from 12 meters as the analysis was conducted in metric units) as shown in Figure 38. This threshold for repair is consistent with the existing width of relatively level ground (taken as land at or above the 16 foot NAVD88 contour) located between the runway safety area (RSA) and top of bank for the beach as shown in the airport plan, Figure 15. The width between the top of bank (assumed for the purposes of this study to be 16 feet above NAVD88) and the RSA is about 40 feet on average although it is wider near the middle portion of

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[114] USACE 2015b

the runway (about 60 feet) and narrower at each end (about 25 feet). The beach repair and threshold for damage are set to be consistent with the existing beach along the airport. This is intentional since the repair to the airport is not intended to provide any improvements to the existing facility but simply to maintain the existing condition. Over the first half of the project analysis period (2016 through 2100), consisting of 45 years from 2016 through 2060, the beach model yielded five repairs or, on average, about a ten year return interval.

In the latter part of the century as sea level rise is accelerating, per the RCP 8.5 climate scenario, the frequency of damage needing repair based on a 39.4 foot threshold begins to increase rapidly. Therefore, for the latter portion of the century, 2061 through 2100 the threshold distance is increased to 73.8 feet (i.e. 22.5 meters), yielding, on average, a repair every ten years. Thus, it is assumed that repairs will be made differently later in the century as sea levels rise. Again these repairs are random but represent a ten year average return interval based on the climate data for the RCP 8.5 scenario. A conceptual sketch of the repair threshold is illustrated in Figure 38 for the period 2061 through 2100.

When the beach erosion distance triggered a repair, it was assumed that 50% more material than is calculated as the volume lost by the model would be used for repair. This additional material provides some advance maintenance allowing a buffer of material to displace along the beach with the longshore sediment transport regime. Also, it was assumed that, at most, one repair is incurred in a given year. There are a few reasons for this assumption. The first is that, once damage to a beach occurs, recovery after the storm may be relatively rapid: two studies, one in Southern California and one in New Jersey, each show recovery of about half the lost dune volume within three weeks and two days, respectively, through natural processes.[115] The recovery continues after the initial rapid recovery phase, of days to weeks, but this longer term recovery process can take months or even years for a full recovery.

A practical repair will also not likely occur during the same season as the damage since it will take some time to mobilize construction equipment for repairs in remote Kivalina. Also, observation based experience with the shoreline at Kivalina indicates the beach tends to repair itself over the summer and early fall season before the heavy storms begins in late fall.[116] Thus, if the beach does not need repair in a given year, it was assumed that it undergoes a full recovery in the spring and summer before the next year's storm season begins. For these reasons a single beach repair is assumed in any year where the calculated beach erosion distance exceeds the assumed threshold.

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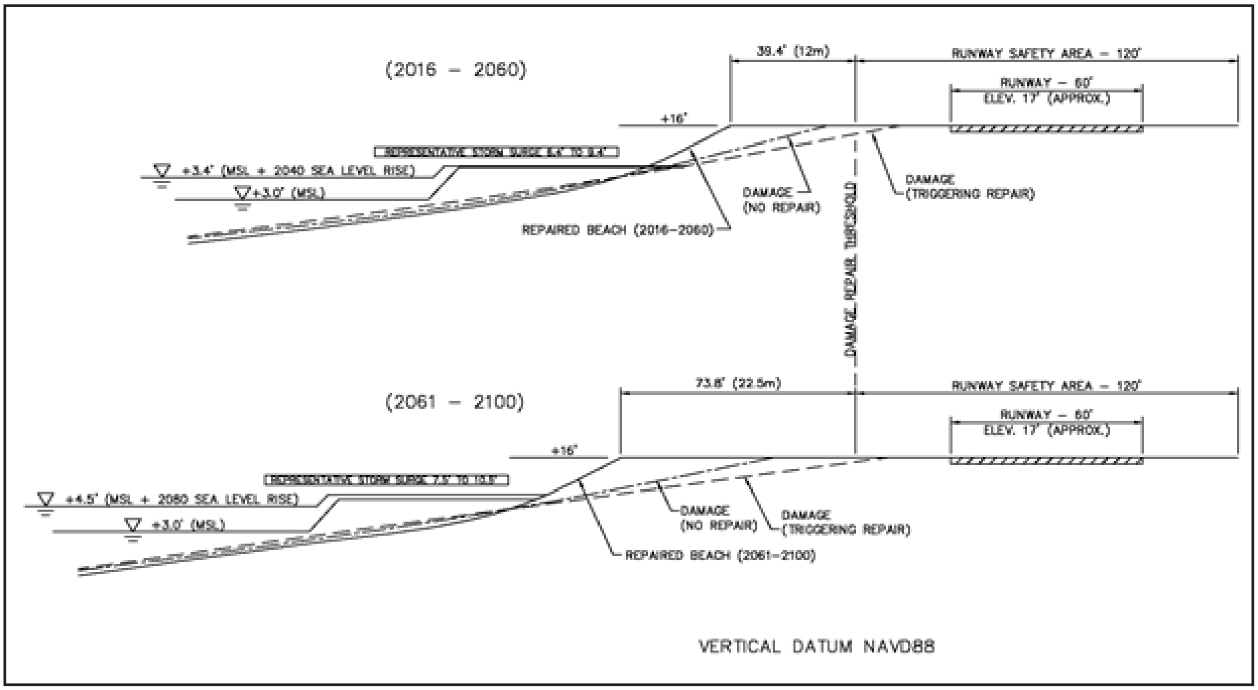
[115] Komar 1998

[116] Carter and Smith 2015

Figure 38: Schematic of RSA and Beach Width Designs used for the First Half and Latter Half of the Project Life[117]



Costs for beach repair are based on bids for previous revetment construction in Kivalina.[118] The cost information includes the engineer's estimate and bids from four contractors. For the purposes of this study, the mobilization cost and sand cost were obtained from this bid information by eliminating both the highest and lowest bid then averaging the remaining three. The resulting mobilization cost is $1,670,000 per repair and the cost per cubic foot of sand is $1.56. These costs are based on construction estimates from 2008 and are escalated to current costs in Step 8 of this case study.

The resulting beach repair costs for the storm sequence tested are shown below in Table 3 where the first cost is incurred in 2016 due to a storm event. The thresholds for repair noted above resulted in four additional repairs over the 45 year period in the first part of the century and four more repairs during the latter 40 years of the century. The resulting cumulative undiscounted cost for beach repairs is approximately $50 million under this storm sequence if the airport design remains unchanged.

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[117] Note: Beaches, including repaired and damaged ones, are not to scale and are provided for illustrative purposes only

[118] USACE 2008

Table 3: Beach Repair Events and Associated Undiscounted Costs between 2016 and 2100[119]

Year Ending	No. of Years (Years)	Number of Repairs (-)	Cumulative Number of Repairs (-)	Repair Cost ($ Millions)	Accrued Cost ($ Millions)
2010	5	0	0	0.0	0.0
2020	10	1	1	5.0	5.0
2030	10	0	1	0.0	5.0
2040	10	1	2	5.1	10.1
2050	10	3	5	16.4	26.5
2060	10	0	5	0.0	26.5
2070	10	0	5	0.0	26.5
2080	10	1	6	5.5	32.1
2090	10	1	7	5.8	37.8
2100	10	2	9	11.5	49.3

The significant increase in threshold distance from 39.4 feet to 73.8 feet after 45 years does not translate into an equivalent increase in percent of beach volume needed for repair as seen in the slight increase in repair cost between the early and latter part of the century. This is due to the decreasing ratio of the top of dune to surge level (i.e. the freeboard), which decreases as sea level rise progresses. Thus, for a given surge height the resulting elevation of the water level increases relative to the top of bank for later periods in the century. The resulting calculated repair volume is dependent on this elevation difference, between the surge level and top of bank, resulting in lower volumes for repair than what would seem intuitive given the greater erosion distance used for the repair threshold. The beach repair volume increased about 15% between the first and last 40 years of the century. This is an aspect of the analysis that needs further investigation and refinement in future work. For example as opposed to a jump in the threshold distance mid-century, this could be adjusted based on sea level rise and changes to surge levels. However, since the repair volumes did not change significantly the benefit may not warrant such refinement. As sea level rise progresses, its effect in conjunction with the ongoing sediment supply may yield a gradual increase in the elevation of the spit provided the wind driven dune building deposits are not removed from the runway or adjacent areas. For this analysis it is assumed the elevation of the runway and protective dune remains fixed.

STEP 6—IDENTIFY ADAPTATION OPTION(S)

Since significant damage costs are likely to be incurred to the airport under the RCP 8.5 scenario, adaptation options were explored to determine if damages could be reduced in a cost effective way. For shoreline erosion there are several different types of shoreline protection options. These should be assessed on a project-by-project basis since some may conflict with various aspects of the site such as sediment transport, site use or setting, hydraulic stresses, etc. Many of these options are described in a

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[119] Note: All costs are based on 2008 construction costs

recent USACE climate change study[120] for the North Atlantic Coast which outlines several options within three categories: (1) non-structural, (2) structural, and (3) natural/nature-based features. For the town of Kivalina, site specific shore protection options considered in previous studies[121,122] are listed below:

1. Community relocation
2. Offshore berm
3. Sandbag revetment
4. Gabion[123] revetment
5. Rock revetment
6. Articulated concrete mat
7. Sheet-pile wall

The above concepts were screened and eliminated by the USACE in favor of the rock revetment. For this study, the adaptation option selected is also a rock revetment to be consistent with the approach used by the USACE. Other adaptation options may be viable but, due to scope limitations for this study, the revetment option was the only adaptation analyzed.

Another potentially promising intermediate beach stabilization strategy worth exploring in future studies is dynamically stable shorelines wherein cobble or small boulders are used on relatively steeper slopes near the shoreline and transition into the existing sand beach further offshore. The cobble moves during storms to a “dynamically stable” position under varying wave and water level conditions. Examples of this strategy are presented in several sources for the contiguous United States, internationally,[124,125] and various projects in Alaska[126] including Homer Fish Lagoon and the Airport beach road in Unalakleet.

The initial design of the revetment for this analysis was assumed to be identical to the facility recently constructed for the protection of the town of Kivalina: this design was then modified to account for projected future changes in storm conditions. The approximate design for the Kivalina revetment shown in the USACE Section 117 document[127, 128] and, more recently, in the USACE Projects and Index book[129], was used as the initial template.

Revetment rock size is primarily driven by the depth limited wave height that occurs in the vicinity of the toe of the revetment and, thus, is highly dependent on the storm induced water levels. The revetment armor rock size is calculated using the van der Meer formula for rock stability under wave action.[130,131] Initially, a present-day 50-year storm surge at Kivalina[132] was used as a basis to calculate scour at the toe of the revetment using empirical information.[133] Since these results are based on laboratory studies and

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[120] USACE 2015b
[121] USACE 2006
[122] USACE 2007
[123] A gabion is typically a wire mesh basket filled with rock and used for erosion protection on embankments and shorelines
[124] Allan, Geitgey, and Hart 2005
[125] Komar and Allan 2009
[126] Smith and Carter 2011
[127] USACE 2007
[128] Glen Gray and Associates 2010
[129] USACE 2011
[130] CIRIA, CUR, and CETMEF 2007
[131] USACE 2002
[132] Chapman, Kim, and Mark 2009
[133] Sumer and Fredsoe 2002

do not include the possible effects of longshore transport, the calculated values were doubled to provide some mitigation relative to this effect. A shoreline response model including cross shore and longshore transport of material during storms (e.g. XBEACH[134]) could be used, in conjunction with associated field data, to assess such factors but is beyond the scope of this study.

The initial revetment design, based on work done for the revetment in Kivalina, used historical climate data for rock sizing, however, for adaptation purposes, future projected climate data must be used when sizing the rocks. This is accomplished here through the use of a damage assessment that optimized rock size based on the sequence of storms used in this assessment. During this century, damage to the revetment option is accrued due to successive storms utilizing the approach based on the van der Meer formula.[135] The damage parameter is defined as the ratio of the eroded area divided by the median stone size squared, yielding a non-dimensional parameter. The damage parameter representing the amount of damage to the revetment is calculated for each storm and, if the incremental damage from a given storm exceeds a damage parameter of 1.5, the damage from the storm is accumulated. For the proposed revetment, with a slope between 1:2 and 1:3, damage levels are defined below:[136]

1. Damage is considered to begin at a damage parameter of two (zero to five percent of armor stones are displaced)
2. Intermediate damage is considered at damage parameters ranging from four[137] to six (five to ten percentof armor stones are displaced)
3. Failure is considered to occur at damage parameters of eight or above (20% or more of the armor stones are displaced and typically the underlayer of stone below the armor layer is exposed)

For this analysis, the revetment repair was assumed to be initiated for an accumulated damage level of six or higher triggering a repair for the upper end of the intermediate damage range. Using the revetment damage model coupled with the environmental stresses, due to waves and storm surge, the lifecycle cost of the structure can be assessed including the capital cost and accumulated repair cost. With such a model, the revetment armor size can be modified and the cost assessed to identify the armor size that minimizes lifecycle cost. This method was used to assess the armor rock size that minimized the lifecycle cost of the revetment over the 45 year period from 2016 through 2060 and the 40 year period from 2061 through 2100. The reason for the breakpoint is both the beach damage and the revetment damage begins to increase as sea level rise becomes more rapid in the latter part of the century based on the RCP 8.5 scenario. Due to the relatively high cost of mobilization to the site, the lowest life cycle cost for both time periods, 2016 through 2060 and 2061 through 2100, is obtained by sizing the rock to avoid any repairs. The relatively modest cost of using slightly larger stone and a slight addition to the revetment volume is lower than use of smaller stones that incur repair costs over the life of the structure. The useful life of revetments is typically in the 25 to 50 year range. Thus, it is unlikely that a single revetment design for 100 years can be installed and expected to provide service over that time frame without sustaining damage or a need for significant maintenance. In addition, the uncertainty in sea level changes and possible climate change induced impacts to storm frequency or intensity 40 years from now will provide invaluable insight for rehabilitation or replacement of a revetment to withstand the subsequent 40 years leading up to 2100.

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[134] Deltares 2015

[135] CIRIA, CUR, and CETMEF 2007

[136] USACE 2002

[137] These damage parameter values versus percent of damage are approximate based on laboratory tests. Thus, the range between a damage parameter of two to four and from six to eight are transitions from no damage to intermediate damage and from intermediate damage to failure, respectively.

For these reasons, a revetment life of about 40 years was targeted for this analysis resulting in the re-assessment of the lowest life cycle cost revetment for the latter part of the century (2061 through 2100).

For a more detailed analysis, the life cycle cost of the revetment could be analyzed across multiple climate model projections and associated climate scenarios. For each climate projection, the damage and associated costs could be accrued for a variety of designs (e.g. revetment slope, rock size, etc.) in order to identify the confidence intervals associated with the life cycle costs. The results would provide a curve of life cycle cost versus a particular design parameter allowing one to select the lowest life cycle cost design with some percent chance that those costs would not be exceeded (e.g. due to additional maintenance).

Revetment capital cost and repair cost are based on bids for previous revetment construction in Kivalina.[138] Following the same calculation method noted in Step 5 for the beach repair costs, the resulting mobilization cost is $1,670,000 and the cost per cubic foot of rock is $13.60 based on 2008 costs. Several armor stone sizes were analyzed to identify the design with the lowest life cycle cost. For a given rock size, the revetment was adjusted based on the ratio of rock size to account for the thicker section and associated volume increase. Based on the life cycle costs, the median rock size (length of an equivalent cube) and weight (assuming a specific gravity of 2.65 and a cube shaped rock) follow:

1. For the early part of the century, 2016 through 2060, the median armor rock size is 2.8 feet with a weight of 1.8 tons
2. For the latter part of the century, 2061 through 2100, the median armor rock size is 3.9 feet with a weight of five tons. This armor rock is assumed to be placed on top of the existing revetment.

This adaptation option, assuming placement of 2.8 foot rocks today with enhancement using 3.9 foot rocks in 2061, is assessed below to determine its performance over the analysis period.

STEP 7–ASSESS PERFORMANCE OF THE ADAPTATION OPTION(S)

The performance of the rock revetment is summarized by decade in Table 4 using a similar format to that used for beach repair costs. Since the rock was optimally sized to avoid repairs for this storm event sequence, repair costs are zero. There are two estimated capital costs shown with the first involving construction of the revetment with the 2.8 foot armor rock for $38.9 million and a second in 2061 involving application of larger armor rock over the top of the previously constructed revetment. The construction in 2061 will involve some repair and re-configuration of the existing revetment to accommodate application of the new larger armor rock. However, use of the existing revetment as the underlayer for the new rock will reduce the amount of material by about half as compared to construction of an entirely new revetment. The revetment volume was scaled using the new rock size for the larger thickness and volume, and then half of the resulting volume was used to price the enhancement involving application of heavier armor stone. The estimated cost of this enhancement is $27.9 million when accounting for the material volumes and mobilization cost. The cost of the two capital projects is $66.8 million, which is about 36% higher than the estimated cost of maintaining the beach.

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[138] USACE 2008

Table 4: Estimated Undiscounted Revetment Costs between 2016 and 2100[139]

Year Ending	Cap. Cost Revetment ($ Millions)	Number of Repairs (-)	Cumulative Number of Repairs (-)	Repair Cost ($ Millions)	Accrued Cost ($ Millions)
2020	38.9	0	0	0.0	38.9
2030	0.0	0	0	0.0	38.9
2040	0.0	0	0	0.0	38.9
2050	0.0	0	0	0.0	38.9
2060	0.0	0	0	0.0	38.9
2070	27.9	0	0	0.0	66.8
2080	0.0	0	0	0.0	66.8
2090	0.0	0	0	0.0	66.8
2100	0.0	0	0	0.0	66.8

STEP 8—CONDUCT AN ECONOMIC ANALYSIS

A benefit-cost analysis of the revetment versus a baseline consisting of beach repairs was conducted to determine the cost effectiveness of the adaptation option. The damages under the adaptation option were evaluated against the baseline alternative (periodic beach repair). The differences between the damage costs that would have been experienced under the baseline and those expected under the adaptation measure represent the net benefit of the adaptation strategy. The difference in cost expenditures between the baseline and the adaptation measures represent the net costs of the adaptation option. From this information, a benefit-cost ratio and a net present value was developed for the adaptation option to inform the decision-making process.[140]

The stream of benefits and costs were discounted using a three percent real discount rate and a 2015 base year. The analysis length was 85 years, starting in 2016 and ending in 2100. The adaptation option was assumed to be fully in place starting in 2016 and a major rehabilitation cost was assumed to be incurred in 2061 as discussed in previous steps.

Calculation of Costs

Total construction and rehabilitation costs of the revetment were calculated in 2015 dollars per the discussion in previous steps assuming no real growth in the future costs. The construction cost of the adaptation option was assumed to occur in 2016, while the corresponding rehabilitation costs was assumed to occur in 2061. The costs for the adaptation strategy and the baseline, in both undiscounted and discounted 2015 dollars, are detailed in Table 5 below.

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[139] Note: All costs are based on 2008 construction costs

[140] To achieve greater ease in interpreting the final results, the avoided repairs under the adaptation strategy were recorded as net benefits (added to the numerator) instead of cost savings (subtracted from the denominator). This was performed in order to ensure that the analysis did not generate negative costs and therefore cause complications for the interpretation of the benefit-cost ratio. For instance, if avoided repairs and associated damages were to be captured as costs savings and thus subtracted from the denominator, then it would have been possible to produce negative benefit-cost ratios, although the net present value for the analysis was positive. In order to avoid these complications, the avoided damages (repairs and disruptions) were recorded as net benefits and added to the denominator.

Table 5: Construction Costs for Beach Repair and the Revetment Option

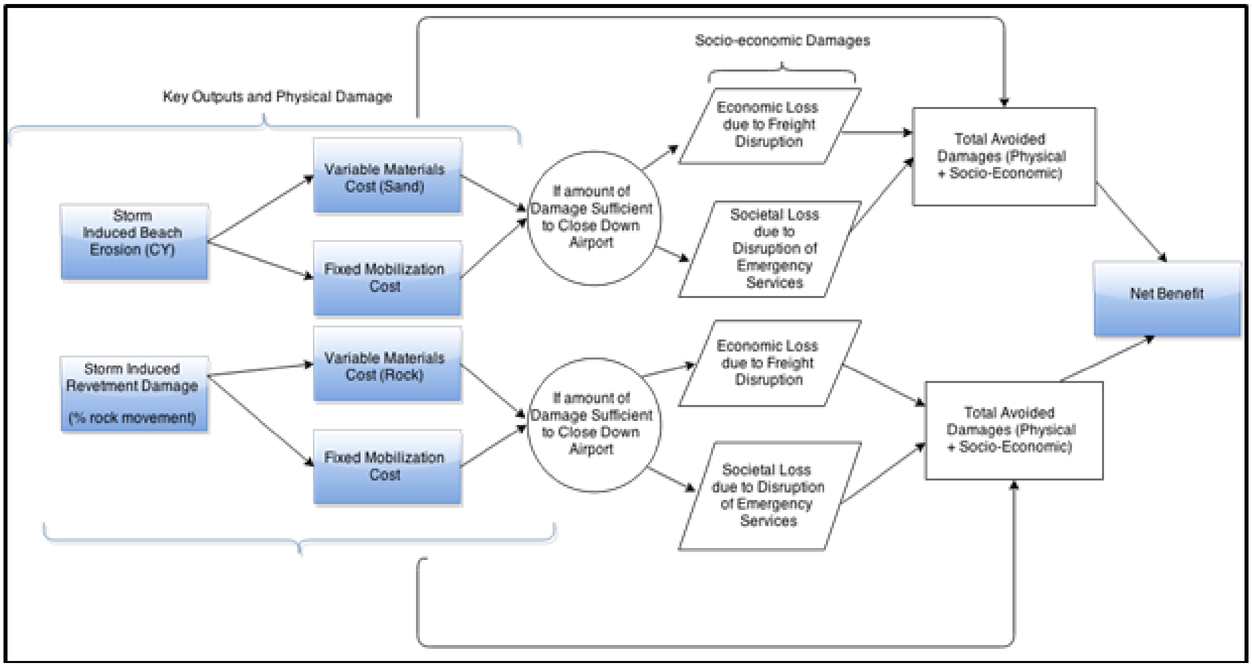
Alternative	$2015 Undiscounted Capital Costs	$2015 Undiscounted Repair Costs (2016-2100)	$2015 Discounted Capital Costs	$2015 Discounted Repair Costs (2016-2100)
Baseline Beach Repair	N/A	$49,348,061	N/A	$16,510,505
Adaptation Option: Revetment Construction	$66,807,213	N/A	$46,105,567	N/A

Calculation of Benefits

As discussed previously, for purposes of this analysis, a single sequence of storm events was considered. Therefore, the results represent the cost effectiveness of the adaptation strategy under the assumed sequence of events. A more comprehensive analysis would consider a probabilistic sequence of possible events under different scenarios. In this case, for every scenario, thousands of possible events would be simulated and statistical results would produce an expected sequence. The assumed sequence of events could potentially impact the economic results, as the occurrence of higher magnitude events earlier in the analysis would increase results by increasing the present value of the benefits. Moreover, use of a probabilistic framework, via Monte Carlo simulation, would allow for the construction of confidence intervals and thus further inform the decision making process by providing probabilistic ranges to the economic results.

The benefits of the adaptation option were calculated by taking the sum of the total avoided physical (avoided repairs) and socioeconomic damages that would result from implementing the revetment construction. The resultant stream of benefits was then discounted using the aforementioned three percent real discount rate and 2015 base year. Figure 39 below outlines the process by which benefits are calculated under the adaption option.

Figure 39: Flow Chart Illustrating Calculation of Benefits



The estimation of societal losses due to disruptions of emergency services was not considered in the analysis, as little data was available. While the airport serves as a major transportation mode that provides access to health care providers, the majority of the trip traffic that results from this purpose is due to routine health care checkups. From conversations with the Maniilaq Association, the organization responsible for managing health care on the island, we concluded that, while an appreciable percentage of health care related trips result from emergency health care needs, little data is available to estimate this amount. Accordingly, societal losses that would result from airport disruptions affecting access to health care providers were not accounted for in this analysis.

The following section discusses the calculation of the physical damage and socioeconomic costs in detail along with how they were tallied to arrive at cumulative benefits.

Calculation of Physical Damage Costs

As mentioned above, the physical damages for this analysis consist of the avoided repairs that would have been incurred under the baseline beach repair option. The cost of beach repairs is shown in Table 5 above. The cost represents the cumulative costs of repairs over the course of the analysis length: the beach repairs arise from the magnitude of the erosion experienced during the analysis length. The total cost of these repairs was estimated to amount to $49,348,061 in undiscounted $2015 and $16,510,505 in discounted $2015.

Estimation of Socioeconomic Costs

Total socioeconomic costs for both the baseline and the adaption option are estimated given the projected percent damage experienced under each case. If the damage is sufficient to close the airport, a disruption event is assumed to occur and, subsequently, the airport is assumed to be closed for the next seven days. Given the simulation of potential damage events, airport shutdowns are only expected to occur under the baseline case. Accordingly, these damages are captured as benefits of the adaptation option.

Since the island community of Kivalina receives the majority of its supplies from the airport, a shutdown would result in significant economic disruptions. To estimate the cost of this disruption, the total value of incoming freight tonnage transported through Kivalina is used as a proxy. More specifically, it is assumed that, if an airport disruption occurs during the analysis period, goods will be delayed by eight hours per day to reflect the costs to the shipper. Since goods in transit result in increased carrying cost for shippers, these costs will increase if a shutdown were to occur. We assume a carrying cost of 20 percent of the total value of goods transported (this amount is scaled to an hourly figure) to estimate the cost of this disruption. Given that the maximum disruption only lasts for seven continuous days, residents are unlikely to experience a significant shortage.

The total value of incoming goods transported through the airport, $68,188 per year, was estimated using 2013 freight tonnage data for Kivalina[141] and statewide freight value data (no Kivalina-specific value was available for this study).[142] The data provided an estimate of total incoming goods transported via air modes to Alaska and their value. The state average value per ton was used in this case study analysis as an imperfect yet suitable proxy for Kivalina; it assumes the mix of good types for the state as a whole is representative of the goods being flown into Kivalina. More Kivalina-specific data should be collected and used for a full benefit-cost assessment leading to actual design decisions.

Table 6 below lists the cumulative net socioeconomic damages for the baseline damage repair alternative. As noted above, these damages are captured as avoided damages (benefits) under the adaptation option.

Table 6: Cumulative Socioeconomic Damages at Kivalina

	$2015 Undiscounted	$2015 discounted
Cumulative Socioeconomic Damages (2016-2100)	$1,616,623	$325,078

Findings

To evaluate the efficacy of the adaptation option, the total discounted costs and benefits of the option were compared to calculate a net present value and a benefit-cost ratio. The net present value shows the absolute difference between net discounted benefits and costs whereas the benefit-cost ratio takes the ratio of net discounted benefits to costs and gives an idea of the project's economic efficiency. In general, if the benefit-cost ratio is above one, the project is considered cost effective. If the net present value is greater than zero, then the project is considered cost effective. Because each metric is calculated differently, it is possible for a project to generate a higher net present value than another one yet have a lower benefit-cost ratio.

Overall, as shown in Table 7 below, the revetment adaption strategy fails to generate a suitable benefit-cost ratio (i.e. a ratio greater than one). Under the analysis assumptions, the adaptation option generates a benefit-cost ratio (BCR) of only 0.29 and a net present value (NPV) of negative $29,269,984. This result

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[141] Parsons Brinckerhoff 2014

[142] FHWA 2011

implies that the option is not cost effective as it fails to recoup its cost, in the form of increased societal benefits, over the analysis length versus the baseline alternative. This finding suggests that the most cost-effective alternative, under this single storm event sequence, is to pursue the baseline option of periodic beach repairs.

Table 7: Evaluation Results in Discounted $2015

	Net Costs	Net Benefits	BCR	NPV
Revetment Construction	$41,244,891	$11,974,906	0.29	-$29,269,984

STEP 9—EVALUATE ADDITIONAL DECISION-MAKING CONSIDERATIONS

While the economic analysis provides a starting point and documented basis for making decisions, the numerical results by no means represent the final recommendation in the decision-making process. Many other factors that reflect the reality of the economy, the environment, and the social implications of the adaptation options must be considered. While the economic analysis tends to address some of these issues if all costs are considered, the tolerance for risk, the other needs of the stakeholders, and the ability to fund change are equally, if not more important than the bare numbers. Any decisions made must account for all of these impacts and come from a general consensus of the engineering, planning, operations, and maintenance staff along with the affected stakeholders.

Specific considerations for Kivalina and the airport include items of concern for any typical project such as:

- Broader project sustainability beyond just climate change impacts (i.e., the “triple bottom line” of social, environmental, and economic concerns)
- Project feasibility and practicality
- Ongoing maintenance needs such as those along the shoreline in Kivalina and the emergency repair still in place at the south end of the airport runway
- Maintenance funds availability given the array of villages and towns in rural Alaska with similar erosion problems
- Capital funds availability especially in light of the relatively low population in comparison with the high cost
- Stakeholders’ (public and government agencies) tolerance for risk of service interruption and associated costs of all types (note: this affects how the economic analysis is perceived as well)
- Stakeholders’ expected quality or level of service
- Life safety needs of the community given the airport’s critical role for medical evacuations. It could be especially important to have the airport remain serviceable after major storms which could result in injuries in the town.

After considering all of the above, decision-makers should ask the question “Is this project worth pursuing?" Adaptation of infrastructure in response to the potential for changing climate conditions is proposed to fit within the broader context of erosion and flooding related vulnerability across rural Alaska and associated capital improvement program and ongoing asset management efforts. A particular challenge with Kivalina and several similar towns in rural Alaska involve the relatively low population and exposure to flooding and erosion. Kivalina in particular is located on a narrow strip of land leading to exposure on both sides that over time may need repair or capital projects to mitigate flooding and erosion. The low population in relation to the long shoreline and high exposure to the Chukchi Sea is in some respects similar to other relatively narrow barrier islands in the world with high exposure and low populations, some of which are no longer populated. Adaptation for the sake of adaptation is not expected to meet each of the special considerations noted above and is best viewed as a component of a larger decision-making process.

STEP 10—SELECT A COURSE OF ACTION

The economic analysis showed that the revetment adaptation option proposed is not cost-effective based on the analysis using the RCP 8.5 climate change scenario. The driver of this outcome is the high capital cost of the adaptation option relative to the lower cost of beach repair for the base condition resulting in a heavily discounted NPV. This, coupled with the relatively low value for the socioeconomic damages avoided by the adaptation option, results in the low benefit-cost ratio of 0.29.

That said there is uncertainty in the probability of future conditions, such as sediment budget and transport for the Kivalina area, wind, sea ice extent, waves and storm surge. In addition, for use in planning, financing, and design, a significant additional level of detailed information will be beneficial such as:

- Field work, including nearshore and offshore bathymetry; measurements of nearshore response to seasonal and storm conditions; development of a sediment budget for the area including sediment sources, sinks, and transport; along with wind, water level, wave and current measurements at the project site.
- Modeling, including combined sea level rise, storm surge, and wave modeling; beach response modeling to storm conditions and long-term trends (e.g. seasonal and long-term variation in fetch distances due to reductions in sea ice and sea level rise); more detailed modeling of adaptation alternatives (e.g. accounting for variations in beach nourishment and foreshore configuration as well as revetment design alterations in future years based on sea level rise and modifications to storm conditions such as waves and surge). Examples of this type of detailed modeling are underway in many regions including examples on the United States North Atlantic Coast and northern Alaska.[143,144]
- Accounting for the likely prospect of the City of Kivalina being re-located within the next 10 to 20 year in the economic analysis.
- Inclusion of socioeconomic costs, especially diminished access to medical services, should the airport be damaged in a storm

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[143] USACE 2015b

[144] Ericksen 2015

- Analysis of additional adaptation options such as beach nourishment with targeted use of groins or offshore breakwaters and dynamically stable revetment designs

Collection and analysis of such data would improve decision-making. In addition, assessment of additional climate change scenarios and data from multiple global climate change models should be considered. Monte Carlo simulation could be used to generate multiple realizations of a given model and climate change scenario allowing generation of expected values and associated confidence intervals for the damages and resulting costs. Thus, the results of this analysis should only be seen as preliminary and an example of how to implement a framework for doing this type of assessment; they are very much subject to change pending the additional field work and detailed analyses suggested in this document.

Furthermore, this study did not include a component engaging local stakeholders in a dialogue over which design would be “best” and there is no way to predict what decisions such a discussion would lead to. The dialogue would no doubt be heavily shaped by local risk tolerance and other factors and may very well lead to a different decision than one would make without the benefit of local perspective.

STEP 11—PLAN AND CONDUCT ONGOING ACTIVITIES

Regardless of which design option is chosen (if any), the effects of climate change on the shoreline cannot be expected to remain constant. Thus, the climate stressors and the shoreline’s performance should be monitored after the project is constructed and the effects on the shoreline must be revisited and periodically assessed to determine if the shoreline’s critical design thresholds are being reached. Such monitoring and periodic assessment can help indicate if it might be necessary to implement additional improvements, change design guidelines, and/or alter operation and maintenance practices.

For the beach, monitoring would include cross-section surveys in addition to collecting more detailed data on trends in climate stressors including wind, sea ice extent, waves, sea level rise, and storm surge (e.g. is storm surge becoming more frequent, intense, or both?). Both seasonal and storm-specific impacts to the beach profile should be monitored for use in calibrating predictive models of shoreline response. For the revetment, the same climate stressors should be monitored in addition to periodic inspections of the revetment, revetment toe (including scour depth), and lateral transitions at each end of the revetment.

Conclusions

This case study has, using the 11-Step Process for adaptation assessments, demonstrated how a shoreline can be analyzed for climate change impacts resulting from future projections of wind, sea ice extent, and sea level rise. Due to the limited scope of this project, one climate scenario, RCP 8.5, and one adaptation option were analyzed. The adaptation option, an armored revetment, was identified and tested using a benefit-cost framework. Ultimately, this information must be shared with local stakeholders and discussed before any locally preferred decisions can be made on what adaptive actions (if any) would be appropriate for the community. In addition, as discussed in Step 10, significant field work and analysis would be needed as a basis upon which to identify a recommended course of action. Some in the community have already expressed an interest in relocation which has been discussed and assessed in previous studies and could have an important influence on what to do for the airport.

The process shown is broadly applicable to other shore protection projects in Alaska although, for locations exposed to the Pacific Ocean and Bearing Sea, a global ocean modeling framework is advised for the prediction of wave conditions at the site. The empirical methods used in this study appear to reasonably represent conditions at the project site for the more limited ocean extent in the Chukchi Sea and portions of the Arctic Sea. However, there may be instances of particular storms with characteristics that require more detailed simulation to adequately capture the wave conditions or surge levels. For an application involving high capital costs and high social or environmental consequences an approach analogous to the recently released North Atlantic Coast Comprehensive Study[145] should be considered. However, until such time that a similar effort is undertaken, many smaller projects will need to rely on targeted site specific study somewhere within the range of this case study and a more detailed study which may include field data collection and numerical modeling of storms and nearshore conditions.

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[145] USACE 2002

Slope Instability Related to Permafrost Thaw and More Intense Precipitation—The Igloo Creek Landslide

Introduction

Transportation infrastructure commonly traverses a variety of terrain, including areas on or near steep slopes. This infrastructure and surrounding terrain can be highly sensitive to environmental stressors, like those brought on by climate change, which may affect slope stability. The loss of slope stability can result in landslides. In additional to blocking access, the force of landslides can also damage and destroy transportation infrastructure. This section of the report illustrates how the 11-Step Process can be applied to a roadway traversing steep terrain by using the Igloo Creek Landslide in Denali National Park and Preserve (Park) as an example.

The Igloo Creek Landslide (see Figure 40) was discovered by Park staff near mile 38 on the Denali Park Road on October 23, 2013. The slide was measured to be 600 feet long, 110 feet wide, and up to 35 feet thick. Park staff estimated 30,000 cubic yards of rock, soil (including melting permafrost), and vegetative matter were contained within the slide. Although the road had been closed for the season, Park staff were able to mobilize to the site, assess the hazard, and clear the road. Earth moving operations occurred October 25-28, 2013. Working twelve hours shifts, Park crews were able to clear the slide and avoid removing a large frozen mass when the road reopened in the spring.[146]

Figure 40: Images of the Igloo Creek Landslide

The goal of this case study was to develop and assess the cost effectiveness of adaptation strategies to deal with possible future ground movements in the vicinity of the Igloo Creek Landslide and other locations within the park; ground movements that could be exacerbated by climate change induced permafrost thaw and precipitation intensification. This assessment does not go into all the details on landslide analysis, rather it focuses on identifying plausible scenarios and adaptations at the case study site. It is organized around the 11 steps in the Process.

STEP 1—DESCRIBE THE SITE CONTEXT

The 92 mile long Denali Park Road is the only road in the Park and the slide event cut off vehicular access

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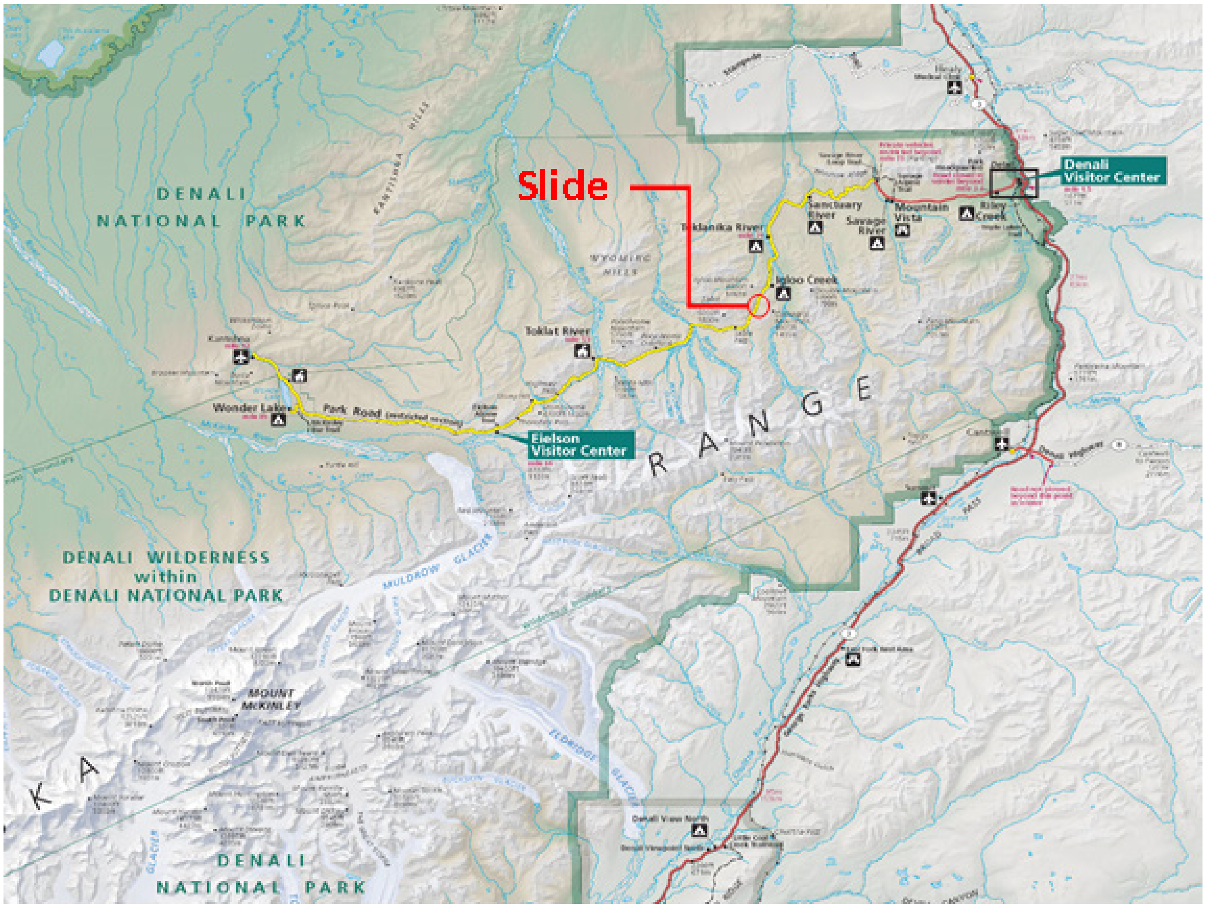
[146] NPS 2014a

to all points west along the road between miles 38 and 92 (see Figure 41). The road is paved to Savage River (mile 15 from the park entrance) and then transitions to gravel for the remaining 77 miles prior to dead-ending at Kantishna (a historic mining community with private inholdings). Private vehicles are generally prohibited beyond Savage River and, thus, through the slide area. The road beyond Savage River is a narrow, low speed route that traverses the dramatic terrain of the Park. Traffic along the Denali Park Road is managed in accordance with the Vehicle Management Plan.[147] Beyond mile 15, a maximum of 160 vehicles per 24-hour period are allowed during the visitor season (approximately late May through mid-September). This daily limit applies to all motorized vehicles including transit and tour buses, National Park Service (NPS) vehicles, professional photography/commercial filming vehicles, and inholder vehicles.

Figure 41: Location of the Igloo Creek Landslide at Mile 38 of the Park Road[148]



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147 NPS 2012

148 Image source: National Park Service (as modified)

Additionally, vehicle use is managed to maintain or improve the visitor experience and natural resource conditions along the Denali Park Road. This is achieved by monitoring the following indicators and adjusting vehicle use as required:

- Sheep gap spacing
- Nighttime traffic levels
- Large vehicle traffic
- Vehicles at a wildlife stop
- Vehicles in a viewscape
- Wait time for hikers
- Vehicles at rest areas and Eielson Visitor Center

In September of each year and in the spring, after/before the bus season has ended, private vehicles are allowed on the Denali Park Road for five days via a road lottery. One-day road passes are given to 400 vehicles per day. Four days are open to the general public and the fifth is reserved for Alaska based active duty military personnel. Vehicles are allowed to travel as far as Mile 85, weather permitting.

The landslide site is located within the foothills north of the Alaska Mountains and part of the sub-arctic continental (Interior) climactic zone. The foothills are generally separated by broad, sediment-filled glacial valleys that drain the region from south to north.[149] The site is mapped as having volcanic and sedimentary rocks of the Cantwell Formation which include sequences of andesite, basalt, rhyolite, sandstone, siltstone, mudstone, shale, and conglomerate.[150] The permafrost at the site is mapped as sporadic, that is permafrost underlying ten to fifty percent of the ground surface.[151]

Importantly, from a policy context, in 1980 Congress passed the Alaska National Interest Lands Conservation Act (ANILCA) which, among other things, designated approximately two million acres of Denali National Park and Preserve as wilderness, requiring these lands to be administered in a manner consistent with the Wilderness Act of 1964.

Although the Denali Park Road and a corridor extending 150 feet from either side of the road centerline is not designated as wilderness, the road is managed to preserve its character and purpose as outlined in the Consolidated General Management Plan for Denali National Park and Preserve:

> “Engineered structures such as bridges are used only as necessary to protect the resource or preserve the road. Signs and related items are kept to a minimum. The character of the road is in keeping with the character of the land: a primitive, low-speed road located in a wild and pristine land.”[152]

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[149] NPS 2010a
[150] NPS 2010a
[151] NPS 2014b
[152] NPS 2006

Areas beyond the road corridor, including a portion of the slide area, are designated as wilderness and are managed to show a very limited human imprint. Activities within the park are analyzed using a minimum requirement/minimum tool process which gives more weight to the potential disruption of wilderness character and the physical resource than economic efficiency and convenience. The steps outlined in the minimum requirement/minimum tool process are as follows: [153]

- Identify the problem/issue that may require action
- Analyze whether the issue needs to be resolved in wilderness
- Evaluate whether resolving the issue protects wilderness character and values identified in the Wilderness Act
- Identify and describe a range of alternatives
- Select the method or tool that allows the issue to be resolved (or action implemented) with a minimum of impacts to the wilderness

It is anticipated for this study that adaptation options would be analyzed following the minimum requirements process prior to implementation.

STEP 2—DESCRIBE THE EXISTING FACILITY

The Igloo Creek Landslide occurred near the western edge of Igloo Creek Canyon. In this area, the road is located along the western slope of the Canyon, approximately 60 to 80 feet above the valley floor. The road is generally on cut material toward the inboard (upslope) side and fill materials toward the outboard (downslope) side. The ridges above are up to 1,000 feet above the road level.

The landslide material generally consisted of blocks of permafrost up to 15 feet thick containing unconsolidated sediments including cobbles, silt, and clay. This layer of permafrost slid on an unfrozen layer of clay. Smaller slides had previously occurred at the site over a period of decades and groundwater seepage was present.[154] The cause of the slide is unknown although unfrozen layers of soil and seepage are thought to be contributing factors.

The study limits were bounded by the ridges surrounding the slide area. These limits define the plausible extent of sliding attributable to similar mechanisms of failure (i.e. relatively shallow soil failures) at this location. Figure 42 displays the vicinity, slide limits (white dashed line for the Igloo Creek Slide of 2013, white dotted line for an earlier slide in the 1980s), and study limits for this project (red dashed line). Park staff have implemented a monitoring program at the site that consists of the development of an elevation model, time lapse photography related to rain gauge data, and frequent site visits.[155]

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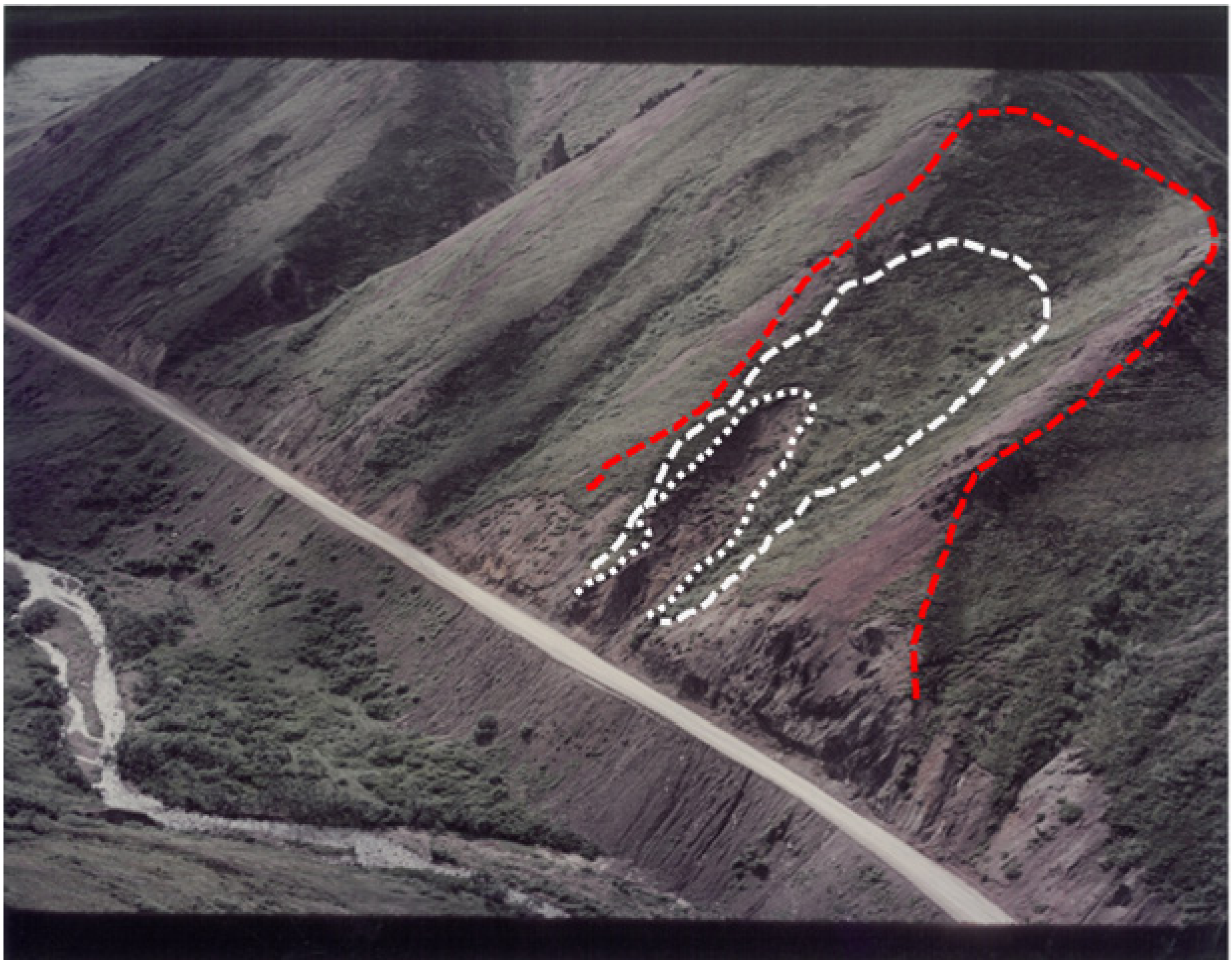
[153] NPS 2006
[154] NPS 2014a
[155] NPS 2014a

Figure 42: Aerial Photo of the Park Road and Igloo Creek Slide Vicinity circa 1996, Prior to the 2013 Igloo Creek Slide[156]



STEP 3—IDENTIFY CLIMATE STRESSORS THAT MAY IMPACT INFRASTRUCTURE COMPONENTS

Changes in temperature and precipitation patterns due to climate change could affect landslide hazards along Denali Park Road. Sustained temperature increases could lead to a loss of permafrost. Loss of permafrost could reduce the strength of soils on the slopes and increase the risk of landslides. High resolution permafrost modeling of the Park has recently been completed by the Geophysical Institute Permafrost Laboratory at the University of Alaska Fairbanks.[157] Observations from 1950-1959 and 2000-2009 were combined with five global climate models using the A1B (moderate) greenhouse gas emissions scenario to develop permafrost predictions within the Park. The modeling effort predicted that the stable near surface permafrost under 49% of the Park during the first decade of this century may decline to six percent by the 2050s and to one percent by the 2090's. At the end of this century, only isolated limited areas of high elevation northfacing slopes are predicted to have stable near surface permafrost.[158] Figure 43 displays the permafrost modeling projections for the Park.

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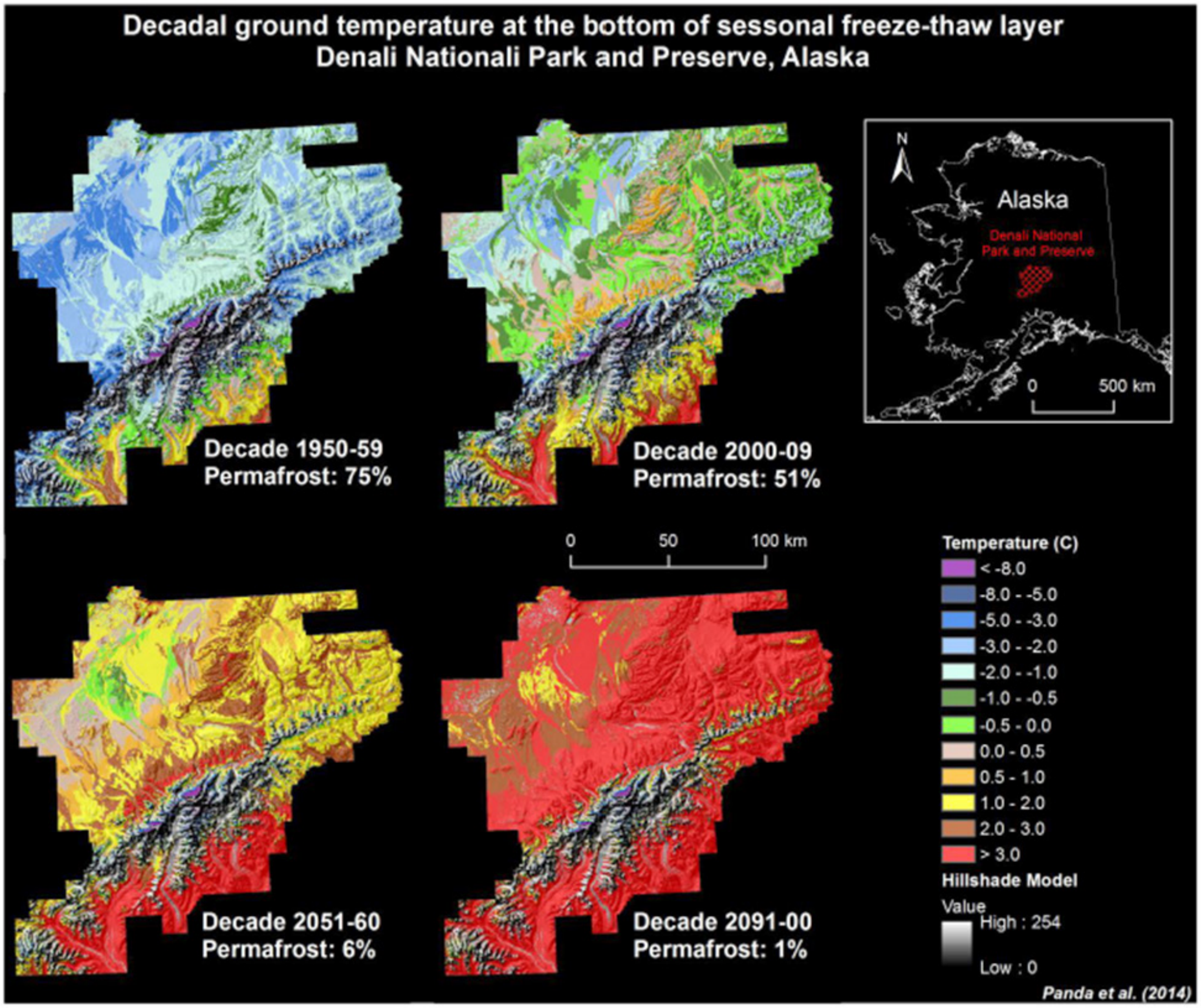
[156] Photo source: National Park Service. Note that the white dotted line displays the extent of a slide that occurred in the late 1980s. The white dashed line displays the approximate extent of the 2013 Igloo Creek Slide. The red dashed line displays the study limits of this assessment.

[157] Panda, Marchenko, and Romanovsky 2014

[158] Panda, Marchenko, and Romanovsky 2014

Figure 43: Permafrost Projections for Denali National Park and Preserve, A1B Scenario[159]



Beyond the thawing of permafrost, higher temperatures during the winter could also increase the frequency of freezethaw cycles which may also reduce slope stability. With respect to precipitation, projected increases in heavy rainfall events with climate change could increase erosion, soil moisture levels, and seepage within slopes, all of which will negatively affect the stability of slopes.

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[159] Image source: Panda, Marchenko, and Romanovsky 2014. Negative temperature values, shown as shades of green and blue, indicate the presence of near surface permafrost. Positive values, shown as shades of brown and red, indicate the absence of near surface permafrost.

STEP 4—DECIDE ON CLIMATE SCENARIOS AND DETERMINE THE MAGNITUDE OF CHANGES

While predicting localized conditions and responses to future climate stressors is difficult at best, climate and permafrost modeling indicate widespread loss of permafrost within the Park. These changes are likely to affect the landscape dramatically, with increased slope instability probable as unconsolidated sediments thaw. In addition, as mentioned above, more severe freeze-thaw cycles and heavier rainfall events could also reduce slope stability. Although advanced monitoring efforts continue, the data gathered to this point does not allow for a detailed engineering analysis of the slope with respect to changing climate variables. Uncertainty remains regarding the composition of the slope, permafrost extent, drainage regime, and overall stability of the slope.

The uncertainty regarding the composition of the slope and its response to climate variables led the study team to take a different approach to this case study; the development of several *plausible* scenarios that bound the range of likely future slide movements. These plausible scenarios can then be used to assess the performance of the facility and adaptation options and, when more data has been gathered on the slide, the most pertinent plausible scenario can be selected. If none of the plausible scenarios tested exactly matches what the detailed data says will most likely occur, the assumptions of the closest matching scenario can be adjusted accordingly and the analysis framework provided here can then be applied to make a final decision on an adaptation option.

Each plausible scenario consists of a combination of individual future landslide events at the Igloo Creek site over a 50-year analysis period. Landslide events that were considered plausible ranged in size from minor raveling and shallow sloughs (10 cubic yards of earth movement) to an event of 50,000 cubic yards of earth movement, nearly twice the size of the 2013 event. These events are considered possible given the study area topography and likely soil composition of the slope. The soils of the study area likely consist of unconsolidated sediments of clay, silt, sand, gravel, and boulders overlying bedrock with depths ranging from within several feet of the surface to tens of feet. The largest event considered was bounded by the study area limits, although larger events are plausible elsewhere within the Park. The individual slide events considered in this study include:

- 10 cubic yards
- 100 cubic yards
- 1,000 cubic yards
- 10,000 cubic yards
- 50,000 cubic yards

Several scenarios were developed that consist of one or more events occurring during the analysis period. The scenarios were chosen to provide a broad range of potential outcomes to bound the problem, ranging from minor sloughing events occurring intermittently to a series of large events impacting the road several times over the 50 year analysis period. Again, the broad range of scenarios was chosen because the engineering details of the slope are not currently known. Table 8 summarizes the study scenarios.

Table 8: Description of Igloo Creek Landslide Scenarios

Scenario Number	Description
Scenario 1	A 50,000 CY event in year 1 followed by a 10,000 CY event every 10 years. A smaller 1,000 CY event occurs after each larger event.
Scenario 2	A 50,000 CY event in year 30.
Scenario 3	A 10,000 CY event in year 1 followed by a 1,000 CY event every 10 years.
Scenario 4	A series of smaller events leading to a 10,000 CY event in year 5 followed by 100 CY events every 10 years.
Scenario 5	1,000 CY event every 10 years and a 100 CY event every 5 years (100 CY events do not occur when 1,000 CY events occur).
Scenario 6	100 CY event every 2-3 years.
Scenario 7	100 CY event every 10 years.

STEP 5—ASSESS THE PERFORMANCE OF THE FACILITY

The base case alternative (i.e. the "do-nothing" alternative) includes monitoring the site via remote instrumentation (time lapse photography, rain gauge, etc.) and periodic site visits, both actions that are currently occurring. Landslide events are addressed as they happen. This case does not prevent landslides from impacting the road, however, steps may be taken to protect the public if indications of imminent sliding are observed.

Performance in this case study is defined in terms of the ability for vehicles to traverse the roadway. If a slide does occur, Table 9 summarizes the estimated time required to reopen the roadway following a landslide event within the study area using methods similar to those used to clear the Igloo Creek Landslide (bulldozers and front end loaders disposing slide material over the side of the road). For this analysis each event is treated as a discrete occurrence; it is assumed the time required to reopen the road is sufficient to address the safety of the public and no additional instability is present until a new event occurs.

Table 9: Summary of Assumed Time Required to Reopen the Park Road after Various Slide Events

Event Size (CY)	Assumed Time Required to Clear and Reopen Road.
10	< 4 hours
100	~ 4 hours
1,000	8 hours
10,000	2 days
50,000	5 days

As noted in Step 4, under all the plausible scenarios tested, future slide events will continue to occur in the study area. Thus, performance of the roadway will be affected under each scenario and adaptation options are required to prevent harmful impacts.

STEP 6—IDENTIFY ADAPTATION OPTIONS

A variety of common landslide mitigation techniques were considered to mitigate the impacts associated with the various scenarios. Techniques that were considered but deemed infeasible for the study area are listed first and those found to be potentially feasible (subject to further detailed analysis) and carried forward in the analysis are discussed next. The general descriptions of landslide mitigation presented below were developed and paraphrased from the following references: *Landslides: Investigation and Mitigation*[160] and *Landslides in Practice*.[161]

Adaptation Options Considered Infeasible

Infeasible adaptation options included avoidance, selective stabilization, maintenance of the current thermal state of the permafrost, active heat removal from the permafrost, and a variety of other methods. Each of these are discussed in more detail below.

Avoidance

Avoidance of landslides may be less expensive than remediation in some circumstances; however, at this location the expense of avoidance may be prohibitive. Possible avoidance mitigations include:

- Moving the roadway into stable hillside
- Moving the roadway onto the valley floor
- Constructing a bridge over the landslide
- Tunneling to avoid the landslide

Moving the Roadway into Stable Hillside

This mitigation is often performed when the outer edge of the roadway fill becomes unstable. Realignment to avoid landslides that are upslope of the existing roadway may require extensive relocation of the roadway. A new alignment should be located to avoid destabilizing additional slope locations, which may not be feasible.

Wilderness boundaries and permitting is expected to affect the viability of this adaptation option. The maximum road grade in the Tattler Creek to East Fork section is 13%. Assuming a 13% grade and a roadway 300 feet above the current grade, 4,600 feet would be the minimum required to pioneer a new roadway above the existing slide. This adaptation is thus considered infeasible because of environmental impact, excessive cost, and uncertain hazard avoidance.

Moving the Roadway onto the Valley Floor

This adaptation option entails relocating the road to the valley floor. Difficulties arise when the valley floor is a wetland, floodplain, and/or river channel as is the case in the study area. Wilderness boundaries and permitting is expected to affect the viability of this mitigation as well. In addition, it is not clear that the valley floor would be completely clear of future slide areas. This adaptation is therefore also considered

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[160] TRB 1996

[161] Cornforth 2005

infeasible because of environmental impacts, excessive cost, and uncertain hazard avoidance.

Constructing a Bridge over the Landslide

A bridge over a landslide would need to clear span the entire potential slide mass, both horizontally and vertically. It is estimated that a span length of at least 200 feet and a clear height of 40 feet would have been required for a bridge at the Igloo Creek Landslide site to not be impacted during the 2013 event. This adaptation option is not appropriate for locations with uncertainty regarding exact location and volume of future potential sliding and is considered infeasible in this study area because of potential environmental impacts and excessive cost.

Constructing a Tunnel

Realigning the roadway to avoid a landslide via a tunnel would involve costly engineering and construction efforts. This adaptation option is considered infeasible because of excessive cost and environmental impacts.

Selective Stabilization

A portion of a landslide can be selectively stabilized while the remainder of the landslide is untreated. An example of selective stabilization would be to construct a retaining wall that supports the upper portion of a landslide but not the slope below the retaining wall. However, this mitigation is not applicable when the roadway is downslope of the landslide as is the case in the study area and this option was not considered in the analysis.

Maintaining Current Thermal State

In locations where thawing of permafrost is caused by construction activities, mitigation that maintains the pre-construction thermal state may be feasible. However, based on the modeled loss of permafrost throughout the Park,162 maintaining the current thermal state on a slope above the roadway system is considered infeasible.

Active Heat Removal

Heat may be removed from the ground by active refrigeration methods. Due to high operating costs, active refrigeration is typically only used for temporary stabilization, such as during construction of excavations or tunnels. Based on the remote location and high cost, active refrigeration is considered infeasible in the study area.

Other Mitigation Methods

Several additional landslide mitigation methods were screened but considered infeasible due to high cost, environmental impact, and/or the unproven nature of the technique. These include chemical treatment and electrosmosis.

Adaptation Options That May be Feasible but were not Carried Forward for Analysis

Several potential landslide mitigation methods were screened that may be feasible but were not carried

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162 Panda, Marchenko, and Romanovsky 2014

forward for analysis due to high uncertainty in design methodologies or environmental impacts.

Remove Unstable Materials

This mitigation is well suited where small volumes of excavation are involved and where poor soils are encountered at shallow depths. It may be costly to control the excavation and may not be practical for larger landslides. Analysis is required to determine the extent of excavation needed to ensure stability. This adaptation option may selectively occur with ongoing observation and maintenance. This option would require earthmoving equipment to remove unstable materials and may result in the compromising of the character of the land, which is an important factor within a national park. Given the unknown extent of potentially unstable material in the study area, this option may not be feasible because of environmental impacts and wilderness boundary restrictions.

Provide Surface Drainage

Providing surface drainage can reduce landslide driving forces from surface infiltration or seepage due to surface infiltration. Surface drainage can direct water away from the face of the slope. Slope vegetation can promote rapid runoff and improve slope stability. It is typically appropriate to always consider surface drainage treatment. This option is potentially feasible although it was not carried forward for analysis on its own as it was only used to supplement the adaptation options analyzed and described below.

Install In-Situ Reinforcement

In-situ reinforcement can be used to increase the resisting forces in a slope by installing reinforcing elements in the soil. Examples include launched soil nails, micropiles, and plate piles. Because these methods are relatively new and have not been used as extensively as other adaptations, the design methods are not as well established as other landslide mitigation methods. A thorough soils investigation and properties testing program should be conducted and long term durability of reinforcement must be considered. This option is potentially feasible; however, it was not carried forward due to design complexities, cost uncertainties, and visual aesthetics.

Passive Heat Removal

Heat may be removed from the ground using passive refrigeration methods such as heat pipes or passive air ventilation. Passive air ventilation is most commonly used to stabilize building foundations via surface manifolds that maintain a pressure differential allowing cold air to flow through the pipes. Heat pipes are closed tubes filled with a liquid that boils at temperatures below freezing. When the ground is near freezing the liquid boils and rises to the top of the tube. During the winter season cold air passes over the tubes causing the liquid to condense, fall back to the bottom of the tube, and extract heat from the ground causing the liquid to boil again. When the air temperature is higher than the ground temperature the heat pipes are inactive. Passive refrigeration may be feasible at the site; however a dense array of heat pipes that would extend several to tens of feet above the ground surface would be required. Because of the wilderness boundary, view-shed considerations, and the cost to install and maintain the apparatus, this option was not carried forward.

Feasible Adaptation Options Carried Forward for Analysis

Adaptations selected for analysis in this project were chosen to highlight different methodologies of adapting to the risk of landslides. Adaptation options analyzed may or may not actually be feasible depending on the detailed engineering characteristics of the site, environmental conditions, and political considerations, information that was not available for this case study. The options presented below are intended to show a range of adaptation options and should be adjusted as this/other projects are considered. Adaptation options considered in this analysis include:

- Attempting to reduce the landslide hazard through marginal stabilization, in this case slope revegetation, that will reduce the likelihood of small (100 cubic yard or less) events
- Attempting to eliminate the landslide hazard through slope mitigation, in this case horizontal drains
- Partially protecting the road from landslide hazards but not preventing the hazard, in this case a retaining wall that can protect the roadway from small (100 cubic yard or less) events
- Fully protecting the road from landslide hazards but not preventing the hazard, in this case a hardened landslide protection shed

Adaptation 1—Reducing the Hazard through Marginal Stabilization (Revegetation)

This adaptation option involves revegetating the slope that was exposed as a result of the Igloo Creek Landslide with native plants. It is assumed that revegetation would prevent shallow sloughing and raveling type events (generally 100 cubic yards or less) but would not prevent larger events. It is assumed that revegetation is feasible at this location and a period of two years is sufficient to reestablish permanent ground cover at the site. The Native Plant Revegetation Manual for Denali National Park and Preserve163 provides guidance for revegetation of disturbed sites within the Park. The severe disturbance and steepness of the slope may reduce the revegetation techniques that would be successful, however, salvage and transplant techniques (such as placing tundra mats that have been cut from elsewhere) and placing seedlings, cuttings, or container plants may be applicable.

Adaptation 2—Eliminating the Hazard through Subsurface Drainage (Horizontal Drains)

This adaptation option involves the installation of horizontal drains to reduce slope instability and prevent landslide events at the site. Horizontal drains are installed to reduce excess pore water pressure which will increase ground stability.[164] Excess pore water pressure may be the result of confined ground water (for instance, ground water capped by impermeable permafrost), in which case horizontal drains would relieve the "pressure" by lowering the piezometric head.[165] If the slope is experiencing unconfined ground water flow (for instance, surface water from upslope permeating into the ground) horizontal drains would intercept and divert ground water to lower the ground water surface.[166]

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163 Densmore, Vander Meer, and Dunkle 2000

164 USDA 1994

165 Piezometric head is a measure of fluid pressure, typically stated as an equivalent height of fluid above a point

166 USDA 1994

The spacing and length of horizontal drains for landslide stabilization depends on several factors including the following.[167]

For lateral spacing:

- Soil permeability
- Height and volume of the potentially unstable mass
- The suspected lateral drainage pattern
- The quantity of water tapped in the first several installations

For drain length:

- Location of the slip plane or firm material
- Distance from the slope face to the location of the water source
- Distance from the crown to toe of the potentially unstable mass

To develop a cost estimate, a total footage of 6,000 feet of horizontal drain installation was assumed. It is estimated that four to six installation locations would be required, with several drains installed at each location in a “fan” pattern. Installation locations would require temporary drilling benches for equipment access. The road may be sufficient to serve as a drilling bench at some installation locations.

An instrumentation program should be developed to determine the effectiveness of horizontal drains. Such a program would likely include the evaluation of groundwater levels including baseline conditions prior to installation and monitoring after installation.[168]

Adaptation 3—Partially Protecting the Road with a Retaining Wall

This adaptation option involves the construction of a retaining wall to reduce the likelihood of a landslide event impacting the road. This option does not reduce the likelihood of a landslide event occurring.

It is assumed a retaining wall can protect the roadway from small (100 cubic yards or less) events. Larger events are assumed to partially damage or completely destroy a retaining wall.

Adaptation 4—Completely Protecting the Road with a Hardened Structure

This adaptation option involves the construction of a hardened, shed type structure to prevent any landslide event from impacting the road. Hardened sheds are constructed facilities located at the roadway level, which allow debris flows to pass over the road. Hardened sheds do not limit the onset of a landslide, but mitigate the hazardous consequences of the slide on the road. They have very large initial capital costs. These structures are massive, covering the entire span of roadway. A landslide shed might not integrate into the character of the surrounding area and, in the case of the historic Denali Park Road, might alter the historical setting of the roadway. It is assumed a shed would prevent all landslide events from impacting the road.

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[167] Lee 2013

[168] Lee 2013

STEP 7—ASSESS THE PERFORMANCE OF THE ADAPTATION OPTIONS

The performance of the adaptation options is summarized below. The performance is characterized by preventing or not preventing an event from affecting the roadway. For the scenario analyses, it is assumed that the adaptation option is repaired following all events that are not prevented by that adaptation.

- Adaptation 1—Revegetation: Prevents 10 and 100 cubic yard events and does not prevent larger events
- Adaptation 2—Horizontal drains: Prevents all events
- Adaptation 3—Retaining walls: Prevents 10 and 100 cubic yard events from impacting the roadway, is 25% destroyed for the 1,000 cubic yard event, is 50% destroyed for the 10,000 cubic yard event, and is completely destroyed for larger events
- Adaptation 4—Hardened structure: Prevents all events from impacting the roadway.

STEP 8—CONDUCT AN ECONOMIC ANALYSIS

A benefit-cost analysis of the different adaptation strategies was conducted to determine the most cost effective protection measure under each plausible slide scenario over the 50-year analysis period. For each scenario, the damages under each adaptation option were evaluated against the baseline alternative (monitoring and cleanup after events). The differences between the damage costs that would have been experienced under the no action baseline and those expected under the adaptation measure represent the net benefit of each adaptation strategy. The difference in cost expenditures between the baseline and the adaptation measures represent the net costs of each strategy. From this information, a benefit-cost ratio was developed for each adaptation option by dividing the net project benefits by its net costs.[169]

For each scenario and adaptation strategy, the stream of benefits and costs were discounted using a three percent real discount rate and a 2015 base year. The individual adaptation strategies were assumed to be fully in place starting in 2015 with no lag accounting for construction or implementation.

Calculation of Costs

For each adaptation strategy, total construction and periodic rehabilitation costs were calculated in 2015 dollars assuming no real growth in the future costs. The construction costs for each adaptation option were assumed to occur in 2015, while the corresponding rehabilitation costs were assumed to occur at a future date according to a specific time interval. The specific costs for each adaptation strategy, in both undiscounted and discounted 2015 dollars, are detailed in Table 10 below. Note that the base case "do nothing" alternative entails annual costs of $5,000 for slope monitoring. Adaptation options 1, 3, and 4 were assumed to have negligible maintenance costs. For adaptation option 2, horizontal drains, the only adaptation option with assumed significant ongoing maintenance costs, rehabilitation costs were assumed

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[169] To achieve greater ease in interpreting the final results, the operations and maintenance savings under each adaptation strategy were recorded as net benefits (added to the numerator) instead of cost savings (subtracted from the denominator). This was performed in order to ensure that the analysis didn't generate negative costs and therefore cause complications for the interpretation of the benefit-cost ratio. For instance, if operations and maintenance savings were to be captured as costs savings and thus subtracted from the denominator, then it would have been possible to produce negative benefit-cost ratios, although the net present value for the analysis was positive.

to be $15,000 every ten years. In undiscounted dollars, this totaled $75,000 over the 50-year analysis period while in discounted dollars this cost totaled $34,676.

Table 10: Construction and Maintenance Costs for Each Adaptation Option

Alternative	$2015 Undiscounted Costs	$2015 Discounted Costs
Adaptation Option 1 Revegetation	$15,000	$15,000
Adaptation Option 2 Horizontal Drains	$425,000 + $75,000 in rehabilitation costs	$425,000 + $34,676 in discounted rehabilitation costs
Adaptation Option 3 Retaining Wall	$400,000	$400,000
Adaptation Option 4 Hardened Structure	$7,100,000	$7,100,000

Calculation of Benefits

The benefits for each adaptation option under each scenario were calculated by taking the sum of the total *avoided* physical and socioeconomic damages (relative to the base case, “do nothing” alternative) due to implementing that adaptation option. In addition, the total baseline operations and maintenance costs of $5,000 per year, reflective of the current monitoring regime, were added to the undiscounted benefits. The resultant stream of benefits for each strategy and scenario were then discounted using the aforementioned three percent real discount rate and 2015 base year. The equation below describes the benefit calculation for each strategy and event magnitude.

$$\text{Benefit}_{tij} = \Delta\text{Physical Damage Costs}_{tij} + \Delta\text{Socioeconomic Costs}_{tij} + \text{Avoided O\&M Costs}_{t}$$

Where, Benefit_{ti} represents the total benefit for event i at time t given adaptation strategy j. Since we are primarily interested in differences from the alternative, in order to determine the net benefit, the Δs in the equation denotes differences from the base case. The remainder of this section discusses the calculation of the physical damage and socioeconomic costs in detail along with how they were tallied to arrive at cumulative benefits.

Calculation of Physical Damage Costs

Table 11 below details the assumptions used to estimate the total physical damages for each adaptation strategy under each type of landslide event. For the revegetation and retaining wall adaptation options, if the adaptation option fails due to an event magnitude exceeding its protection threshold (for these options, landslides of 1,000 cubic yards or greater), then total physical damages for the strategy are equal to the cleanup costs from the baseline *plus* any additional costs needed to rebuild that adaptation.

Estimation of Socioeconomic Costs

Total socioeconomic costs for each landslide event were calculated by estimating the potential loss of economic activity due to closure of the roadway. Events of less than 10,000 cubic yards were assumed to produce no significant impact on economic activity as the duration of the potential disruption will be minimal. Events greater than 10,000 cubic yards were characterized as generating significant economic disruptions in the form of less visitor spending as it was assumed that a portion of visits to Denali (namely those with destinations beyond the study area) would be scaled back or completely forgone.

To calculate the loss of economic activity, the estimated spending per visitor in real terms ($260), as determined by the National Park Service,[170] was multiplied by the average amount of visitors per day past the Teklanika rest stop (located just east of the study area). Given that the park is only open during the summer season, approximately four months, and assuming the probability of some slide event occurring is independent of the season, the average was calculated using 365 days instead of the duration of the open season. To remain conservative in the analysis, total visits were fixed at 206,102 per year (the total number of 2014 bus-visitors) and total spending per visitor was also assumed to have no real growth throughout the analysis period. These assumptions result in an estimated socioeconomic impact cost of $146,812 per day.

Next, the daily amount of socioeconomic damages was multiplied by the estimated number of days to complete the cleanup process for each magnitude of slide event as shown in Table 12 below. If the expected duration of the disruption was less than five days but greater than two, then the gross economic impact was reduced by half to reflect the fact that it is unlikely that all visitors would be deterred from traveling to the park given such a short duration event.

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170 NPS 2010b

Table 11: Net Physical Damages per Landslide Event by Adaptation Option ($2015)

Performance of Adaptation Options by Event

Event Size (CY)	Base Case—maintain, observe, remove as events happen/remove prior if feasible	1—Additional Cost to Revegetate		2—Horizontal Drains	3—Retaining Wall	4—Hardened Structure (rock shed)
	Event Cost	Assumed event surface area (acres)	Cost @$10,000/ acre, min $1,000	Cost Incurred Per Event	Cost Incurred Per Event	Cost Incurred Per Event
10	$536	0.002	$0	$0	$0	$0
100	$715	0.01	$0		$0	
1,000	$2,961	0.05	$1,000 + $2,961		$100,000 + $2,961	
10,000	$7,349	0.5	$5,000 + $7,349		$200,000 + $7,349	
50,000	$23,694	2.5	$25,000 + $23,694		$400,000 + $23,694	
100,000	$57,272	4	$40,000 + $57,272		$400,000 + $57,272	

Table 12: $2015 Socioeconomic Damages per Event and Adaptation Option

Event Size (CY)	Assumed Duration (days)	Baseline Damage	1–Revegetate Damage	2—Horizontal Drains Damage	3—Retaining Wall Damage	4—Hardened Structure Damage
10	0.17	$0	$0	$0	$0	$0
100	0.17	$0	$0	$0	$0	$0
1,000	0.33	$0	$0	$0	$0	$0
10,000	2.00	$146,812	$146,812	$0	$146,812	$0
50,000	5.00	$734,062	$734,062	$0	$734,062	$0
100,000	5.00	$734,062	$734,062	$0	$734,062	$0

Lastly, to calculate damages for each adaptation option, a binary approach is implemented such that if the strategy completely protects against the specific event then no damages are incurred. However, if the strategy fails then all baseline damages are incurred. Note that the risks of injury or death to park visitors from slide events was also considered but, given the difficulty in assigning accident rates to the specific events under each adaptation option, the injury costs resulting from a slide event affecting a vehicle passing by was not included in this analysis.

Findings

To evaluate the efficacy of each adaptation option, the total discounted costs and benefits of the option were compared under each adaptation scenario to calculate a net present value and a benefit-cost ratio. The net present value shows the absolute difference between net discounted benefits and costs, whereas the benefit-cost ratio takes the ratio of net discounted benefits to costs and gives an idea of the projects' efficiency or its "bang for the buck." In general, if the benefit-cost ratio is above one the project is considered cost effective. If the net present value is greater than zero, then the project is considered cost effective. Because each metric is calculated differently, it is possible for a project to have a higher net present value yet have a lower benefit-cost ratio.

Overall, the only adaptation strategy that produced a positive net present value and consistently high benefit-cost ratios is the revegetation option. The results indicate that this strategy is the most cost effective given the range of plausible landslide scenarios evaluated. Table 13 shows the benefit-cost ratios for each adaptation strategy under each scenario and Table 14 shows the net present values.

STEP 9—EVALUATE ADDITIONAL CONSIDERATIONS

Visitor access and economic implications are just two of many factors that need to be balanced in selecting a response strategy; especially given the special setting of the site in Denali National Park. Additional considerations that should be evaluated prior to choosing an appropriate adaptation option include:

Table 13: Benefit-Cost Ratios for Each Adaptation Option by Scenario

Scenario:	1	2	3	4	5	6	7
Adaptation Option 1 Revegetation	6.20	8.13	8.13	8.57	8.74	9.38	8.94
Adaptation Option 2 Horizontal Drains	2.73	0.99	0.99	0.60	0.31	0.31	0.29
Adaptation Option 3 Retaining Wall	(2.57)	(0.09)	(0.09)	(0.57)	(0.49)	0.35	0.34
Adaptation Option 4 Hardened Structure	0.18	0.06	0.06	0.04	0.02	0.02	0.02

Table 14: Net Present Values for Each Adaptation Option by Scenario

Scenario	1	2	3	4	5	6	7
Adaptation Option 1 Revegetation	$77,962	$106,900	$110,197	$113,577	$116,113	$125,695	$119,162
Adaptation Option 2 Horizontal Drains	$795,815	$(5,617)	$(166,162)	$(182,329)	$(315,446)	$(318,981)	$(325,515)
Adaptation Option 3 Retaining Wall	$(1,428,561)	$(437,230)	$(698,667)	$(628,594)	$(596,750)	$(259,305)	$(265,838)
Adaptation Option 4 Hardened Structure	$(5,844,509)	$(6,645,941)	$(6,806,486)	$(6,822,653)	$(6,955,770)	$(6,959,305)	$(6,965,838)

- Analysis of adaptation options using the minimum requirement/minimum tool process discussed in Step 1 and outlined in the Consolidated General Management Plan171
- Potential impacts of adaptation options to wilderness areas (all areas beyond the 300 foot wide roadway corridor) and protecting the character of the land

It is likely that these non-economic factors will play a larger role in driving the preferred course of action in a national park than in traditional transportation applications, given the specialized function of the roadway, its historic nature, and the priorities placed on environmental stewardship in a national park setting.

STEP 10—SELECT A COURSE OF ACTION

Selecting a course of action is not possible at this time due to the lack of detailed engineering data on the slope. A slope investigation and strength and stability analysis would need to be performed to develop the necessary information. A slope investigation could include the following components:

- Surface observation and geologic mapping
- Soil/rock borings
- Field and laboratory testing of soil/rock
- Geophysical testing
- Permafrost investigation
- Groundwater conditions investigation
- Ground-penetrating radar

A slope stability analysis would include the determination of soil/permafrost strength characteristics followed by analysis of the slope. The slope analysis would consider the existing conditions of the slope as well as possible changes due to the loss of permafrost and more intense precipitation. These conditions, coupled with the slope geometry and strength characteristics, would be used to assess stability of the slope. With this additional information, an appropriate adaptation option can be selected using the evaluation framework provided here and illustrated with the plausible scenarios.

STEP 11—PLAN AND CONDUCT ONGOING ACTIVITIES

Once an adaptation option is selected and in place, periodic monitoring should be performed to ensure the anticipated and continuing performance desired is being achieved. If the horizontal drain option is chosen, special attention should be paid to the change in groundwater levels brought about by their installation. Maintenance should also be performed as needed on all adaptations.

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171 NPS 2006

5. Lessons Learned

Lessons Learned

This section presents the lessons learned from this project, which range from those specific to applying climate data, to engineering applications, and to potential policy considerations for longer term implementation of the processes outlined here.

Data Application

- SNAP represents a viable source of information for downscaled climate data for use in engineering applications which incorporate future climate trends or changes. However, data may need to be clarified or specified for work at the individual project level. The development of a data agreement between SNAP and AKDOT&PF and FLMA agencies would be appropriate for future efforts.

- Future efforts to incorporate changing climate conditions into engineering decision-making will require a coordinated effort among federal agencies, state agencies, and academic or research institutions that focus on climate forecasts. The data generated by these institutions is often not specific to a project site and thus some effort will be needed to translate the more aggregate forecasts to site-specific data. This might require assumptions on how this data can be used at a particular site (where the forecasts may already contain large potential error ranges), and might require more local condition data collection to determine the existing baseline on which to project identified changes. This effort is complex and currently challenging to implement requiring significant dialogue on specific assumptions and outputs of data models.

- The process of developing input data requires significant coordination between climate scientists and engineers. There is a potential for this process to continue as a potentially challenging exercise on a project-by-project basis. There should instead be a defined and refined process for doing projects by this method to keep all future projects from becoming extensive research efforts moving forward. The development of an implementation team across disciplines would help facilitate the generation of this data moving forward.

- The Dalton Highway case study included an assessment of various methods to determine potential thaw rates for permafrost in areas of warming climate conditions. The original case study effort, along with the follow-up TEACR project, has resulted in an ongoing and continuous effort to refine the understanding of thawing permafrost in the study area. Due to the complexity of understanding permafrost thaw and the time needed to assess the full implications at the Dalton Highway site, the TEACR project will pick up the analysis where this study has left off.

- The effort to define longer term climate change exposure in Alaska would benefit from more data on transportation assets including information on surrounding environmental conditions (e.g. permafrost measurement), site conditions (e.g. elevations), construction assumptions/methods, and any noted maintenance records that focus on environment-related problems.

- There are a contributory set of challenges that were faced on this project that should be outlined, particularly relative to the Dalton Highway project where the use of specific climate data was applied to the project to identify thaw in a complex environment. The challenges included:

- Primary – the climate data was applied originally as a direct output from the SNAP temperature data. Later data analysis pointed to the need to make adjustments to this climate data to reflect historic conditions (calibration) before developing future temperature estimates used in the thaw estimates.

- Secondary – the methods employed increased in complexity, from the application of Stefan's equation to determine initial thaw estimates, to the development of a software thaw model. Each successive effort led to the identification of additional points of clarification or additional data points that would be required to reflect the multi-dimensional issue of permafrost thaw.

- Tertiary – Permafrost thaw itself is a contributor a changing environment, which then leads to a requirement to reflect those changing conditions into the model to accurately reflect the change. Thawing ground compresses and changes the assumptions built into the original model assumptions. This dynamic relationship would need to be reflected to develop a relatively accurate depicting of thaw and settlement for decision-making.

Case Study Approach

- The engineering approach applied on this project allows for the documentation of assumptions on the dynamic changes to conditions currently observed and projected into the future. The analysis of costs and benefits over time helps facilitate the selection of the best solution. This approach, while based on a number of assumptions, is a method that could be employed to assess planning and design projects and allows for information to be presented to stakeholders or interested parties interested in understanding how final policy decisions are determined.

- The application of the Process for adaptation assessments is outside of normal engineering practice and requires significant commitment and coordination for successful application as it is a new process requiring the development of information not currently prepared for other engineering projects. Utilizing this approach as a part of agency policies in the future will require a period of training within infrastructure agencies if it is to be applied to projects.

- Engineering practitioners who traditionally base their decisions on statistically derived historic data are often hesitant to move away from such data to using projected climate data for design and investment decision-making. Shifting to a more risk-based decision-making framework will help facilitate this process moving forward.

Policy Decisions

- The commitment to provide transportation access throughout Alaska is different from other states in that significant investments are made for the good of a small number of individuals. The significance of this commitment will not be reflected in traditional benefit-cost assessments, which are primarily measures of movement (people and freight). Traditional benefit-cost assessments may need to consider broader factors of concern to reflect appropriate response measures.

- The conduct of the case studies yielded recommendations that were relatively low cost options for implementation, contrary to most perceptions about incorporating future change into project decision-making. It has been an instructive exercise in assessing the cost and other implications of a warming climate on project decision processes.

- The state of Alaska has developed a long range transportation plan which identifies the need to incorporate changing climate conditions as a part of its investment strategy. While FLMA agencies have also completed a multi-agency long range transportation plan that includes climate change as a goal area, a similar policy regarding investment strategies could be a recommended outcome of this work effort. The risk-based engineering approach defined and applied on this project could be carried forward as agency policy on future project efforts statewide.

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