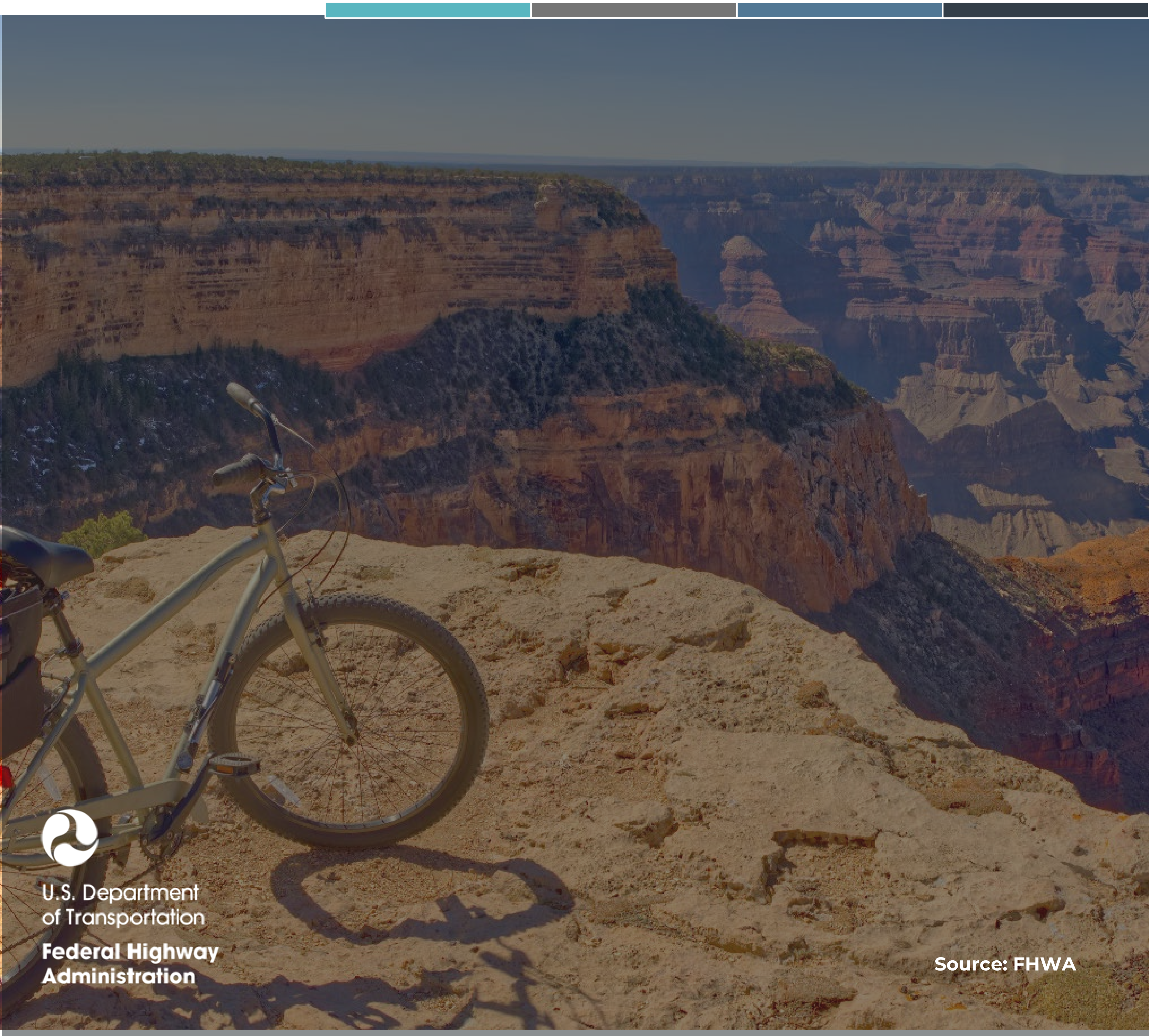
Building Resiliency through Maintenance Activities, Low-volume Roads, and Public Lands Roadways



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Changing climate conditions are impacting road infrastructure on federal lands, including low-volume roads in national parks. Limited funding availability impedes the implementation of known solutions, exacerbated by a lack of necessary data and evidence for such solutions. In response, a data-driven framework is proposed in this report to justify investments in maintenance interventions that reduce climate risks and demonstrated through a case study. Moreover, a data collection tool is proposed to streamline capturing the necessary data to support investment justification. The report offers recommendations to enhance data collection, management, and analysis to enable investment in maintenance.</td></tr>
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Acronyms and Abbreviations

AFS	Administrative Financial System
BCA	Benefit-Cost Analysis
BCR	Benefit-Cost Ratio
FHWA	Federal Highway Administration
FMSS	Facility Management Software System
LiDAR	Light Detection and Ranging
MORA	Mount Rainier National Park
NOCA	North Cascades National Park
NPS	National Park Service
NPV	Net Present Value
Olympic	Olympic National Park
PMIS	Project Management Information System
PTATS	Parks Transportation Allocation and Tracking System
RCP	Representative Concentration Pathway
SD-	Minus one standard deviation
SD+	Plus one standard deviation

Executive Summary

The evolving landscape of climate conditions leads to more frequent and intense natural hazard events, affecting low-volume roads on federal lands. Despite the existence of known maintenance solutions to reduce these impacts, the limited funding availability hinders the implementation of these solutions at scale. This funding limitation is compounded by the absence of necessary data and evidence to effectively substantiate and support the implementation of such solutions. Research is insufficient regarding maintenance as a means to improve low-volume road resilience. This gap underscores the need to investigate current maintenance practices and their efficacy in reducing the effects of climate-related hazards on such infrastructures.

In response to these challenges, a data-driven framework has been designed to compare road sections with interventions aimed at reducing climate risks to those without such interventions. This comparison allows national parks to assess the effectiveness of such interventions and justify investment in maintenance interventions that reduce climate risks. Three national parks were visited to gain insights into climate hazards and their impacts and help inform the design of the framework. A case study was conducted within one of these parks to illustrate the application of the developed framework. The case study findings underscore the significance of early investment in interventions to reduce climate risks. Delaying such interventions will likely result in higher financial costs.

Additionally, a data collection tool is proposed to support the application of the framework. This tool is conceptualized as a mobile application, aiming to streamline and enhance the efficiency of data collection. Integral to the developed framework, the data collection tool will gather information on assets, climate hazards, and their impacts. In addition, stemming from common issues identified during site visits, several other recommendations such as integration of climate data and standardization of data formats and terminology are put forth to enhance the process of data collection, management, and analysis.

1. Introduction

National parks play a crucial role in preserving biodiversity and cultural heritage and are important for environmental conservation and scientific research. The transportation system on these federal lands provides essential access to visitors and park staff, enables efficient management operations, and supports economic activity. Some national parks are home to Native American tribes and transportation infrastructure in these parks is crucial for mobility of tribal members and their access to surrounding communities. However, aging infrastructure due to use and environmental exposure and the impacts of climate change have made it increasingly challenging to maintain the performance of federal lands transportation infrastructure. Natural hazards, such as extreme temperatures, heavy precipitation, and flooding which have been exacerbated by climate change, are known to reduce the service life of this infrastructure, leading to more frequent infrastructure expenditures. As climate change impacts are expected to intensify in the coming decades, it is necessary to prepare for these changes to ensure the functionality, safety, and reliability of federal lands transportation infrastructure. National parks have continuously experienced difficulties securing funding for investment in roadway infrastructure. The disparity between available funding and the required resources to reduce the impact of climate-related hazards is widening, especially with the increased impact of these hazards in the parks. Missing opportunities to proactively invest in roadway interventions will lead to exacerbated impacts in the future.

The impacts of climate change on federal lands transportation infrastructure are widespread and varied. Changes in temperature and precipitation patterns can cause significant damage to pavement, bridges, and culverts. For instance, pavement is susceptible to the formation of potholes, cracking and rutting due to expansion and contraction caused by increased temperature fluctuation and precipitation (Knott et al. 2019; Zhang et al. 2018). Bridges may experience corrosion and scour (Imam 2019) and culverts may face clogging and reduced hydraulic efficiency (Panda 2022). Sea level rise can impact coastal highways and bridges, and increased frequency and intensity of extreme weather events such as storms, floods, and wildfires can lead to landslides, washouts, air pollution, and other hazards.

The combination of these impacts can cause significant disruptions to transportation infrastructure, which can have cascading effects on the economy, environment, and society. For example, in 2022, Yellowstone National Park experienced devastating flooding and landslides caused by extreme precipitation. The compounding impact of these climate hazards led to significant disruptions and challenges in the park's accessibility and mobility. Similarly, Glacier National Park faced a comparable situation with floods and landslides in 2023, resulting in damage to its road infrastructure.

To address the impacts of climate change on transportation infrastructure in federal lands, it is necessary for the parks to investigate the effectiveness of current risk-reduction maintenance practices and evaluate the return on investment. Changing climate conditions pose a growing threat to federal lands transportation infrastructure, causing increased damage and strain on existing systems. Insufficient budget exacerbates these challenges by hindering the implementation of solutions that are often known to reduce climate risks. Although viable solutions exist, the lack of comprehensive data limits the justification of investments in these solutions. It is imperative for the parks to develop compelling cases and substantiate the need for investment in such solutions to increase the resilience of federal lands transportation assets.

1.1. Chronic and Acute Stressors

Roadway infrastructure is subject to various stressors that can be broadly classified as either chronic or acute disturbances. Chronic stressors are persistent disturbances causing ongoing and progressive changes leading to continuous impacts that affect roadway assets. Environmental factors such as temperature changes, precipitation, and freeze-thaw cycles can lead to pavement cracking, which can compromise the structural integrity of the roadway over time (Llopis-Castelló et al. 2020). For instance, extreme heat can increase pavement rutting by lowering the stiffness modulus of pavements and damage bridges by expanding joints and cracks. Freeze-thaw cycles during extreme cold can make pavement brittle and prone to crack. In extreme precipitation, pavement can experience moisture damage, permeability reduction, and bonding failure, while bridges might be impacted by the deterioration of the deck and substructure. Considering changes in climate conditions, investments in assets can result in the improved performance of such assets against chronic stressors. For example, enhancements to pavement could involve using materials that will increase the resistance to freeze-thaw cycles in cold climates and heat absorption in hot climates.

In addition to chronic stressors, acute stressors can cause sudden and severe damage to roadway infrastructure. Examples of acute stressors include natural hazards such as floods, earthquakes, hurricanes, and wildfires. These events can cause extensive damage to roadway systems, including washouts and bridge collapses, which disrupts transportation networks and isolates communities (Zhang and Alipour 2020). The impacts of these events can be particularly challenging for vulnerable populations, who typically have limited alternative transportation options. The monetized consequences of acute stressors can also be significant, with disruptions in connectivity and increased transportation costs affecting local businesses and industries.

Recovering from the effects of acute stressors can be a lengthy and expensive process. After more than a year since the historic 500-year flood and landslide in 2022, Yellowstone National Park is still recovering from impacts with an estimated cost of $1 billion (Bailey 2022).

Climate change has intensified the impact of chronic and acute stressors on transportation infrastructure. For instance, in Denali National Park, the compounding effect of higher temperature and heavy precipitation due to climate change has led to permafrost thaw. This caused several landslides and floods, which led to road damage (NPS 2023a; Crossman et al. 2013). Sea level rise projections have also illustrated potential inundation in national parks by 2100 (NPS 2018).

1.2. Interventions

To reduce the impact of stressors on roadway assets, different maintenance strategies are implemented. Roadway asset maintenance interventions can be categorized into three types: routine, preventive, and corrective maintenance (FHWA 2014).

- *Routine maintenance*: refers to daily activities aimed at preserving the conditions of the system. These activities include cleaning roadside ditches and structures, maintaining pavement markings, and filling cracks and potholes.

- *Preventive maintenance*: involves planned and cost-effective strategies to preserve the condition of pavement and bridge assets and maintain their functionality. Some examples of preventive maintenance include asphalt crack sealing, chip sealing, slurry or micro-surfacing, thin and ultra-thin hot-mix asphalt overlaying, concrete joint sealing, and diamond grinding. For bridges, preventive maintenance is defined as cyclical maintenance (FHWA 2018).

- *Corrective maintenance*: involves reactive maintenance works in response to deficiencies in roadway assets that impact the safety and efficiency of roadway operations. For bridge assets, corrective maintenance is defined as condition-based maintenance (FHWA 2018). Examples of corrective maintenance include joint replacement, pothole repair, and patching of pavement deterioration.

To reduce the impact of climate hazards, transportation agencies and infrastructure owners implement interventions focused on climate risk reduction. These interventions involve the implementation of strategies and practices that aim to reduce the probable impacts of climate hazards on transportation assets. These interventions can be part of routine, preventive, or corrective maintenance activities and may include improving drainage systems, strengthening embankments, stabilizing slopes, dredging riverbeds, and enhancing the durability of roadway assets. The understanding of these interventions and their effectiveness is essential for decisions and investments that protect roadway assets from climate change impacts.

1.3. Project Objectives and Scope

There is a lack of research on how maintenance activities can enhance the resilience of transportation systems, particularly for low-volume roads. This study aims to address this gap by identifying and evaluating existing maintenance practices, determining their effectiveness in reducing the impacts of climate change stressors, and estimating their return on investment. The objective of the project is to create a data-driven framework that supports investment in such maintenance interventions for low-volume roads on federal lands.

The results of this research will inform future maintenance decision-making and investment, providing a clearer picture of effective maintenance practices that can enhance the resilience of roadway assets in low-volume roads to climate change. The outcome of this research will provide national parks, federal lands' road managers, and low-volume road managers with the tools to make informed decisions to better develop climate resilience plans and strategies for funding and financing resilience projects.

1.4. Report Structure

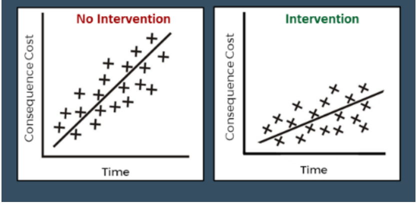
The remainder of this report is organized in four key sections. Section 2 Data-driven Framework for Justification of Investments in Resilience provides an in-depth examination of the developed framework. Section 3 Site Visits provides an overview of site visits, detailing the observations pf the impact of past events, challenges, and best practices in each park. Section 4, Application of the Framework, delves into site selection, case study, data collection, and cost and performance analysis. Section 5, Conclusions and Recommendations, outlines the proposed roadmap for the investment justification and operationalization of the developed framework.

2. Data-driven Framework for Justification of Investments in Resilience

The framework is designed to gather essential information about how climate change conditions affect transportation assets, considering the monetized consequences of climate hazards. By comparing monetized consequences with respect to maintenance intervention expenditures to reduce climate risk, the framework determines the effectiveness of these interventions and informs future decision-making.

The framework comprises three key steps: data collection, risk estimation, and benefits/costs determination (Figure 2-1).

Figure 2-1: Data-Driven Framework for Justification of Investments in Resilience

1- Collect Data	**2- Estimate Risk**	**3- Determine Benefits/Costs**
—Assets (e.g., roads, bridges) —Climate Hazards (e.g., type) —Consequences (e.g., repair type, repair cost) — Risk Reduction Interventions (e.g., intervention type, intervention cost)	—Assets Clustering —Trend Analysis 	—Estimation of future costs and benefits —Comparison of benefits and costs for two groups

Source: FHWA

1. **Collect Data:** The first step is focused on data collection. The purpose of this step is to gather comprehensive information regarding assets, climate hazards and their monetized consequences, and interventions.
    - *Assets*: detailed information about existing assets and their characteristics.
    - *Climate Hazards*: types of climate hazards potentially impacting assets and their details.
    - *Consequences*: impacts of climate hazards, including damages, and the details of repair activities to address these damages, including their monetization.
    - *Maintenance Interventions*: activities implemented to reduce the risks posed by climate hazards.
2. **Estimate Risk:** In this step assets are grouped based on asset type and risk reduction interventions for risk assessment.
    - *Asset Clustering:* categorizes assets based on type of asset (e.g., bridge, culvert, road section) and past implementation of maintenance interventions, creating two groups for each asset type: *Intervention* and *No Intervention*. Intervention assets are those with past implementation of maintenance interventions designed to reduce climate risk. No Intervention assets do not have past implementation of such maintenance interventions. Clustering helps comparing assets and determining the effectiveness of maintenance interventions.

- *Trend Analysis:* evaluates the two groups based on monetized consequences over time. Trend analysis was used to compare consequence costs of hazard damage between the two groups. This process involved analyzing the historical data of damage costs within each group to identify patterns in damage costs over time. By examining these trends, the risk profiles of the two groups of assets were assessed. Accounting for uncertainty in risk assessment is important as it allows for a more comprehensive understanding of potential outcomes. This uncertainty is considered in risk assessment of the two groups of assets.

3. **Determine Benefits/Costs:** This step is focused on estimating the benefits and costs of risk reduction interventions and comparison of the two groups of assets.
   - *Estimation of Future Costs and Benefits*: assesses the future costs of maintenance interventions and the benefits of their investment in terms of reduced monetized consequences.
   - *Comparison of Benefits and Costs*: compares the performance of the two groups of assets to determine the return of investment in maintenance.

3. Site Visits

3.1. Identify Sites and Assets

In the initial phase of this project, three national parks in Washington State were identified as potential case study locations: Olympic National Park (Olympic), Mount Rainier National Park (MORA), and North Cascades National Park (NOCA). To gain a better understanding of the environmental conditions and past climate events that have impacted these national parks, on-site visits were conducted to meet with the National Park Service (NPS) staff and maintenance team in each park. This section provides an overview of the site visits, detailing the findings that were key in understanding climate hazards, monetized consequences, and asset conditions, as well as best practices implemented by the parks to reduce climate hazards. These insights were crucial in the case study selection.

3.2. Olympic National Park

Olympic is one of the 15 national parks in the state of Washington and covers an area of approximately 572 square miles, as depicted in Figure 3-1. It was established as a national park in 1939, and in 1981 it was designated as a United Nations Educational, Scientific and Cultural Organization World Heritage Site. Olympic features three distinct ecosystems, including glacier-capped mountains, a rainforest, and over 60 miles of coastline along the Pacific Ocean (NPS 2022).

The park is home to a diverse range of plant and animal species, with more than 1,000 native plants and hundreds of animals inhabiting the region. Additionally, Olympic has significant cultural and historical importance, with numerous archaeological sites and connections to eight Native American tribes, including the Port Gamble S'Klallam, Skokomish Indian, Jamestown S'Klallam, Lower Elwha Klallam, Makah, Quileute Nation, Hoh, and Quinault Indian Nation. Olympic attracts approximately 3.4 million visitors annually, who come to experience the park's vast wilderness and engage in a variety of outdoor activities such as camping, hiking, boating, fishing, and wildlife viewing (NPS 2022).

3.2.1. CLIMATE HAZARDS IN OLYMPIC NATIONAL PARK

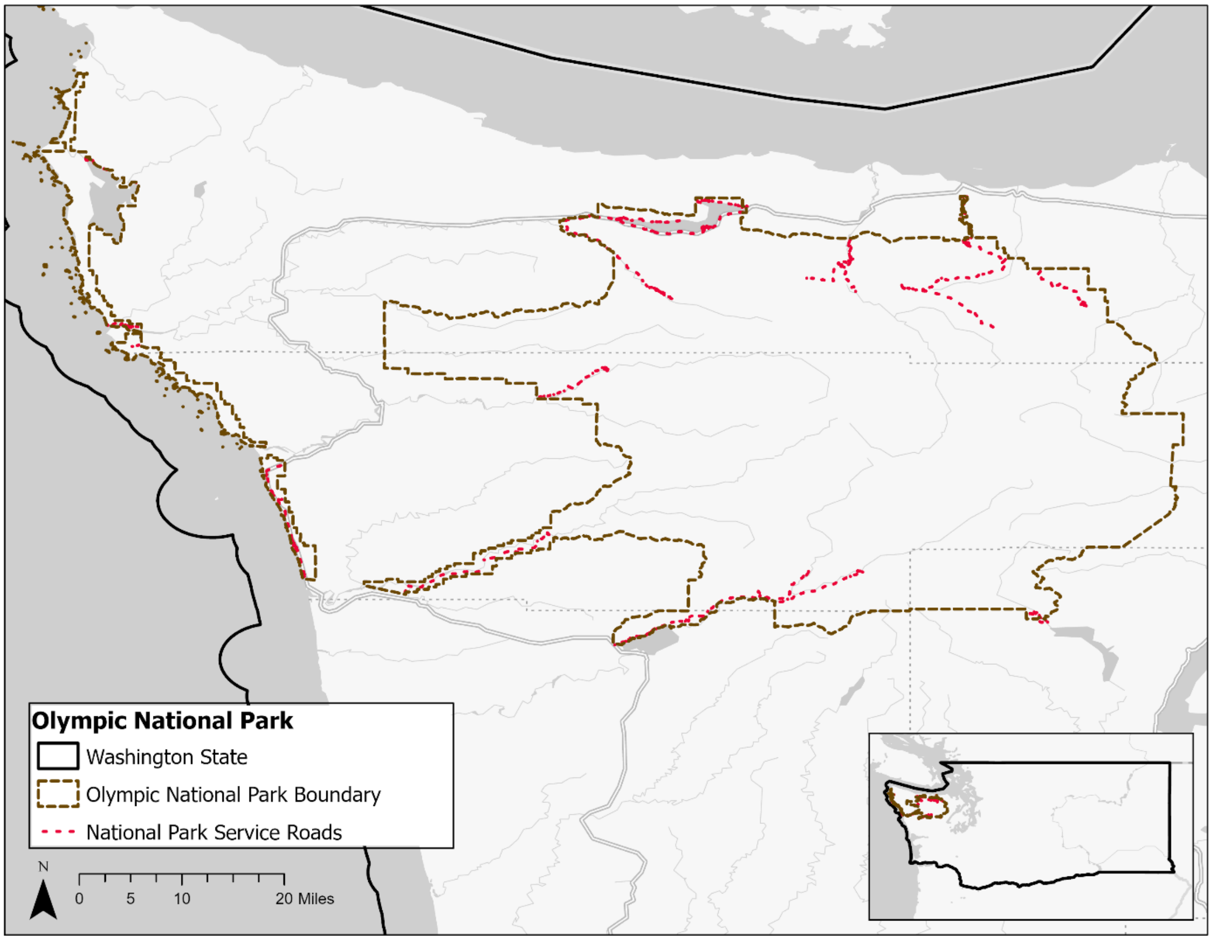
Olympic is prone to different natural hazards. Floods, storms, landslides are the common climate hazards in this park.

Floods

Olympic has a vast network of 15 rivers that span a combined length of approximately 3,500 miles. Flooding remains a significant natural hazard in this park. In recent times, the effects of climate change have become increasingly evident, manifesting in higher precipitation rates and snowmelt. As a result, Olympic has experienced flooding almost every year. For example, in November 2018 a rainfall of 7-8 inches resulted in flooding and the temporary closure of certain sections of the park. Notably, Elwha Valley Road, the unpaved Graves Creek Road, and Hoh River Road (including National Park Service and county road segments) are among the roads that frequently experience flooding in Olympic.

Olympic is facing the impacts of rising temperatures in the Pacific Northwest region. Heatwaves are intensifying the melting of glaciers, leading to an increase in floods in the park. The frequent floods and storms in the park have also caused erosion and landslides. The unstable slopes resulting from such events often lead to road closures in Olympic.

Figure 3-1: Olympic National Park



Credit: ESRI ArcGIS

Storms

Olympic is also susceptible to Pacific Northwest windstorms, which have increased in frequency in the past two decades. These storms can cause damage to park facilities and block roadways by uprooting trees or causing floods that wash out roads. A notable example occurred on August 29, 2015, when a windstorm struck Olympic. This storm caused heavy rain and power outages, uprooted trees, closed roadways, and unfortunately resulted in fatalities (Figure 3-2).

Figure 3-2: The Impact of the 2015 Windstorm in Olympic

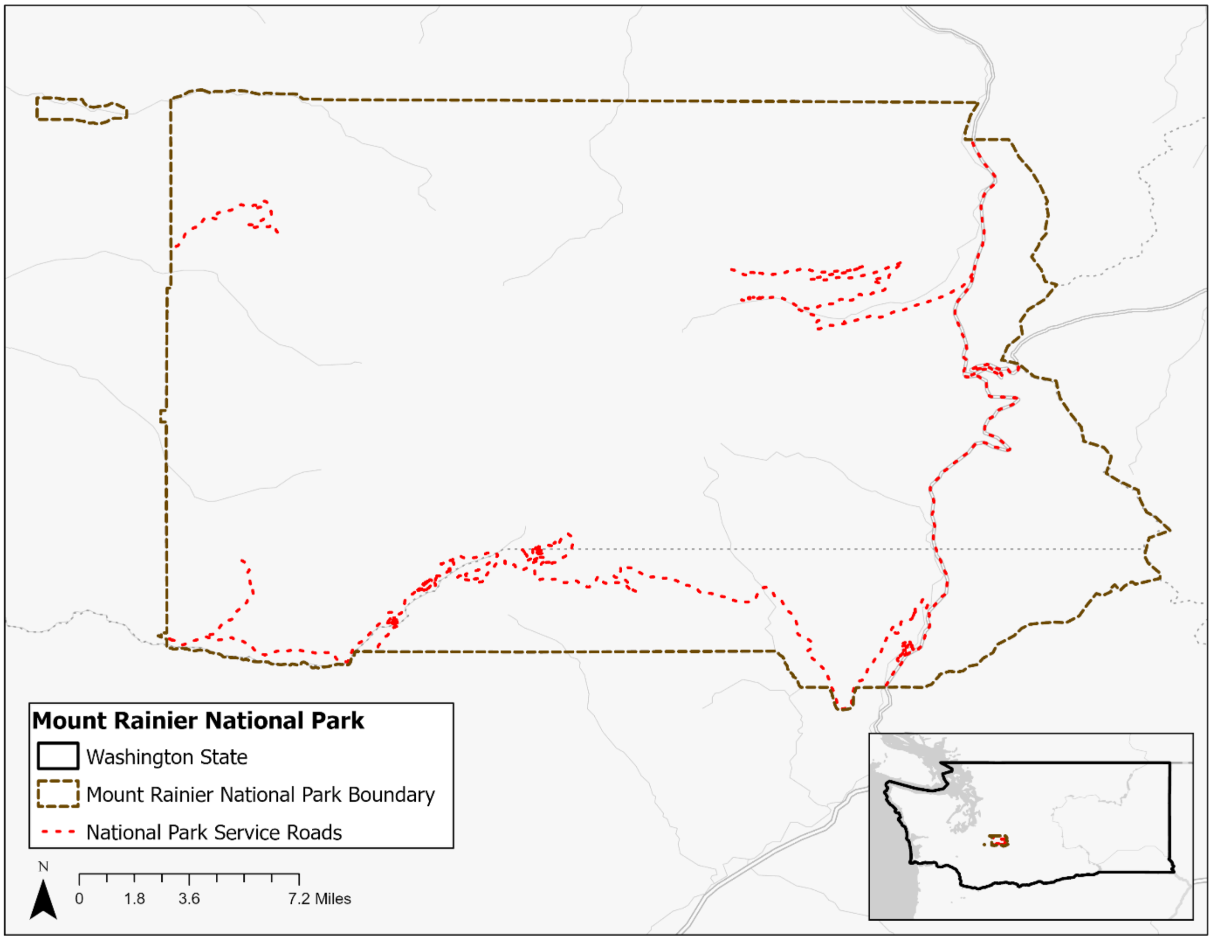
Source: NPS 2022

Other natural hazards in Olympic include wildfires, earthquakes, and tsunamis.

3.3. Mount Rainier National Park

MORA is located in the west-central region of Washington, covering an area of 369.3 square miles (Figure 3-3). It is located approximately 70 miles southeast of Seattle and was established as a national park in 1899, becoming the fifth national park in the United States. The most significant feature of MORA is its active volcano, which is also the most glaciated peak in the contiguous US. The park is the origin of five major rivers: Cowlitz, Carbon, Puyallup, Nisqually, and White. Additionally, it has a rich and diverse fauna and flora, being the habitat of nearly 300 animal species and more than 1200 plant species (NPS 2023c).

Figure 3-3: Mount Rainier National Park



Credit: ESRI ArcGIS

MORA also has significant traditional and cultural importance. Historically, Indigenous Americans have lived in the park, which is the land of six Indigenous American tribes: Cowlitz, Muckleshoot, Nisqually, Puyallup, Squaxin Island, and Yakama. Annually, the park attracts nearly two million visitors, who come to experience the various hikes, trails, lakes, and waterfalls in the park, as well as its archaeological, historical, and cultural features (NPS 2023c).

3.3.1. CLIMATE HAZARDS IN MOUNT RAINIER NATIONAL PARK

Mount Rainier is an active volcano that has a potential risk of eruption and lahars, although no lahars have occurred in historical times. Due to the history of major lahars in the park, it is ranked as the third most hazardous volcano in the US. However, the most common natural hazards in MORA are floods and debris flows.

Floods

Flooding is the major natural hazard in MORA. The height of the rivers in the park has increased over the past three decades, and their aggradation rate is 6 ft per decade, significantly higher than the historical average of 3 to 5 feet per decade. As a result, the capacity of rivers is reduced, increasing the likelihood of flooding. The frequency and intensity of floods in the park have increased in the past two decades. In November 2006, an 18-inch rainfall inundated the park, causing significant damage to roads, hiking trails, and bridges (Figure 3-4) and forcing the park to shut down for six months.

Figure 3-4: The Impact of the 2006 Flood on Mount Rainier National Park Roadway Assets

Source: NPS 2023c

In February 2020, a heavy rainfall caused flooding in MORA, resulting in damage to the park's roadways. The flood eroded fill slopes, undermined asphalt pavement, plugged a culvert, and washed roads out. Moreover, a 4-5 ft thick mudflow with a 300 ft length crossed over Forest Road 59. The Detailed Damage Inspection Report estimated the total cost of the impact of the flood on MORA roadways to be over $540,000. Nisqually-Paradise Road, White River Campground Road, Highway 410, the unpaved roads of Westside Road, and Carbon River Road are the most vulnerable roads in MORA to flooding and have frequently experienced floods. The incident underscores the significant impact of climate hazards, such as floods, on MORA's roadway infrastructure.

Debris Flows

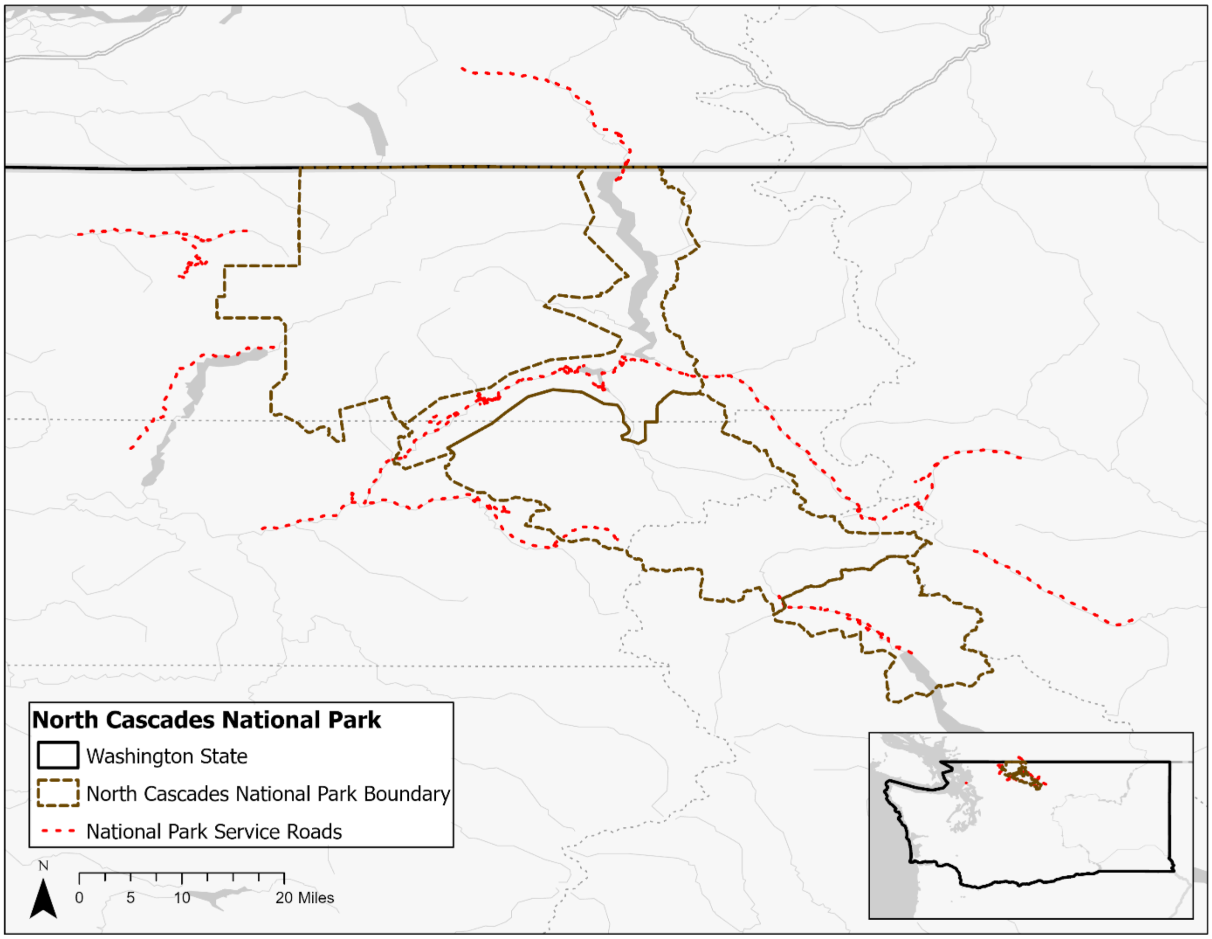
Debris flows are a mixture of water, rock fragments, and sediments that flow down the slopes of a mountain to river valleys. The peak discharge of debris flows can be 50 times greater than typical floods. Debris flows can be induced by outburst floods or rainfalls. Since 1926, at least 60 debris flows have occurred in MORA, causing significant damage. The largest recorded debris flow was the 1947 Kautz Mudflow, which was induced by heavy rainfall and mobilized approximately 3.8×107 cubic meters of debris.

Climate hazards such as floods and debris flows have had significant impacts on MORA, resulting in damages to its roadways, campgrounds, trails, and utility infrastructures.

3.4. North Cascades National Park

NOCA is a federally protected area located in the northeastern part of Washington State, along the Canadian border (Figure 3-5). Established in 1968, NOCA is composed of three distinct units: North Cascades National Park, Ross Lake National Recreation Area, and Lake Chelan National Recreation Area, with a total size of approximately 1070 square miles. The park has more than 300 glaciers, the largest concentration in the contiguous United States, as well as waterfalls, peaks, and forested valleys. NOCA also has a high degree of biodiversity and is home to over 1,600 plant species and 1,600 animal species. Each year, nearly 30,000 people visit the park, with the entire complex attracting over 828,000 visitors annually (NPS 2023b).

Figure 3-5: North Cascades National Park



Credit: ESRI ArcGIS

3.4.1. CLIMATE HAZARDS IN NORTH CASCADES NATIONAL PARK

Floods and landslides are the major natural hazards in NOCA. The warming temperature in the Pacific Northwest region has exacerbated these natural hazards, resulting in increased impact on the park's infrastructures.

Floods

In recent decades, the glaciers in NOCA have significantly decreased in size due to rising temperatures, which has resulted in flooding within the park. A severe storm in 2006 caused extensive flooding in NOCA and inflicted damage on the park's infrastructure. As a result, the Colonial Creek Campground was closed, and the Cascade River Road and parts of the Stehekin Valley Road were washed out. Similarly, in 2013, a flood washed out the Cascade River Road in NOCA (Figure 3-6). Figure 3-6 shows debris, including rocks and tree limbs, on the Cascade River Road resulting from recent floods. The Stehekin Valley Road, which is partially paved, the Cascade Pass Road, and Highway 20 (not owned by the National Park Service) are among the roads in NOCA that frequently experience flooding.

Landslides

Landslides are a significant natural hazard in NOCA, often triggered by floods and storms in the park. Rockfall is the most common type of landslide in NOCA, accounting for 68 percent of occurrences, followed by debris avalanches (17 percent), debris torrents (10 percent), and slumps/creeps (4 percent). The park has experienced several landslides in recent years, including a massive mud and rockslide in September 2013 due to a storm. These landslides have caused damage to the park's infrastructure system and impacted its services.

Figure 3-6: The Impact of a Flood on Cascades River Road

Source: FHWA

3.5. Summary of Climate Hazards

During the site visits, areas affected by flooding (Figure 3-7), debris flows, landslides (Figure 3-8), and storms (Figure 3-9) were examined and assessed, which facilitated a deeper understanding of the climate impacts, and asset vulnerabilities.

Figure 3-7: Flood Damage in Olympic National Park: (a, b) Roadway Washout, (c) Bridge Damage

Source: FHWA

Source: FHWA

Source: FHWA

Figure 3-8: Landslide Damage: (a) Mount Rainier National Park, (b) North Cascades National Park

Source: FHWA

Source: FHWA

Figure 3-9: Storm Damage in North Cascades National Park

Source: FHWA

3.6. Maintenance Interventions

Additionally, some of the maintenance interventions to reduce climate risks implemented in these parks were examined. For example, in Olympic, in response to riverbank erosion along the Elwha River, the park implemented measures to protect the roads and control erosion. The implementation included the use of riprap and planting trees along the riverbanks (Figure 3-10).

Figure 3-10: Maintenance Interventions in Olympic National Park: Riprap and Vegetation

Source: FHWA

In MORA, a road with a wooden engineered log jam foundation was constructed in response to the 2016 debris flows that destroyed roads (Figure 3-11). The construction of this road aimed to enhance the roughness and stability of the road, and its estimated cost was $260,000. All materials, except for the ripraps, used for building this road were native to the park. This road has demonstrated the effectiveness of maintenance interventions in withstanding a debris flow in 2019 and several floods.

Figure 3-11: Mount Rainier National Park Road with Engineered Log Jam Foundation

Source: FHWA

Additionally, log jam structures have been constructed in riverbanks (Figure 3-12) to reduce erosion and rehabilitate the river. Although the engineered road has been reinforced, aggradation continues to be a challenge for the park.

Figure 3-12: Mount Rainier National Park Roadway Erosion Reduction Measures: Engineered Log Jam

Source: FHWA

3.6.1. CLIMATE RISK REDUCTION CHALLENGES

The challenges faced by national parks to proactively address climate hazards can be broadly categorized as funding and data. Funding challenges includes issues related to the availability, flexibility, and adaptation of funding sources.

The limited maintenance and damage repair budget has hindered the ability of park staff proactively respond to potential climate hazards. There is a demonstrated need for more financial resources for annual maintenance activities to prevent costly damage repairs in the future. Emergency relief funding is typically limited to restore damaged roadway assets to their pre-disaster level of performance unless a case for betterment can be made to build resilience. As a result, parks face constraints when trying to be proactive in addressing potential climate hazards that may impact roadway assets in the future.

Furthermore, data collection, management, and analysis also present challenges for the parks. Staff shortages and seasonal data collection limit the extent of climate hazard monitoring and make it difficult to track the dynamic changes in rivers and their impact on roadway assets. Improving collection and management of the roadway asset conditions, maintenance and damage repair, and climate data is necessary to ensure that the park staff has the information needed to make informed decisions about proactive maintenance. It is also essential to have a better understanding and analysis of local climate events and their frequency as well as past maintenance and damage repair records to effectively plan and allocate resources.

4. Application of the Framework

4.1. Case Study: Nisqually-Paradise Road

Following site visits and consultation with the parks, Nisqually-Paradise Road in MORA was selected as the case study for the implementation of the framework. Constructed between 1904 and 1915, the Nisqually-Paradise Road provides direct access from Seattle to the park. As the only road in MORA that remains open year-round, it provides access to important facilities, including the main administrative hub at Longmire, the main visitor center, two historic inns, Cougar Rock campground, and various trails. Spanning 17.6 miles, the road includes Nisqually Glacier, Tahoma Creek, Kautz Creek, and Edith Creek bridges in addition to more than 300 culverts.

The Nisqually-Paradise Road is frequently threatened by floods caused by rainfall, snow and ice melting, and glacier outbursts. These climate hazards lead to debris flows, which pose significant challenges for road infrastructure management. For instance, the 2006 flood washed out parts of the road. Due to the vulnerability of the road to such climate hazards and its importance to the transportation in the park, this road was selected for study. In addition, the park has implemented maintenance interventions in some sections of the road to reduce climate risks, which makes it an ideal case study location.

4.2. Collect Data

The data collection process involved gathering financial data of maintenance and damage repair works from Federal Highway Administration (FHWA) to support the study—indeed, information on damage repairs were also included in the financial dataset. These data are a combination of records from different NPS sources, such as:

- The accounting system (Administrative Financial System [AFS])
- The project management system (Project Management Information System [PMIS])
- The FHWA tracking system (Parks Transportation Allocation and Tracking System [PTATS])
- The facility, inventory, and work order system (Facility Management Software System [FMSS])

To complement and cross-validate the FHWA financial data, additional maintenance and damage repair information was obtained from the park. Data records from 2006 to 2018 were reviewed in both datasets. This review revealed significant data gaps and missing detailed records, particularly concerning interventions designed to reduce the impacts of climate change. These data are limited primarily because there has not been a need for such data collection in the past. This unavailability of data made it difficult to understand the effectiveness of previous interventions. The absence of detailed information pertaining to the geolocation of road sections and that of performed maintenance interventions, hindered the ability to accurately associate interventions to the different road sections of the Nisqually-Paradise Road.

Due to these challenges, a synthetic dataset was created using the FHWA maintenance and damage repair financial data and the MORA work orders (see Appendix A: Sample Synthetic Data). Records such as the Nisqually to Paradise Road Rehabilitation Environmental Assessment (NPS 2012) were also reviewed. In addition, anecdotal information played a crucial role in this process. Interactions with the MORA park staff, and the available visual records provided firsthand insights and qualitative information that complemented the quantitative data records.

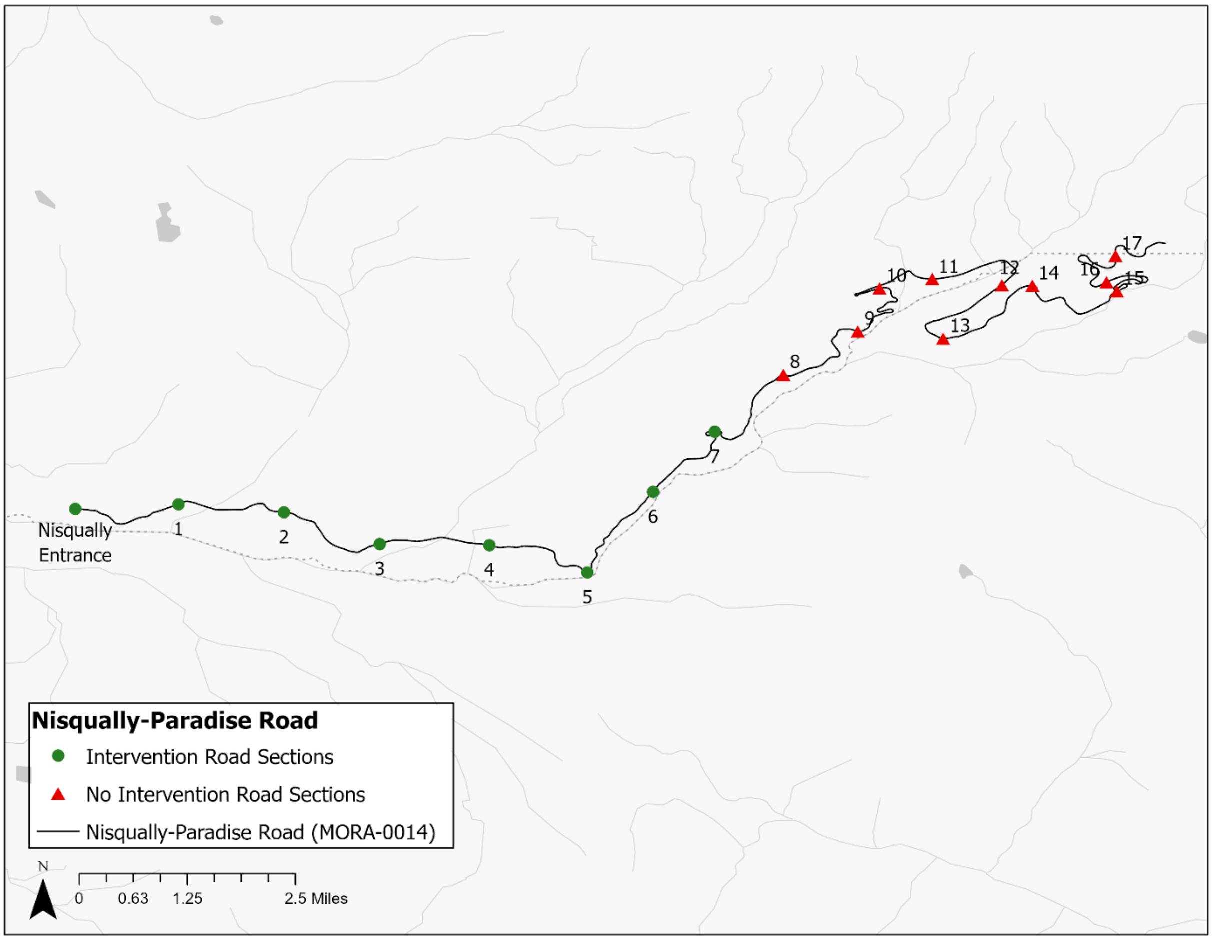
The synthetic dataset incorporated detailed information on maintenance interventions that are designed to reduce climate risks and damage repair activities at different road sections and in different fiscal years. The newly created dataset provided the foundation to help assess the effectiveness of maintenance interventions in reducing impacts from climate change.

4.3. Estimate Risk

4.3.1. ASSET CLUSTERING

The Nisqually-Paradise Road was segmented into two groups of road sections, as illustrated in Figure 4-1.

Figure 4-1: Nisqually-Paradise Road: Intervention and No Intervention Road Sections



Credit: ESRI ArcGIS

The Intervention group is a collection of road sections from mile-point 0 to mile-point 7. The assumption is that maintenance interventions were conducted along these road sections in 2006 to reduce climate risk. The cost of interventions in each road section is assumed to be

$150,000 in 2006. The road sections from mile-point 7 to mile-point 17 are assumed to be areas where no maintenance interventions had been implemented. These road sections are classified as the "No Intervention" group. The assumptions for the analysis are:

- Road sections have the same length (1 mile).
- There are two groups of road sections: *Intervention* (seven sections) and *No Intervention* (10 sections).
- Monetized consequences, or the cost related to damage repairs (i.e., expenditures between 2006 and 2018) are allocated as follows:
    - No Intervention: 70 percent
    - Intervention: 30 percent
- Funding was assigned randomly to increase financial data resolution in the absence of more precise data.

The only synthetic data used in this study are the financial data of damage repairs and interventions. These data are applied to the Nisqually-Paradise Road, which is a flood-prone road in MORA with a history of flood damage. To complement the data generated records of past events, interventions and anecdotal accounts related to this particular roadway have been incorporated into the analysis to enhance the accuracy of the analysis and the relevance of the findings.

4.3.2. TREND ANALYSIS

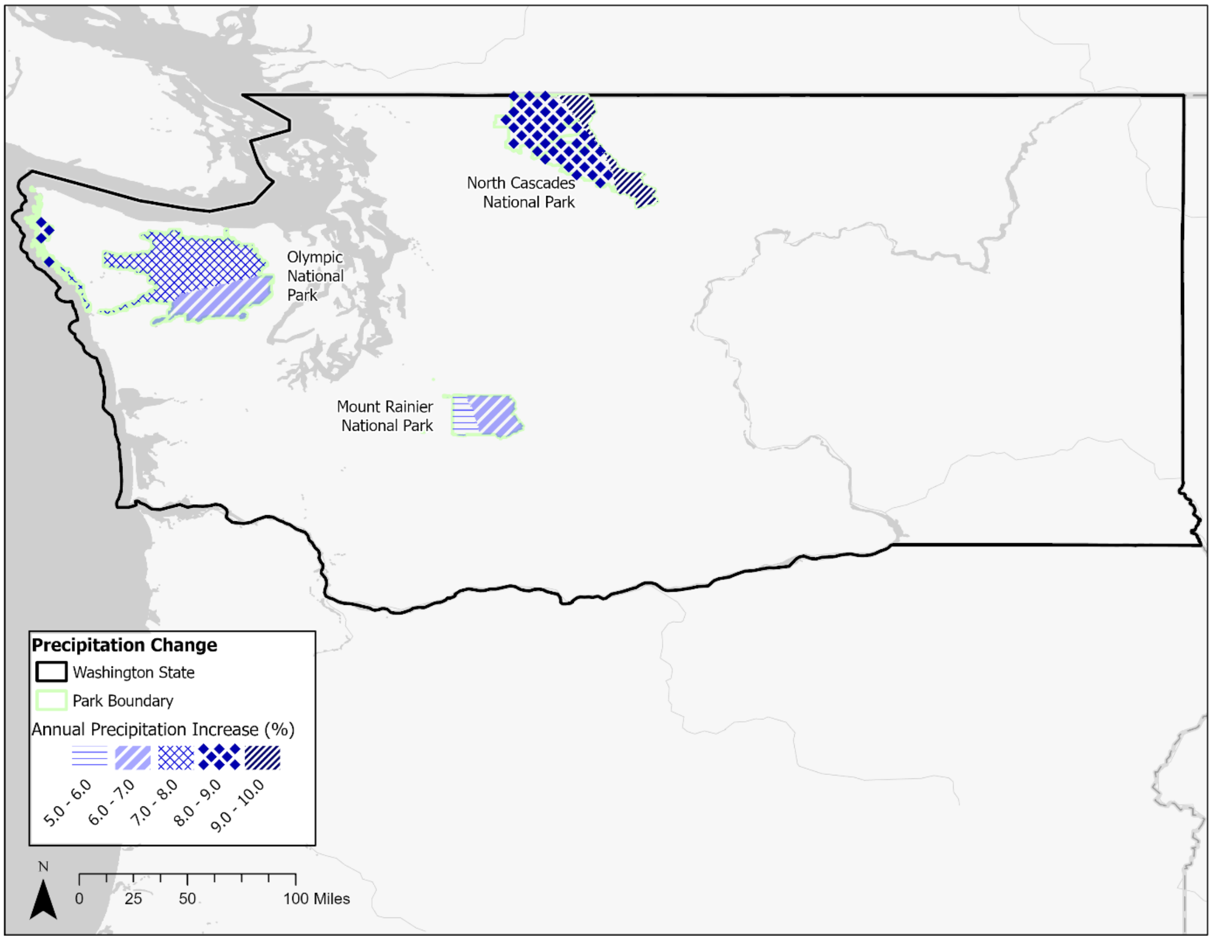
The projected annual precipitation changes in the Northwestern part of the contiguous United States, where the three national parks are located, reveals an increasing trend by the end of the century (Gonzalez et al. 2018).

Many parks are projected to see an increase in precipitation by the end of the century. MORA is projected to see an increase between 5.39 and 6.70 percent; Olympic, between 6.65 and 8.43 percent; and NOCA, between 8.03 to 9.57 percent under high emissions scenario—Representative Concentration Pathway 8.5 (RCP 8.5). Figure 4-2 illustrates the ranges of precipitation change across the three parks. This higher level of precipitation poses an increased risk of flooding, thereby impacting roadway infrastructure in the parks. The raising damage repair cost in the no intervention scenario until 2040 reflects the likely increased impact by higher precipitation caused by climate change. Similarly, the three parks are expected to experience higher temperatures, specifically between 3 and 5.19 degrees Celsius (between 5.4 and 9.3 degrees Fahrenheit) by the end of the century (Figure 4-3). This temperature rise will impact the roadway assets and can also trigger glacier melting, leading to increased flooding and debris flows, further exacerbating challenges for the roadway assets.

Two scenarios are considered in trend analysis: the "no intervention" scenario and the "Intervention" scenario. In the no intervention scenario, no maintenance interventions to reduce climate risk are implemented on the road sections categorized as *No Intervention* in 2023. Conversely, in the intervention scenario, it is assumed that such interventions are implemented in the *No Intervention* group road sections in 2023.

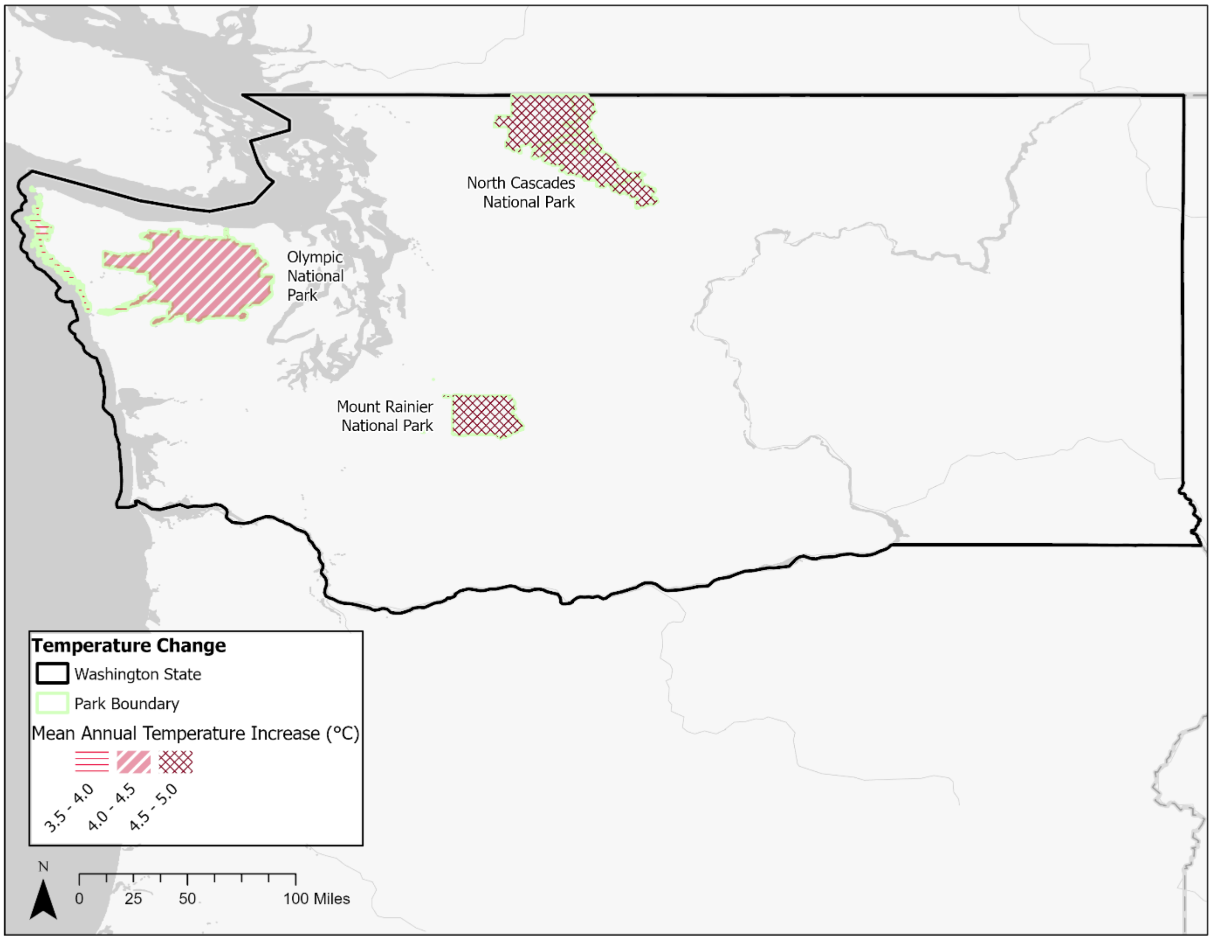
Figure 4-4 illustrates the projected annual damage repair cost for an individual road section in the no intervention and intervention in 2023 scenarios. The projected values for these two scenarios are based on the historical damage repair costs (2006 to 2018) of all road sections in each group. The projected annual damage repair cost indicates that these costs for the no intervention scenario steadily increase until 2040. Conversely, these costs for the intervention scenario, remains relatively stable until 2040. The difference between the damage repair costs in the two scenarios in 2040 amounts to $584,152. While the presented damage repair cost in this graph exhibits a linear trend, in reality these costs do not follow a strict linear pattern as they are subject to stochasticity.

Figure 4-2: Annual Precipitation Change (% Century^{-1}) RCP 8.5



Credit: ESRI ArcGIS

Figure 4-3: Mean Annual Temperature Change (°C Century^{-1}) RCP 8.5



Credit: ESRI ArcGIS

4.4. Determine Benefits/Costs

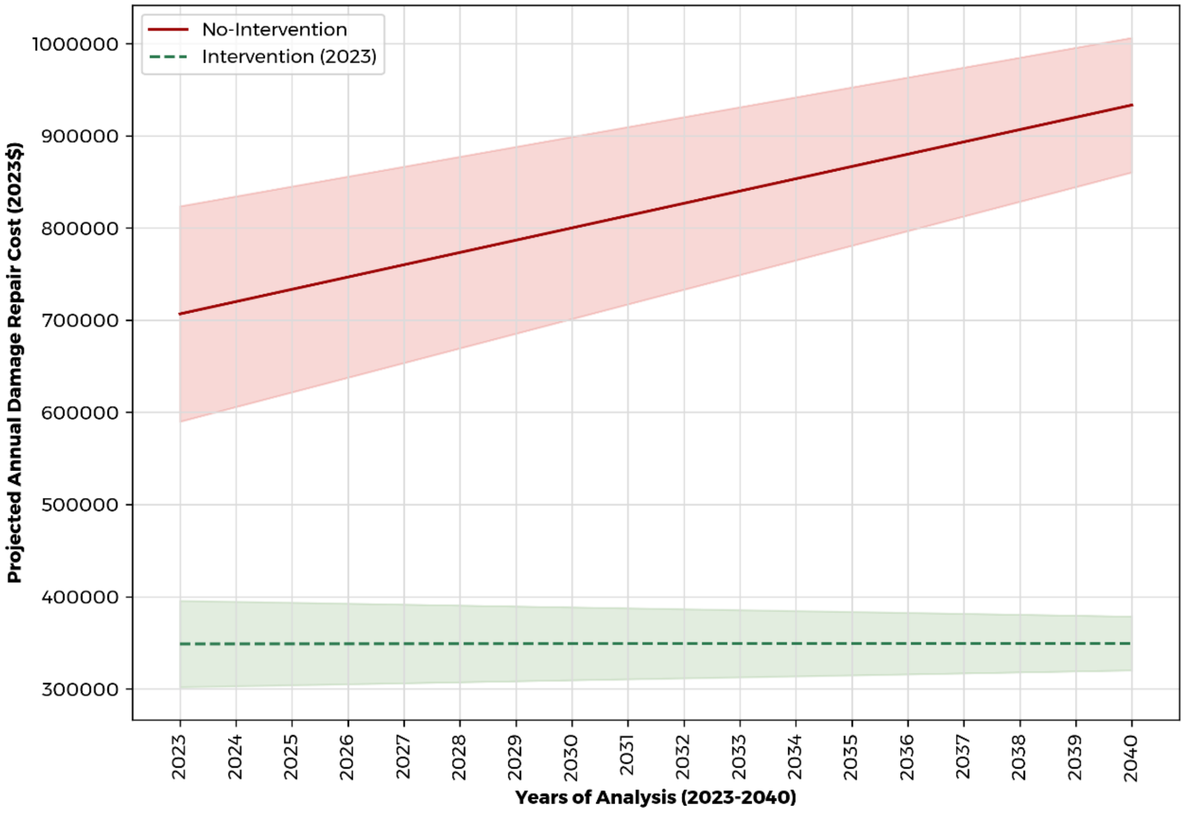
The estimated damage repair costs between 2006 and 2018 were used to project the benefits of interventions in individual road sections from 2023 to 2040, where benefits are the difference between the monetized consequences in the intervention scenario and those of the no intervention scenario.

A benefit-cost analysis (BCA) was conducted using the costs of maintenance interventions to reduce climate risk. A 2 percent discount rate was considered based on the Guidelines and Discount Rates for Benefit-Cost Analysis of Federal Programs (Executive Office of the President 2023).

Table 4-1 shows the BCA summary. The Net Present Value (NPV) and Benefit-Cost Ratio (BCR) values indicate the maintenance intervention project's economic feasibility. The results highlight that the NPV of improving a No Intervention road section in 2023 is $6,869,934.

With a BCR of 31.33, the benefits of maintenance interventions to reduce climate risks significantly outweigh the cost of the intervention. These findings suggest that the project holds promise for generating positive net benefits.

Figure 4-4: Projected Annual Damage Repair Cost for Assets with and without Past Intervention



Source: FHWA

Table 4-1: Benefit-Cost Analysis Summary

Scenarios	Baseline	Sensitivity Analysis (SD-)	Sensitivity Analysis (SD+)
Damage Repair Cost 2023-2040 (No Intervention)	$12,432,835	$10,959,228	$13,906,441
Damage Repair Cost 2023-2040 (Intervention)	$5,336,401	$4,744,964	$5,927,837
Maintenance Intervention Benefit (in 2023 US Dollars*)	$7,096,434	$6,214,264	$7,978,604
Maintenance Intervention Cost (in 2023 US Dollars)	$226,500	$226,500	$226,500
NPV	$6,869,934	$5,987,764	$7,752,104

BCR	31.33	27.44	35.23

Note: * Discount Rate: 2 percent

Key: BCR = Benefit cost ratio; NPV = Net present value; SD- = One standard deviation minus; SD+ = One standard deviation plus

4.5. Sensitivity Analysis

To account for the uncertainty associated with the input data, a sensitivity analysis was performed as part of the BCA for Nisqually-Paradise Road to assess the maintenance intervention's economic feasibility under different cost scenarios. The sensitivity analysis involved considering one standard deviation from the damage repair costs in each group which is a widely adopted method in sensitivity analysis. Two cases were considered for the sensitivity analysis (shaded areas in Figure 4-4): one standard deviation minus (SD-) and one standard deviation plus (SD+) to the damage repair costs for each road section in each year in the baseline scenario. The sensitivity analysis, therefore, changes the input data and in turn the projected trends, which are not necessarily parallel to the original trend line. One of the key advantages of sensitivity analysis is its ability to highlight the maintenance intervention's sensitivity to changes in the input variables.

In the SD- case, the BCA analysis revealed that the NPV is lower compared to the initial BCA analysis (Table 4-1). Despite this decrease, the NPV still indicates positive financial viability for the maintenance intervention. The BCR is reduced to 27.44, indicating that the benefits still are still expected to outweigh the costs. These results suggest that although that the maintenance intervention's economic performance is slightly affected by the lower damage repair costs, the investment in 2023 remains promising.

In the SD+ case, the BCA analysis demonstrates an increase in the NPV compared to the initial BCA analysis (Table 4-1). Additionally, the BCR increases by 12 percent from the initial BCA analysis. These findings indicate that even with higher damage repair costs, the maintenance intervention's financial viability is enhanced, and the results suggest feasibility for investment in 2023. The projected annual damage repair cost in SD- and SD+ are shown by the error bands in Figure 4-4, illustrating the potential impact of varying damage repair costs on the maintenance intervention's financial performance.

The sensitivity analysis of the BCA for the Nisqually-Paradise Road indicates that maintenance interventions remain economically viable, despite variations in damage repair costs. The NPV and BCR results consistently support the feasibility of investment in 2023 in both sensitivity analysis scenarios.

4.6. Year of Investment

The intervention scenario assumes the implementation of maintenance interventions in 2023 to reduce climate risks. However, it is important to note that these interventions can be done throughout the analysis period (2023–2040). Therefore, investment scenarios within this timeframe were examined by adjusting the intervention year to each year between 2023 and 2040 in the Intervention scenario. This analysis provides insights into the potential benefits and trade-offs associated with different investment scenarios, allowing for a more comprehensive evaluation of the long-term implications of risk-reduction interventions.

Changing the base year of investment to future years in the BCA offers valuable insights in assessing the financial feasibility and long-term implications of a maintenance intervention. By shifting the base year beyond the present, updated information can be incorporated into the assessment to make more informed investment decisions. This approach allows for a comprehensive evaluation of the maintenance intervention’s viability by considering the anticipated costs and benefits in the context of the projected future conditions.

For the Nisqually-Paradise Road maintenance interventions, the base year of investment was modified from 2023 to each subsequent year until 2040. Table 4-2 presents the outcomes of the analysis for the baseline analysis, as well as the SD- and SD+ analysis, reflecting the effects of changing the base investment year from 2023 to each subsequent year until 2040. Table 4-2 captures the NPV and BCR for each analysis, providing a comprehensive view of the maintenance intervention’s financial performance under different investment years. For example, the NPV of investing in maintenance interventions in 2023 is $6,869,934. If such interventions are implemented in 2040, accumulating less benefits over the years, the NPV of such investment is $190,680. Therefore, investing in maintenance in 2023 generates a NPV 36 times larger.

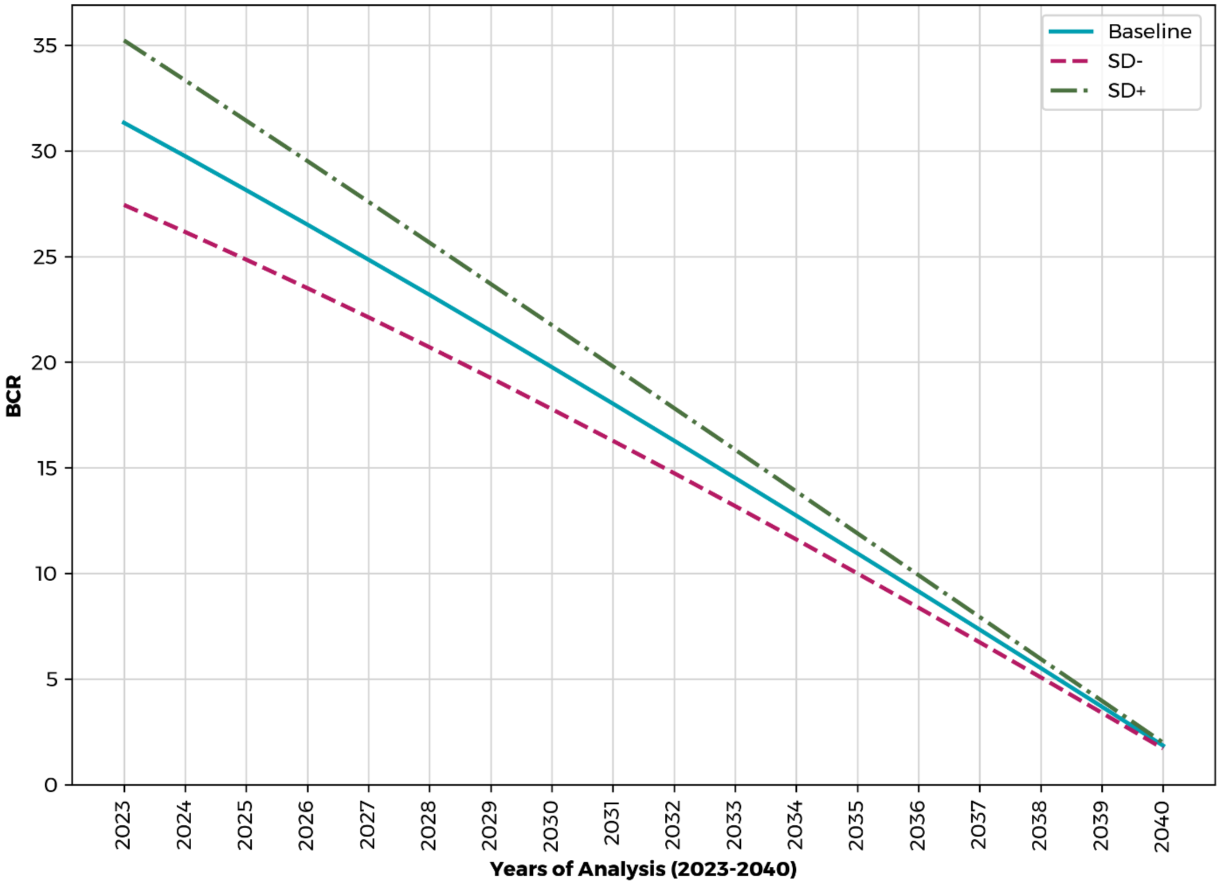
Table 4-2: Benefit-Cost Analysis Summary for Different Base Investment Years

Base Investment Year	**NPV**			**BCR**		
	Baseline	SD-	SD+	Baseline	SD-	SD+
2023	$6,869,934	$5,987,764	$7,752,104	31.33	27.44	35.23
2024	$6,511,811	$5,699,628	$7,323,993	29.75	26.16	33.34
2025	$6,147,674	$5,402,594	$6,892,755	28.14	24.85	31.43
2026	$5,777,898	$5,097,121	$6,458,676	26.51	23.50	29.52
2027	$5,402,844	$4,783,654	$6,022,034	24.85	22.12	27.59
2028	$5,022,860	$4,462,624	$5,583,096	23.18	20.70	25.65
2029	$4,638,285	$4,134,449	$5,142,121	21.48	19.25	23.70
2030	$4,249,444	$3,799,531	$4,699,357	19.76	17.77	21.75
2031	$3,856,653	$3,458,262	$4,255,043	18.03	16.27	19.79
2032	$3,460,215	$3,111,020	$3,809,410	16.28	14.74	17.82
2033	$3,060,425	$2,758,169	$3,362,682	14.51	13.18	15.85
2034	$2,657,568	$2,400,063	$2,915,072	12.73	11.60	13.87
2035	$2,251,916	$2,037,044	$2,466,787	10.94	9.99	11.89
2036	$1,843,734	$1,669,443	$2,018,025	9.14	8.37	9.91
2037	$1,433,278	$1,297,578	$1,568,977	7.33	6.73	7.93
2038	$1,020,793	$921,758	$1,119,828	5.51	5.07	5.94
2039	$606,517	$542,282	$670,753	3.68	3.39	3.96
2040	$190,680	$159,436	$221,923	1.84	1.70	1.98

Key: BCR = Benefit cost ratio; NPV = Net present value; SD- = One standard deviation minus; SD+ = One standard deviation plus

The results of the three scenarios reveal a consistent trend: as the base investment year is shifted to later years, both the NPV and BCR show a decreasing trend. This finding emphasizes the importance of early investment in this maintenance intervention, as postponing the intervention initiation leads to less financial benefits. Figure 4-5 provides a graphical representation of the changes in BCR across the three scenarios as the base investment year shifts to later years. The downward slope of the BCR curves signifies that delaying the initiation of the maintenance interventions results lower return of investment, underscoring the importance of timely decision-making and resource allocation for infrastructure improvement projects.

Figure 4-5: BCR Changes in Different Base Investment Year



Source: FHWA

4.7. Additional Considerations

Various approaches can be employed to conduct a BCA. For example, the U.S. Army Corps of Engineers considers a range of factors including national economic development, regional economic development, other social effects, and environmental quality benefits in their BCA framework (USACE 2000; Briceno et al., 2019). In this example, the BCA focused solely on the costs associated with maintenance interventions to reduce climate risks and the monetized consequences to show the application of the approach. However, a comprehensive BCA requires a broader consideration of factors such as safety, environmental sustainability, travel patterns, and socioeconomic factors. In addition, this example focused on one specific road in MORA. The three national parks in this research share similar climate conditions, both current and projected. The types of natural hazards they experience are also similar. Therefore, similar studies in Olympic and NOCA are expected to yield comparable results; hence, the analysis conducted in this example and the findings can be extended to Olympic and NOCA.

5. Conclusions and Recommendations

5.1. Conclusions

Environmental conditions are shifting with climate change, leading to increased damage to low-volume road assets on federal lands. While solutions to protect these assets are available, budget constraints present challenges. Additionally, limited evidence to make a compelling case for such solutions poses challenge in their investment justification. The primary objective of this study was to establish a data-driven framework to justify investment in maintenance interventions in low-volume roads to assist national parks in their development of resilience investment plans and funding strategies. To achieve this goal, an investment justification framework was developed and applied to the Nisqually-Paradise Road in the MORA park.

The developed framework serves an example of an approach that integrates crucial data on assets, climate hazards and their monetized consequences (e.g., damage repair costs), and maintenance interventions to reduce climate risks. However, it is important to acknowledge that due to the limitations of obtaining comprehensive real data, the application of the developed framework was based on synthetic data generated from various sources including existing financial records, past reports, and anecdotal records. This study serves as a crucial initial step in identifying the gaps and challenges in adequately maintaining low-volume roads.

The findings of this study highlight the need to update data collection and management practices within the parks to generate reliable and comprehensive data sources for improved maintenance decision-making. Obtaining accurate and extensive data is essential for making informed decisions regarding maintenance interventions and assessing their financial viability. Without reliable data, it becomes challenging to accurately estimate the potential benefits and costs associated with different maintenance interventions. The proposed framework is valuable in justifying investment in such interventions.

The steps outlined in the following section provide a roadmap for updated data collection and management practices by the parks and how a support tool can be used.

5.2. Proposed Roadmap for Building Resilience through Maintenance Activities

This section outlines the necessary processes that must be developed to effectively implement the proposed framework introduced in Section 2.

5.2.1. DEVELOPMENT OF A SUPPORT TOOL

Initial Data Collection and Tool Implementation

Current data collection practices for maintenance and damage repair activities lack essential information to determine the resilience of roadways. This limitation poses significant challenges when attempting to trace performed maintenance and damage repair work back to specific roadway assets at a granular scale. Consequently, there is a need to bridge this gap and improve the overall data collection processes.

The initial step in the data collection process involves identifying the essential information required to use the resilience investment justification framework effectively. This information can be categorized into three essential areas:

- *Assets*: captures detailed information about road assets, their dimensions, and location.

- *Maintenance Interventions*: project implementations to protect road assets from climate hazards and ensuring their resilience.
- *Damage Repairs*: interventions employed to repair damaged assets and restore their functionality.

To address the data collection challenges, implementing a data collection tool that can be used by maintenance staff on mobile devices even in offline environments is recommended. This tool would be a cloud-based solution that can store data locally and synchronize to facilitate the sharing of collected data. This recommendation stems from the issues encountered by the parks in terms of processes, standards, and systems for data collection. Figure 5-1 provides a summary of the information that the data collection tool should capture. Figure 5-2 depicts a representation of a mobile application version of this data collection tool that can be developed for seamless digitized data collection. A user guide for the tool is provided in Appendix B: Data Collection Tool User Guide and an implementation plan is summarized in Appendix C: Implementation Plan.

For consistency across all systems, programs, and datasets, some of the details in the data collection tool can be extracted from sources such as the Road Inventory Program, and datasets such AFS, PMIS, PTATS, and FMSS. While this list of datasets captures the most fundamental information, it can be expanded based on needs to consider specific assets, climate hazards, and interventions.

To overcome challenges related to data collection in areas with limited accessibility, particularly the dynamics of river conditions, drones and Light Detection and Ranging (LiDAR) systems can be used. These technologies can provide valuable data on riverbank erosion, river avulsion, waterflow patterns, and other critical parameters.

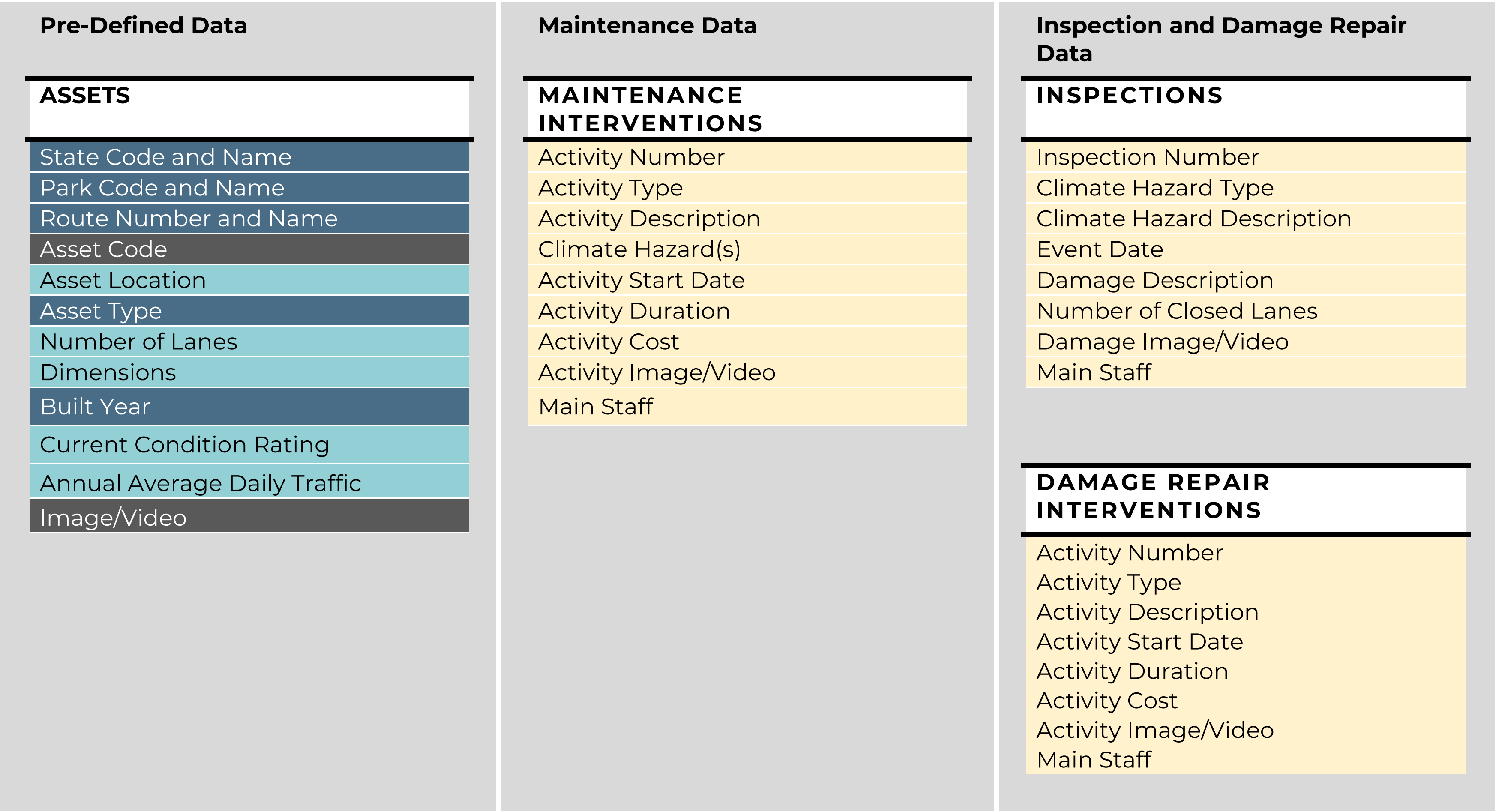
Standardization of Data Formats and Terminology

The review of past maintenance and damage repair records revealed a discrepancy in terminology and record data entry. This inconsistency poses challenges for data analysis, comparability, and effective decision-making. Establishing standardized data formats and terminologies is essential. This standardization will facilitate data collection, sharing, comparability, and compatibility between different datasets. By adopting common data formats and terminology, maintenance and damage repair activities can be consistently documented, enabling comprehensive analysis and benchmarking across different regions. One can consider the use of data from a park by another park to support the determination of maintenance effectiveness should the asset and conditions be comparable—as with the initial data collection tool, this analysis would be best supported by a cloud-based system.

Integration with Asset Management Systems

To further improve data management and decision-making processes, it is essential to integrate asset management systems with the data collection tool. Asset management systems enable comprehensive tracking of the life cycle of road assets, including maintenance and damage repair schedules, condition assessments, and financial records. By integrating these systems with the data collection tool, park authorities can gain a holistic view of their assets' performance, maintenance and damage repair requirements, and associated costs for more informed decision-making regarding maintenance and damage repair activities and investment priorities.

Figure 5-1: Data Categories in Data Collection Tool



Pre-Defined Data

ASSETS

- State Code and Name
- Park Code and Name
- Route Number and Name
- Asset Code
- Asset Location
- Asset Type
- Number of Lanes
- Dimensions
- Built Year
- Current Condition Rating
- Annual Average Daily Traffic
- Image/Video

Maintenance Data

MAINTENANCE INTERVENTIONS

- Activity Number
- Activity Type
- Activity Description
- Climate Hazard(s)
- Activity Start Date
- Activity Duration
- Activity Cost
- Activity Image/Video
- Main Staff

Inspection and Damage Repair Data

INSPECTIONS

- Inspection Number
- Climate Hazard Type
- Climate Hazard Description
- Event Date
- Damage Description
- Number of Closed Lanes
- Damage Image/Video
- Main Staff

DAMAGE REPAIR INTERVENTIONS

- Activity Number
- Activity Type
- Activity Description
- Activity Start Date
- Activity Duration
- Activity Cost
- Activity Image/Video
- Main Staff

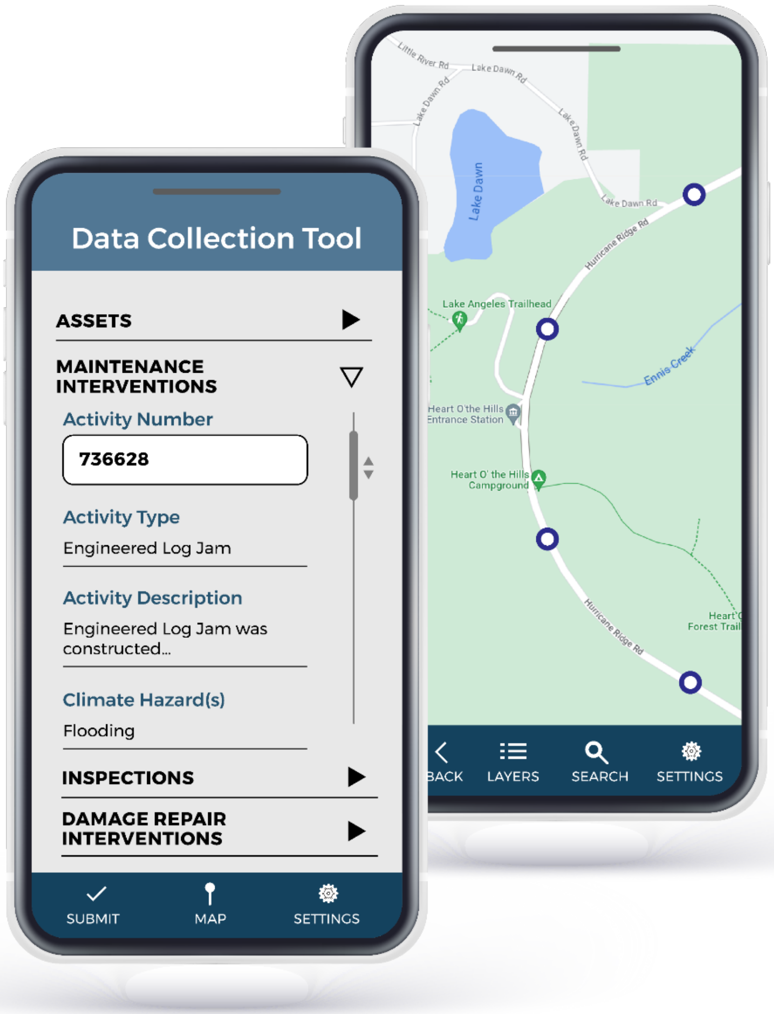
Existing: available data.

Available-Requires Processing: data that is accessible but needs to be linked.

Unavailable: data that is currently not available but essential for the dataset.

Dynamic: data collected during each inspection/intervention.

Figure 5-2: Conceptual Data Collection Tool Mobile Application



Data Collection Tool

Activity Number: 736628

Activity Type: Engineered Log Jam

Activity Description: Engineered Log Jam was constructed...

Climate Hazard(s): Flooding

Source: FHWA

Integration of Climate Data

Historical and projected climate hazard event data should be related to each asset based on its geolocation. This crucial addition to the data collection tool enhances the ability of the parks to assess the vulnerability of their road assets to climate stressors and in the future make informed decisions regarding maintenance interventions across their system. This addition provides parks with insights into the past climate events, enabling them to identify trends and recurring events. This historical information enhances the understanding of asset performance patterns in relation to climate stressors. Furthermore, incorporating projected climate hazard data into the system allows parks to anticipate future climate hazard events and their potential monetized consequences on road assets. This integration helps to proactively plan and implement maintenance interventions to enhance the resilience of the road assets. This may involve prioritizing interventions for assets projected to experience increased climate impacts and considering climate-informed designs in asset rehabilitation and construction projects.

5.2.2. USE OF COLLECTED DATA IN THE JUSTIFICATION OF INVESTMENTS

This recommendation is focused on the use of the collected data in the existing framework to justify maintenance intervention decisions. As outlined in Section 2, the data entered through the data collection tool will be utilized to cluster assets and assess their performance during climate hazard events. Moreover, the data, including maintenance intervention investments, can be used in the BCA described in Section 2.

5.2.3. INVESTMENT PLANS FOR ASSET RESILIENCE

There is a clear need to create practical investment plans at the park level based on the application of the framework at the road system level. These plans should specify clear strategies (i.e., combinations of interventions throughout the system) and the timing of interventions. The goal in this phase is to establish a roadmap for future actions that optimizes resource use while achieving improvements in roadway assets resilience.

The results obtained from the BCA can guide the prioritization of interventions, enabling the formulation of systemwide investment plans. It is important to note, however, that prioritization of investments require the consideration of various factors other than resilience.

Following the development of investment plans, parks will be in a favorable position to develop financing and funding strategies. By providing a clear and data-driven understanding of the potential risks, associated costs, and benefits of interventions, plans can help make a compelling case for resilience investment, demonstrating the economic viability.

6. References

Bailey, Dan. 2022. “The Long Road to Recovery at Yellowstone.” National Parks Conservation Association Blog. Available at https://www.npca.org/articles/3214-the-long-road-to-recovery-at-yellowstone.

Briceno, T., Cousins, K., Madsen, T., Soares, J., 2019. *Accounting for Environmental Change: A Modernized Approach to Benefit-Cost Analysis on the Upper Mississippi River*. Earth Economics: Tacoma, Washington.

Crossman, Jill, Martyn N. Futter, and Paul G. Whitehead. 2013. “The Significance of Shifts in Precipitation Patterns: Modelling the Impacts of Climate Change and Glacier Retreat on Extreme Flood Events in Denali National Park. Alaska” *PLOS ONE* 8(9): e74054. https://doi.org/10.1371/journal.pone.0074054.

Executive Office of the President. 2023. “2023 Discount Rates for OMB Circular No. A-94.” Washington, DC: Office of Management and Budget. https://www.whitehouse.gov/wp-content/uploads/2023/02/M-23-12-Appendix-C-Update_Discount-Rates.pdf.

FHWA (Federal Highway Administration). 2018. Bridge Preservation Guide: Maintaining a Resilient Infrastructure to Preserve Mobility.

Gonzalez, P., Wang, F., Notaro, M., Vimont, D. J., & Williams, J. W. 2018. “Disproportionate Magnitude of Climate Change in United States National Parks.” *Environmental Research Letters* 13(10), 104001.

Imam, Boulent. 2019. “Climate Change Impact for Bridges Subjected to Scour and Corrosion.” *Climate Adaptation Engineering*, edited by Emilio Bastidas-Arteaga and Mark G. Stewar. Butterworth Heinemann: 165–206.

Knott, J. F., Sias, J. E., Dave, E. V., & Jacobs, J. M. 2019. “Seasonal and Long-Term Changes to Pavement Life Caused by Rising Temperatures from Climate Change.” *Transportation Research Record* 2673(6), 267–78.

National Park Service (NPS). 2012. Nisqually to Paradise Road Rehabilitation Environmental Assessment. Washington, DC: U.S. Department of the Interior. https://parkplanning.nps.gov/document.cfm?parkID=323&projectID=26061&documentID=51228.

NPS (National Park Service). 2018. Sea Level Rise and Storm Surge Projections for the National Park Service. Natural Resources Report Series NPS/NRSS/NRR—2018/1648. Fort Collins, Colorado: U.S. Department of the Interior. https://www.nps.gov/subjects/climatechange/upload/2018-NPS-Sea-Level-Change-Storm-Surge-Report-508Compliant.pdf.

NPS (National Park Service). 2022. “Learn About the Park.” Olympic National Park Washington. Last Update: September 2022. Accessed October 17, 2023. https://www.nps.gov/olym/learn/index.htm.

NPS (National Park Service). 2023a. “Pretty Rocks Landslide.” https://www.nps.gov/dena/learn/nature/pretty-rocks.htm#:~:text=A%20recent%20shift%20in%20mean,of%20many%20landslides%20in%20Denali.

NPS (National Park Service). 2023b. “Learn About the Park.” North Cascades National Park Washington. Last Update: November 2023. Accessed October 17, 2023. https://www.nps.gov/noca/learn/index.htm.

NPS (National Park Service). 2023c. “Learn About the Park.” Mount Rainer National Park Washington. Last Update: December 2023. Accessed October 17, 2023. https://www.nps.gov/mora/learn/index.htm.

Panda, S. S., Amatya, D. M., Grace, J. M., Caldwell, P., & Marion, D. A. 2022. “Extreme precipitation-based vulnerability assessment of road-crossing drainage structures in forested watersheds using an integrated environmental modeling approach.” *Environmental Modelling & Software* 155, 105413.

Smith, K. D., Harrington, D. S., Pierce, L., Ram, P., & Smith, K. L. 2014. *Concrete Pavement Preservation Guide*. No. FHWA-HIF-14-014. U.S. Federal Highway Administration.

Strauch, R., Istanbulluoglu, E., & Riedel, J. 2019. “A New Approach to Mapping Landslide Hazards: A Probabilistic Integration of Empirical and Physically Based Models in the North Cascades of Washington, USA.” *Natural Hazards and Earth System Sciences* 19(11), 2477–95.

USACE (U.S. Army Corps of Engineers). 2000. *Planning Guidance Notebook*. Engineer Regulation 1105-2-100. Department of the Army, U.S. Army Corps of Engineers: Washington, DC. https://www.publications.usace.army.mil/portals/76/publications/engineerregulations/er_1105-2-100.pdf

Zhang, Chao, Yiqiu Tan, Yangming Gao, Yongkang Fu, Jilu Li, Shuai Li, Xingye Zhou. 2022. “Resilience Assessment of Asphalt Pavement Rutting Under Climate Change.” *Transportation Research Part D: Transport and Environment*, 109, 103395.

Zhang, N., and A. Alipour. 2020. “Multi-Scale Robustness Model for Highway Networks Under Flood Events.” *Transportation Research Part D: Transport and Environment*, 83, 102281.

Appendix A: Sample Synthetic Data

This section illustrates sample synthetic data used in this study. The data represent the corresponding damage repair costs for road sections for both groups, Intervention and No Intervention, between 2006 and 2018.

Fiscal Year	**No Intervention**			**Intervention**		
	Road Section	Damage Repair Cost	Damage Repair Cost (2023$)	Road Section	Damage Repair Cost	Damage Repair Cost (2023$)
2006	MP 7.0 - MP 8.0	$311,420	$470,244	MP 0.0 - MP 1.0	$217,320	$328,153
2006	MP 9.0 - MP 10.0	$212,500	$320,875	MP 1.0 - MP 2.0	$225,017	$339,776
2006	MP 11.0 - MP 12.0	$165,739	$250,266	MP 6.0 - MP 7.0	$182,710	$275,892
2007	MP 8.0 - MP 9.0	$279,790	$414,089	MP 1.0 - MP 2.0	$244,620	$362,038
2007	MP 12.0 - MP 13.0	$386,500	$572,020	MP 2.0 - MP 3.0	$198,177	$293,302
2007	MP 13.0 - MP 14.0	$351,002	$519,483	MP 6.0 - MP 7.0	$232,172	$329,684
2008	MP 10.0 - MP 11.0	$191,200	$271,504	MP 2.0 - MP 3.0	$217,420	$308,736
2008	MP 11.0 - MP 12.0	$450,100	$639,142	MP 3.0 - MP 4.0	$239,860	$340,601
2008	MP 14.0 - MP 15.0	$412,200	$585,324	MP 4.0 - MP 5.0	$190,400	$270,368
2008	MP 15.0 - MP 16.0	$395,400	$561,468	MP 1.0 - MP 2.0	$318,900	$452,838
2009	MP 7.0 - MP 8.0	$354,200	$502,964	MP 5.0 - MP 6.0	$300,190	$426,270
2009	MP 10.0 - MP 11.0	$311,211	$441,920	MP 3.0 - MP 4.0	$242,100	$334,098
2009	MP 11.0 - MP 12.0	$489,700	$695,374	MP 0.0 - MP 1.0	$219,800	$303,324
2009	MP 15.0 - MP 16.0	$412,600	$585,892	MP 1.0 - MP 2.0	$289,900	$394,264
2009	MP 16.0 - MP 17.6	$311,700	$442,614	MP 3.0 - MP 4.0	$287,690	$391,258
2010	MP 8.0 - MP 9.0	$496,400	$685,032	MP 4.0 - MP 5.0	$212,500	$280,500
2010	MP 15.0 - MP 16.0	$412,500	$569,250	MP 5.0 - MP 6.0	$312,200	$412,104

Appendix B: Data Collection Tool User Guide

The described data collection tool ensures accessibility and ease of use for maintenance staff. It supports the digital input of detailed information into the mobile application through specific tabs that cover different data categories. By adopting a streamlined format, this tool simplifies the data collection process, enabling staff to efficiently document inspections and activities. This approach aims to enhance data accuracy, enabling the digital transformation of maintenance and damage repair data documentation processes.

The data collection tool comprises two main sets of data. The first set is predefined data, which is centered on asset details. The second set of data is dedicated to maintenance and damage repair data, facilitating collection of key information regarding the details of past maintenance interventions to reduce climate risks, the post-inspection condition of assets, the observed impacts, and the interventions applied to repair damages.

The following paragraphs provide users with a data dictionary outlining the specific data that can be collected using the tool and their details.

B.1. Predefined Data

The predefined data refer to specific information about assets and their specifications, pre-populated by asset location and generally remain constant during inspections. Certain details, such as annual average daily traffic and current condition rating may require periodic updates to ensure accuracy and relevance over time. These datasets serve as asset identification and provide a general overview of asset characteristics. These data will be sourced from various datasets of the National Park Service, including those discussed in this research, such as the Project Management Information System.

B.1.1. ASSETS

The assets category serves as the cornerstone of the data collection tool, capturing essential information on asset specifications. These factors are predefined within the tool, assisting data collection staff in accurately and easily identifying assets, ensuring efficient and precise data entry processes. The details of data in this category are:

Asset Data	Description
State Code	Unique code identifying the state where the asset is located.
State Name	Name of the state where the asset is located.
Park Code	Unique code for each national park where the asset is located.
Park Name	Name of the park where the asset is located.
Route Number	Number assigned to the road for identification.
Route Name	Name of the road.
Asset Code	Unique number to identify each asset.
Asset Location	Geographical coordinates (i.e., latitude, longitude) specifying where the asset is located.
Asset Type	Type of asset, (e.g., road, bridge, or tunnel; more granular categorization is possible).
Number of Lanes	Number of lanes on the asset.
Dimensions	Physical dimensions of the asset (e.g., length, width, height).
Built Year	Year when the asset was constructed.
Current Condition Rating	A rating indicating the current state of the asset, obtained from other data collection processes.
Annual Average Daily Traffic	Average number of vehicles passing by daily, indicating road usage.
Image/Video	Visual documentation of asset's condition and surroundings, aiding in assessments.

B.2. Maintenance Data

In the maintenance category, essential data concerning proactive measures to reduce probable climate hazard impacts on road assets will be gathered. Staff will document the key factors related to interventions.

B.2.1. MAINTENANCE INTERVENTIONS

Maintenance Data	Description
Activity Number	Provides a unique identifier for each intervention.
Activity Type	Assigns the type of intervention implemented.
Activity Description	Describes the scope of the intervention, including problems to address and details.
Climate Hazard(s)	Specifies the type or types of climate hazards targeted by the intervention.
Activity Start Date	Marks the start date of the intervention.
Activity Duration	Specifies the timeframe required to complete the intervention.
Activity Cost	Documents the cost of the intervention.
Activity Image/Video	Offers visual documentation of the intervention.
Main Staff	Records names of key project personnel for accountability and enhanced coordination.

B.3. Inspection and Damage Repair Data

In the damage repair category, maintenance staff will collect information regarding the inspection of climate hazard impacts on road assets and the damage repair activities performed. These data are essential for understanding the extent of damage and the subsequent interventions for asset restoration.

B.3.1. INSPECTIONS

Inspection Data	Description
Inspection Number	Provides a unique identifier for each inspection activity.
Climate Hazard Type	Specifies the type of the current climate hazard (e.g., floods, storms, or landslides).
Climate Hazard Description	Describes the details of the climate hazard.
Event Date	Records the specific date when the climate hazard impact occurred.
Damage Description	Provides a detailed account of the damage sustained, aiding in documentation and evaluation.
Number of Closed Lanes	Details the impact of the climate hazard on the closure of the road section.
Damage Image/Video	Presents visual documentation of the asset’s post-hazard condition.
Main Staff	Records names of key inspection personnel for accountability and enhanced coordination.

B.3.2. DAMAGE REPAIR INTERVENTIONS

Damage Repair Data	Description
Activity Number	Assigns a unique identifier to each activity.
Activity Type	Specifies the category or nature of the activity (e.g., repairs, rehabilitation, or reconstruction).
Activity Description	Provides specific information about the activity.
Activity Start Date	Marks the start date of the activities, providing a timeframe for the damage repair process.
Activity Duration	Specifies the duration of damage repair activities, facilitating the assessment of consequences.
Activity Cost	Records the cost of damage repair activities.
Activity Image/Video	Provides visual documentation of the intervention process.
Main Staff	Records names of key project personnel for accountability and enhanced coordination.

Appendix C: Implementation Plan

In this section, the implementation plan for the data collection tool is presented. The primary objective is to collect feedback from the national parks on the tool design and enhance its functionality. In the long-term, the tool will enable the parks to effectively evaluate maintenance and damage repair options, establish strategic investment plans, and develop funding strategies for long-term resilience plans. This section also addresses the potential challenges during implementation and provides practical solutions to ensure the tool’s successful deployment.

C.1. Implementation Steps

Step	Action
1. Develop an Excel-based Data Collection Tool	• Design an Excel-based tool with organized tabs for each data category for maintenance staff to populate using entered synthetic data as a reference. • Develop data entry guidelines. • Conduct interactive in-person/virtual workshop to gather feedback from the Olympic, MORA, and NOCA park maintenance staff—feedback to be related to expectations, preferences, and potential challenges related to the data, processes, and the tool. • Update Excel-based tool and data entry guidelines according to feedback.
2. Test the Excel-based Data Collection Tool in One of the Parks	• Select pilot park to test the Excel-based tool. • Meet in person/virtually with the selected maintenance staff to outline the pilot testing goals and the use of the Excel-based tool. • Test the Excel-based tool on site using different asset categories, climate hazard conditions, impacts, and interventions. • Gather additional feedback from the maintenance staff—feedback is to be focused on functionality, effectiveness of the tool and potential challenges prior to development. • Integrate feedback from the Excel-based tool testing phase into the tool and the data entry guidelines.
3. Develop Prototype Mobile Data Collection Application	• Develop a prototype mobile application of the data collection tool. • Develop user guidelines.
4. Test the Prototype Mobile Data Collection Application in Three Parks	• Select three parks for pilot testing the developed prototype mobile application. • Meet with the maintenance staff to outline the pilot testing goals and the use of the prototype mobile application. • Test the prototype mobile application in the three pilot parks. • Gather feedback from the maintenance staff, centered on the functionality and effectiveness of the prototype mobile application and the identification of potential challenges during deployment. • Update the prototype mobile application per feedback, along with user guidelines.
5. Draft Recommendations for Mobile Data Collection Implementation and Deployment	• Make the prototype mobile application available to a larger number of parks for additional feedback. • Update the prototype mobile application according to received feedback, along with data entry instructions. • Document the specifications of the final mobile application and deployment plans.

C.2. Barriers and Solutions

Barrier	Description	Solution
1. Pre-defined Data Fields	Some of the fields including essential details such as asset number and their location (coordinates) are not defined or recorded yet.	• Asset numbers can be defined based on the mile-point of roads. • The coordinates of the assets can be derived from geospatial files of assets.
2. Integration of Historical Data	Historical maintenance and damage repair data collected, including the details of activities, their location, cost, and duration are likely not available or digitized.	• Available data should be digitized, and maintenance staff can be involved to integrate past maintenance and damage repair data into the data collection tool.
3. Lack of Climate Data	While some historical and projected climate data is available for parks (e.g., temperature and precipitation), a comprehensive park specific climate data is not available in many cases.	• Climate data analysis is required to incorporate publicly available data or generate data for each climate hazard.