Alaska Highway - Infrastructure Vulnerability and Risk Assessment due to Changing Climate and Extreme Weather Events

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ABSTRACT

This paper describes the methodology used to conduct the Study on the Infrastructure Vulnerability and Risk due to a Changing Climate and Extreme Weather Events along the Alaska Highway. The Study was carried out using the methodology documented under the Vulnerability Assessment and Adaptation Framework (FHWA, 2017). The Framework provides a structured process for conducting a vulnerability assessment for the infrastructure assets. The Study assessed the impacts of climate change on drainage and geotechnical assets. It provided a specific analysis of projected changes in temperature and precipitation-related parameters as predicted by climate change models to establish a probable range of future climate conditions to which these assets may be subjected. A Life-Cycle Cost Analysis (LCCA) was carried out to identify and select the most cost-effective adaptation alternatives. This economic analysis monetized the costs and benefits associated with multiple adaptation strategies over a 60-year analysis period. The costs considered in the LCCA include both "direct costs," the cost directly incurred by the asset owners, and "user costs," costs that users of the road would incur through delays and detours. A total of 410 culverts, 74 geotechnical assets and 24 bridges along the highway were identified for consideration in this Study. The methodology is intrinsically compatible for integration into Transportation Asset Management Plans and cross-asset optimization.

Keywords: Transportation Asset Management, Climate Change Adaptation, Climate Vulnerability, Risk Based Asset Management, Sustainability and Resilience, Transportation Systems Resilience, Risk and Resilience Management, Natural Hazards and Extreme Weather Events, Climate Change, Vulnerability and Resilience Assessment, Critical and Lifeline Infrastructure, Hazard Mitigation, Vulnerability and Threat Assessment

1.0 INTRODUCTION

In 2020, a consultant, Tetra Tech Canada Inc. (Tetra Tech) and Public Services and Procurement Canada (PSPC), collectively referred to as The Team, performed studies on Infrastructure Vulnerability and Risk due to a Changing Climate and Extreme Weather Events (the Study) for the Alaska Highway km 133-968, British Columbia and Yukon.

The project limits are shown in the **Figure 1**:

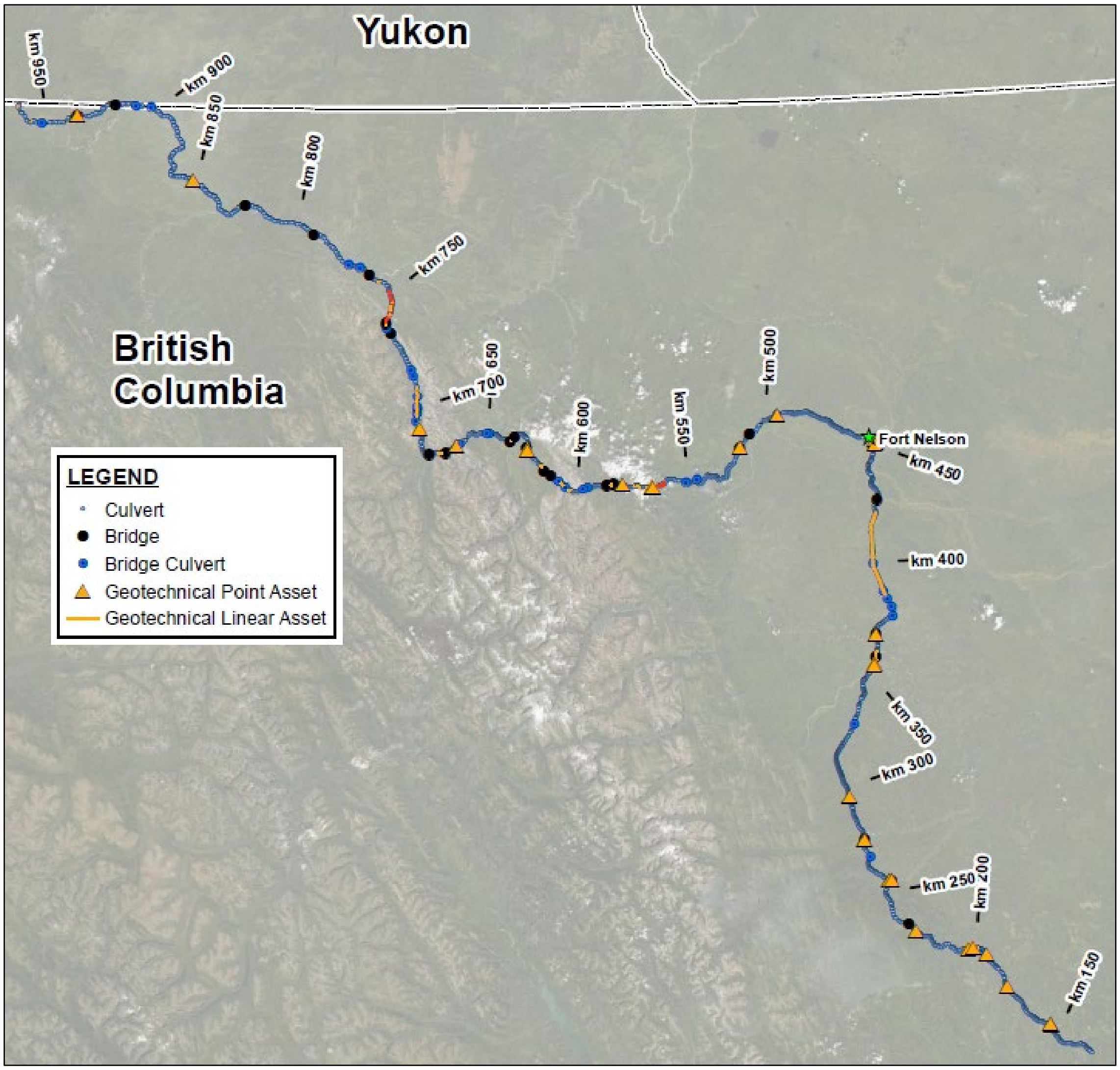

Figure 1: Infrastructure Assets within Project Limits

The Alaska Highway stretches 2,450 kilometres through northern BC, the Yukon and the State of Alaska. Eighty percent (1,960 km) of the Alaska Highway is in Canada. The highway starts at Mile "Zero" (or "Kilometre Zero") in the City of Dawson Creek, BC, and terminates in Delta Junction, Alaska. Responsibility for the 835 km section from km 133, north of City of Fort St. John, BC to km 968 at the BC/Yukon border, rests with PSPC.

The primary objective was to assess and quantify the costs of the risks and the costs of potential risk mitigation options to the critical drainage and geotechnical assets and incorporate the assessment results into the PSPC's decision-making.

2.0 LITERATURE REVIEW

The Climate Change & Extreme Weather Vulnerability Assessment Framework (FHWA, 2012) was developed by Federal Highway Administration as a guide for transportation agencies to assess the vulnerability of climate change and extreme weather events. The framework draws heavily from previous work published by FHWA and experience of transportation agencies involved in the FHWA's 2010-2011 Climate Change Vulnerability and Risk Assessment Pilot Program. The framework consisted of three key steps: defining study objectives and scope; assessing vulnerability; and incorporating results into decision making. The established framework is considered as the first guide in formalizing a framework for vulnerability assessment studies for transportation infrastructure.

FHWA worked with state transportation agencies to undertake vulnerability assessment studies on the basis of a previously developed framework. The results and lessons learned from the studies were summarized in the report (FHWA, 2016). The report provided a description of unique approaches conducted for vulnerability assessment and evaluating adaptation options. The pilot studies and lessons learned were used to update the framework.

Simultaneously, the Canadian Council of Professional Engineers (Engineers Canada) Public Infrastructure Engineering Vulnerability Committee (PIEVC) (Engineers Canada, 2016) developed a protocol for owners and operators to assess vulnerability due to climate change of infrastructure assets. The PIEVC protocol provides a systematic approach to review historical climate information, project, nature, severity, and probability of future climate changes and events. The protocol enables practitioners to identify higher-risk components and the nature of the threat from the climate change impact.

The FHWA's Vulnerability Assessment and Adaptation Framework, third edition (FHWA, 2017) (the Framework) was based on the experiences and lessons learned from the previous pilot program. The framework provided a step-by-step standardized approach for transportation agencies to carry out a vulnerability assessment study. The steps consisted of Articulate Objectives and Scope, Obtain Asset Data, Obtain Climate Data, Assess Vulnerability, Identify, Analyze and Prioritize Adaptation Options, Incorporate Assessment Results in Decision Making, and Monitor and Revisit. Each section of the framework provides examples from previously completed pilot projects. The Framework was adapted for carrying out the vulnerability assessment and adaptation for this Study.

The engineering informed vulnerability assessment in the Study was carried out using life-cycle cost analysis and comparison of economic metrics. The NCHRP report on Incorporating the Costs and Benefits of Adaptation Measures in Preparation for Extreme Weather Events and Climate Change Guidebook (NCHRP, 2020) provides a summary of the current state of the practice on the use of cost-benefit analysis (CBA) in the decision-making process within transportation agencies.

3.0 METHODOLOGY

The Infrastructure Vulnerability Assessment was carried out using the methodology documented under the FHWA's Vulnerability Assessment and Adaptation Framework (FHWA, 2017) (the Framework). The Framework provides an in-depth and structured process for conducting a vulnerability assessment for the infrastructure assets. The work for this project included the completion of the steps described in the Framework.

The Framework describes several steps involved in conducting a vulnerability assessment. The methodology adopted to complete each step is provided in the sections below:

- Step 1: Articulate Objectives and Scope
- Step 2: Obtaining Asset Data
- Step 3: Obtaining Climate Data
- Step 4: Assessment of Vulnerability
- Step 5: Identify, Analyze and Prioritize Adaptation Options
- Step 6: Incorporate Assessment Results in Decision making
- Step 7: Monitor and Revisit

4.0 STEP 1: ARTICULATE OBJECTIVES AND SCOPE

The concept behind the Study is that the monetized benefit ($Benefit) expressed in terms of reduction in monetized risk ($Risk) of added adaptive resilience must be greater than the cost of adding resiliency. The $Risk can be quantified by multiplying the probability of unsatisfactory performance (P_{UP}) by the economic consequence of failure ($Consequence) as shown in equation 1.

$$\$Risk\ = [P_{UP}\ due\ to\ asset\ deterioration + \ P_{UP}\ due\ to\ climate\ events]\ x\ \$Consequence \qquad (1)$$

The scope of the assessment encompassed using future climate projections and related expertise, the current design, construction, operation and management of this infrastructure, as well as known planned upgrades or major rehabilitation projects in the planning stages to address the potential impacts of future climate conditions for the asset(s) 60-year analysis period.

The vulnerability assessment scope included the selection and characterization of important transportation assets to study and identify key climate variables that could impact these assets. The scope included the following:

- The infrastructure to be considered in this Study will comprise of bridges, culverts, embankments, structures, bridge piers, cut/fill slopes, rock slopes, etc.
- Using professional judgment and experience, review climatic projections relative to the project location and assessment time horizon. Establish for each climate parameter and infrastructure indicator (relevant infrastructure, climate performance, design/operation criteria) the probability of a climate event (current and future) affecting the infrastructure or infrastructure component in a manner that adversely affects the performance of the infrastructure.
- Undertake consultations with the relevant PSPC representatives, planning, engineering, operations and maintenance staff regarding historical performance.
- Provide recommendations to address the engineering vulnerabilities based on the critical infrastructure-climate interactions identified in previous steps.
- Prepare a report that clearly documents and synthesizes the work completed and that includes an Executive Summary, description of the baseline and projected climatic parameters,

identification and description of the infrastructure components, and the assessment of the engineering vulnerabilities and recommended remedial actions.

- The assessment is to be carried out using the U.S. Department of Transportation Federal Highway Administration (FHWA) titled Vulnerability Assessment and Adaption Framework (FHWA, 2017), third edition, published in 2017 climate risk assessment process and follows ISO 31000 (ISO, 2018) on Risk Management.

- The results of this Study are intended to inform, where appropriate, investment and asset management decisions by PSPC as the owner and operator of the asset. The results of this project may also be analyzed with other climate risk assessment case studies to develop recommendations around reviews of codes, standards and engineering practices.

4.1 Selection and Characterization of Relevant Assets

The Team utilized several data sources provided by the PSPC to establish the criteria for the selection and characterization of relevant assets. The transportation infrastructure (e.g., bridges, culverts, embankments, shore-banks structures, rock slopes, etc.) were selected based on factors like jurisdiction, geographic location, relevance, historical performance, age, risk and consequence of failure, and other factors. The selection process looked at both existing and planned assets.

4.2 Evaluation of Risk and Consequence of Failure

The risk and consequence of failure of infrastructure assets was assessed by analyzing multiple aspects:

- Length of a detour route in the event of failure;
- Immediate, direct and substantial disruption to the transportation system at the national level;
- Use/operation of each link or node on the highway. Highly used (in terms of volume) connections are considered more important than lesser used segments;
- Access and connections to major cities along the highway; and
- Extreme weather vulnerabilities of the asset.

The following criteria were established to assist in the selection of the drainage assets considered critical infrastructure.

4.2.1 *Bridge Assets*

All 24 bridge crossings are considered critical.

4.2.2 Culvert *Assets*

More than 2,400 culverts service the Alaska Highway throughout the 835 km section from km 133, north of Fort St. John, BC, to km 968 at the B.C./Yukon border. The following criteria were used in selecting culvert crossings for evaluation:

- All culverts with diameter ≥ 1 m.
- All culverts with diameter < 1 m with embankment cover > 5 m.

- All culverts with diameter < 1 m installed alongside one or more other culverts with diameter ≥ 1 m.

The proposed criteria allowed for the selection of 361 culvert crossings.

These were either the larger crossings along the highway with defined watercourses having potential for failure during flood flow, or smaller diameter culverts installed in high embankments with longer spans. Both arrangements are likely the most expensive to repair in case of failure.

The inclusion of smaller culverts under deep embankments recognized the risk of culvert blockage and possible headwater buildup leading to piping failures. Deep culverts are difficult to reach and maintain. A small amount of debris can easily block the inlet end of a culvert and promote a deep pool's formation, adding porewater pressure through the road embankment. This, in turn, can promote piping failures.

In summary, the selection was based on the consequence of failure and the associated costs tied to the re-opening of the highway to public traffic.

4.2.3 *Geotechnical Assets Criteria*

Available alignment information was reviewed for cut slopes (in soil and rock) and fill slopes (i.e., likelihood that a slope failure would affect highway capacity). The asset information included slope angles, height, soil or rock type (where available). The exclusion criteria for geotechnical assets were fill slopes lower than 3 m high and cut slopes lower than 6 m high. There was no exclusion for rock slopes due to the consequence of rockfall. There was also no exclusion for debris flows. A total of 74 geotechnical assets were considered in this Study. Reference information included:

- Large scale surficial geology map of Canada (Canada, 1995);
- Georeferenced right-of-way images were collected in 2012 and 2018 to identify possible assets with failure potential. The assets included ravelling cut and fill slopes, bank erosion in river crossings;
- A journal paper on rain-induced debris flows which closed the highway in 1988 (Clague & Evans, 1989); and
- Historical information from previous failures from other studies provided by PSPC.

4.3 Identification and Selection of Key Climate Variables

The Team identified key climate variables, which were the focus of the vulnerability assessment. The key climate variables for the vulnerability assessment are temperature, precipitation, freeze/thaw cycles and rainfall/snowfall events. The Team assessed the collected information related to assets **exposure** to climate variables in the region, **sensitivity** to climate variability and assets **adaptive capacity** to existing climate variability or future climate impacts. The key climate variables were selected based on those likely to have the greatest impact on the highway due to climate change. The impacts of various climate and weather stressors on the infrastructure transportation assets were studied to determine which climate variables will most affect transportation assets.

4.4 Asset Sensitivity to Climate Stressors

The climate stressor, also referred to as a hazard or a threat, is the magnitude of the climate variable likely to damage the asset. The Team determined the likelihood and the degree of the impact on transportation assets posed by each variable or stressor. The analysis narrowed the range of climate variables to study. Assessment of the asset sensitivity to climate stressors included the review of the following:

- PSPC's past experiences with assets performances, especially during extreme weather conditions, e.g.;
  - Consulting PSPC's maintenance, emergency management, and engineering logs to determine types of weather events that caused damage and disruption to an asset;
  - Review of PSPC mitigation plans; and
  - Review of assets condition data collected by PSPC at regular intervals can indicate assets requiring recurring repairs and reconstruction.
- Design Standards and Guidelines for the asset to indicate assets sensitivity to a particular climate variable;
- Past studies, analyses and reports on climate change in Western Canada; and
- Existing climate models used by various agencies and examine the model outputs for their applicability in Western Canada.

5.0 STEP 2: OBTAIN ASSET DATA

There have been multiple data collection surveys over the past several years, including data collections surveys in 2012, 2016 and 2018. Each data collection survey's scope and scale are different depending on the collection requirements at the time. The data include the right-of-way images, panoramic images, LiDAR data, detailed bridge, culvert and geotechnical asset condition surveys.

5.1 Drainage Assets Data

Asset data for minor drainage infrastructure along the highway (culverts) consisted of inspection reports from 2010 and 2011. Based on the established inclusion criteria, 361 culvert crossings were selected from these inspections for analysis. The drainage assets data included culvert inventory and condition parameters such location coordinates, linear referencing on highway, culvert diameter, culvert length, embankment height, embankment slopes, cover height, culvert material type, culvert invert and outlet condition data.

5.2 Geotechnical Assets Data

Geotechnically, the asset types of interest are slopes (either in rock or soil) and debris flow fans, potentially closing a portion of the highway during a movement event. Each asset type's relevant characteristics, depending on available information, included slope heights, slope geometry, visual indicators of movement, records of the previous movement, and slope aspect for rock slopes. Debris flows would include an assessment of the historical return period (given sufficient data) and, if not, a high-level desktop assessment of the debris flow fan and watershed for future debris flow potential.

A literature search was undertaken for Alaska Highway closure due to hazards. Alaska highway has previously been closed due to debris flow (Clague & Evans, 1989). Large-scale landslide complexes or long stretches of the highway subject to increased riverbank erosion or scour are difficult to quantify and beyond our current proposed Study.

6.0 STEP 3: OBTAIN CLIMATE DATA

The Team assessed climate change projections to provide a specific analysis of changes in temperature- and precipitation-related parameters as predicted by Global Circulation Models (climate change models). This established a probable range of future climate conditions to which assets may be subjected. This analysis primarily includes analysis and presentation of model results, and it is important to note that the outcome of this work does not implicitly define a relationship between climate change and its physical impact on engineering-related aspects of highway assets (e.g. hydrology, hydrogeology, failure criterion, etc.).

6.1 Climate Change Model Scenarios

Data used in this Study was obtained from the Pacific Climate Impacts Consortium (PCIC). PCIC is a regional climate service centre, located at the University of Victoria that provides information on the physical impacts of climate variability and change in the Pacific and Yukon regions of Canada.

As part of its publicly disseminated climate change data products, PCIC offers statistically downscaled daily Canada-wide climate scenarios using a variety of global climate model (GCM) projections, also known as climate change model projections.

6.1.1 *Statistically Downscaled Climate Scenarios*

The downscaled climate scenarios are at a gridded resolution of 300 arcseconds (~ 10 km) simulated for the years 1950-2100. Variables included in the data are the projected daily minimum surface-air temperature, maximum surface-air temperature, and precipitation flux (mass of water-equivalent precipitation per square metre each day).

Statistically downscaled outputs are based on GCM projections from the Coupled Model Intercomparison Project Phase 5 (CMIP5; (Taylor, Stouffer, & Meehl, 2012)) and historical daily gridded climate data for Canada ((McKenney, et al., 2011); (Hopkinson, et al., 2011)). PCIC provides downscaled projections from 27 GCMs and three global emissions scenarios (Representative Concentration Pathways); however, they provide a recommendation of an ensemble of 12 GCMs to provide the widest spread in projected future climates for the region. Using data from an ensemble of models rather than any single model provides a range of results that also allows for the consideration of natural climate variability, especially as different models are calibrated to different environmental conditions.

6.1.2 *Representative Concentration Pathways*

Representative Concentration Pathways (RCPs) are global greenhouse gas concentration trajectories adopted by the Intergovernmental Panel on Climate Change (IPCC) to be used in assessing future climate. Each pathway describes different climate change futures, each of which is considered possible depending on the level of greenhouse gases emission in years to come. For each pathway, the number (i.e., 2.6 in RCP2.6) refers to the level of stabilized radiative forcing (in W/m^2) predicted to occur before the year 2100.

GCMs are typically run for four future greenhouse gas concentration trajectories. The statistically downscaled future climate scenarios available from PCIC are for three of the four RCPs:

- RCP8.5
- RCP4.5

- RCP2.6

RCP8.5 was initially intended to represent a very high, conservative future emissions scenario with minimal greenhouse gas emissions mitigation. RCP4.5 represents a stabilization scenario with fossil fuel usage curtailed by climate policy and emissions peak around 2040. RCP2.6 represents a stabilization scenario with radiative forcing peaking at 3.1 W/m^2 by mid-century and returning to 2.6 W/m^2 by 2100 with a prompt start to concerted action adopted in all countries, both developing and developed.

In 2019, the global CO_2-equivalent concentration of GHGs (CO_2eq) concentration was 454 ppm and continues to rise exponentially. As dedication to implementing climate policy and investment in renewable energy varies among nations and will likely continue to do so for the foreseeable future, the future CO_2eq pathway likely lies somewhere between RCP4.5 and RCP8.5. Therefore, to provide a representative range of plausible climate change scenarios for the purpose of asset management, the Team included both the RCP8.5 and RCP4.5 ensemble predictions in its statistical analysis (a total of 24 predictions), from which trendlines and statistically-likely gridded climate projections for the length of the highway can be provided.

6.2 Data Analysis

The Team considered climate change parameters related to temperature and precipitation from the gridded daily downscaled GCM ensemble output along Highway 97 between km 133 and the Yukon border (km 968). As mentioned above, the climate parameters, predicted by the 24 model predictions (12 models for each of the RCP4.5 and RCP8.5 scenarios) were analyzed to delineate the statistically likely projections.

6.3 Climate Parameters

From the reduction of the base data, the Team analyzed the following data parameters relevant to Highway 97 asset management as the projected change from baseline to horizon years 2050 and 2080:

- Mean annual temperature (in addition to mean highs and lows);
- Number of annual freeze-thaw cycles (defined by temperature fluctuations about 0°C);
- Annual precipitation;
- Annual water-equivalent snowfall (inferred from precipitation when the air temperature is below 0°C);
- The number of days in a year with precipitation;
- The number of days in a year with snowfall (inferred from precipitation when the air temperature is below 0°C);
- The number of days in a year with heavy precipitation (more than 10 mm per day);
- The number of days in a year with extreme precipitation (more than 33 mm per day); and
- Maximum 3-day precipitation event (annual, winter, summer).

7.0 STEP 4: ENGINEERING INFORMED VULNERABILITY ASSESSMENT

The Framework suggests the following three approaches to assessing the vulnerability of assets:

1. Stakeholder Input Approach
2. Indicator-Based Desk Review Approach
3. Engineering Informed Assessments

For the Study, the engineering informed assessment was used. It is characterized by a greater level of asset-specific data and analysis. The approach was based on the previously developed in-house methodology (St. Michel, Reggin, & Leung, 2017) which is based on the U.S. Army Corps of Engineers published guide (USACE, 2011) to the risk and reliability -based engineering. The selected assessment approach is risk and Life Cycle Cost Analysis (LCCA) based methodology.

In essence, this approach relies on assessing the magnitude of various return period extreme climate events for each asset in 2020 and, after allowing for predicted climate stressors, assessing the magnitude of the same return period events in 2080. It assumes a linear change in exceedance probability (P_{up}) annually over this 60-year analysis period for the various events. The sum of the Net Present P_{up} values is the cumulative P_{up} over the 60-years for each return period (20, 50, 100, 200, 500, 1000 year return periods). This can be added to the annual P_{up} due to structural deterioration in order to establish the overall cumulative P_{up}.

The vulnerability assessment, therefore, focused on establishing these parameters in the predicted climate environment.

The engineering informed assessment approach is then combined with a set of capacity/stability improvement treatment options (added resiliency/adaptation), established under Framework Step 5 to be used to carry out an economic analysis to establish an optimal adaptation strategy for the vulnerable assets as required in Step 6 for incorporation into decision making.

7.1 Geotechnical Analysis

Changes in climate affect factors that may lead to slope instability, rockfalls and debris flows. For example, increases in precipitation frequency, duration and intensity can affect surface runoff (increasing erosion potential) and water infiltration, which affect soil saturation, groundwater level and pore water pressures, which can increase the likelihood of soil slope instability. The increase in freeze-thaw cycles will increase the rock weathering and rockfalls' rate. However, the threshold at which these variables' changes result in increased slope instability and rockfalls was unknown.

Key gaps exist in understanding the relationships between the changes in climate and the impacts on geotechnical assets. This analysis aims to bridge the gaps in understanding the impacts and consequences of future climate changes based on available limited information. The geotechnical analysis was performed with the following caveats:

- The analysis is considered to be a high-level desktop study. This is intended to guide future work or planning that would need to be performed at a finer resolution for particular assets. In the event that additional assets are identified additional review may be appropriate.

- Large-scale landslide complexes and/or highway subject to increased riverbank erosion/scour may not be captured in this Study due to the lack of information and records. These large-scale risks are difficult to quantify but have the potential to have greater failure consequences.
- The analysis results were focused on general concepts that may provide the decision-makers with cost-comparisons and potential strategies for the assets.
- The adaptation options presented herein should not be considered recommendations. In most cases, these options would require site-specific supplemental data to provide geotechnical recommendations and more detailed costs and benefits for specific options considered.

7.1.1 Basis of Geotechnical Analysis

The existing condition of each geotechnical asset was initially assessed and rated as low, moderate and high for each considered hazard, including stream/river erosion, minor landslides, rockfall and debris flow. For each geotechnical asset, an initial annual probability of failure (return period or recurrence interval) was assigned based on the risk assessment results. For example, the asset that is currently failed or has failed in the past was assigned to have a return period of 10 years, considering the available dataset provided covers approximately ten years (since 2011). For an asset that has completed remediate measures, the return period is assumed to be between 50 and 100 years, depending on the remediate measure's design life. It is expected that similar slopes will be assigned with similar probabilities. Where there is insufficient data to estimate a probability of unsatisfactory performance, a subjective assessment was made.

Due to climate change, the reduced return period (or annual probability of failure) of each geotechnical asset is estimated to be the initial return period multiplied by the percent change from the climate stressors for the future 60-year climate conditions.

7.2 Hydrotechnical Analysis

The hydrotechnical portion of this assessment aimed at quantifying the flood flow magnitudes at each of the evaluated watercourse crossings. Flows were estimated for both present-day and future projections capturing the anticipated effects of climate change. These flows were then used to evaluate the hydraulic performance of the existing bridges and culverts. The risk was then quantified by comparing the magnitudes of flood flows to the capacity of the crossing.

Changes in climate will have a profound effect on the hydrology of the watercourses crossing the Alaska Highway. Annual peak flows on watercourses with small watershed areas (<10 km^2) are highly affected by changes in the magnitude of short-duration rainfall events, while larger watersheds (>1,000 km^2), are more sensitive to changes in winter snowpack and the associated spring freshet. Middling watershed areas can be sensitive to a combination of the two.

7.2.1 *Basis of Hydrotechnical Analysis*

The hydrotechnical analysis encompassed a total of 385 crossings (361 culvert crossings and 24 bridges). The analysis consisted of two components: a hydrologic analysis, to estimate flood flows at present and into the future with anticipated climate change effects, and a simplified hydraulic analysis to verify the capacity of each culvert and bridge. This information was used to identify which assets are at greatest risk of failure at present and into the future. Failure of drainage infrastructure was assumed to be possible in one of two manners: either through an inadequate hydraulic capacity to accommodate the flood flow, or through an eventual material failure of the structure itself (end of its service life).

7.2.2 *Hydrologic Analysis*

The hydrologic analysis was undertaken to develop flood flow estimates for each selected drainage asset across a range of return periods (2-year to 1000-year) for all years between 2020 and 2080. These flood flow estimates were determined based on the asset's watershed area and its location along the highway alignment.

The subject watersheds vary greatly in size from several hectares up to thousands of square kilometres. Given the large range of areas, a variety of governing flood mechanisms are expected across the subject watersheds. To accommodate the range of hydrologic regimes two different methods were used:

- A regional hydrologic analysis (for the larger watersheds); and
- A rainfall-runoff analysis (for the smaller watersheds).

A regional hydrologic analysis utilizes historical flow data measured on regional watercourses that are situated in similar physiographic settings to an ungauged watercourse(s) of interest. Flows of the gauged watercourses can then be transposed to the ungauged watercourse based predominantly on the ratio of their watershed areas. It is typically a highly effective method for estimating flood flows on large watercourses, but it can be less effective for smaller watersheds due to complexities in the flood mechanics typical to small watercourses and a general lack of available gauged flow data for smaller watersheds.

A rainfall-runoff analysis is better applied to small catchments where the flood hydrology is purely governed by the rainfall-runoff of a summer/fall storm. This approach utilizes computational rainfall-runoff models to simulate each small watershed hydrologic response to design storm (rainfall) events.

7.2.2.1 Watershed Delineation

Watershed areas of the 385 crossings were delineated utilizing 1:50,000 NTS data. Preliminary delineations were completed from a digital elevation model (DEM) through watershed delineation algorithms available in the software Global Mapper v19. Each watershed area was then further refined manually to better reflect additional drainage areas that would contribute to the subject culverts through roadside ditching that was not captured within the NTS DEM. **Figure 2** shows the delineated watershed areas in ArcGIS.

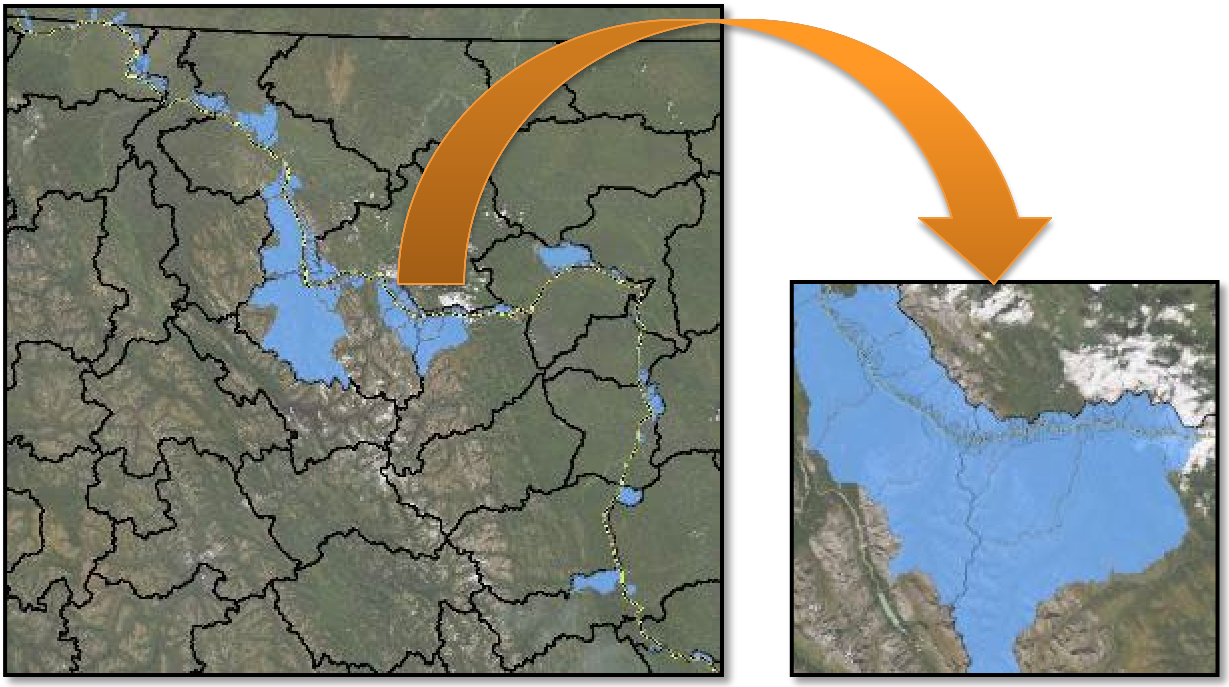

Figure 2: Watershed Areas in ArcGIS

7.2.2.2 Adjustments to Flood Flow Hydrology for Climate Change

Adjustments were made to the flood flow calculations to reflect anticipated changes in hydrology for the Year 2080 due to climate change. A hybrid approach utilizing two separate methods was employed to depict the nuances in climate change effects on both small and large watersheds.

7.2.2.2.1 Medium Watersheds (10 to 1,000 km^2)

Watercourses with medium watersheds ranging from 10 to 1,000 km^2 had their flood hydrology updated for climate change effects through interpolation.

7.2.2.2.2 Climate Change Adjusted Hydrological Results

The year 2080 flood flow estimates of the seven sub-10 km^2 watersheds were plotted alongside the 2080 updated flow estimates for 100 and 1000 km^2 catchments. Curves were produced through these points to define a relationship between watershed area and peak flow for each of the nine return periods of interest in each of the five hydrological zones. Two separate curves were produced, one defining flood flow for watersheds under 10 km^2 in area and one defining flood flow for watersheds greater than 10 km^2 in area. Flood flows estimates for all years between 2020 and 2080 were calculated through linear interpolation.

7.3 Calculating Risks

Risk is defined as the effect of uncertainty on objectives and is expressed in terms of the likelihood of occurrence of an asset failure and the consequence of damage given such an event. The United States Army Corps of Engineers (USACE, 2011) guide to risk and reliability-based engineering as related to civil structures uses the same generally accepted definition of risk as to the product of the probability of an event happening and the economic consequences of the event (Equation 2).

$$\$Risk = [Pup(Design\ Event\ Occurrence) + Pup(Structural\ Failure)]x\ \$Consequence \quad (2)$$

Where:

$\boldsymbol{Pup(Design\ Event\ Occurrence)}$ is the probability of failure of asset due to design event occurrence.

$\boldsymbol{Pup(Structural\ Failure)}$ is the probability of structural failure, e.g., collapse due to the ageing factors such as corrosion for culverts etc.

$\boldsymbol{\$Consequence}$ is the monitory value of the loss in terms of direct cost to the owner and cost to the road users in the event of failure due to any of the failure mechanisms. The USACE methodology applies the concept of monetizing the consequences of unsatisfactory performance, placing a financial value on the economy for such things as loss of use.

As a structure ages, its capacity is reduced through material degradation such as corrosion, disintegration and erosion of embankments, while at the same time, loading demand may be increased through frequent shorter return periods from the structure's original design event. The reliability is the probability of loading demand remaining less than structural capacity in a given year of a structure's life. The USACE guide expresses the reliability of a structure in terms of the inverse of its P_{up}. The P_{up} is typically near zero when a structure is new and approaches unity when the structural demand is expected to exceed structural capacity.

Probability is a number between 0 and 1.0 that expresses the chance of asset failure in a decimal form due to the occurrence of a particular failure mechanism (e.g. structural culvert failure, culvert washout, etc.). The probability of asset failure was estimated using the probability of failure due to design event and the probability of failure due to structural deterioration.

8.0 STEP 5: IDENTIFYING AND ANALYZING ADAPTATION OPTIONS

The Team analyzed natural, structural, or policy-based adaptation options to address vulnerabilities identified. The adaptation strategies were developed for the assets based on combinations of the following criteria:

- Assets identified as most at-risk by the Team;
- Studying a range of asset types or identified vulnerabilities; and
- Selecting assets that have a high likelihood of having an economically feasible adaptation solution.

The adaption options were evaluated through economic analysis. The economic analysis approach evaluates alternative adaption options by comparing the reduced risk of each approach's unsatisfactory performance, costs, and benefits in a systematic and transparent approach.

After developing adaptation options, we have used the economic analysis method to select the most appropriate option.

8.1 Identification of Adaptation Options

8.1.1 Drainage Assets Adaptations Options

The adaptation treatment for culverts consists of upgrading the hydraulic capacity with an existing size multiple culverts, upgrading the flow capacity with larger size single or multiple culverts, and replacing the culvert with the same size culvert at the end of its service life.

The upgrade strategies are applicable due to climate change when the 2080 flow is higher than the existing culvert capacity at a site. The flood flow was calculated for 2080 to develop climate change adaptation strategies for 100-Year, 200-Year, 500-Year and 1000-Year. A culvert, which required a diameter larger than 2.7 m, was replaced with a conversion to bridge-culvert strategy, while the remaining were replaced with a regular circular culvert. The culverts, which required a pipe with a diameter less than 2.7 m, further consisted of either replacement through an open-cut method or replacement through trenchless installation. The two different replacement methods for treatments were used for smaller diameter culverts to evaluate the best option for culvert replacement depending on the cover height and culvert diameter.

The replacement strategy due to the end of service life was applied when the culverts forecasted service life will end in the next 10 years.

Table 1 provides the adaptation treatments considered for each culvert.

Table 1: Adaptation Treatments for Culverts

Strategies	Adaptation Treatments
Climate Change Adaptation Strategies	▪ **Open-Cut Replacement** – Culvert Upgrade with 100 Year flood flow – Culvert Upgrade with 200 Year flood flow – Culvert Upgrade with 500 Year flood flow – Culvert Upgrade with 1000 Year flood flow ▪ **Trenchless Treatments** – Culvert Upgrade with 100 Year flood flow – Culvert Upgrade with 200 Year flood flow – Culvert Upgrade with 500 Year flood flow – Culvert Upgrade with 1000 Year flood flow ▪ **Bridge-Culvert Treatments** – Culvert Upgrade with 100 Year flood flow – Culvert Upgrade with 200 Year flood flow – Culvert Upgrade with 500 Year flood flow – Culvert Upgrade with 1000 Year flood flow
End of Service Life due to Effective Age	▪ **Culvert Replacement** – Minimum Construction Cost of Open-Cut and Trenchless Method ▪ **Culvert Replacement Bridge-Culvert**

8.1.2 Geotechnical Assets Adaptation Strategies

Each geotechnical asset was considered for a range of viable mitigation options based on the previous experiences with projects under similar conditions along the highway. Mitigation strategies were developed for each site ranged from no initial construction ("Do Nothing") to the most significant construction option (e.g. highway realignment). As expected, strategies with no or small initial costs have a smaller effect on the site and will require more maintenance and ongoing traffic impact. On the other hand, permanent mitigation efforts have a higher initial construction cost will generally result in less maintenance and disruption to the traffic over time.

The first "Do Nothing" option is the option for all geotechnical assets where no capital expenditures for construction would be spent. Maintenance work to restore the highway would be relied upon to keep the highway in a serviceable condition. As climate change impacts the instability of geotechnical assets, so would the amount of required maintenance work. This option provides a baseline estimate of the level of service disruption and the cost to maintain the highway in its present condition.

Potential strategies have been considered for each asset to improve geotechnical stability and/or extend the highway's life. **Table 2** presents the potential adaptation treatments for each asset type. These options could also be used to reduce the maintenance cost and frequency of the highway closure.

Table 2: Adaptation Treatments for Geotechnical Assets

Asset Type	Treatment
Cut Slope / Fill Slope	Regrading – flatten the slope
Cut Slope / Fill Slope	Toe buttress
Cut Slope / Fill Slope	Hydroseeding / Vegetation *
Cut Slope / Fill Slope and Bank Erosion	Retaining Structures
Cut Slope / Fill Slope	Soil Nails
Fill Slope	Lightweight Fill (EPS)
Rock Slope	Rock Mesh
Rock Slope	Barriers – Rock Fall
Rock Slope	Rock Bolt
Bank Erosion	Riprap Protection
Bank Erosion and Flooding	Elevate Roadway with Riprap Protection
Debris Flow	Basins – Debris Flow
Debris Flow	Highway Realignment

* Hydroseeding / Vegetation may be required to combine with other treatments.

Different mitigation strategies were considered for each geotechnical asset, and the initial construction costs for each strategy were estimated based on past experiences along the highway.

9.0 STEP 6: INCORPORATE ASSESSMENT RESULTS IN DECISION-MAKING

The vulnerability assessment results were integrated into the PSPC's Strategic Asset Management Plan (SAMP) for this transportation corridor. All potential improvement strategies to the corridor are evaluated based (rank) on a similar benefit-cost ratio index. By using the same prioritization methodology with these drainage and geotechnical assets, they can be readily incorporated into the SAMP process on an equitable basis. The incorporation will ultimately involve geographic synchronization of the projects across all asset classes.

The vulnerability assessment findings inform project prioritization by highlighting projects that will improve the resilience of the Alaska Highway transportation assets system.

9.1 Economic Analysis

Economic analysis was carried out to identify and select the most efficient strategy alternative, including a do-nothing scenario. The adaptation options were evaluated through economic analyses, as it monetizes the costs and benefits associated with adaptation strategies over a specific analysis period to be compared. The economic analysis for climate change adaptation options quantifies the extent of cost and benefit of adaptation options under each climate change scenario.

9.1.1 *Scope of Economic Analysis*

The life-cycle cost analysis calculates each strategy's total cost over the analysis period. The total cost includes direct/agency costs (the capital cost to stakeholders arising out of repairing/replacing the asset after a climate-related event, ongoing maintenance and residual value, if applicable) as well as road user costs (vehicle operation costs, delay/detour costs, environmental cost and so forth).

The total life-cycle cost for each strategy under consideration is compared to the life-cycle costs of a hypothetical "do-nothing" strategy, which is essentially the status quo maintenance regime. Any reduction in life-cycle cost, relative to the do-nothing strategy, represents the "Net Benefit" of applying a particular strategy. All costs are computed in terms of present dollar-cost terms using a discount rate.

The cost of the initial implementation of a Strategy, (called an improvement treatment(s)), is the Capital Costs of the initial improvement. Subsequent downstream costs are expressed in terms of $Risk. A cost/benefit, or net benefit, comparison between developed adaptation strategies for identified assets, was carried out.

9.1.2 *Economic Metrics*

The economic metrics are calculated through the life-cycle cost analyses of the adaptation strategies and ultimately used to inform strategies' comparison. Economic metrics include:

- Net Present Value (NPV) of Benefits
- Benefit-Cost Ratio (BCR)

9.1.2.1 Present Value (PV) and Net Present Value (NPV)

Present value (PV) benefits or costs are the discounted benefits or costs over the asset's life cycle at the selected discount rate. Net present value is the difference between the strategy's discounted total benefits and the discounted total costs. If the NPV is greater than zero, the project is considered cost-effective and is expected to pay for itself over time. When comparing adaptation options, the option with the highest NPV is the most cost-effective one.

The benefits, cost and risks were calculated in terms of the following indices:

- **Net Present Value Cost**: The Present Value Cost is the discounted total expenditures by the agency in terms of the annual maintenance cost, treatment (strategy) cost, end-of-life replacement cost and the benefits in terms of salvage value during the considered analysis period of 50 years. When comparing similar alternate strategies, the lowest NPV cost strategy is considered the most cost-effective one.

- **Present Value $Risk:** The Present Value $Risk is the discounted total monetary risk of the asset over the asset's life-cycle due to the probability of unsatisfactory performance due to Extreme Weather event and/or Structural Failure, depending on the asset.
- **Present Value $Benefits in Reduced $Risk:** Net Present Value $Benefits is the difference between the Present Value $Benefits (reduction in $Risk over base case strategy) for each strategy and the Net Present Value Cost for each strategy over the analysis period. When comparing alternate strategies, the highest NPV $Benefits strategy is considered the most cost-effective one.

9.1.2.2 Benefit-cost ratio (BCR)

The benefit-cost ratio is a numeric ratio that expresses the discounted total benefits of the strategy relative to its discounted total costs. If the BCR is above one, the strategy is considered cost-effective. When comparing adaptation options, the option with the highest BCR is the most cost-effective one.

The benefit-cost ratio was assessed in terms of the following indices:

- **PV $Benefits in Reduced Risk over PV Cost Ratio:** The numeric ratio expresses the PV $Benefits (in Reduced Risk) of the strategy relative to PV Cost. When comparing alternatives, the strategy with the highest PV $Benefits and PV Cost Ratio is the most cost-effective one.
- **Incremental PV $Benefit in Reduced Risk over PV Cost Ratio:** The numeric ratio expresses the PV $Benefits (in Reduced Risk) of the strategy relative to the incremental additional PV Cost of the strategy as compared to the "base-case" strategy.

Each economic metric provides different answers on the preferred measure, and it is useful to consider more than one economic metric in selecting the optimum strategies. For instance, NPV indicates the magnitude of the net benefits of an option, while the comparison of the BCR indicates the option that maximizes net benefit. As such, the BCR is frequently used to select among projects when funding restrictions apply.

The economic metric selected is consistent in revealing whether a strategy is cost-effective, but rank the preferred measures differently. Both BCR and NPV were evaluated to provide a complete picture of decision-making.

A discount rate of 4.0% was used in this Study.

9.2 Estimated Owner Costs

The incremental life-cycle costs for implementing each adaptation strategy and do-nothing strategy were calculated. The costs considered in the LCCA include both "direct costs," the cost directly incurred by the PSPC, and "user costs," costs that users of the road would incur rather than the PSPC.

Agency cost consisted of:

- Treatment costs;
- Ongoing maintenance costs;
- Salvage Value (where applicable).

9.3 Indirect / User Cost

The unit cost rates for various user costs were based on the default values provided in the *Default Values for Benefit-Cost Analysis in British Columbia in 2018* (Apex Engineering Limited, 2018) for the *British Columbia Ministry of Transportation and Infrastructure* (BCMoT). The user costs considered in this analysis are generally divided into three categories.

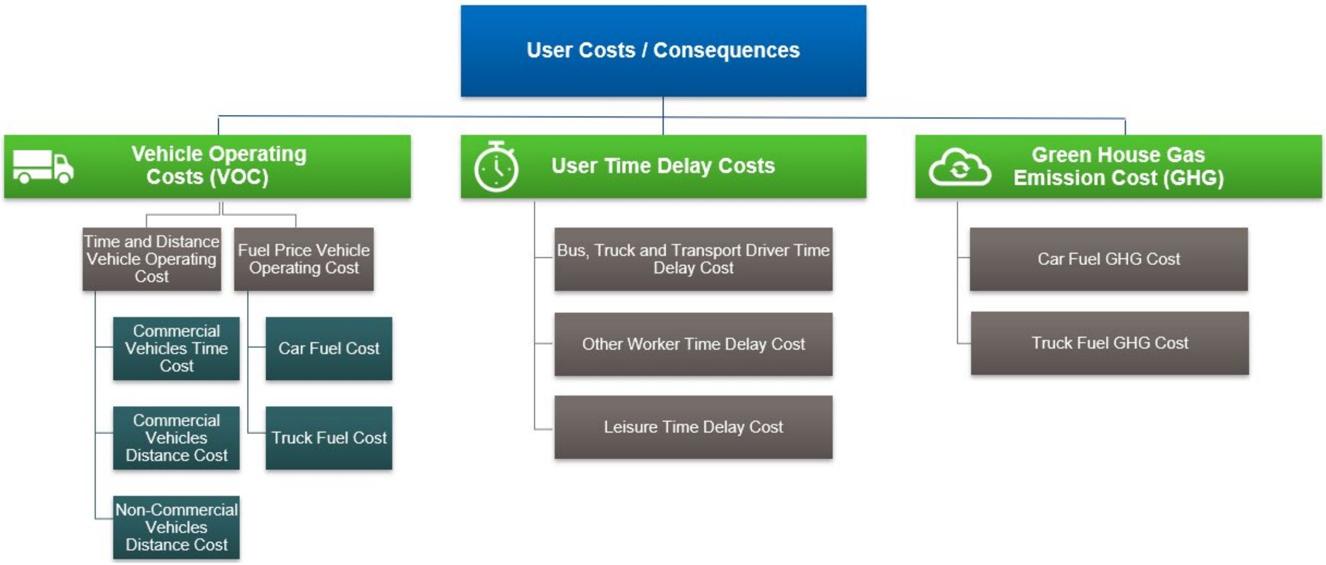

Figure 3: User Costs/Consequences components

The consequences for all assets were accounted for in the analysis in terms of owner and user consequences. For drainage assets such as a culvert, the failure mechanism will either be a culvert's washout due to extreme events or structural failure. The failed culvert is replaced with a new culvert as a direct consequence of asset failure. The failure consequence of geotechnical assets is owner consequence in terms of restoration of the failed asset and the affected road.

9.4 User Failure Consequences

The user consequence is the monetary loss to users of the road due to the traffic flow disruption because of the asset's failure or unsatisfactory performance. For drainage assets and geotechnical assets, user consequence is equal to the user costs calculated earlier (Equation 3 and 4).

$$User\ Consequence = User\ Cost_{VOC} + User\ Cost_{Time\ Delay} + User\ Cost_{GHG} \tag{3}$$

$$User\ Cost_{VOC} = VOC_{Time\ and\ Distance} + VOC_{Fuel} \tag{4}$$

9.5 Vulnerability and Risk Assessment Modelling

The Team used Deighton's Total Infrastructure Management System (dTIMS) software for data analysis and modelling. The vulnerability and risk assessment modelling methodology (St. Michel, Reggin, & Leung, 2017) and multi-strategy life cycle cost analysis were carried out in the software.

9.6 Analysis Results

9.6.1 Drainage Assets

The cost-benefit analysis included 410 selected culverts across 361 sites. The culvert condition survey result showed that the effective age of 197 culverts would exceed the effective design life between 2020 and 2030.

The engineering informed vulnerability assessment results for drainage culvert assets show that many culvert assets are undersized to accommodate a 200-year flood; however, to narrow the study results, Bridge-Culverts were identified with insufficient capacity to convey a 100-year return period event, or higher than 1% annual exceedance probability 2020 and remaining culverts were identified with insufficient capacity to convey a 20-year return period event, or higher than 5% annual exceedance probability 2020. The CBA results indicated 39 culverts meeting the above criteria. These assets may be undersized, and a site-level investigation should be carried out to confirm the analysis results. **Figure 4** shows the list of culverts at the union of two criteria replacement due to age within 10 years and replacement due to high annual exceedance probability.

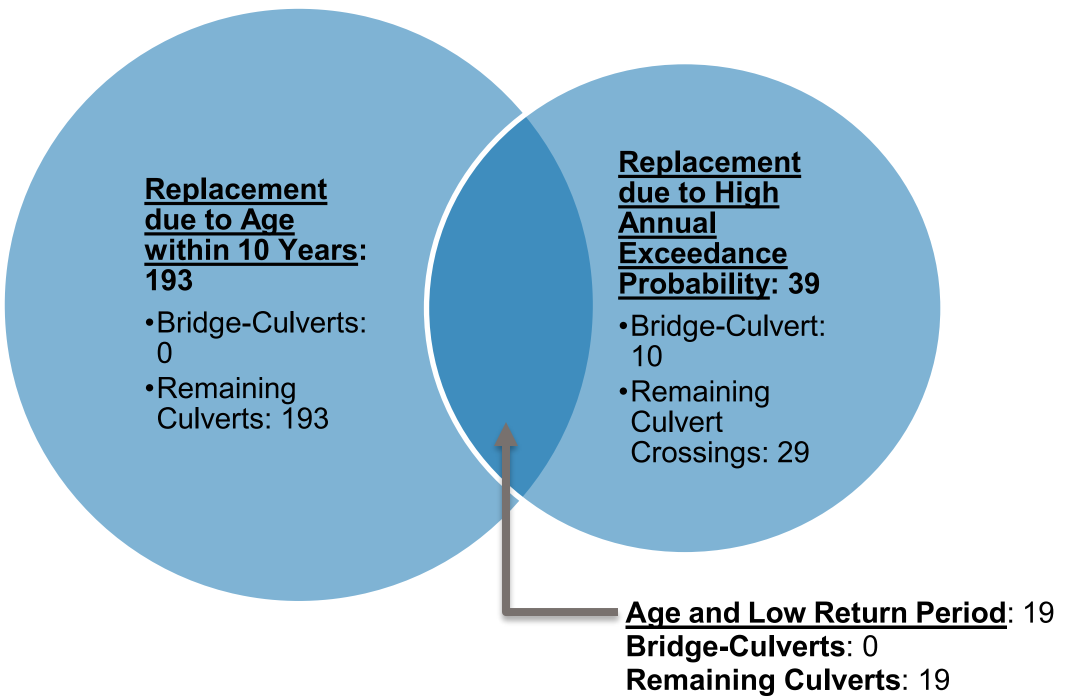

Figure 4: Replacement Due to Age and High Annual Exceedance Probability

Table 3 provides the treatment cost distribution of the 213 culverts (meeting the criteria of replacement due to age and high annual exceedance probability).

Table 3: Culvert Treatment and Cost Distribution

Culvert Treatment	No of Culvert Crossings	Cost Distribution
Culvert Replacement	115	25.91%
Culvert Replacement Bridge-Culvert	4	8.62%
Bridge-Culvert (100 Year Return Period)	12	27.44%
Open Cut Method (100 Year Return Period)	27	5.10%
Trenchless Method (100 Year Return Period)	6	5.60%
Bridge-Culvert (200 Year Return Period)	3	6.53%
Open Cut Method (200 Year Return Period)	13	3.44%
Trenchless Method (200 Year Return Period)	2	0.82%
Bridge-Culvert (500 Year Return Period)	3	7.31%
Open Cut Method (500 Year Return Period)	6	1.10%
Trenchless Method (500 Year Return Period)	7	2.52%
Bridge-Culvert (1000 Year Return Period)	1	3.11%
Open Cut Method (1000 Year Return Period)	9	1.27%
Trenchless Method (1000 Year Return Period)	5	1.24%

9.6.2 Geotechnical Assets

Based on the cost-benefit analysis results, there are nineteen (19) geotechnical assets that have a benefit-cost ratio larger than or equal to 1.0. Among the nineteen assets, there are seven (7) geotechnical assets with a benefit-cost ratio larger than 1.5, which indicates that there are significant benefits to improving the asset's current condition. **Table 4** provides the cost distribution of the geotechnical treatments by asset class from the Study.

Table 4: Cost Distribution of Geotechnical Treatment by Asset Class

Asset Class	Geotechnical Treatments	Cost Distribution
Cut Slope	Elevated with riprap	4.49%
	Flatten Slope	1.06%
	Retaining Structures	5.20%
	Riprap Protection	1.67%
	Toe Buttress	0.62%
	Vegetation	1.43%
	Cut Slope Subtotal	**14.47%**
Debris Flow	Barriers	2.39%
	Basins	1.51%
	Debris Flow Subtotal	**3.91%**
Fill Slope	Elevated with riprap	8.58%
	Highway Realignment	3.86%
	Retaining Structures	1.09%
	Riprap Protection	12.72%
	Toe Buttress	8.22%
	Fill Slope Total	**34.47%**
Rock Slope	Barriers	32.22%
	Rock Bolts	13.77%
	Rock Mesh	0.66%
	Rock Slope Total	**46.66%**
Subgrade	Lightweight Fill	0.49%
	Subgrade Total	**0.49%**

9.7 Integrating Results into Transportation Asset Management (TAM) Plan

The Framework identifies five decision-making strategies by effectively incorporating results into:

- Project Level Design and Engineering;
- Asset Management;
- Transportation Planning;
- Project Development and Environmental Review; and
- Transportation Systems Management and Operations, Maintenance, and Emergency Management.

10.0 CONCLUSION

Because the results from the Study are expressed in terms of $Benefits and costs, they are readily integrated into PSPC's overall Transportation Asset Management Plan. These potential adaptation projects can compete equitably with any other transportation asset class for limited funding.

The adaptation to climate change requires continues improvements and iterations which are achieved by Step 7 Monitor and Revisit of the FHWA Frameworks. The Study utilized the culvert condition and inventory inspection data collected in 2010 and 2011, which was found to have gaps in terms of the current condition of the culvert inventory. As a result of the Study, PSPC initiated recollection of the approximately 2,300 culvert's condition and inventory data on the Alaska Highway. The Team completed the recollection of culvert inventory and condition data based on the data collection criteria developed on the basis of the AASHTO Culvert and Storm Drain System Inspection Guide (AASHTO, 2020). Culvert Inspection consists of collecting two data types: Inventory and Condition. The inventory inspection involves verifying and updating the existing culvert database locations, culvert type, geometry, inlet and outlet-specific information. The inventory inspection also included the addition of new or missing culverts in the existing inventory and identifying culverts in existing inventory that do not exist anymore. The condition inspection consists of visual assessment and condition rating of individual components of the culvert such as approach roadway, embankment, channel, end treatments, and appurtenant structures, barrel alignment, barrel, joins, and seams.

Building upon the results of the climate vulnerability and risk assessment study and the renewed culvert inventory and inspection data, the Team is currently developing a culvert asset management framework that will generate a culvert capital works program for managing Alaska Highway culverts to incorporate into the SAMP.

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