FINANCIAL ACCOUNTABILITY OFFICE OF ONTARIO

# COSTING CLIMATE CHANGE IMPACTS AND ADAPTATION FOR PROVINCIAL AND MUNICIPAL PUBLIC INFRASTRUCTURE IN ONTARIO

## DELIVERABLE #10 – FINAL REPORT (VERSION 2)

### TORONTO, ONTARIO

WSP REF.: 211-00531-00

DATE: 21 MARCH 2023

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FINAL VERSION 2

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**Reference to mention:**

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# EXECUTIVE SUMMARY

Costing the Impacts of Climate Change to Public Infrastructure in Ontario (CIPI) is an attempt to quantify the cost of anthropogenic climate change to public infrastructure at the provincial or territorial scale. The Financial Accountability Office (FAO) of Ontario publishes a long-term budget outlook every two years, which forecasts the fiscal position of the Government of Ontario (the Province) given current fiscal policies and the FAO's long-term demographic and economic projections. A significant input into the long-term budget outlook is the Province's capital spending, which to date has been projected in the absence of climate change considerations. The focus of this project is for CIPI to support improved long-term planning in Ontario, which accounts for the impacts of climate change.

CIPI fills an important knowledge gap: while it is well established in Canada that physical infrastructure is one of the sectors with the greatest risk from the impacts of climate change and has the most to gain from adaptation, decision makers lack an understanding of the potential magnitude of that impact (national and provincial building codes will consider some of the effects of climate change on design standards only in 2025) and its disaggregation at the provincial/territorial scale or within asset classes. Both the *knowledge* of the magnitude of costs and the *methodology* of how to calculate costs are critical building blocks in Canada's adaptation to a changing climate.

CIPI is ambitious in its scope and scale. Methodologically, this project combines the established fields of asset management and climate science with the emerging field of climate resilience economics. CIPI developed and is testing the novel application of "climate-cost elasticities" – the relative variation in the condition of an asset for a given change in a climate indicator – within the FAO's existing model for asset deterioration and associated costs.

There are numerous potential interactions between climate change and infrastructure in Ontario. Dozens of climate hazards can be considered, both acute and chronic, as well as a multitude of different types of infrastructure in owned and operated by public agencies. An important aspect of CIPI's methodology is that the project team has disaggregated the infrastructure sector into asset classes – buildings, transportation, water – and sub-asset classes such as roads or rail (within transportation). At the beginning of the project, the WSP and FAO teams agreed on the most impactful interactions between climate hazards and sub-asset classes. These are summarized in Table 8 to Table 12 of this report.

This report presents the results of two phases within the CIPI project: Phase 1, which includes the development of the methodology and testing on a select number of climate-infrastructure interactions (buildings); and Phase 2, which integrates the lessons learned from Phase 1 and extends the model to the remainder of the climate-infrastructure interactions retained by the FAO-WSP project team (mostly linear assets). In both phases, the project focused on assessing the impacts of climate change on four types of costs: changes in useful service life (USL), in operations and maintenance requirements (O&M), in retrofit costs and renewal costs.

This report summarizes the complete results of Phases 1 and 2, and includes four main sections:

- Section 1: An introduction to the report and the project.
- Section 2: An overview of the methodology.
- Section 3: A summary of the results, including the rationale for how climate-cost elasticities were quantified.
- Section 4: A discussion on the main lessons and limitations.

The first phase delivered preliminary results which demonstrate the potentially significant impact of climate change on Ontario's public buildings. Through 2080, in a high-emission scenario (aligned to the high-range of the RCP8.5 scenario), buildings will most likely have a 13% reduction in their USL; see an increase of two thirds in their O&M costs (from 1.5% to 2.5% of asset value); and their repair and renewal costs would increase by 22.5% and 40%, respectively. These increases reflect the need to spend more money on waterproof foundations, repairs to the envelope due to heat deterioration or the addition of air conditioning capacity to buildings, for example.

The second phase delivered results which confirmed the potentially significant and complex impacts of climate change on Ontario’s public infrastructure by completing the assessment on other asset classes, which mostly comprised linear infrastructure such as water or wastewater pipes, and roads. Once again, through 2080, in a high-emission scenario (aligned to the high-range of the RCP8.5 scenario), roads, which will be affected by extreme heat, extreme precipitation, will most likely have a 36% reduction in their USL (optimistic: 27%; pessimistic: 44%), increase in their O&M costs (future annual share: 5% to 9% of asset value); and their retrofit and renewal costs would increase by 52% and 107%, respectively. These increases in cost reflect the need to spend more money on the maintenance of asphalt roads needing more crack sealing to prevent water infiltration or on the addition of cement additives to concrete during renewal, for example. The impacts of freeze-thaw cycles, while relevant, were excluded.

For stormwater and wastewater assets, which will be mostly affected by extreme precipitation, it is important to note that the necessity of adding capacity to maintain the expected level of service is not captured by the USL coefficient of the deterioration model. Therefore, given that these assets are not directly or significantly impacted from a physical or structural condition perspective to the selected climate hazards (the basis of the model), the impact on the USL of stormwater and wastewater assets is negligible, except for sanitary forcemains. The latter will experience more frequent and intense infiltration issues, reducing their USL by 11%. More frequent maintenance and inspection will increase O&M (from 1% to 5%, depending on the asset sub-type). Additional capacity will be required due to more intense and frequent extreme rainfall, increasing renewal/retrofit costs by 25% on average, respectively.

The projected reduction in the number of freeze-thaw cycles should extend the USL by maximum 6% and reduce the annual O&M expenses for bridges and large culverts, that are mostly made of concrete. We do not expect the reduction in the number of freeze-thaw cycles to reduce the cost of renewal and retrofit, as we assume it is not likely that design and standards will ease in response. However, more intense rainfall will increase the costs of renewal and retrofit for both assets by 13% and 27%, respectively, which will be mostly due to erosion protection, runoff control and the replacement of culverts.

Finally, the USL of transit assets (combining rolling stocks, alignments, equipment and finishing, and associated structures) are expected to be reduced by between 10% and 23%, with a most-likely value of 16% under the 2080 extreme temperature condition of high-emission RCP 8.5. More frequent maintenance, operational costs and preventive repair will drive the O&M costs up to 5% of the total current replacement value (CRV). To ensure an equivalent level of safety/service, retrofit and renewal costs should also increase by 18% and 26%.

The CIPI methodology is subject to certain limitations and assumptions. At a high level, the CIPI project results presented in this report show that the impacts of climate change on Ontario’s public assets are significant, and at this order of magnitude, are relevant for Ontario’s long-term infrastructure and capital planning.

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# 1 INTRODUCTION

The purpose of this Final Report is to provide the final climate-cost elasticities, to outline WSP's methodology for deriving them, and to reflect on what has been achieved in the CIPI project. In addition, the report provides the detailed and reproducible methodology for estimating the effect of climate hazards on assets, and the results of the application of the sample model relationships applied to the asset-hazard interactions. While a solid rationale based on engineering standards is provided for each model relationship, the report also emphasizes the limitations of the approach applied here (mainly, quality of climate data and assumptions on asset conditions). Based on learning gained from the application of the methodology by the FAO, aspects of the first report were reviewed and updated. This updated version reflects the learning from the FAO.

## 1.1 CONTEXT

The impact of human activities on the climate system is now unequivocal. Global temperature rise has increased by approximately 1°C to date, relative to the end of the 19th century, due to increasing quantities of greenhouse gases (GHGs) in the atmosphere (Bush and Lemmen, 2019). Should human activities continue to emit GHGs at the same rate as recent decades, the province of Ontario is projected to experience a temperature rise of 2.3°C in the upcoming decades, and 6.3°C by the end of the century (Bush and Lemmen, 2019). These shifts in average temperature could also result in other changes in climate conditions, such as an increase in extreme heat events, a redistribution of freeze-thaw cycles, and changes in precipitation patterns leading to more extreme precipitation events and periods of drought.

It is acknowledged that infrastructure is one of the sectors most at risk from the impacts of a changing climate, but also one that has high capacity for adaptation (Canadian Council of Academies, 2019). The Financial Accountability Office of Ontario (FAO) has faced a knowledge gap on this issue as, up until now, it has not been possible to account for the cost of the impacts of climate change on public infrastructure, nor on the benefits of climate-resilient infrastructure. This project, Costing the Impact of Climate on Public Infrastructure (CIPI), is an important step in addressing that gap.

The FAO uses its Provincial Asset Inventory Deterioration (PAID) model (from the Ministry of Infrastructure (MOI) of Ontario) to assess how public infrastructure in Ontario may deteriorate over time and the cost of managing this deterioration. The PAID model considers rehabilitation, operations and maintenance (O&M), renewal, and retrofit operations. The model is designed to reflect province-wide asset management practices to provide estimates and forecasts of the condition of assets and infrastructure backlog. Whereas access to climate data is expanding rapidly, incorporating climate projections into the evaluation of asset conditions is still at an early stage. Initially, the PAID model had not been developed to account for the effects of climate change.

In response to the above, the CIPI project was designed with two phases:

- **Phase 1** included developing the methodology and piloting the impact of extreme heat, extreme rainfall, and freeze-thaw cycles on building asset classes; and
- **Phase 2** extended the methodology to an additional seven hazard-asset interactions across other assets including roads, transit, bridges and culverts, stormwater and wastewater infrastructure.

## 1.2 VERSION 2

Finally, in 2023, an updated version of the present report was published to align its content with lessons learned throughout the Costing Climate Change Impacts to Public Infrastructure Project. The methodology in Version 2 describes more accurately the methodology and model relationships applied by the FAO. The main changes made in this second version are the following:

- Precisions on weighted & unweighted climate-cost elasticity were made (see *Section 3.1* and *Appendix A*)
- The overall methodology was adjusted to reflect *ex-post* adjustments made by FAO during the calculations. These *ex-post* adjustments are the following (see *Section 3.1*, *3.2* and *Appendixes* for more details):
  - Roads Pavement retrofits and replacement coefficients were combined
  - Pavement x FTC was not applied by the FAO and therefore was removed in the present version. This conservative approach was motivated by the divergent climate trends relating freeze-thaw cycles, leaving uncertainty on the cost trajectory.
  - Wastewater/Stormwater retrofit, and replacement coefficients were combined.
  - USL impacts for gravity sewers were zeroed.
  - USL impacts on Sanitary forcemains were adjusted.
- A new case study on gravity sewer has replaced the previous applied example on ditches. (See *B. Adaptation as a single option.)*

## 1.3 OBJECTIVE

In this context, the CIPI project aimed to deliver a quantitative assessment of how climate change impacts the deterioration of provincial and municipal public infrastructure in Ontario and the costs associated with potential adaptation measures. To assess impacts, WSP defined a set of relationships between climate indicators and infrastructure costs, termed “climate-cost elasticities”, based on climate projections for the province, consultation with subject-matter experts and best practices. These climate-cost elasticities are sensitive to climate data and can be directly integrated into the PAID model to estimate the influence of climate change on four distinct types of costs. This provides insight to the following questions:

- **Useful service life**: What would be the variation of useful service life under the influence of the evolution of each climate hazard for each asset and component?

- **O&M costs:** What would it cost annually, as a share of the current replacement value (CRV), to operate and maintain the expected deterioration rate under future climate conditions?

- **Costs of retrofitting**: What would it cost to retrofit an existent asset, i.e., to make it resilient to climate change? These costs are likely to address damages to certain components of a system (e.g., repairs of sections of pipe) due to climate impacts.

- **Additional renewal costs:** What are the additional costs of designing a brand-new climate resilient asset that has the same expected functionality as before? Complete renewal can be required due to lack of capacity of the system or condition of the system. It is likely that renewal will be more costly than retrofit.

Three climate hazards of interest (extreme rainfall, heat waves and freeze-thaw cycles) were initially selected by WSP and the FAO. This preliminary selection was based on the qualitative perception of the potential financial impacts, the reliability and availability of the climate data, and the utility of results. The selection of the final climate hazards used in this study was based on discussions between the team members (FAO, WSP), consultations with subject-matter experts, and relevant literature.

Table 1 shows the asset-hazard interactions considered in the analysis with the team focusing on the top priority interactions based on the literature and the experience and knowledge of the subject-matter experts involved. In determining whether an asset-hazard interaction should be analyzed, WSP considered potentially significant direct climate impacts on the assets and expected financial implications. Where a “No” has been assigned to a specific interaction, it indicates that:

- There is negligible or no interaction between the asset component and the evolution of the climate hazard under changing climate conditions; or
- The financial impact of the climate hazard on the asset component has been deemed negligible compared to the CRV and O&M costs. For example, extreme heat events may increase O&M costs for potable and fire-protection water services, but these costs are considered negligible compared to additional O&M costs due to freeze-thaw cycles on the building envelope.

**Table 1: Asset-hazard interactions considered in the project**

| **Building Components** | **Subcomponents** | **Extreme heat** | **Extreme rainfall** | **Freeze-thaw cycles** |
|---|---|---|---|---|
| Structure | | N | Y | Y |
| Envelope | | Y | Y | Y |
| Mechanical and Electrical Systems | | Y | N | N |
| Civil Infrastructure | | Y | Y | Y |
| Landscaping | | Y | Y | Y |
| Equipment and Finishing | | N | Indirect | Y |
| **Road Components** | **Road Subcomponents** | **Extreme heat** | **Extreme rainfall** | **Freeze-thaw cycles** |
| Pavement | Surface | Y | Y | Y |
| | Base and subbase | | | |
| Road Associated Structures | Embankments | Y | Y | Y |
| | Erosion protection | | | |
| | Barriers | | | |
| | Pavement markings | | | |
| **Transit Components** | **Transit Subcomponents** | **Extreme heat** | **Extreme rainfall** | **Freeze-thaw cycles** |
| Alignments | Level crossings | Y | N | N |
| | Tracks | | | |
| Rail Associated Structures | Noise / crash walls | Y | N | N |
| Equipment and Finishing | Power and communications | Y | N | N |
| | Signal and control equipment | | | |
| Rolling Stocks | Locomotives / passenger cars | Y | N | N |
| | Maintenance equipment | | | |
| **Bridges and Culverts Components** | **Bridges and Culverts Subcomponents** | **Extreme heat** | **Extreme rainfall** | **Freeze-thaw cycles** |
| Bridges | Ancillary | N | Y | Y |
| | Foundations | | | |
| | Substructure | | | |
| | Deck | | | |
| | Deck barriers | | | |
| Large Structural Culverts | Channel protection | N | Y | N |
| | Culverts | | | |
| | Wingwalls and headwalls | | | |
| **Stormwater and Wastewater Components** | **Stormwater and Wastewater Subcomponents** | **Extreme heat** | **Extreme rainfall** | **Freeze-thaw cycles** |
| Pipes | | N | Y | N |
| Ditches | | N | Y | N |
| Small Non-structural Culverts | Channel protection | N | Y | N |
| | Culverts | | | |
| | Wingwalls and headwalls | | | |
| Gravity Sewer | | N | Y | N |
| Sanitary Force Mains | | N | Y | N |

## 1.4 OUTLINE OF THE REPORT

This Final Report is intended to provide a scalable framework for FAO. Our approach aimed to be flexible to allow the FAO to integrate different climate change scenarios in their infrastructure deterioration model. Therefore, it includes all assumptions and limitations of the proposed methodology, so that it can be readily and carefully replicated to other asset-hazard interactions. The report includes the following sections:

- **Approach and Methodology**: Description and justification of the project approach, including supporting literature. This section also outlines a step-by-step methodology to assess the model relationships, and a description of how outcomes from consultation with subject-matter experts has been incorporated.
- **Results**: Presentation of final model relationships for each asset-hazard interaction. This section includes a summary of hypotheses and rationale to define all climate-cost elasticities, a description of how to use the results of this analysis to incorporate the influence of climate change into the PAID model, and two hypothetical applications of the results.
- **Discussion**: Interpretation of the results and discussion of limitations and uncertainties of the approach and methodology.
- **Lessons learned**: Suggestions for how the methodology can be improved or expanded in the future, as well as potential downscaling to regions or subsets of assets.
- **Acronyms.**
- **Glossary.**
- **References.**

The main report is supplemented with appendices that provide additional technical details, including

- **Appendix A:** Complete hypotheses and rationales for each asset-hazard interaction, including professional judgment from subject matter experts.
- **Appendix B:** Final climate-cost elasticities for each asset-hazard interaction.

## 1.5 LIMITATIONS

The CIPI project was constrained to a degree by data, time, and budget limitations. Beyond these typical project constraints, the project team (WSP and FAO) identified several unique challenges for CIPI that should be considered when interpreting the results. These are summarized below and explored in further detail in Discussion:

1. **Asset types and broad classification**:
    - The project team worked with the asset classification used by the FAO for both buildings and linear infrastructures, and assumed that climate change will affect all assets within an asset class in the same way.
    - Depending on age, different assets can be constructed to different codes or standards, have varying uses, and be maintained differently, these nuances were not fully distinguished within the CIPI framework.
2. **Cascading effects**:
    - The CIPI project focused on three climate hazards occurring independently. The framework did not account for overlapping hazards or cascading impacts.

3 **Tipping points**:

- The CIPI project assumed that climate-cost elasticities will remain constant over time, which suggests a linear relationship between climate and costs of climate change.
- The CIPI project considered that the variables influencing future climate-related costs comprise changes in the frequency of selected climate parameters. Built assets are complex systems of interdependent components that are affected over their life cycle by a multitude of factors such as design criteria, construction and material quality, local soil, hydrological and climate conditions, and externalities such as site services or impacts from adjacent assets (built or natural). Operations and maintenance practices vary across a portfolio, and the assets' useful life and costs are influenced (positively or negatively) by financial and budget decisions over the analysis period that may not be related to the level of deterioration of the assets. These decisions about rehabilitation, retrofit or renewal, which is not always a direct result of the state of good repair of the asset, may be influenced by changes in asset function, requirements for additional capacity to meet demand, or changes in regulations. These factors, which are typically considered at the project (asset) level by asset managers, are not included in this portfolio analysis.

4 **Cumulative climate costs:**

- The CIPI project considered the costs of three climate hazards individually then summed them to arrive at a total cumulative impact.
- However, the true cumulative impact of the three hazards, and other climate events not considered in the analysis, may be smaller or larger than a straight summing of the impacts. For example, an event may weaken components of the asset which may make it more vulnerable to other climate hazards.
- For transportation assets, like roads, the cumulative impact was revised down significantly. This operational decision was put in place to limit unlikely high projected costs when applying the alpha coefficients to actual climate data (e.g., in some cases the combined effects led to a reduction in useful life greater than 100%, which is clearly not possible). These operational decision interventions are listed in the report.
- The synergies of moving to a new climate. For example, replacing stormwater pipes will involve replacing the overlying road in a single project, or retrofit of a building envelope can improve the building energy performance, offsetting increases in cooling loads and helping to further reduce heating loads.

5 **Energy transition**:

- Climate action can have two components. Adaptation refers to adjustments in systems in response to the expected impacts of climate change. Mitigation refers to efforts in reducing the greenhouse gas emissions to prevent climate warming. The CIPI project only considered climate change adaptation, as climate change mitigation is beyond the scope of the project.
- There may be opportunities to integrate adaptation with mitigation efforts, such as energy efficiency retrofits to improve building performance, enabling asset managers to leverage funding and look for synergies in capital projects.

6 **Level of service and replacement**:

- The project team considered the correlation between climate change and increased physical deterioration; however, assets that no longer deliver the expected level of service may be replaced before the end of their USL.
- This issue is particularly pronounced for linear assets relating to stormwater and wastewater. As such, the project team addressed this asset management implication by removing the USL impact and including the adaptation cost of retrofitting at first rehabilitation for these assets.

# 2 APPROACH AND METHODOLOGY

This section describes the general approach used to design the methodology, which is supported by the academic literature. It also includes a step-by-step methodology to assess the model relationships that can enable the PAID model to reflect the influence of climate change. This methodology is described through an example of building assets exposed to extreme heat events, extreme rainfall, and freeze-thaw cycles, but can also be replicated for additional asset-hazard interactions.

## 2.1 SUPPORTING MATERIAL

Before initiating this study, the project team conducted a review of the literature and the best practices on which the CIPI project should align. The main conclusions of this research were

- Quantifying the infrastructure damages of climate change is complex and requires projecting monetized impacts on different types of cost. A climate-cost elasticity is a simplified expression of economic costs or benefits, as a function of climate inputs, such as changes in average precipitation or temperature (Neumann et al., 2020; Kotz et al., 2021).
- Many asset management deterioration models use a deterministic approach to forecast the future condition state of an asset and its components. However, two assets constructed using the same materials and type of construction may not deteriorate at the same rate given the many factors that impact deterioration rates. This uncertainty is expected to decrease when a portfolio is considered rather than a single asset (Bush et al., 2017). To address the uncertainty arising from a wide portfolio (component age, design, and construction variability) WSP used an expert-based data collection approach to identify a range of impacts that climate change might have on a portfolio of assets. This methodology was adopted because it maintained the greatest amount of information and allowed experts some leeway in describing anticipated effects.
- Given the uncertainty regarding emission scenarios decades into the future, economic studies must address the range of possible emissions trajectories. Representative Concentration Pathways (RCPs), a type of scenario used by the Intergovernmental Panel on Climate Change (IPCC), have been used in several economic studies for examining physical risks (Ens and Johnston, 2020). Since climate interannual and model variability can translate into significantly different economic outcomes, using high- and low-value percentiles of these distributions as inputs adds robustness to the forecast.

## 2.2 APPROACH

The CIPI project methodology built on a general understanding of how climate change affects public infrastructure and thus the approach represents a next step from previous work on costing the impacts on built assets. The hypotheses in the methodology were supported by specific case studies, federal and provincial design standards, and data collected from engineers and practitioners specialized in various infrastructure sectors (hereafter, subject-matter experts, or SMEs).

Figure 1 summarizes the approach to developing the methodology and to assess the model relationships for each asset-hazard interaction. This figure highlights the importance of iterative processes and ongoing conversations between all stakeholders. Due to the innovative nature of the project and the complex nature of the performance of built assets and systems, it was essential that all the assumptions made were suitable for every asset or system type so that the implementation of the results in the PAID model was coherent and consistent. After adopting the methodology, WSP defined model relationships through several rounds of consultation with SMEs, tailoring this engagement based on respective knowledge and fields of expertise. This process involved frequent and ongoing conversations between the project team and SMEs to improve accuracy and justification for estimates of climate-cost elasticities for each asset-hazard interaction.

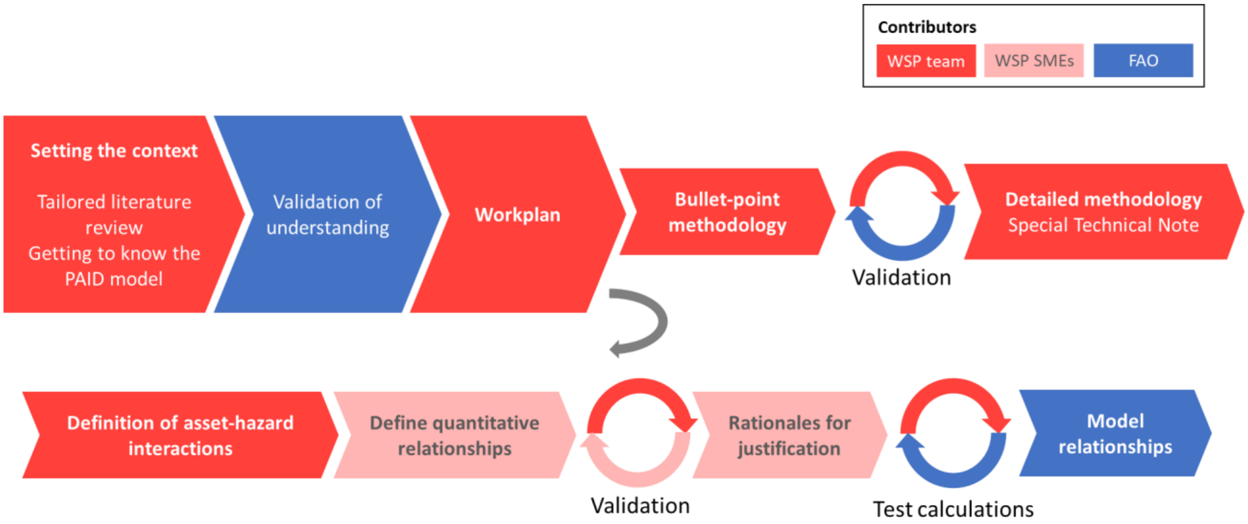

Figure 1: Approach workflow

Inspired from the economic concept of elasticity, the series of climate-cost elasticity coefficients ($\alpha$) measures the relative response of cost-related parameters $p$ of an asset component $I$ to a change in the climate indicator $c$, which can be expressed as:

$$\alpha_{i,c,p} = \frac{\Delta\, p_i}{\Delta\, c_i}$$

Where:

- $p$ = model parameter of interest such as the implied USL, O&M shares of the CRV, and the cost of adaptation to the climate hazard as a retrofit or asset renewal;
- $c$ = climate indicator of interest for a specific asset component and a specific climate hazard; and
- $i$ = asset component under consideration

These climate-cost elasticities ($\alpha$) can be interpreted as a direct relationship between the evolution of a climate indicator under climate change and the projected changes (increase or decrease) in service life and costs for a given asset or component.

In this framework, the relative variation in a cost parameter is derived from a bottom-up approach (starting with the impacts on the asset components) on how a climate hazard interacts with a given asset. In other words, the variation in a cost parameter at the asset level is the cumulative variation in cost of its components. The general steps to develop these relationships are:

- **Define a qualitative hazard-infrastructure interaction**: Isolate and define the possible asset-climate interaction at the component level, including a qualitative appreciation of damage produced (e.g., pavement will be affected by extreme heat due to softening and asphalt bleeding).

- **Specify and source the climate indicators:** Select the most appropriate climate indicator available to proxy the defined interaction, based on the physical process leading to deterioration and climate data availability (e.g., 1:100 event to represent extreme rainfall impacts on stormwater management systems).
- **Calculate the projected changes in climate ($\Delta c$):** Calculate the projected change in climate under the high range of RCP8.5 to propose a scenario with the most significant change in the selected climate indicators.
- **Estimate cost impacts ($\Delta p$) from changes in climate indicators:** Define a theoretical quantitative relationship for the expected climate change impacts on a given asset or component as a function of the change in the selected climate indicator. Consult SMEs to estimate a range of changes in infrastructure cost parameters given the change in climate indicators (e.g., extreme heat will result in increased deterioration of a component, leading to a X% reduction in its USL).
- **Aggregate SME responses and derive the range of climate cost elasticities:** Calculate the $\alpha$ coefficients as the ratio between the pooled responses from the SMEs ($\Delta p$) and the projected changes in climate ($\Delta c$).
- **Verify:** Run test calculations to verify that the model parameters yield reasonable results, refining the approach as needed.

## THE ROLE OF SUBJECT-MATTER EXPERTS

The data collection approach used to capture the effect of climate change on public infrastructure was inspired by the Delphi method (Skulmoski et al., 2007), and supplemented with participatory data collection. These methods are often used by asset management professionals to estimate the likelihood of future events and their potential consequences, drawing on the professional judgment of expert practitioners when empirical data is not readily available. During this project, SMEs were consulted, applying their experience and knowledge of the different infrastructure types, to estimate how they would be impacted by the changes in the selected climate parameters. Individual SME contributions were not shared with the rest of the group to avoid a decision process leading automatically to a consensus. Instead, WSP used statistical aggregation techniques considering a wide range of uncertainties.

The SMEs that were included on the project team were selected based on their field of expertise. This team included experts in asset management, in infrastructure design or in specific material (e.g., pavement), with a deep understanding of the Ontario context. Through different rounds of consultation, WSP and the SMEs derived model relationships that were realistic and justifiable given recent knowledge on climate impacts to selected assets. Essentially, SMEs were consulted to:

- Confirm the component breakdown of each asset category;
- Define the qualitative asset-hazard interaction;
- Identify the climate indicators that best proxy the asset-hazard interactions; and
- Evaluate quantitatively the cost impacts of climate change on the infrastructure.

SMEs based their inputs on decades of project experience, literature (when available), relevant codes and standards and their understanding of the provincial context.

## 2.3 METHODOLOGY

### A. DEFINE ASSET COMPONENTS

The asset components that were defined for the CIPI project are presented in Table 1. The asset categorization being based on the FAO asset classes. More information is available in the FAO's report *A Review of the Province's Infrastructure and an Assessment of the State of Repair*[1]. However, the FAO report splits the buildings in function (e.g., hospitals, schools, etc.) rather than by component. The design and the materials of the different systems are the key driver of the deterioration rate. For example, the buildings were divided in their principal systems: structure, envelope, mechanical and electrical, civil infrastructure, landscaping, and equipment and finishing. The cost impacts on each of these systems were then weighted by an estimated share of the CRV.

### B. DEFINE A QUALITATIVE ASSET-HAZARD INTERACTION

At the onset of the project, WSP and the FAO agreed that the project would focus on the three following hazards:

1. **Extreme rainfall:** Extreme rainfall refers to short duration precipitation events of high intensity. During these events, the quantity of precipitation may exceed the infiltration rate or surrounding drainage capacity, which would lead to flooding, infiltration or increased erosion of infrastructure components. Extreme rainfall is usually defined as daily to sub-daily rainfall events for a return period varying from two to 100 years. The impacts of riverine and fluvial flooding, which may result from factors such as rapid, widespread snowmelt, extended periods of widespread heavy precipitation, or both, are not considered. Extreme rainfall events are considered acute hazards that the model will average out across regions and over a long period of time.

2. **Extreme heat:** Extreme heat refers to events where the atmospheric temperature exceeds the capacity of infrastructure or its components, resulting in increased stress on material (e.g., steel expansion causing buckling of rails) or impacts on the operations and maintenance. Extreme heat can be both considered a chronic and acute hazard. For example, rail bucking during a high-magnitude heat wave is an acute impact, but the accelerated degradation of mechanical equipment that is more frequently used in warmer conditions is a chronic impact.

3. **Freeze-thaw cycles (FTCs):** FTCs refer to the situation when temperatures fluctuate above and below the freezing point, resulting in a phase change in water (from liquid to solid or vice versa). Given the high expansion rate of water when it freezes, melting and refreezing of water will accelerate the weathering of material, potentially causing significant damage to many infrastructure components that are exposed to the atmosphere. The impacts of FTCs are therefore caused by the combination of temperature fluctuations and the presence of water.

   Differentiation was made in relation to the average daily temperature when the FTC occurred as illustrated in Figure 2.

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[1] https://www.fao-on.org/en/Blog/Publications/provincial-infrastructure-2020

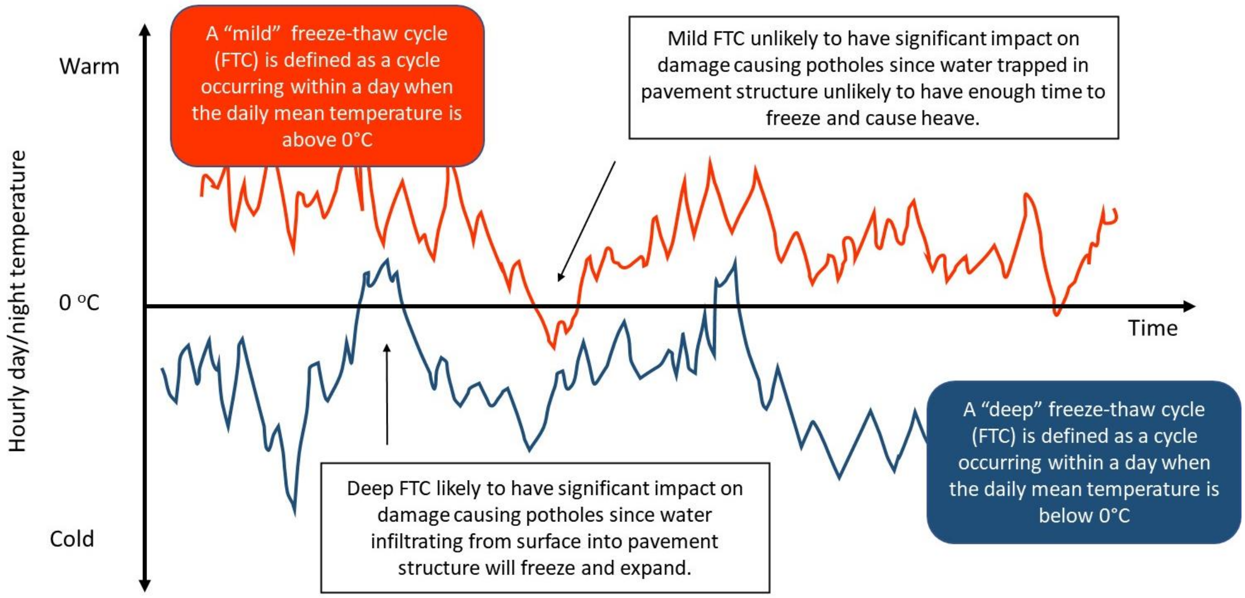


Figure 2: Illustration of impacts of mild and deep freeze-thaw cycles

**a** For vertical infrastructure (e.g., buildings), the annual number of FTCs was considered a good proxy to this hazard since water will not accumulate as much due to runoff by gravity. The notion of deep FTCs has also been considered to represent the specific impacts of FTCs when the mean daily temperature is below 0°C. This definition is used for all interactions considered, except for equipment and finishing of buildings, for which the total annual number of FTCs better represent the impacts on cost already observed when a "mild" FTC occurs (i.e., when the daily mean temperature is above 0°C).

**b** For horizontal infrastructure, particularly roads, the project team also considered that water accumulation on the surface and its potential to penetrate the sub-layers and thus, impact the performance of these elements. Therefore, a composite index considering FTCs and liquid precipitation intensity in winter was initially used as the relevant climate indicator. These coefficients are available in first version of this report. However, the FAO finally did not use the cost projections for FTCs due to divergent trends between annual FTCs (decreasing) and liquid precipitation intensity in winter (increasing). Therefore, interactions FTCs and pavement is not available in Version 2.

## C. SPECIFY, SOURCE AND JUSTIFY THE CLIMATE INDICATORS SELECTED

WSP began by selecting climate indicators that best represented the three major climate hazards to each asset class component. The indicators were selected based on data availability and direct physical impact on specific asset components (

Table 2).

Table 2: Definition and source of each climate indicator used in the analysis

| CLIMATE HAZARD | CLIMATE INDICATOR | DEFINITION | DATA SOURCE |
|---|---|---|---|
| Extreme rainfall | IDF 24-hr 1:2 | Daily maximum rainfall event with a return period of 2 years (mm). | Historical IDF statistics are available for a collection of weather stations on Climate Data for a Resilient Canada (CRIM, 2019). WSP suggests building interpolated time series from subsequent periods using the Clausius-Clapeyron relationship (i.e., 7% increase per °C of warming, using annual mean temperature). "Mean temperature" variable is also available as annual statistics on Climate Data for a Resilient Canada. |
| | IDF 24-hr 1:10 | Daily maximum rainfall event with a return period of 10 years (mm). | |
| | IDF 24-hr 1:100 | Daily maximum rainfall event with a return period of 100 years (mm). | |
| | Average annual precipitation | Total amount of precipitation received in one year (mm) | "Total precipitation" variable available as annual statistics on Climate Data for a Resilient Canada. |
| | Maximum 5-day precipitation | The maximum amount of precipitation within a year received during five consecutive days. This metric can be used to assess the impacts on hydraulics of the channel infrastructure. | "Maximum 5-day precipitation" variable available as annual statistics on Climate Data for a Resilient Canada. |
| Freeze-thaw cycles | Annual number of freeze-thaw cycles | A freeze-thaw cycle happens when the daily maximum temperature is above 0°C and the daily minimum temperature is below 0°C. Under these conditions, it is likely that some water at the surface is both liquid and solid at some point during the day. The annual number of cycles is then the number of days with a cycle considering all month in the calculation. | Using the "minimum temperature" and "maximum temperature" variables as daily statistics, the FAO can select days corresponding to the criteria and build statistics directly from the dataset. |
| | Number of deep freeze-thaw cycles | A deep freeze-thaw cycle is defined by a cycle occurring within a day when the mean daily temperature is below 0°C. Depending on the infrastructure type under study, this type of cycle can have a greater impact than a "mild" freeze-thaw cycle (see below). They are more likely to occur during winter months. | Using the definition of the annual freeze-thaw cycles, the FAO can apply another filter to select only days when the mean daily temperature is negative. The daily mean temperature can be obtained by computing the average of the "minimum temperature" and "maximum temperature" variables available as daily statistics on Climate Data for a Resilient Canada. |
| | Winter Rain | Total amount of liquid precipitation averaged daily on the length of winter, defined as the period between the first day of frost and the last day of frost. A day of frost is defined by a negative daily minimum temperature. | Using the "precipitation" and "minimum temperature" variables as daily statistics on Climate Data for a Resilient Canada. |

| CLIMATE HAZARD | CLIMATE INDICATOR | DEFINITION | DATA SOURCE |
|---|---|---|---|
| Extreme heat | Mean July daily maximum temperature | Monthly average of daily maximum temperature in July | "Maximum temperature" variable available as monthly statistics on Climate Data for a Resilient Canada. |
| | 2.5% July daily maximum temperature | 97.5th percentile of the distribution of daily maximum temperature in July | Using the "maximum temperature" variable as daily statistics and selecting only data for July, the FAO can create annual distributions and identify the appropriate percentile values. |
| | Annual number of hot days | The number of days within a year when the maximum temperature reaches 30°C or more. | "Days with Tmax > 30°C" variable available as annual statistics on Climate Data for a Resilient Canada. |
| | Annual highest temperature | The highest temperature reached within a year (corresponds to the annual maximum of the daily maximum temperature). | "Hottest Day" variable available as annual statistics on Climate Data for a Resilient Canada. |
| | Annual number of cooling degree-days | Annual sum of daily degrees above 18°C, based on daily mean temperature, directly linked to cooling demand to maintain average air conditions in the building interior.<br>Example: if the average daily temperature is 30°C on each day of July, and below 18°C for the rest of the year, the annual number of cooling degree-days will be 31*(30-18) = 372. | "Cooling degree days" variable available as annual statistics on Climate Data for a Resilient Canada. |

Each component has the potential to react differently to climate hazards, and so WSP selected climate indicators that best reflect the impact of a given hazard on each component. Based on codes and standards, the first round of SME consultation enabled to identify a climate indicator for each asset-hazard interaction (Table 7 to Table 7).This selection is justified here, whereas the rationales behind the final climate-cost elasticities are described in detail in Section 3.2.

## BUILDINGS

- Structure is impacted by humidity and freeze-thaw cycles if cracks in the material are present. Average annual precipitation has been recorded as a relevant design parameter in the National and Ontario Building Codes. These hazards have the greatest impact on horizontal structure components that are exposed (substructure, foundations and roof structure), where water accumulation is most likely.
- The envelope is very likely the component most impacted to climate conditions. Erosion of porous material, corrosion and leakage represent most of the damages on the envelope. Short-duration rain events, as opposed to average or daily rainfall statistics, have similar effects on cladding and roofing, and to a lesser extent on curtain walls and windows (CSA S478:19 standard). FTCs play a major in envelope deterioration and cracking (ASTM C67 standard). This is also relevant to the impermeability of window framing. Peak temperatures in summer tend to foster thermal dilatation of materials, decreasing the performance of the building itself. The 2.5% July daily maximum temperature is part of the design criteria in the National and Ontario Building Codes.

- Under changing climate conditions, the performance of mechanical and electrical systems is also likely to severely impacted, but the consequences will depend on the thermal isolation of the envelope and on the capacity of mechanical systems to maintain ambient air in specific conditions (temperature and humidity). The annual number of cooling degree-days is the best indicator to link O&M costs, retrofit or renewal costs, when the performance of mechanical systems will become insufficient in projected new climate conditions.

- Civil infrastructure components of a building mainly consist of water management systems. Among the three climate hazards considered in the analysis, extreme rainfall is then the most likely to have a direct impact. Typical municipal design standards for water management systems adopt IDF statistics to assess their performance. Daily statistics with a return period of two- or five years, and 50 to 100 years – representing operational and extreme events' considerations, are generally used. Moreover, daily extreme rainfall is a parameter considered as a design criterion referenced in the National and Ontario Building Codes. For civil infrastructure, the evolution of the number of freeze-thaw cycles is likely to cause changes in O&M and retrofit costs for exposed components.

- Asphalt and concrete are sensitive to high temperatures and freeze-thaw cycles. This can lead to additional O&M and retrofit costs. Impacts due to extreme rainfall are considered minimal of paving, surfacing and walkways, but may affect the drainage system which is considered as a separate asset. Design documents for low-impact development of landscape architecture are available on the Credit Valley Conservation website.

- Interior finishes vary considerably, and their durability is highly dependent on the performance of the envelope. For example, drywall behind a properly built wall that is not exposed to water could last 100 years or more, as the only deterioration would be wear and tear from the occupants. Conversely, drywall exposed to leakage through the envelope may quickly develop mould or deteriorate to the point of requiring replacement. Leakage would be the main driver of deterioration of interior finishes and impact durability of assets.

**Table 3: Selection of climate indicators for each asset-hazard interaction of buildings**

| CLIMATE HAZARD | EXTREME HEAT | EXTREME RAINFALL | FREEZE-THAW CYCLES |
|---|---|---|---|
| Structure | | Average annual precipitation | Annual number of deep freeze-thaw cycles |
| Envelope | 2.5% July daily maximum temperature | IDF 15-min 1:10 | Annual number of deep freeze-thaw cycles |
| Mechanical and Electrical Systems | Annual number of cooling degree-days | | |
| Civil Infrastructure | Mean July daily maximum temperature | 0.5 * IDF 24-hr 1:5 + 0.5 * IDF 24-hr 1:100 | Annual number of deep freeze-thaw cycles |
| Landscaping | Mean July daily maximum temperature | IDF 15-min 1:10 | Annual number of deep freeze-thaw cycles |
| Equipment and Finishing | | IDF 15-min 1:10 | Annual number of freeze-thaw cycles |

## ROADS

### *Extreme rainfall*

The most extreme precipitation event (i.e., the 100-year return period event) could most likely result in increased deterioration, as roads are usually considered resilient to rainfall (deficiencies in the drainage system may have local impacts but stormwater management assets are considered separately).

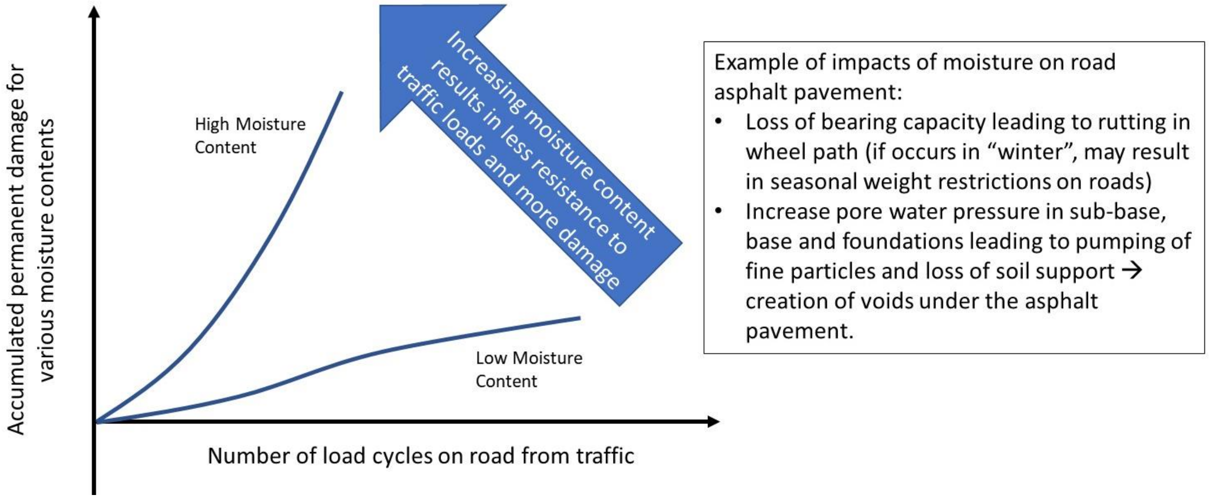
### *Extreme heat*

The occurrence of extremely high ambient temperatures over the 30°C makes the asphalt pavement become softer, because dissipation of heat is less efficient. Asphalt temperature can typically be more than 20°C to 25°C higher than the ambient air temperature due to low albedo. Asphalt temperature design criteria is typically 59°C or 64°C.

### *Freeze-thaw cycles*

The project team and SMEs, when selecting the climate indicators that generate damages to roads in winter, identified two key parameters: surface water accumulation (which penetrates the base of the road softening it and creating voids that further cause damages), and FTCs.

When considering the impacts of water accumulation at the surface of the pavement and potential penetration into the road base, a key design principle is to “keep the water out”. This is done, for example, by having the proper road cross-section geometry to drain water away from the road surface, stormwater management systems (catch basins and pipes, or ditches). Figure 3 illustrates the impacts of moisture content in the road structure on the accumulated damage in relation to the number of load cycles from traffic.



Example of impacts of moisture on road asphalt pavement:

- Loss of bearing capacity leading to rutting in wheel path (if occurs in “winter”, may result in seasonal weight restrictions on roads)
- Increase pore water pressure in sub-base, base and foundations leading to pumping of fine particles and loss of soil support → creation of voids under the asphalt pavement.

**Figure 3: Illustration of impacts of moisture on the weathering efficiency of freeze-thaw cycles on asphalt pavement roads.**

For this analysis, the team considered that winter operations would remove snow accumulations from the road surface and therefore water penetration from snow melt would have insignificant impacts on the cost parameters considered. However, the primary mechanism leading to road damage (which generates potholes) was assumed to be predominantly influenced by two climate indicators: deep FTCs (as defined at the beginning of Section 2.3 B) and winter rain (liquid precipitation between the first and last day of frost). Indeed, winter rain is responsible for the saturation of the granular material in the base and sub-base of roads. As such, given that roads are designed to prevent water from penetrating its base, through surfacing and sloping of the road, the problem with winter rain will occur when rain intensity exceeds the drainage capacity of the roads. As such, average winter rain intensity (the sum of liquid precipitation between the first and last day of frost divided by the number of days between the first and last day of frost) was deemed the best proxy for moisture content in the road structure. Figure 3 illustrates this hypothesis.

However, the impacts of FTC or moisture condition to road infrastructure are always studied independently in the literature. The lack of research on the cumulative impacts of moisture and frost conditions prevents firm conclusions for the specific weight of each parameter in defining a single climate indicator. For this report, both deep FTCs and winter rain intensity were attributed a 50% weight for the final indicator of FTC damage to roads, although future research should be conducted on this topic.

For this reason and to produce conservative but reflective estimates, the FAO excluded the costing results for FTC on roads.

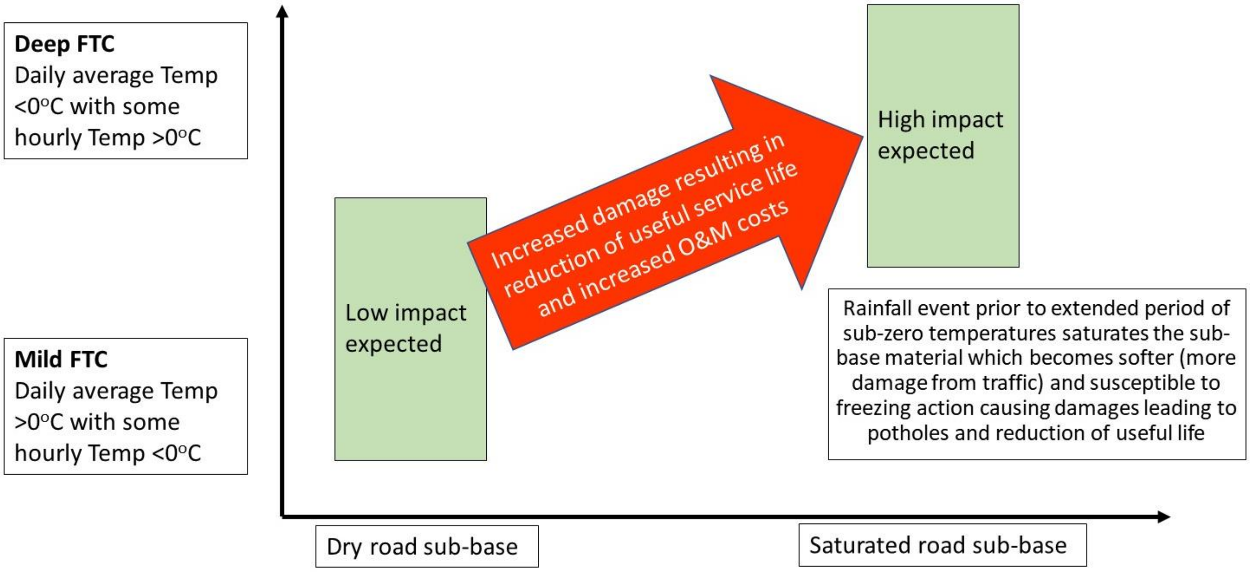


Figure 4: Illustration of impacts of freeze-thaw cycles on asphalt pavement roads

- It should be noted that mechanism for the impacts on the pavement on bridge decks is different since the layer below the asphalt pavement in bridges in impervious (steel, concrete) and therefore will not be impacted in the same manner as granular materials in roads.

Table 4: Selection of climate indicators for each asset-hazard interaction of roads

| CLIMATE HAZARD | EXTREME HEAT | EXTREME RAINFALL | FREEZE-THAW CYCLES |
|---|---|---|---|
| Pavement | Annual number of hot days | IDF 24-hr 1:100 | 0.5*Winter rain intensity + 0.5*Annual number of deep freeze-thaw cycles |
| Road Associated Structures | Annual number of hot days | IDF 24-hr 1:100 | 0.5*Winter rain intensity + 0.5*Annual number of deep freeze-thaw cycles |

## TRANSIT

- Rails are made of steel which expands as it heats up. Under these conditions and at high speed, trains risk buckling the track. Temperature on tracks can exceed 50°C during heat waves. Just a few hours of above-average heat are enough to cause problems. During periods when the ambient air temperature is expected to be high or when the temperature is rising rapidly, additional track inspections may also be required (Transportation Safety Board of Canada, 2002).

- Continuously welded rails are generally pre-stressed to a rail neutral temperature of 90°F (32°C) in Canada. Thus, increasing temperature will probably increase the production costs of transit (National Research Council of Canada, 2018).
- The mean July daily maximum temperature represents the impact of extreme heat on vinyl-covered walls and living (vegetated) wall deterioration and maintenance, which occurs when a certain threshold of temperature is exceeded.
- In terms of power supply and communication, these components are vulnerable to extreme temperature, especially if located in a structure with insufficient cooling capacity. The highest annual temperature was considered the best proxy for this interaction.
- Passenger cars may require more cooling resulting in higher operating cost, which is best assessed by the evolution of the annual number of cooling degree-days.

**Table 5: Selection of climate indicators for each asset-hazard interaction of transit**

| CLIMATE HAZARD | EXTREME HEAT | EXTREME RAINFALL | FREEZE-THAW CYCLES |
|---|---|---|---|
| Alignments | Annual number of hot days | | |
| Rail Associated Structures | Mean July daily maximum temperature | | |
| Equipment and Finishing | Annual highest temperature | | |
| Rolling Stocks | Annual number of cooling degree-days | | |

## BRIDGES AND CULVERTS

- Freeze-thaw cycles and extreme precipitation are both considered as they were identified to contribute significantly to the four costs parameters.
- Freeze-thaw cycles are identified as the main climate deterioration driver in Ontario, in terms of direct climate interactions with the infrastructure. A reduction of the annual number of freeze-thaw cycles will most likely be translated into a benefit regarding USL and O&M.
- Runoff is more a concern than rainfall, but extreme rainfall is a good proxy for runoff which depends on the hydrological characteristics of the watershed and the channel (area, permeability, topography, etc.).
- High-intensity short-duration precipitation events are used a proxy to floods. The design criteria in terms of the return period of the extreme event depends on the culvert span and the type of road above (freeway/urban arterial, rural/collector or local). No data is available to cross-reference these two categories and apply the specific IDF curve to each sub-type of structural culvert. Regardless, because the increase in extreme rainfall will be based on a percentage increase per degree of warming, the magnitude of change will be the same irrespective of the selected duration and return period.

**Table 6: Selection of climate indicators for each asset-hazard interaction of bridges and culverts**

| CLIMATE HAZARD | EXTREME HEAT | EXTREME RAINFALL | FREEZE-THAW CYCLES |
|---|---|---|---|
| Bridges | | IDF 24-hr 1:100 | Annual number of freeze-thaw cycles |

| CLIMATE HAZARD | EXTREME HEAT | EXTREME RAINFALL | FREEZE-THAW CYCLES |
|---|---|---|---|
| Large Structural Culverts | | IDF 24-hr 1:100 | |

## STORMWATER AND WASTEWATER

- In Ontario, regulatory agencies, such as the Ministry of Transportation (MTO), Ministry of Environment and Climate Change (MECC), Ministry of Municipal Affairs and Housing (MMAH), and Conservation Authorities mandate the use IDF statistics as one of the major criteria in the design of stormwater management systems.
- Extreme rainfall has an impact on every component of stormwater and wastewater (especially for combined systems) since intensities are usually directly linked to the design criteria. Design criteria depend on the component under study:
  - Pipes are usually designed to address more frequent events. In Toronto, storm sewers are designed to convey a 2-year return period storm in order to avoid overflows during these storm events (City of Toronto, 2009). Therefore, the 2-year return period IDF curve was selected.
  - Ditches and small culverts are more vulnerable to large overflow events. A heavy rainfall event lasting one to six hours might be more significant for filling the ditches and overflowing the roadways. In recent urban areas, the major system must be able to convey the flow resulting from a 100-year return period event without causing damages to private property and with minimum inconvenience to the public.
  - Gravity sewer pipes are installed with a gradient, allowing wastewater to flow by gravity from the source to the treatment facility. Gravity pipes are not directly designed based on IDF criteria as their intent is to carry wastewater, but infiltration and combined systems (wastewater and stormwater) makes intensity of rainfall a relevant factor. The maximum 5-day precipitation is used as a proxy for infiltration. Due to the complexity of modeling snow melt, only rain-on-rain events are considered.
  - For sanitary force mains, we consider that the longer term and most extreme events would better reflect the expected impact as more volume may need to be conveyed by the system resulting in potentially greater pressure, representing a higher failure risk. The impact being structural rather than performance, it is therefore expected that long duration, extreme events would have the biggest impacts.
  - In some cases, freeze-thaw cycles can increase deterioration of wastewater and stormwater components that are close to the surface or exposed; these are considered negligible since most of these assets are buried underground. Similarly, extremely high temperatures can have a marginal impact on the deterioration of PVC components near the ground surface, for instance.

**Table 7: Selection of climate indicators for each asset-hazard interaction for stormwater and wastewater infrastructure**

| CLIMATE HAZARD | EXTREME HEAT | EXTREME RAINFALL | FREEZE-THAW CYCLES |
|---|---|---|---|
| Pipes | | IDF 24-hr 1:2 | |
| Ditches | | IDF 24-hr 1:100 | |
| Small Non-structural Culverts | | IDF 24-hr 1:100 | |
| Gravity Sewer | | 0.5 * IDF 24-hr 1:2 + 0.5 * Maximum 5-day precipitation | |

| CLIMATE HAZARD | EXTREME HEAT | EXTREME RAINFALL | FREEZE-THAW CYCLES |
|---|---|---|---|
| Sanitary Force Mains |  | IDF 24-hr 1:100 |  |

## D. CALCULATE THE PROJECTED CHANGES IN CLIMATE (∆C)

High-range projections from the RCP8.5 scenario (relative to a recent baseline) in three Ontarian representative regions were used to benchmark expected climate change impact on the FAO model parameters during the second phase of the SME consultation. Climate variations are defined as follows:

$$\varDelta c\ (\%) = (c_{2051-2080} - c_{1976-2005})/c_{1976-2005}$$

For temperature-based indicators measured in °C, this variable is calculated as a level change.

$$\varDelta c\ (°C) = (c_{2051-2080} - c_{1976-2005})$$

Projections in the percentage of some temperature metrics based on counts, such as the annual number of hot days, have high values; this reflects the influence of low historical values. For example, going from one to 10 hot days would represent a 900% increase.

The most-likely climate variation was calculated as the weighted average of the geographical distribution of assets (represented by their CRV) of Ontario’s public assets provided by the FAO in recent studies (FAO, 2020) with the following weights:

- North: 9%.
- Centre: 19%.
- South: 72%.

Historical IDF statistics are based on observation datasets available on Climate Data for a Resilient Canada (file named “Short Duration Rainfall Intensity−Duration−Frequency Data (TXT)”, Table 2a). A representative weather station has been selected for each of the three predefined regions:

- North: Peawanuck (AUT) – ID 6016295.
- Centre: Timmins Victor Power A – ID 6078285.
- South: Waterloo Wellington A – ID 6149387.

Future values of IDF statistics are computed using the Clausius-Clapeyron relationship, stating that IDF statistics increase by 7% for each degree Celsius added to the local annual mean temperature (CSA PLUS 4013:19 Standards). Mean temperature increase is obtained from the annual time series of the “mean temperature” variable available on Climate Data for a Resilient Canada to apply the following equation:

$$\Delta IDF\ (\%) = \left(1.07^{T_f - T_b} - 1\right) \cdot 100$$

Where:

- $T_f$ = the future annual mean temperature averaged between 2051 and 2080 (10th percentile of RCP4.5 for the low-range of RCP4.5 and 90th percentile of RCP8.5 for the high-range of RCP8.5)

- $T_b$ = the baseline annual mean temperature between 1976 and 2005 (mean of RCP4.5).

Temperature and additional precipitation data for all climate indicators have been extracted from the grid cell containing:

- North: the mouth of the Kapiskau River;
- Centre: the City of Timmins; and
- South: the City of Kitchener.

## E. ESTIMATE THE IMPACTS ON COST FROM CHANGES IN CLIMATE INDICATORS (∆P)

After evaluating different types of costs for all components, WSP assessed impacts to the entire asset class and distributed impacts across all components relative to their given share of the CRV or USL. This process is illustrated in Figure 5 below.

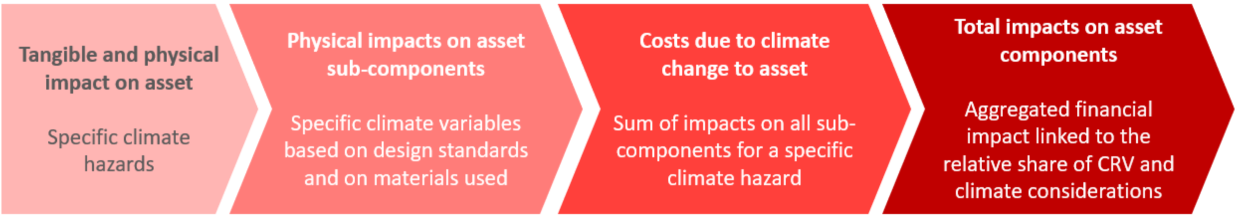


**Figure 5: Process of cost estimation based on asset subcomponents**

This step required a second round of SME consultation. The SMEs were required to complete the following tasks:

1 **Estimation of costs due to the occurrence of each climate hazard identified:**

  - Given the projected changes for Ontario on each pre-defined climate indicator selected during the first round of consultation, estimation of the range of damage cost impacts (in the absence of adaptation measures) to each asset component on USL, and O&M costs, as well as the range of potential adaptation costs to retrofit or renew the asset to avoid these damage costs.
  - To quantify climate impacts at the asset class level (which is the scale required to implement parameters in the PAID model), WSP addresses the expected impacts for the asset, given high-range (i.e., 90th percentile) climate projections of RCP8.5 by 2051–2080. The selection of high-range climate projections of RCP8.5 was intended to provide a scenario with the largest change in climate conditions. Given that the model assumes a linear relationship between the change in cost and the change in a selected climate indicator, and the complex interactions and interdependencies between asset components, SMEs were better positioned to identify impacts in a scenario that was significantly different than baseline conditions.
  - The archetypical infrastructure asset is deconstructed in a set of components, which are in turn also deconstructed into subcomponents. After evaluating different types of costs for all subcomponents of a typical asset with respect of its specific climate hazards vulnerability, WSP aggregated these impacts at the component and then at the asset level according to their estimated share of the total CRV. For instance, pavement is not a specific asset class accounted by the FAO. Only roads are considered. However, the different sub-components of pavement (surface, base, and subbase) are affected differently compared to other road components (e.g., embankments). Base, subbase and pavement material must be differentiated as well. Thus, after having estimated all expected variation of costs for each subcomponent of pavement, the

results are then weighted by the estimated average relative share of pavement subcomponents over road assets across Ontario.

- The WSP team formulated specific questions that are understandable and applicable to engineering criteria, under the assumption that all assets are in a state of good repair, and that the identified impacts are those that would occur to well-maintained assets:
  - Useful service life: By 2051–2080 following the high-range RCP8.5 scenario, what would be the variation of service life under the influence of the evolution of each climate hazard for each asset and component?
  - O&M costs: Compared to the current annual share, what would it cost annually, as a share of the current replacement value, to operate and maintain the expected deterioration rate under future climate conditions (under high-range RCP8.5 scenario)?
  - Renewal costs: Imagine you are designing a brand-new climate resilient infrastructure that has the same expected functionality of the 1976–2005 period, but for climate conditions of 2051–2080 under the high-range RCP8.5 scenario). What would be the cost as a share of the current CRV?
  - Retrofit costs: What would it cost to retrofit, as a share of current replacement value, to make the infrastructure resilient to climate change (given the climate projections of a high-range RCP8.5)?
- All coefficients ($\Delta p$) estimated by SMEs coefficients are expressed as a percentage.

2 **Justification of the expected value of climate change costs with respect of the subcomponent properties:**

- Each SME was asked to produce a most-likely distribution of subcomponents (as a share of CRV) within a typical infrastructure (e.g., for buildings: envelope contains cladding, joints, membrane). SMEs also confirmed values they suggested based on their assumptions. Answers collected were used to formulate detailed and qualitative rationales for each climate-cost elasticity assessed.

## AGGREGATION OF RESULTS

For each asset-hazard interaction and a given Δc, engineers may have different opinions on what the related impact on costs could be. During the consultations, SMEs worked independently (i.e., their judgements were not influenced by “group-thinking” or an attempt to reach group consensus), leading to a range of different responses. This range among the $\Delta p$ values reported by the SMEs represents an uncertainty based on data availability and variability at the portfolio level and the ensuing professional judgment. For each asset class, WSP surveyed between four and eight experts, whose names are listed in the production team list.

To account for this variability in responses, WSP analyzed the statistical distributions of $\Delta p$ values reported. Adopting a relevant distribution allows the FAO to test the sensitivity of their results to the underlying assumptions on cost. This step does account for this asset data and professional uncertainty, whereas climate uncertainty is considered in the assessment of $\Delta c$ values. The method of statistical aggregation is described below. $\Delta p$ values are therefore considered to be uncertain, and thus went through an assessment of their statistical distribution. There are numerous ways to model cost distributions to generate sample values. The following text expands on three of these: uniform distribution, triangular distribution, and PERT[2] distribution (Vose, 2008; Figure 6).

### UNIFORM DISTRIBUTION

The uniform distribution is the most straightforward possible distribution for sampling a range of estimates. In this model, every value – from the minimum to the maximum – is equally likely. Most phenomena are not uniformly distributed, and in many cases, it may be possible to get an additional estimate of the

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[2] PERT stands for Project Evaluation and Review Techniques

expected, or most likely, value (Structured Data LLC, 2021). The uniform distribution was not retained for this analysis.

### TRIANGULAR DISTRIBUTION

Having a most likely estimate, in addition to the minimum and maximum estimates, enables the construction of a probability distribution shaped from the most likely value. The distribution has a triangle shape with the most likely value (referred to as the mode) at the top of the triangle.

However, by using a straight linear shape, the triangular distribution may place disproportionate weight on the most likely value. This can come at the expense of the values to either side. While the triangular distribution is easy to calculate and generate, its ability to model real-world estimates is considered limited (Structured Data LLC, 2021). This distribution was not retained for the analysis.

### PERT DISTRIBUTION

The PERT distribution also uses the most likely value, but it is designed to generate a more realistic probability distribution. Depending on the initial data, the PERT distribution can provide a close fit to the normal or lognormal distributions. Assuming that many real-world phenomena are normally distributed, the PERT distribution can produce a curve similar to the normal curve in shape without knowing the specific parameters of the related normal curve. This distribution was retained for the subsequent steps in the analysis.

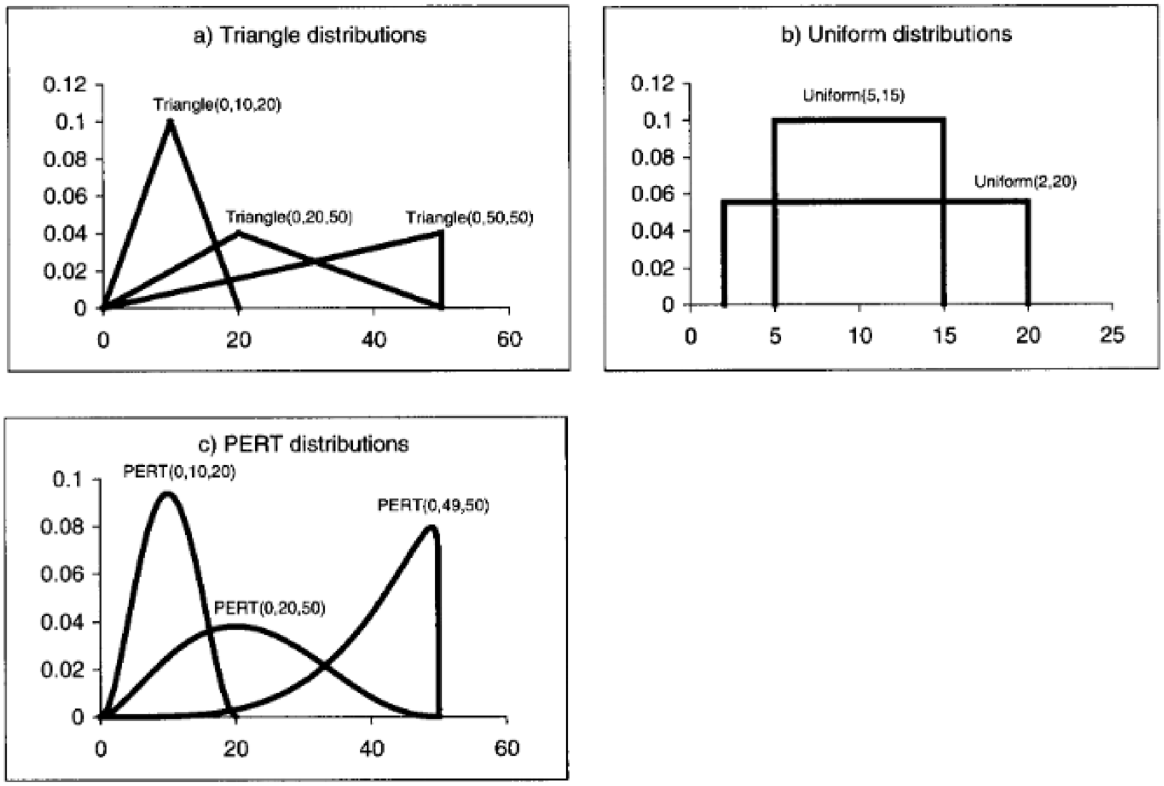

**Figure 6: Examples of distribution considered for construction costs (adapted from Vose, 2008). The y axis corresponds to frequency and the x axis, to hypothetical values.**

### MONTE CARLO SIMULATION

The Monte Carlo simulation method was used to propagate uncertainty in the selected method. The simple case of the PERT distribution takes a minimum, maximum, and most likely value. This option uses inputs to generate a random sample from the distribution. A second function uses the same distribution but takes only parameters at the 1$^{0t}$h and 9$^{0t}$h percentile values. This function is used in order to exclude the unlikeliest probabilities. The 5$^{0t}$h percentile values are the most-likely scenario.

A three-point PERT probability distribution function (optimistic, most-likely, and pessimistic values) was developed for each of the aforementioned attributes. These results were aggregated using a Monte Carlo simulation that was formulated on a linear-pool analysis (LPA) approach (Clemen et al., 2007). LPA is a recognized approach that can be used to aggregate probability distributions developed using social research approaches. In this context, the opinion of each SME is weighted according to their relative expertise in the SME pool. In this study, each opinion was assumed to be equal, with each having the same value between 0 and 1 (i.e., 1 / number of SMEs).

In the survey that was provided during the second round of consultations, SMEs were asked to provide insights into the lowest possible change, the most likely, and the highest possible change.

Values provided by SMEs were inputs into a Monte Carlo simulation, which was then run 1,000 times. The median value across all SME inputs, asset types and climate metrics, was used for the most-likely value and is the one used in the development of the $\Delta p$ coefficients for each climate metric. To ensure the maximum retention of data, the 0th percentile and the 100th percentile values were also recorded, although there is no guarantee that the Monte Carlo simulation would have included the absolute end cases. The minimum value can be interpreted as the impact that climate change has on better-performing assets, whereas the maximum value would represent the impact on worst-performing assets.

The final set of coefficients ($\Delta p$) reflects the expected range of variation for a typical asset by 2051–2080 under high-range projections of RCP8.5.

## F. GET THE CLIMATE-COST ELASTICITIES

As mentioned in Section 2.2, the ratio between $\Delta p$ and the expected climate variation by 2051–2080 under high-range projections of RCP8.5 ($\Delta c$) is called a climate-cost elasticity ($\alpha$). Similar to the economic concept of elasticity, $\alpha$ coefficients represent the relative variation of cost parameter in % for a variation in % of the selected climate indicator. When a climate indicator is expressed in °C, the climate-cost elasticity represents the variation of a parameter of interest in % for a variation in °C of the relevant climate indicator.

These elasticities can directly be implemented in the PAID model by the FAO. The values are then implemented in testing sessions to verify the behavior of the model to climate change impacts.

## G. IMPLEMENTING CLIMATE-COST ELASTICITIES WITHIN THE PAID MODEL

Testing sessions and implementation of the climate-cost elasticities within the PAID model during the *Costing Climate Change Impacts to Public Infrastructure Project* showed that additional decision rules had to be created to realistically reflect the financial & management dynamics of transportation and water assets. These decision rules are presented below.

**Water (stormwater & wastewater)**: Retrofit and renewal costs were folded together as the suite of interventions is ultimately the same: limit water flows into the system in some way or enlarge the asset.

More specifically, wastewater separated systems, which is assumed to represent the greater share of wastewater systems in Ontario, increased flows due to infiltration only will likely cause a performance failure due to capacity rather than a material or structural failure. Therefore, the impacts on USL, has been assumed to be zero.

**Transportation**: Climate impacts of extreme rain, extreme heat and FTCs on road assets are not fully additive. Yet, some Ontario regions, under highest projected climate variations of RCP 8.5, useful service life reductions of roads reach 100% in the 2090s, which is very unlikely. Accordingly, a cumulative 60% USL reduction for roads was considered the worst case in RCP8.5 high (pessimistic), thus representing and assumed maximal effect. Other coefficients were also scaled accordingly to maintain relative consistency in this asset class. The limiting combined effect was achieved by swapping out the delta Cs generated as 2050–2080 averages for delta Cs by the 2090–2100 average, which lowers the original Alphas (ER by 46%, FTC by 2% and EH by 23%, roughly). This manipulation thus was considered more reflective of the "worst-case scenario" that surveyed SMEs were envisioning in the survey.

Similarly, for water assets, retrofit and renewal costs were folded together as the nature of interventions are similar.

# 3 RESULTS

This section describes the final results statistically aggregated from the SME consultations, detailing justification rationales for each coefficient based on engineering standards, best practices and specific examples. These results consist of a summary of $\Delta p$ , $\Delta c$ and α parameters. Guidelines are also detailed for the FAO for insights on how to use the results in the PAID model, and case studies are presented.

## 3.1 FINAL RESULTS

Table 8 through Table 12 present the results from the statistical aggregation. All rows represent an individual asset-hazard interaction and can be interpreted as the expected change of cost parameters ($\Delta p$) given the expected climate change for 2051–2080 of high range RCP8.5 ($\Delta c$). The climate indicators are defined in the glossary below.

The ratio between the variation of cost parameters ($\Delta p$) and the climate variation ($\Delta c$) can be used to compute the climate-cost elasticities (α).

Furthermore, cost parameters $\Delta p$ are outlined in three scenarios (pessimistic, most-likely and optimistic, see Section 2.3) regarding their vulnerability. The vulnerability here expresses the expected financial impacts resulting from living under RCP 8.5 climate conditions.

- **Pessimistic**: Assigned to more vulnerable assets.
- **Most-likely**: Representative of the overall portfolio of public infrastructure assets; and
- **Optimisti**c: Assigned to less vulnerable assets. Under the optimistic scenario, it is assumed that all assets are in a state of good repair, and that the cost impacts are conceived of as impacts that would occur to well-maintained assets.

### *WEIGHTED AND UNWEIGHTED RESULTS*

In the following tables, some delta-Ps are presented as *weighted* (buildings and roads and transit). Others are non-*weighted* (water and bridges). This approach was used, to align with the FAO’s asset data granularity.

In the public infrastructure inventory, certain assets have a greater level of component detail, versus some others that are described at asset levels. For example, buildings are heavily componentized, but bridges are not componentized. In the componentised ones, the effects are “diluted” through apportionment to each sub-component, but in assets with a single component the full effect is applied at asset levels. For instance, the inventory used by the FAO does have granular information about the building’s components, such has the structure or M&E systems. However, climate-cost elasticities project the costs attributed to one component, at the asset level. The climate-cost elasticity that is applied is *weighted* by the relative share of the CRV’s component on the total asset CRV.

See Table 13 to see which climate-cost coefficients are weighted and unweighted.

### *A. BUILDINGS*

The climate impacts considered negligible are based on the following assumptions:

- Extreme heat is not expected to significantly impact building structure or building equipment and finishing; and

- Extreme rainfall and changes in freeze-thaw cycles are not expected to significantly affect mechanical and electrical systems since the bulk of the equipment is located inside the building. Flooding of buildings due to extreme rainfall was considered as an impact to the envelope.

The building assumed component relative weights are:

- Civil and Landscaping: 5%
- Structure: 35% (30–40%)
- Envelope: 20% (15–25%)
- Equipment and Finishing: 10%
- Mechanical and Electrical: 30% (20–40%)

**Table 8: Final results for buildings statistically aggregated from SME consultation (delta P results are weighted by the relative share of each component in the average building, by CRV)**

| **Climate Hazard** | **Building Component** | **Climate Indicator** | **Climate Change ($\Delta c$)** | **USL ($\Delta p$) (%)** | | | **O&M Costs ($\Delta p$) (%)** | | | **Renewal Costs ($\Delta p$) (%)** | | | **Retrofit Costs ($\Delta p$) (%)** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Pessimistic | Most-likely | Optimistic | Pessimistic | Most-likely | Optimistic | Pessimistic | Most-likely | Optimistic | Pessimistic | Most-likely | Optimistic |
| **Extreme heat** | Civil and Landscaping | Mean July daily maximum temperature | 7.4°C | -1.4 | -0.9 | -0.5 | 0.1 | 0.1 | 0.0 | 1.9 | 1.8 | 1.8 | 2.8 | 2.5 | 2.2 |
| | Structure | N/A | Negligible climate impact | | | | | | | | | | | | |
| | Envelope | 2.5% July daily maximum temperature | 7.1°C | -1.8 | -1.3 | -0.8 | 0.1 | 0.1 | 0.1 | 2.7 | 2.6 | 2.6 | 4.0 | 3.5 | 2.9 |
| | Equipment and Finishing | N/A | Negligible climate impact | | | | | | | | | | | | |
| | Mechanical and Electrical | Annual number of cooling degree-days | 338% | -1.9 | -1.3 | -0.8 | 0.1 | 0.1 | 0.1 | 2.4 | 2.4 | 2.3 | 5.6 | 4.8 | 4.0 |
| **Extreme rainfall** | Civil | 0.5 * IDF[3] 24-hr 1:5 + 0.5 *IDF 24-hr 1:100 | 37% | -1.2 | -0.9 | -0.5 | 0.1 | 0.1 | 0.1 | 0.9 | 0.9 | 0.8 | 1.9 | 1.7 | 1.5 |
| | Landscaping | IDF 15-min 1:10 | 32% | -1.2 | -0.9 | -0.5 | 0.1 | 0.1 | 0.1 | 0.9 | 0.9 | 0.8 | 1.9 | 1.7 | 1.5 |
| | Structure | Average annual precipitation | 31% | -0.5 | -0.4 | -0.2 | 0.1 | 0.1 | 0.0 | 2.4 | 2.4 | 2.4 | 4.4 | 4.1 | 4.0 |
| | Envelope | IDF 15-min 1:10 | 32% | -2.3 | -1.7 | -1.0 | 0.2 | 0.2 | 0.2 | 2.3 | 2.3 | 2.3 | 4.2 | 3.8 | 3.4 |
| | Equipment and Finishing | IDF 15-min 1:10 | 32% | -2.1 | -1.5 | -0.9 | 0.1 | 0.1 | 0.1 | 0.9 | 0.9 | 0.9 | 2.6 | 2.3 | 2.0 |
| | Mechanical and Electrical | N/A | Negligible climate impact | | | | | | | | | | | | |

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[3] IDF = intensity-duration-frequency.

| Climate Hazard | Building Component | Climate Indicator | Climate Change ($\Delta c$) | USL ($\Delta p$) (%) | | | O&M Costs ($\Delta p$) (%) | | | Renewal Costs ($\Delta p$) (%) | | | Retrofit Costs ($\Delta p$) (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Pessimistic | Most-likely | Optimistic | Pessimistic | Most-likely | Optimistic | Pessimistic | Most-likely | Optimistic | Pessimistic | Most-likely | Optimistic |
| Freeze-thaw cycles | Civil and Landscaping | Number of deep freeze-thaw cycles | -15% | 0.3 | 0.2 | 0.1 | 0.0 | 0.0 | 0.0 | -0.2 | -0.2 | -0.2 | -0.6 | -0.5 | -0.5 |
| | Structure | Number of deep freeze-thaw cycles | -15% | 0.2 | 0.1 | 0.1 | 0.0 | 0.0 | 0.0 | -0.7 | -0.7 | -0.7 | -1.2 | -1.1 | -1.0 |
| | Envelope | Number of deep freeze-thaw cycles | -15% | 0.4 | 0.3 | 0.2 | 0.0 | 0.0 | 0.0 | -0.7 | -0.7 | -0.6 | -1.0 | -0.9 | -0.8 |
| | Equipment and Finishing | Annual number of freeze-thaw cycles | -36% | 2.2 | 1.6 | 1.0 | -0.1 | -0.1 | -0.1 | -1.1 | -1.1 | -1.1 | -3.9 | -3.4 | -2.9 |
| | Mechanical and Electrical | N/A | Negligible climate impact | | | | | | | | | | | | |

## B. ROADS

There will probably be some FTC impacts, but since the direction of the results was uncertain due to conflicting trends between decreasing FTCs and increasing winter rain intensity, the FAO finally did not end up using the FTC coefficients due to uncertainty around the sign of the trajectory. Therefore, the results are not displayed in the table below.

The following ex-post adjustments to the publication of results were made to reflect FAO's actual application:

- Swapped delta Cs generated as 2050–2080 averages for delta Cs as the 2090–2100 average, which lowered the original calculated climate-cost elasticities, or alphas. For instance, the annual number of hot days delta-c's went from 846% to 1140%. For instance, in the North, the number of goes from 2 hot days per year during the historical period to 50 hot days by late century. Without this, the projected costs for roads would have been overestimated.
- An outlier in the survey data was removed from the original O&M sample, therefore reducing O&M costs.
- Retrofit costs ($\Delta p$) were aligned with renewal costs ($\Delta$) as retrofits to the road surface would happen at the time of repaving and not at other times.

The roads assumed component relative weights are:

- Pavement: 85%
- Road Associated Structures: 13%
- Road Equipment and Finishing: 2% (excluded from estimation)

Table 9: Final results for roads statistically aggregated from SME consultation (delta P results are weighted by the relative share of each component in the average road structure, by CRV)

| Climate Hazard | Road Component | Climate Indicator | Climate Change ($\Delta c$) | USL ($\Delta p$) (%) | | | O&M Costs ($\Delta p$) (%) | | | Renewal Costs ($\Delta p$) (%) | | | Retrofit Costs ($\Delta p$) (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Pessimistic | Most-likely | Optimistic | Pessimistic | Most-likely | Optimistic | Pessimistic | Most-likely | Optimistic | Pessimistic | Most-likely | Optimistic |
| Extreme heat | Pavement | Annual number of hot days | 1140% | -22 | -17 | -13 | 1.0 | 0.8 | 0.7 | 14 | 11 | 9 | 14 | 11 | 9 |
| | Road Associated Structures | Annual number of hot days | 1140% | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 2 | 2 |
| Extreme rain | Pavement | IDF 24-hr 1:100 | 66% | -22 | -18 | -14 | 1 | 0.8 | 0.7 | 20 | 14 | 10 | 20 | 14 | 10 |
| | Road Associated Structures | IDF 24-hr 1:100 | 66% | -2 | -2 | -1 | 0.2 | 0.1 | 0.1 | 3 | 2 | 1 | 5 | 3 | 2 |

## C. TRANSIT

The transit assumed component relative weights are:

- Alignments: 54%
- Rail Associated Structures 15%
- Equipment and Finishing: 31%

Table 10: Final results for transit statistically aggregated from SME consultation (delta P results are weighted by the relative share of each transit component by current replacement value)

| Climate Hazard | Rail Component | Climate Indicator | Climate Change ($\Delta c$) | USL ($\Delta p$) (%) | | | O&M Costs ($\Delta p$) (%) | | | Renewal Costs ($\Delta p$) (%) | | | Retrofit Costs ($\Delta p$) (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Pessimistic | Most-likely | Optimistic | Pessimistic | Most-likely | Optimistic | Pessimistic | Most-likely | Optimistic | Pessimistic | Most-likely | Optimistic |
| Extreme heat | Alignments | Annual number of hot days (>30°C) | 846% | -10 | -8 | -5 | 2 | 1 | 1 | 9 | 6 | 3 | 19 | 17 | 16 |
| | Rail Associated Structures | Mean July daily maximum temperature | 7.4 °C | -3 | -2 | -1 | 1.5 | 1.2 | 0.9 | 4 | 3 | 1 | 5 | 4 | 2 |
| | Equipment and Finishing | Annual highest temperature | 8.0 °C | -8 | -6 | -4 | 4 | 3 | 2 | 8 | 6 | 4 | 7 | 5 | 2 |
| | Rolling Stocks | Annual number of cooling degree-days | 338% | -5 | -3 | -1 | 2 | 1 | 0 | 14 | 9 | 0 | 4 | 2 | 1 |

## D. BRIDGES AND CULVERTS

The following ex-post adjustments to the previous publication results were made to reflect FAO’s actual application:

- FTCs costs for bridges were assumed to be zero for Renewal Costs and Retrofit Costs, assuming engineers would not design to lower standards.
- An outlier survey datum was removed from the original Renewal results that were collected, reducing Renewal costs.
- Bridges and large structural culverts coefficients were considered as a single component, thus no component apportionment was applied.

Changes in freeze-thaw cycles are not expected to significantly impact large structural culverts.

**Table 11: Final results for bridges and culverts statistically aggregated from SME consultation, unweighted.**

| **Climate Hazard** | **Bridge / Culvert Component** | **Climate Indicator** | **Climate Change ($\Delta c$)** | **USL ($\Delta p$) (%)** | | | **O&M Costs ($\Delta p$) (%)** | | | **Renewal Costs ($\Delta p$) (%)** | | | **Retrofit Costs ($\Delta p$) (%)** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | **Pessimistic** | **Most-likely** | **Optimistic** | **Pessimistic** | **Most-likely** | **Optimistic** | **Pessimistic** | **Most-likely** | **Optimistic** | **Pessimistic** | **Most-likely** | **Optimistic** |
| **Extreme rain** | Bridges | IDF 24-hr 1:100 | 49% | -10 | -7 | -5 | 1 | 1 | 1 | 13 | 5 | 1 | 8 | 6 | 4 |
| | Large Structural Culverts | IDF 24-hr 1:100 | 49% | -33 | -25 | -18 | 2 | 2 | 1 | 26 | 20 | 15 | 56 | 47 | 38 |
| **Freeze-thaw cycles** | Bridges | Annual number of freeze-thaw cycles | -17% | 7 | 3 | 0 | 0 | 0 | 0 | -1 | -1 | 0 | -3 | -1 | 0 |
| | Large Structural Culverts | N/A | Negligible climate impact | | | | | | | | | | | | |

## E. STORMWATER AND WASTEWATER

Retrofit and renewal costs were folded together as the suite of interventions is ultimately the same: limit water flows into the system in some way or enlarge assets.

The stormwater assumed component relative weights are:

- Pipes (45%),
- Ditches (50%)
- Small Non-structural Culverts (5%).

The wastewater assumed component relative weights are:

- Gravity Sewer (95%),
- Sanitary Force Mains (5%).

**Table 12: Final results for stormwater and wastewater statistically aggregated from SME consultation, unweighted**

| **Climate Hazard** | **Stormwater / Wastewater Component** | **Climate Indicator** | **Climate Change (Δc)** | **USL (Δ*p*) (%)** | | | **O&M Costs (Δ*p*) (%)** | | | **Renewal Costs (Δ*p*) (%)** | | | **Retrofit Costs (Δ*p*) (%)** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Pessimistic | Most-likely | Optimistic | Pessimistic | Most-likely | Optimistic | Pessimistic | Most-likely | Optimistic | Pessimistic | Most-likely | Optimistic |
| **Extreme rainfall** | Pipes | IDF 24-hr 1:2 | 48% | 0 | 0 | 0 | 5 | 4 | 2 | 74 | 59 | 49 | 74 | 59 | 49 |
| | Ditches | IDF 24-hr 1:100 | 49% | 0 | 0 | 0 | 2 | 2 | 1 | 75 | 59 | 48 | 75 | 59 | 48 |
| | Small Non-structural Culverts | IDF 24-hr 1:10 | 49% | 0 | 0 | 0 | 3 | 2 | 2 | 77 | 68 | 60 | 77 | 68 | 60 |
| | Gravity Sewer | 0.5*IDF 24-hour 1:2 + 0.5* Maximum 5-day precipitation | 52% | 0 | 0 | 0 | 3 | 2 | 2 | 80 | 61 | 50 | 80 | 61 | 50 |
| | Sanitary Force Mains | IDF 24-hr 1:100 | 49% | -17 | -11 | -6 | 3 | 2 | 1 | 68 | 52 | 39 | 68 | 52 | 39 |

## 3.2 ASSUMPTIONS AND RATIONALES

**WORD OF CAUTION**

The results presented below are a summary of the rationales of the SMEs to explain their appreciation of changes in cost due to climate change. The SMEs were asked to provide an optimistic, most likely and pessimistic percent change in the four types of cost based on a set of climate projections that was provided. These climate projections were extracted from three localities in Ontario for RCP8.5 90th percentile scenario, which could be considered as the worst-case scenario in terms of magnitude of change in climate.

As the FAO will use the full regional climate projections provided by ECCC under different climate change scenarios, **it is expected that the FAO's result will differ from the results from the SME consultation developed below**.

This subsection describes hypotheses and rationales implicit in the final results. Assumptions are detailed with respect to the relative weight of each infrastructure component and the extent to which a climate indicator of interest might exceed a specific design parameter in applicable codes and standards.

Summarized below are the overall hypotheses and consideration for each infrastructure component. Complete and detailed rationales by coefficient can be found in Appendix A.

### *A. BUILDINGS*

As described in Section 1.5, to estimate the impact of climate change on buildings in the provincial and municipal asset inventory, a "typical building" was defined with the help of SMEs. A typical publicly owned building in Ontario was defined as having five components: structure, envelope, mechanical/electrical systems, equipment and finishing, and civil infrastructure and landscaping. Each of these building components (e.g., envelope) had to be disaggregated into subcomponents (e.g., curtain wall, cladding, roof, etc.) due to consideration of specific interactions between materials and climate conditions. For example, extreme precipitation will not affect the roof the same way that it affects curtain walls. Thus, SMEs have considered:

- The relative contribution at the building level of each component with respect to the four types of climate change costs defined over each table in section 3.1 and in Appendix B.
- The relative contribution at the component level of each subcomponent for the four types of climate change costs; and
- The estimated share of subcomponents within a given building component is detailed in the *Hypotheses* paragraph within each subsection described below.

#### 3.2.A.1 STRUCTURE

A typical building structure includes a superstructure, foundations, and a roof structure. The superstructure represents approximately 8% of the building current replacement value, followed closely by the foundations (7%) and finally by the roof structure (6%). Most of the time, foundations are made of cast-in-place concrete, but stone or metal are also used. Metal is more resistant than concrete and stone to freeze-thaw cycles, and its implied useful life is not affected significantly. Freeze-thaw cycles are the most problematic climate hazard for shallow foundations, followed by extreme rainfall which increases the risk of water infiltration.

Under the influence of climate change, foundations may require more O&M activities, resulting in higher annual costs, especially for concrete shallow foundations, which are estimated to be in place for approximately 80% of all public buildings in Ontario. Extreme heat events should not affect these components significantly.

Thus, the cost of building a more resilient structure increases when the structure is made of concrete. However, retrofit costs are relatively less important for concrete compared to other materials. Steel is the material of choice when it comes to roof structure, but roof structures can also be made of reinforced concrete or timber. Roof structure deterioration, maintenance and retrofit are more impacted by extreme rainfall compared to extreme heat events or freeze-thaw cycles.

- **Extreme heat events** do not have a significant impact on the structure since this component is mostly protected by the envelope. For Canada, WSP considers that the actual structure design requirements and standard materials can bear temperature increase without being significantly impacted.
- **Extreme rainfall** may cause:
  - A reduction in the building USL between 0.2% and 0.5%, with a most-likely value of 0.4%. The exterior of structural components will be exposed to varying extents.
  - An O&M absolute increase of 0.1%. O&M impacts are most likely related to inspections and repairs after the occurrence of severe events.
  - An increase of 2.4% in the cost of renewal for a building with the same functionality as before; this could include the addition of waterproof membranes and drains.
  - An additional cost of retrofitting (to make the building more climate resilient) between 4 and 4.4%, with a most likely value of 4.1%. All exterior building components will require adaptive measures (such as waterproofing membranes for the foundation) and increased CRV costs.
- **Freeze-thaw cycles** may cause:
  - An improvement in the building USL between 0.3% and 0.7%, with a most-likely value of 0.5%. Freeze-thaw cycles will mostly affect exposed subcomponents, like stone or exposed concrete foundation elements.
  - An absolute decrease in O&M costs of less than 0.05%. Additional O&M such as decreased inspections and minor repairs are expected to be required as freeze-thaw cycles deteriorate concrete structure building.
  - A decrease of 3.1% in the cost of renewal for a building with the same functionality as before.
  - A reduction in the cost of retrofitting between 4.5% and 5.3%, with a most likely value of 4.9% as the foundations will be less affected by FTC.

### 3.2.A.2 ENVELOPE

A typical building envelope represents approximately 20% of the CRV of a building. It typically includes claddings, doors, glazing, and a roof.

Cladding represents approximately 11% of the building CRV and, for public buildings in Ontario, is commonly composed of concrete, brick, stone, cementitious materials (e.g., stucco), vinyl, or metal. Extreme heat could increase the range of operative temperatures for brick walls or metal panels, increasing thermal expansion beyond its historic range.

The curtain wall represents approximately 5% of the CRV. Bitumen/asphaltic materials are the most frequent flat roofing materials for roofing, but PVC, various metals, slate, and cedar are also used. Extreme heat events could increase deterioration of PVC membrane systems and associated sealants. Extreme heat can also impact fasteners/holes in sheet-metal roofing and flashings.

- **Extreme heat** may cause:
  - A reduction in the building USL between 0.8% and 1.8%, with a most-likely value of 1.3%. Envelope materials will likely experience accelerated deterioration due to changes in the temperature regimes and therefore have reductions in USL.
  - An O&M absolute increase of 0.1%. The building envelope and finishes are likely to require additional inspections and maintenance to preserve the integrity of the components.
  - An increase of 2.6% in the cost of renewal for a building with the same functionality as before.
  - An additional cost of retrofit (to make the building more climate resilient) between 2.9 and 4%, with a most likely value of 3.5%. Retrofit costs are expected to be higher for the envelope since it is expected that retrofits will be designed to maintain the thermal protection of the indoor environment and thus shield other building components from much of the stress of extreme heat events.
- **Extreme rainfall** may cause:
  - A reduction in the building USL between 1% and 2.3%, with a most-likely value of 1.7%. Rainfall is expected to impact the envelope and exterior finishing more than other components.
  - An O&M absolute increase of 0.2%. Repairs are expected after the occurrence of severe events, and as a result of cumulative impacts of increased rainfall. Impacts are most likely related to inspections and ensuring roof drainage systems are operating at capacity, as well as clearing up debris and repairs after the occurrence of severe events.
  - An increase of 2.3% in the cost of renewal for a building with the same functionality as before.
  - An additional cost of retrofitting (to make the building more climate resilient) between 3.4% and 4.2%, with a most likely value of 3.8% The building envelope is expected to need higher retrofit costs relative to other building components for the impacts of the rainfall parameters selected for this analysis. Retrofits are likely to be focused on improvements at waterproofing openings.
- **Freeze-thaw cycles** may cause:
  - An improvement in the building USL between 0.7% and 1.6%, with a most-likely value of 1.2%. Thaw followed by sub-zero temperatures contributes to damaging to joints and cracks which may result in damage to components or increase cracking, allowing more water infiltration during the next cycle. A reduction in FTC will therefore be beneficial.
  - An O&M absolute decrease of 0.1%.
  - A decrease of 2.9% in the cost of renewal for a building with the same functionality as before.
  - A decreased cost of retrofitting (to make the building more climate resilient) between 3.7% and 4.6%, with a most likely value of 4.1%.

### 3.2.A.3 MECHANICAL AND ELECTRICAL SYSTEMS

Mechanical and electrical systems comprise a significant portion of the building CRV (between a quarter and a third of the total CRV). Some subcomponents vulnerable to temperature changes, and associated retrofit requirements, are found in almost every building: boilers, air terminal AV box, ductwork, roof top air conditioner, panel board, motors, conduits, and wiring. Most of these components can be individually replaced but also could trigger other rehabilitation work or renewal consideration. For example, increasing the capacity of a building's air-conditioning system may necessitate changes to transformers, wiring, electrical panels, and condenser units, which may in turn trigger changes to interior walls, roofing, conduits, etc. to install or upgrade components.

- **Extreme heat events** may cause:
    - A reduction in the building USL between 0.8% and 1.9%, with a most-likely value of 1.3%. The main impact of mechanical equipment will be on HVAC units due to significant increases in cooling degree-days (CDD) across the province, albeit greater changes are projected in northern Ontario.
    - An O&M absolute increase of 0.1% as HVAC systems will likely operate at higher intensity and in cases close to or at maximum capacity (particularly older systems), projected primarily due to increases in CDD. HVAC systems are expected to require more frequent inspections and maintenance, and increased interventions by operators to ensure the functionality of the systems. Shifts in the seasonal occurrence of higher temperatures are also likely require additional balancing.
    - An increase of 2.4% in the cost of renewal for a building with the same functionality as before. Renewal costs for HVAC systems in northern Ontario, or the addition of A/C in southern buildings that have no central air conditioning may result in substantial costs of adaptation in some buildings.
    - An additional cost of retrofitting (to make the building more climate resilient) between 4.0% and 5.6%, with a most likely value of 4.8%. As for the envelope, retrofit costs are expected to be high due to an increase of 338% of the number of cooling degree-days.
- **Extreme rainfall and freeze-thaw cycles** are expected to have a negligible impact on mechanical and electrical systems. Mechanical and electrical systems primarily relate to thermal behaviour, energy usage, lighting, ventilation, etc.

### 3.2.A.4 EQUIPMENT AND FINISHING

Equipment and finishing represent a relatively small component in terms of the attributed CRV of the building (less than 10%). Exterior subcomponents are found in every building. These include painting, high-performance coatings, and staining, and account for the bulk of equipment & finishing costs and are highly vulnerable to climate change impacts. Equipment subcomponents include parking control, loading docks, and waste handling. Only a small share of the total cost of climate change can be attributed to equipment.

- **Extreme heat events and freeze-thaw cycles** have a negligible materials' impact on equipment and finishing. Temperature variations defined by the selected climate indicators are not expected to impact the USL of equipment.
- **Extreme rainfall** may cause:
    - A reduction in the building USL between 0.9% and 2.1%, with a most-likely value of 1.5%. Mostly exterior finishes are affected.
    - An O&M absolute increase of 0.1%. O&M impacts are most likely related to inspections and clearing up debris, maintaining the safety of building access, and repairs after the occurrence of severe events.
    - An increase of 0.9% in the cost of renewal for a building with the same waterproofing as before.
    - An additional cost of retrofit (to make the building more climate resilient) between 2% and 2.6%, with a most likely value of 2.3%. The building finishing is expected to produce among the highest retrofit costs caused by the impacts of the rainfall parameters selected for this analysis, because it is generally directly exposed to precipitation.

### 3.2.A.5 CIVIL INFRASTRUCTURE AND LANDSCAPING

Civil infrastructure and landscaping react differently to climate change stresses but were grouped together for this exercise since both accounts for a small percentage of the attributed CRV of a building. Civil infrastructure is most vulnerable to extreme rainfall, and landscaping is more impacted by extreme heat events and freeze-thaw cycles. Asphalt, concrete walkways and surfacing accounts for the most important subcomponents in terms of total CRV. WSP assumed that half of the total value of this component can be attributed to these subcomponents which are sensitive to freeze-thaw cycles and high temperatures. WSP assumed that approximately 40% of the total value could be attributed to vertical water infrastructure. Freeze-thaw cycles can affect the deterioration process of these subcomponents and their climate design are directly linked to extreme rainfall indicators. Finally, vegetation, accounting for approximately 10% of the total value, is considered affected by all hazards.

- **Extreme heat events** may cause:
  - A reduction in the building USL between 0.5% and 1.4%, with a most-likely value of 0.9%. Costs are primarily related to vulnerability of vegetation and thermal expansion.
  - An O&M absolute increase of 0.1%.
  - An increase of 1.8% in the cost of renewal for a building with the same functionality as before.
  - An additional cost of retrofit (to make the building more climate resilient) between 2.2% and 2.8%, with a most likely value of 2.5%.
- **Extreme rainfall** may cause:
  - A reduction in the building USL between 0.5% and 1.2%, with a most-likely value of 0.9%.
  - An O&M absolute increase of 0.1%. O&M impacts are most likely related to inspections and ensuring drainage systems are operating at capacity; clearing up debris and maintaining the safety of building access; and repairs after the occurrence of severe events.
  - An increase of 1.7% in the cost of renewal for a building with the same functionality as before. Civil infrastructure and landscaping (particularly drainage systems) may require improvements for onsite stormwater management.
  - An additional cost of retrofit (to make the building more climate resilient) between 1.5% and 1.9%, with a most likely value of 1.7%. The additional cost includes the need for increased drainage.
- **Freeze-thaw cycles** may cause:
  - A reduction in the building USL between 0.9% and 2.0%, with a most-likely value of 1.4%. Exposed elements of civil infrastructure are likely to be exposed to surface damage that could affect the overall component USL.
  - An absolute increase of less than 0.05% of O&M costs.
  - An increase of 1.9% in the cost of renewal for a building with the same functionality as before.
  - An additional cost of retrofit (to make the building more climate resilient) between 3.7% and 4.6%, with a most likely value of 4.1%. Exposed elements of civil infrastructure may require retrofit measures to protect the structural integrity of those components.

## B. ROADS

### 3.2.B.1 PAVEMENT

Pavement on roads and ramps (bridge decks not included in this category) comprise a majority of the CRV for the Roads asset category (85%). The effect of climate hazards on pavement varies greatly depending on the material of the road (asphalt, concrete, or gravel). Asphalt pavement, which represents approximately 60% of all Ontario roads, is more vulnerable to hazards related to temperature (i.e., extreme heat, freeze-thaw cycles). Asphalt sensitivity to extreme heat will result in the material being softer and more vulnerable to rutting and distortion. These distresses may occur deeper in the asphalt layer and therefore require more extensive work to restore. Water infiltration can increase the degradation of the base materials with inefficient drainage and result in further degradation and cracking. The magnitude of freeze-thaw cycles is also a concern, particularly in asphalt pavements when preceded by rain as described in Section 3.1.B. Concrete pavement is generally more resilient than asphalt, though temperature changes may make it difficult to find optimal curing conditions. Gravel roads are projected to be relatively unaffected by temperature changes but may be subject to drainage and erosion issues from extreme rainfall events.

- **Extreme heat events** may cause:
    - A reduction of USL due to pavement deterioration between 13% and 22%, with a most-likely value of 17%. Asphalt is more likely to be negatively impacted than concrete and gravel roads.
    - An O&M cost increase between 0.7% and 1%, with a most-likely value of 0.8%. O&M impacts are most likely related to crack sealing for asphalt roads to prevent water infiltration. O&M costs for concrete and gravel roads is likely to remain similar as currently experienced.
    - An additional cost of renewal/retrofit (to make pavement more climate resilient) between 9% and 14%, with a most-likely value of 11%. Asphalt is likely to require more extensive work, while cost increases for concrete and gravel roads are likely to be negligible. Extreme heat will also require cement additives and measures to maintain optimal concrete curing conditions.
- **Extreme rainfall** may cause:
    - A reduction of USL due to pavement between 14% and 22%, with a most-likely value of 18%. Gravel roads and asphalt that has not properly cured are more vulnerable than cured asphalt and concrete roads.
    - An O&M cost increase between 0.7% and 1%, with a most-likely value of 0.8%. O&M impacts are most likely related to increased need for crack sealing and patching if extreme rainfall speeds up the development of distresses in pavement.
    - A renewal/retrofit cost increase between 10% and 20%, with a most-likely value of 14% for pavement with the same functionality as before. Cost premiums may result from selecting materials to improve permeability and mitigate erosion and deterioration. Resilience costs are most likely related to proof-rolling, material replacement, and improvements to the base and/or subbase. Gravel and asphalt roads are more vulnerable than concrete roads.

### 3.2.B.2 ROAD ASSOCIATED STRUCTURES

Road associated structures (e.g., embankments, retention systems, drainage systems, road finishing) represent a relatively small portion of the CRV of the Roads asset category (15%). Extreme rainfall is the primary concern for road associated structures, with impacts generally relating to deterioration, erosion, washouts, and water penetration of the base and subbase materials. Freeze-thaw cycles may also destabilize base materials to a lesser degree. Hazards related to temperature (e.g., extreme heat, freeze-thaw cycles) are likely to impact both the application and longevity of pavement markings.

- **Extreme heat events** may cause:
    - A negligible impact on USL of road associated structures. Impacts relate primarily to paint markings, covered under retrofits.
    - A negligible impact on O&M costs for road associated structures. Impacts relate primarily to paint markings, covered under retrofits.
    - A negligible impact on renewal costs for road associated structures. Impacts relate primarily to paint markings, covered under retrofits.
    - An additional cost of retrofit (to make structures more climate resilient) of 2%. Cost premiums may result from accelerated aging of pavement markings, the need for more frequent pavement marking, and the need to use paint that has a higher tolerance for heat.
- **Extreme rainfall** may cause:
    - A reduction in structure USL between 1% and 2%, with a most-likely value of 2%. Impacts relate primarily to erosion and washouts, overwhelming of existing drainage features, and water penetration of the base and subbase materials.
    - A negligible impact on O&M costs for road associated structures. Additional inspection and intervention may be required to monitor deterioration from erosion caused by extreme rainfall.
    - A renewal cost increase between 1% and 3%, with a most-likely value of 2% for structures with the same functionality as before. Impacts relate primarily to adding strengthening measures and materials less prone to erosion.
    - An additional cost of retrofit (to make structures more climate resilient) between 2% and 5%, with a most-likely value of 3%. Impacts relate primarily to increased erosion and deterioration. Retrofitting embankments is likely to require additional material and stabilizing measures.

## C. *TRANSIT*

### 3.2.C.1 ALIGNMENTS

Alignments represent 35% of the Transit asset category, and include steel rails, tracks, rail braces, tie plates, insulated joints, and crossings. Contraction and expansion cycles due to extreme heat, combined with the pressure added by rolling stock, should also be considered to minimize risk of failure. Extreme heat can also affect stress-related subcomponents, with plastics, electronics, moving machinery, and asphalt being especially vulnerable. WSP has leveraged its experience on rail and transit operations in hotter climates to determine the total cost of climate change.

- **Extreme heat events** may cause:
    - A reduction in alignment USL between 5% and 10%, with a most-likely value of 8%. High temperatures can cause stress on tracks and all components, including rail braces, tie plates, and insulated joints. USL may also be impacted by higher occurrence of rail buckling, particularly above temperatures of 32°C.

  - An O&M cost increase between 1% and 1%, with a most-likely value of 2%. O&M impacts are most likely related to components made of plastics, hydrocarbons, asphalt, and wood, which are commonly used in level crossings. Steel and concrete components are less vulnerable to high temperatures.
  - A renewal cost increase between 3% and 9%, with a most-likely value of 6% for alignments with the same functionality as before. Impacts relate primarily to the need for increased rail stability, using rubber anchorage, concrete, and asphalt.
  - An additional cost of retrofitting (to make alignments more climate resilient) between 16% and 19%, with a most-likely value of 17%. Generally, crossing surfaces and ties are replaced instead of retrofitted. However, retrofits can include replacing wooden planks and mending cracked asphalt. Retrofitting may also be required for active crossing warning systems.

### 3.2.C.2 RAIL ASSOCIATED STRUCTURES

Rail associated structures (e.g., concrete crash walls, vinyl-covered noise walls and walls with live plants) represent a relatively small portion of the CRV of the Rails asset category (10%). These subcomponents vary depending on the rail infrastructure under consideration. Increased costs of climate change relate primarily to heat stress on plastics and vegetation, resulting in increased deterioration and maintenance. Impacts to concrete should be relatively low.

- **Extreme heat events** may cause
  - A reduction in structure USL between 1% and 3%, with a most-likely value of 2%. Noise walls with live plants and plastic components are more vulnerable to extreme heat, whereas concrete crash walls may not be affected.
  - An O&M cost increase of 1%. O&M impacts are most likely related to increased vegetation care requirements for noise walls with live plants.
  - A renewal cost increase between 1% and 4%, with a most-likely value of 3% for structures with the same functionality as before. Impacts relate primarily to designed materials where costs have increased, including concrete and vinyl. The cost of vegetation for live walls may increase or decrease, depending on availability of suitable species.
  - An additional cost of retrofit (to make structures more climate resilient) between 2% and 5%, with a most-likely value of 4%. The cost of retrofitting concrete and vinyl will depend on whether structural work is required.

### 3.2.C.3 EQUIPMENT AND FINISHING

Rail equipment and finishing make up 20% of the Transit asset category, with subcomponents including power supply and communications systems, and signals and control equipment. Extreme heat may increase deterioration of these systems, especially plastic subcomponents. It may also become more difficult to maintain set operating temperatures for mechanical equipment and associated cooling systems will need to account for higher temperatures.

- **Extreme heat events** may cause:
  - A reduction in equipment and finishing USL between 4% and 8%, with a most-likely value of 6%. Impacts are most likely related to communication devices, power supply transformers, cooling devices, and other electronics and plastic components.
  - An O&M cost increase between 2% and 3%, with a most-likely value of 4%. O&M impacts are most likely related to increased energy costs to power equipment, such as signals and control equipment.

    - A renewal cost increase between 4% and 8%, with a most-likely value of 6% for equipment and finishing with the same functionality as before. Greater power requirements, higher operating temperature requirements, and more stringent design standards will likely increase the cost of new equipment.
    - An additional cost of retrofit (to make equipment and finishing more climate resilient) between 2% and 7%, with a most-likely value of 5%. Equipment may be more expensive because of the need for operating parts that can withstand higher temperatures. It will also be important to consider what can be rebuilt or reused.

## D. BRIDGES AND CULVERTS

### 3.2.D.1 BRIDGES

The Bridge asset category includes several subcategories and components: ancillary structures (e.g., embankments, approaches, retaining walls); decks and barriers; shallow and deep foundations; the substructure (pier caps, columns, wing walls, abutments); and the superstructure (girder, beams, trusses, bearings). In Ontario, most bridges are made of concrete, with only a small portion featuring timber decks and metallic barriers. Most issues for bridges in a changing climate relate primarily to scour, erosion, and wash outs. WSP assumes that exposed assets (e.g., bridge decks) will face greater impacts than non-exposed assets (e.g., deep foundations).

- **Extreme rainfall** may cause:
    - A reduction in bridge USL between 5% and 10%, with a most-likely value of 7%. The main anticipated effect of extreme rainfall on bridges is scouring and erosion of embankments, approaches, and shallow foundations. Deep foundations should not be significantly affected by scour and erosion.
    - An O&M cost increase of 1%. O&M impacts are most likely related to channel protection and maintenance associated with erosion. There is no anticipated impact on buried foundation elements.
    - A renewal cost increase between 3% and 9%, with a most-likely value of 6% for bridges with the same functionality as before. Impacts relate primarily to increased need for erosion protection, runoff control, and drainage. Renewal of shallow foundations is also likely to increase costs, especially if renewed for a deeper foundation.
    - An additional cost of retrofit (to make bridges more climate resilient) between 4% and 8%, with a most-likely value of 6%. Impacts relate primarily to increased need for erosion protection, runoff control, and drainage. Retrofit of shallow foundations is also likely to increase costs, especially if renewed for a deeper foundation.
- **Freeze-thaw cycles** may cause:
    - An increase in bridge USL between 0% and 6%, with a most-likely value of 3%. Freeze-thaw cycles can contribute to cracking of concrete bridge components and heaving of asphalt approaches. If the number of annual freeze-thaw cycles decreases, it is expected the USL would increase.
    - A negligible impact on O&M costs for bridges due to the absence of granular material underneath the pavement on the deck and ramps.
    - A similar renewal cost. Current standard practice of having air entraining concrete already helps to make bridge concrete resistant to freeze-thaw cycles. Even though the number of freeze-thaw cycles is expected to decrease, WSP considers that the design requirements (e.g., as per the Canadian Highway Bridge Code) are not likely to be diminished.

    - No additional retrofit costs. Current standard practice of having air entraining concrete already helps to make bridge concrete resistant to freeze-thaw cycles. It is also important to consider compatibility when matching old and new concrete compared to full replacement.

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### 3.2.D.2 LARGE STRUCTURAL CULVERTS

Large structural culverts include components such as channel protection, the culvert itself, and wingwalls and headwalls. Based on a review of bridges in Ontario, WSP assumes that a typical culvert has a span less than 6 m. Most assets are located in urban settings, where intense short-duration precipitation events will generate more runoff. Overall, WSP assumes that a large portion of this asset class will require replacing for additional capacity. The main impact to channel protection replacement will likely be increased erosion due to extreme rainfall. Culverts are relatively robust and so the primary issue will likely be under sizing and the need for greater capacity. Wingwall and headwall replacement will need to be changed due to their interdependency with the culvert underneath and the fact that they are undersized.

- **Extreme rainfall** may cause:
    - A reduction in large structural culverts USL between 18% and 33%, with a most-likely value of 25%. Similarly, to bridges, the main anticipated effect of extreme rainfall on bridges is scouring and erosion of embankments, approaches, and shallow foundations. Deep foundations should not be significantly affected by scour and erosion.
    - An O&M cost increase between 1% and 2%, with a most-likely value of 2%. Potential increases are most likely related to inspections (before and after extreme rainfall events), debris removal, and repairing scour damage.
    - A renewal cost increase between 15% and 26%, with a most-likely value of 20% for culverts with the same functionality as before. Most existing culverts are under capacity for the peak flow volume of projected extreme rainfalls and culvert replacement requires use of a larger culvert or use of multiple culverts of same size.
    - An additional cost of retrofitting (to make culverts more climate resilient) between 38% and 56%, with a most-likely value of 47%. Retrofitting a culvert to be resilient to extreme rainfall essentially requires replacing it and/or installing additional culverts to increase capacity. These measures can be costly due to environmental requirements for instream works.
- **Freeze-thaw cycles** are expected to have a negligible impact on culverts.

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## *E. STORMWATER AND WASTEWATER*

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### 3.2.E.1 PIPES

Drainage pipes make up 45% of the Stormwater subcategory. In Ontario, the majority (75%) of these are small and medium pipes less than 1,500 mm in diameter, which are usually designed to address more frequent rainfall events. Extreme rainfall is the primary climate hazard of concern for drainage pipes and can result in capacity issues, as the majority of pipes are not sized to capture more frequent and intense rainfall events. Only physical failure is addressed by USL coefficients. Most of these assets are buried underground and should not be exposed to extreme heat and freeze-thaw cycles. Once the failure threshold of this asset has been crossed, increasing the capacity is not an option.

- **Extreme rainfall** may cause:
    - WSP has assumed that USL reduction will not be significant. Pipes are likely to be changed (upsized) due to capacity consideration, which is not captured by the model coefficients. Climate change may somewhat exacerbate internal and external corrosion of pipes, though new pipes are generally more resilient. Pipes will likely fail due to being undersized for extreme rainfall, with consistent failure rates across all pipe material types.
    - An O&M cost increase between 2% and 5%, with a most-likely value of 4%. O&M impacts are expected to be related to more frequent and costly inspections, preventative maintenance, and clearing of debris, sediment, and vegetation.
    - A renewal/retrofit cost increase between 49% and 74%, with a most-likely value of 59% for pipes with the same functionality as before (e.g., meeting the drainage capacity requirement). The need to increase pipe capacity can result in higher replacement costs, including costs for deeper excavations if larger pipes are installed. Renewal may involve upsizing to a larger pipe, twinning pipes, or incorporating green infrastructure to help control stormwater flow. Retrofitting stormwater assets would be either upgrading to a larger pipe (if downstream elements of the system can accommodate increase flow) or incorporating source control measures such as green infrastructure solutions to reduce and slow down stormwater. If the current stormwater system cannot accommodate retrofits on sections or elements, then a complete renewal is required, and the costs would be as above.

### 3.2.E.2 DITCHES

Ditches are very common in Ontario, representing 50% of stormwater infrastructure, and include earth ditches, vegetated ditches, and reinforced ditches that use concrete and geotextiles. Ditches are generally constructed with higher capacity than pipes but are still vulnerable to large overflow events which would not impact the USL significantly. In addition to capacity issues under future climate condition, ditches may require increased sectoral profiling, clearing of debris, and renewal.

- **Extreme rainfall** may cause:
    - Since ditches tend to be constructed with higher capacity, the USL of ditches is not considered to be affected by climate change.
    - An O&M cost increase of 2%. O&M impacts are most likely related to more frequent sectoral profiling, clearing of debris, and pruning.
    - A renewal/retrofit cost increase between 48% and 75%, with a most-likely value of 59% for ditches with the same functionality as before. Impacts relate primarily to reinforced ditches compared to vegetated ditches. Note that it is often less costly to renew ditches compared to retrofitting because the ditch drainage system is gravity-based and requires continuity in slopes to perform properly. Impacts relate primarily to digging out ditches and using concrete or geotextiles to reinforce ditches. Retrofitting to increase capacity will likely have similar costs to constructing new ditches, except for savings from reduced excavation needs.

### 3.2.E.3 SMALL NON-STRUCTURAL CULVERTS

Small non-structural culverts represent a relatively small portion (5%) of the Stormwater subcategory, and include channel protection, the culvert itself, and in some cases wingwalls and headwalls. The main impact to channel protection will likely be increased erosion due to extreme rainfall. Culverts are relatively robust and so the primary issue will likely be under sizing and the need for greater capacity, though they may also be subject to increased damage from debris and scour. Wingwall and headwall replacement will need to be changed due to their interdependency with the culvert structure and the fact that they may be undersized. Enhancing the resilience of small non-structural culverts will involve using a combination of bigger pipes, twinned pipes, and source control.

- **Extreme rainfall** may cause:
  - A reduction in culvert USL assumed to be 0%. The main concern for culverts is insufficient capacity for wingwalls and headwalls facing extreme rainfall, and minimal damage to the structure from debris or scour.
  - A 2% impact on O&M costs for culverts. O&M impacts are most likely related to more frequent inspections and clearing of debris.
  - A renewal cost increase between 60% and 77%, with a most-likely value of 68% for culverts with the same functionality as before. Increases in cost relate primarily to upsizing culverts, with the installation considered as a fixed cost. Retrofitting will primarily involve larger pipes, twinning, and source control.

### 3.2.E.4 GRAVITY SEWER

Gravity sewers are installed with a gradient, allowing wastewater to flow by gravity from a source to a treatment facility. Gravity sewers comprise the majority (95%) of the Wastewater subcategory, including both combined sewers and sanitary-only systems. The primary impact of changing climate conditions will likely be increased inflows (from short duration rainfall and stormwater) and infiltration (from long duration rainfall and groundwater). These impacts are likely to be more problematic for older systems and combined sewer systems. The largest cost of climate change will likely come from upsizing pipes to increase capacity.

  - **Extreme rainfall** may cause:A negligible impact on USL, therefore reduction in gravity sewers of 0%.
  - An O&M cost increase between 2% and 3%, with a most-likely value of 2%. O&M impacts are most likely related to more frequent and costly inspections, preventative maintenance, and clearing of debris.
  - A renewal/retrofit cost increase between 50% and 80%, with a most-likely value of 61% for gravity sewers with the same functionality as before. Renewal can be challenging in urban settings due to the density of other utilities above the sewers, narrow rights-of-way, and sequencing of infrastructure replacement while maintaining service, resulting in additional costs. Retrofitting may involve upsizing to a larger pipe and/or incorporating green infrastructure to help control stormwater flow. Combined sewers are more sensitive to rainfall and stormwater contributions and retrofit efforts should focus on separation projects.

### 3.2.E.5 SANITARY FORCE MAINS

Force main pipes are relatively reliable and could have a slightly reduced service life (Metro Vancouver, 2008). Service life reduction will be more related to wet well size in the buildings which is not captured accurately by this model. A ~50% increase in rainfall will cause significantly more I&I into the sewer system and increasing pumping costs through force mains due to increased friction in the pipe. Greater corrosion will also increase friction. A ductile / cast-iron pipe may fail sooner due to increased stress on joints from increased pumping. An HDPE or PVC pipe are more flexible and may better handle the increased flow.

- **Extreme rainfall** may cause:

  - A reduction in sanitary force main USL between 17% and 6%, with a most-likely value of 11%. Service life reduction will most likely relate to increased inflows and infiltration, increased pumping costs, and greater corrosion, thus more failure risk.
  - An impact on O&M costs between 1% and 3%. Increased inflows and infiltration may increase the need for pumping.

A renewal cost increase between 39% and 68%, with a most-likely value of 52% for sanitary force mains with the same functionality as before. As inflow from the gravity system could increase loads downstream, there will likely be a need to increase capacity of force mains.Retrofitting a force main to make it resilient to extreme rainfall will most likely require upsizing the pipe. This can be challenging in urban settings due to the density of other utilities, narrow rights-of-way, and sequencing of infrastructure replacement while maintaining service, resulting in additional costs.

## 3.3 APPLICATIONS AND LIMITATIONS

The methodology to develop the α coefficients (i.e., climate-cost elasticity coefficients) and the application of selected climate indicators to different infrastructure classes are the final product of the project, which can directly be implemented in the PAID model (final α coefficients are available in Appendix B). These coefficients are applicable to all locations of public infrastructure in Ontario but were specifically developed for a series of climate indicators and applied to the associated infrastructure in this project. The methodology developed can be applied to any climate indicators that may impact built assets and their components; the comparison between various GHG emissions' scenarios is also possible. The methodology requires that the user:

- Defines and obtain the relevant climate indicators (based on current climate conditions and considering future changes in climate including intensity and frequency of occurrence) and the projected future variations based on climate models; and
- Link the estimated changes in the relevant climate indicators with the "climate-cost elasticities" to estimate the expected costs of the climate changes (for the selected climate indicators) on the USL of the asset components (aggregated at the asset level) and on three cost components: O&M, renewal and retrofit.

α coefficients can be used on various time horizons as long as the historical climate baseline and a forecast horizon are properly defined. WSP recommends using the 1976–2005 baseline period due to the following considerations:

- The availability of climate data for this specific period.
- The duration of the baseline period (i.e., 30 years) to properly capture inter-annual variability.
- The age distribution of the current assets' portfolio: the optimal historical baseline should reflect the average construction year of the assets considered in the analysis, weighted by their respective CRV. For instance, a building designed and constructed in 1975 was built following codes, standards and practices that were based on historical climate and did not account for future climate changes (). Therefore, the service life of buildings or components may already have been affected and their USL reduced due to climate changes between 1975 and 2020. To this historical (pre-2021) reduction in service life, a further reduction is applied to consider the impacts of climate change (post-2021 to the end of the USL). Similar reasoning applies to linear assets as well.

WSP also recommends the FAO consider the following assumptions to facilitate the integration and interpretation of their results in the deterioration curves:

- α coefficients can be used to compute the reduction in USL and costs (O&M, renewal and retrofit) related to climate change on an asset, even if a coefficient is related to an interaction between a specific asset component and a climate indicator. In other words, these costs are cumulative at the infrastructure level. However, further research is needed about how to consider components' USL reduction in the overall asset USL when assessing the impacts of climate change at the portfolio level.

- α coefficients are considered constant over time within the periods examined for the purposes of this study. The expected variation of USL and costs will thus change linearly with the evolution of the selected climate indicator. However, for some assets or components, additional costs associated with retrofit or renewal to accommodate the impacts of climate change may not be linear. As an example, when upgrading the stormwater management system in a dense urban core to have greater capacity, the cost of the pipe is minimal compared to all the associated construction works to install the pipe. In those cases, the asset owner may decide to put in place additional stormwater management measures such as source control, retention, etc.

- The reduction of USL and the increase in O&M costs are gradual as climate change intensifies. However, the climate change projections are based on future values for a given time horizon and the methodology used here considers that impacts on cost occur linearly with climate change. Using the coefficients for decadal USL and cost projections may result in over- or under-estimating the projected impacts.

- For this assessment, climate resilient retrofits (i.e., upgrades) or renewal are completed only once and are considered enough to make the asset resilient to future climate conditions (i.e., to 2080 under the RCP8.5 scenario). However, this hypothesis may lead to additional considerations: for example, if an asset component has a shorter USL (e.g., 30 years) than the infrastructure itself (e.g., 60 years) and is renewed, would the USL of the component no longer be affected by climate until the end of the infrastructure USL? Would O&M costs continue to increase since the component now is climate resilient? These could be areas for further research.

- Table 13 details the integration compatibility of climate-cost elasticities within the PAID Model. Complementary to the PAID Model curves, α coefficients are meant to be applied to its respective set of asset subtypes. Depending on existing data granularity, α coefficients are sometime weighted to reflect the attributed contribution of each subcomponent to the cost of climate change on the total value of the asset. The FAO does not account the total value attributed to pavements in the roads CRV, but pavement reacts to climate change very differently than barriers or road paintings. For instance, three α coefficients constitute roads: pavement, associated structure, and equipment and finishing. WSP assumed that in general, 85% of the CRV of roads can be attributed to pavement, which means that the pavement α coefficients contribute to an equal share in the total economic impact for road assets. When the granularity of data collected by the FAO allows it, unweighted alphas coefficients are applied directly to the asset subtype, without making an assumption on its attributed share of the CRV.

Table 13: Integration compatibility of α coefficients within the PAID Model

| α COEFFICIENT | WEIGHTED/ UNWEIGHTED | PAID MODEL CURVES | ASSET SUBTYPES APPLICABILITY |
|---|---|---|---|
| Buildings | W | colleges.buildings | Colleges |
| Buildings | W | corrections.buildings | Corrections buildings |
| Buildings | W | courts.buildings | Courts buildings |
| Buildings | W | govtadmin.buildings | Govt administrative buildings |
| Buildings | W | govtadmin.buildings (20yr, 25yr, 30yr, 35yr, 40yr, 45yr, 50yr) | Govt administrative buildings |
| Buildings | W | grep.buildings | Grep buildings |
| Buildings | W | hospitals.buildings | Hospitals buildings |

| α COEFFICIENT | WEIGHTED/ UNWEIGHTED | PAID MODEL CURVES | ASSET SUBTYPES APPLICABILITY |
|---|---|---|---|
| Buildings | W | police.buildings | Police buildings |
| Buildings | W | schools.buildings | Schools buildings |
| Buildings | W | schools.portables | Schools portables |
| Buildings | W | transit.buildings | Transit buildings |
| Buildings | W | universities.buildings | Universities |
| Buildings | W | socialservices.buildings | Social services buildings |
| Buildings | W | longtermcare.buildings | Long term care buildings |
| Buildings | W | transit.buildings.muni | Transit buildings |
| Buildings | W | buildings.muni | Buildings |
| Buildings | W | water.buildings.muni | Water buildings |
| Buildings | W | wastewater.buildings.muni | Wastewater buildings |
| Buildings | W | stormsewer.buildings.muni | Stormsewer buildings |
| Roads | W | highway.roads.arterial | Arterial roads |
| Roads | W | highway.roads.arterial. muni | Municipal arterial roads |
| Roads | W | highway.roads.collector | Road collectors |
| Roads | W | highway.roads.collector.muni | Municipal road collectors |
| Roads | W | highway.roads.freeways | Freeway roads |
| Roads | W | highway.roads.freeways.muni | Municipal freeway roads |
| Roads | W | highway.roads.local | Local roads |
| Roads | W | highway.roads.loca.muni | Local raods |
| Bridges | W | Bridges | Arterials, Bridges, Collector, Elevated Expressway & Ramps, Footbridges, Highways, Local, Rail Carrying, Rural Highways |
| Bridges | W | bridges.muni | Arterials, Bridges, Collector, Elevated Expressway & Ramps, Footbridges, Highways, Local, Rail Carrying, Rural Highways |
| Large Culverts | W | Culverts | Large culverts |

| α COEFFICIENT | WEIGHTED/ UNWEIGHTED | PAID MODEL CURVES | ASSET SUBTYPES APPLICABILITY |
|---|---|---|---|
| Large Culverts | W | culverts.muni | Large culverts |
| Transit (Rail Associated Structures) | W | transit.me | Rail Associated Structures |
| Transit (Equipment and finishing) | W | transit.me | Equipment and finishing |
| Transit (Alignements) | W | transit.me | Alignements |
| Stormwater (Pipes) | U | stormwater.pipes.small | Small pipes |
| Stormwater (Pipes) | U | stormwater.pipes.medium | Medium pipes |
| Stormwater (Pipes) | U | stormwater.pipes.large | Large pipes |
| Stormwater (Pipes) | U | stormwater.pipes.unknown | Unknown diameter pipes |
| Stormwater (Ditches) | U | stormwater.ditches | Ditches |
| Stormwater (Small culverts) | U | stormwater.culverts | Culverts |
| Wastewater (Gravity sewer) | U | wastewater.pipes.small | Small pipes |
| Wastewater (Gravity sewer) | U | wastewater.pipes.medium | Medium pipes |
| Wastewater (Gravity sewer) | U | wastewater.pipes.large | Large pipes |
| Wastewater (Pipes) | U | wastewater.pipes.unknown | Unknown diameter pipes |
| Wastewater (Sanitary forcemains) | U | wasterwater.forcemains | Sanitary forcemains |

## 3.4 SAMPLE APPLICATION OF RESULTS

### A. COMMON CASE

This subsection shows sample calculations for a fictional provincial government administrative building built in 1990 (Table 14). The state of good repair (SOGR) period is estimated by calculating the implied year of the building at the repair threshold with the PAID Model default parameter. Similarly, useful service life is estimated by calculating the implied year of the building at the intersection with the failure threshold with the appropriate PAID

Model parameter (beta = 45, epsilon = 0.02, failure =0.15 and repair threshold=0.7) for a provincial government administrative building.

Based on PAID Model default parameters, annual O&M represents 1.5% of the CRV. This asset type has a useful service life of 67 years.

**Table 14: Key characteristics of a fictional provincial government administrative building**

| CHARACTERISTIC | VALUE |
|---|---|
| Construction year | Built in 1990 |
| Location | Kapiskau River |
| Asset type | Provincial government administrative building |
| CRV | $1,000,000 |
| Annual O&M | 1.5% of the CRV |
| Implied age | 31 |
| Implied construction year | 1990 |
| SOGR (year of repair) | 37 (2027) |
| Useful service life (year of failure) | 67 (2057) |

Alpha coefficients and climate projections are used to forecast the costs of climate change at the 2080 horizon. The selected climate baseline year is the median value of 1976–2005 and climate projections are weighted by the geographic distribution of current replacement value in Ontario. The climate variation between the forecast horizon and the selected baseline for each relevant climate indicator $j$ correspond to $\Delta c_{j\%}$. Hence, the expected impact (%) of climate change on cost parameters corresponds to the sum of the product between all alpha coefficient $\alpha_j$ and its estimated climate variation $\Delta c_{j\%}$.

$$Impact\ (\%)\ of\ climate\ change\ on\ cost\ parameters\ = \sum_{j=1}^{J} \alpha_j * \Delta c_{j\%}$$

In 2060, according to 90th percentile of RCP 8.5 projections, climate change will decrease the USL of this building by 5.6% (67 years * (100%-5.6%) = 63.2 years) and the O&M costs will be increased by 0.47% (i.e., leads to total O&M cost as a percentage of the CRV of 1.5 + 0.47 = 1.97%). Assuming resilient building codes and standards are going to meet 2080 climate requirements, the cost of renewal would increase by 10.7% and the cost of retrofit by 23.7%. The new annual O&M costs, state of good repair period, USL, and retrofit and renewal costs are presented in Table 15.

Table 15: Sample application of results

| | ANNUAL O&M COSTS (WITH CLIMATE CHANGE) | SOGR PERIOD (YEAR OF REPAIR) WITH CLIMATE CHANGE | USEFUL SERVICE LIFE (YEAR OF FAILURE) WITH CLIMATE CHANGE | RETROFIT COST TO MAKE THE BUILDING MORE RESILIENT TO CLIMATE CHANGE (EXCLUDING REPAIR COST) | RENEWAL COST OF A RESILIENT BUILDING |
|---|---|---|---|---|---|
| Values | 1.97% | 34 (2024) | 63 (2053) | $237,000 | $1,107,000 |

The new useful service life and year of failure with climate change are estimated by applying the impact (%) for USL to the implied age of the asset (for instance, 67*(1–5.6%) ≈ 63) and resolving the condition equation in the PAID Model parameter to find the new beta. Once the new beta is calculated, the SOGR period is recalculated.

Useful service life, O&M costs, renewal costs, and retrofit costs are explored below.

- **Useful service life:** How would the average annual rehabilitation cost of an existing asset change given a change in values of any climate indicators in the absence of adaptation measures?
  - In the absence of adaptation measures, the average annual rehabilitation cost of an existing asset is expected to increase as the SOGR period, and the Useful service life of the building, are reduced (Figure 7). In this sample application, the buildings need to be repaired and renewed three years earlier.

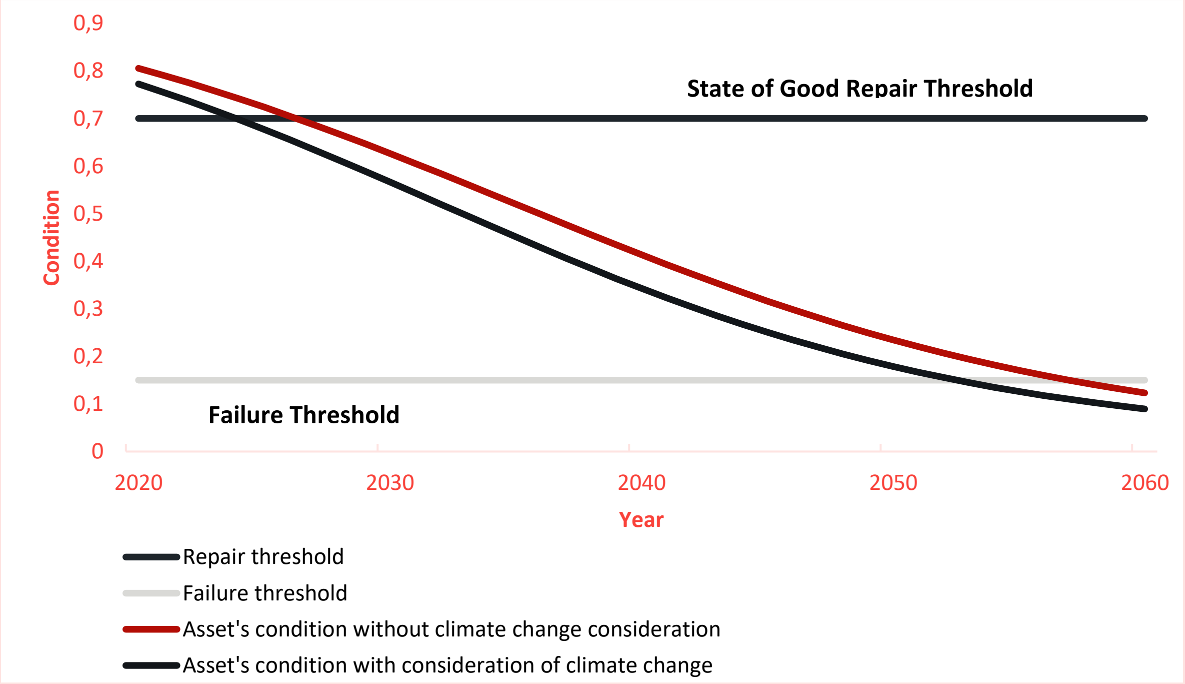

Figure 7: Illustration of the Reduction of USL for the Sample Building

- **O&M costs:** How would annual average O&M costs of existing and new assets change given a change in values of a climate indicator?
  - Mathematically and in the absence of adaptation, the average O&M costs would increase from 1.5% to 1.97% gradually between 2020 and 2060, as climate change impacts increase.

- **Costs of retrofit:** What are the costs of retrofitting the components of existing assets to avoid accelerated asset deterioration or compromised service levels for defined changes in values of climate indicators?
  - The costs of retrofit to meet the climate conditions of 2080 would represent 23.7% of the total CRV. This cost is complementary to repair costs, which means repairs can be performed without retrofit. However, the opposite is not true. Thus, the building must wait until 2024 and 2054 before being eligible for repair and retrofit. Once repaired and retrofitted, buildings deteriorate "normally", but with a higher replacement value and requires 1.97% in annual O&M costs.
- **Additional renewal costs:** What are the one-time costs of renewing existing assets to avoid accelerated asset deterioration or compromised service levels under changing values of climate indicators?
  - The additional cost of renewal is expected to represent $107,000 for a $1,000,000 Building. This additional cost attempts to restore a "standard" deterioration process and an annual O&M costs of 1.5% of CRV.

Therefore, under the CIPI framework, the costs induced by climate change to this theoretical building are above and beyond what is required to maintain SOGR over time.

## B. ADAPTATION AS A SINGLE OPTION

When it comes to climate change-induced additional costs to retrofit or renewal, it is reasonable to assume that sometimes, these additional expenses will have to be made, regardless of any debate on the financial profitability. Furthermore, in practice, drawing the line between retrofit or renewal is sometimes impossible because the work that needs to be done is similar. Pavements, pipes & sanitary forcemains retrofit and replacement coefficients were folded together for this reason. This approach aligns with WSP's understanding of the assets life cycle modeling and consistent with our expert's experience.

Under an *equivalent level of service* assumption, we compute the total cost of climate change by using the four sets of climate-cost elasticities coefficients and comparing it to a baseline scenario, where the older coefficients are used to compute the cost of infrastructure. In this example, we use gravity sewers and explain the model implications and limitation of having:

- USL climate-cost elasticity coefficients = 0.
- Increased O&M due to increased inspection and maintenance; and
- No choice of increasing capacity when replacing or retrofitting (no assumed difference in terms of costs) the assets.

Table 16 presents the key characteristics of two fictional underground sewer pipe sections (1 km length) located in Toronto, Ontario. Both are valued $1M and have an identical condition just under the state of good repair, but still over the failure threshold. Section #1 was built in 1900 while Section #2 was built in the 1920. The diameter of both sections is unknown and both systems are combined. The useful service life of 63 years is exceeded for both sections, even though their physical integrity remains acceptable. However, their level of service is decreasing, causing more frequent stormwater overflow. An annual 1% O&M share of the current replacement value is assumed.

**Table 16: Key characteristics of fictional gravity sewer sections in Toronto**

| | GRAVITY SEWER SECTION #1 | GRAVITY SEWER SECTION #2 |
|---|---|---|
| Construction year | Built in 1900 | Built in 1920 |

| | | |
|---|---|---|
| Location | Toronto | |
| Asset type | Gravity sewer | |
| CRV | $1,000,000 | |
| Annual O&M | 1 % of the CRV | |
| Implied age | 29 | 4023 |
| Implied construction year | 1994 | 2000 |
| SOGR (year of repair) | 30 (2024) | (2030) |
| Useful service life (year of failure) | 63123 (2027) | 123 (2046) |

Table 17 below presents the expected cumulative impact of climate change on these fictional assets from 2020 to 2050.

**Table 17: Sample application of results**

| | ANNUAL O&M COSTS (WITH CLIMATE CHANGE) | SOGR PERIOD (YEAR OF REPAIR) WITH CLIMATE CHANGE | USEFUL SERVICE LIFE WITH CLIMATE CHANGE | COST TO MAKE THE SEWER RESILIENT TO CLIMATE CHANGE (RENEWAL OR RETROFIT) | | |
|---|---|---|---|---|---|---|
| Section 1 | 1.2% | 30 (2051) | 126 (2026) | 610,000 | | |
| Section 2 | 1.2% | 30 (1991) | 126 (2046) | 610,000 | | |

Useful service life, O&M costs, renewal costs, and retrofit costs are explored below in response to the average increase of 52% in the volume of water during a 2-year return period 24-hour precipitation event and the maximum 5 days precipitations, which corresponds to the climate projections for Toronto under the high range of RCP 8.5 scenario by 2050.

- **Useful service life:** How would the average annual rehabilitation cost of an existing asset change given a change in values of any climate indicators in the absence of adaptation measures?
  - For water assets, it is assumed that useful service life is not physically affected by climate change. Therefore, there is no impact projected on the useful service life. The rehabilitation year is not changing.
- **O&M costs:** How would annual average O&M costs of existing and new assets change given a change in values of a climate indicator?
  - For each of these section, 10,000$ is spent annually in O&M, but this amount increases to 12,000$ in 2050 for Section #1. However, both Section O&M's remain at their historical level after the renewal, assuming that it is going to be designed resilient to climate change.
- **Additional renewal costs/Costs of retrofits:** The costs of making the assets resilient to meet the expected climate condition of 2080 represent approximately 61% of the total CRV. The amount is significant and is explained by the addition of capacity. Both sections are eligible to retrofit, however, Section #1 useful service life will be exceeded in 2026 while Section #2 will be exceeded later, in 2046. Since both sections have

exceeded the SOGR, they are theoretically eligible to retrofit until both have reached 2x their USL. The costs would not differ from replacement.

- **Additional considerations:** Frequent overflowing and diminishing level of services are not internalized by the financial model. Even though the physical integrity of the assets is considered acceptable, the risk represents, an economic externality increasing the cost of climate change to society (pollution, damage to nearby buildings, health issues, etc.), but not necessarily to asset owners. This situation highlights the need for integrating wider economic impacts when assessing the return-on-investment for certain climate change adaptation measures.

# 4 DISCUSSION

Overall, WSP identified six notable limitations to consider for future research.

## DATA AVAILABILITY AND GRANULARITY

The CIPI project operates at the portfolio level and makes use of the best available data at the time of the project. While the results are reasonable at the portfolio level, the current methodology would need to be refined to be used at the asset level.

Regarding infrastructure data, there is a significant variation in data availability and quality, especially for the municipal infrastructure. The project team produced their cost coefficient estimates based on the best available data at the time of the project, and their professional judgment. As asset management good practices and AM plans are refined in the province, the quality of data on the state of the infrastructure will improve.

In addition, there were uncertainties associated with the historical and projected climate indicators to select and how best to apply them to the project. The quantitative relationship between climate change and infrastructure damage has not been thoroughly studied. Furthermore, most research focused on a single type of infrastructure or a single asset, while the present project focused on a portfolio of widely varied asset types. The project team needed to limit the selection of climate indicators, even though different materials, different age of constructions, different codes and standards would require more granularity. The scale of the project also brought challenges with area coverage, since we had to use a limited number of locations to represent a wide range of climate conditions.

## ASSET TYPES AND BROAD CLASSIFICATION

To allow the integration of building engineering knowledge in the PAID Model, the WSP team worked with the asset classification based on occupation currently used by the FAO and assumed that climate change would impact all types of buildings similarly. For instance, an x% increase in extreme heat would result in a y% reduction of USL among all types of buildings.

For linear assets, the WSP team worked with the asset classification currently used by the FAO and assumed that climate change would impact all types of assets in a similar way. Some asset classes include a wide range of sub-assets that are going to be impacted differently by climate change (e.g., the FAO makes no distinction between bridges and large culverts).

However, both buildings and linear assets are likely to have been constructed to different codes or standards, have varying uses, and be maintained differently, which is not distinguished within the CIPI framework. For example, it may be useful to first disaggregate all buildings in Ontario into different asset types such as schools, offices, arenas, penitentiaries, and then identify example building components of those sub-asset classes. Future studies by the FAO or other bodies could build on the methodology and coefficients herein by reviewing them by sub-asset class. The methodology could also differentiate the criticality of assets and the needs of the occupants in relation to the expected or acceptable levels of service. Furthermore, it is possible that costs related to climate change impacts may be due to externalities, for example, the need to add a backup power generation due to the fragility of the electricity grid in the area or the economic impacts of heat stress on workers due to lack of cooling capacity.

## TIPPING POINTS

The CIPI project assumes that climate-cost elasticity coefficients will remain constant over time, which suggests a linear relationship between climate and costs of climate change. However, climate change is non-linear and future climate projections may change dramatically depending on tipping points, a threshold beyond which a system reorganizes, often abruptly, and does not return to its initial state even if causes of the change are mitigated (IPCC, 2018). As current climate data available does not include tipping points, the results of this project should be considered as conservative projections within the bounds of an RCP8.5 scenario. They should remain applicable to other scenarios, assuming linearity.

Moreover, the possibility of high-impact, very low probability outcomes cannot be ruled out, but these are difficult to include in this kind of study because their probability of occurrence is unknown. Note that even if these probabilities were known, the approach used in this report would be insensitive to their inclusion. This is because this report considered climate indicators that are chosen as the 90th percentile of responses amongst different climate models under RCP8.5. The low probability of tipping point exceedance implies that the percentile thresholds used in this study are very likely robust to whether the climate models involved do, or do not, include faithful representations of the tipping point processes.

## CUMULATIVE CLIMATE COSTS

The CIPI project considers the costs of three climate hazards individually then sums these to arrive at a total cumulative impact. However, the true cumulative impact of the three hazards and other climate hazards may be larger than a straight summing of the impacts.

Future studies could consider other relationships between climate variables and infrastructure costs, but there is not sufficient literature at present to adopt an alternative assumption. Such a framework would enable reviews and revisions of how climate change impacts the total asset USL and/or CRV (e.g., as a proportion of the components' value).

## ENERGY EFFICIENCY RETROFITS

The CIPI project only considers climate change adaptation, not climate change mitigation. However, there may be opportunities for the asset managers to integrate adaptation with mitigation efforts, such as energy efficiency retrofits to improve building performance, or the choice of materials that are less intensive in carbon dioxide emissions.

The Province of Ontario, the Federal government, transfer payment partners (TPPs), and others are investing significantly in energy efficiency retrofits to address climate change mitigation. For example, the Canada Infrastructure Bank is investing over $1 billion nationally in energy efficiency retrofits for public buildings, of which some portion will be invested in Ontario through TPPs such as the City of Toronto or through Infrastructure Ontario.

There is a well-established disconnect between climate change mitigation and adaptation in practice. In sharing the results of the CIPI project, it will be important to consider whether the costs of adaptation might be integrated with planned energy efficiency retrofits in Ontario. This topic is emerging and there is limited research available, but the City of Toronto's *Resilient Towers* initiative (Morrison Park Advisors, 2019) provides an example in the Ontario context.

By identifying alignment between adaptation and mitigation, organizations may be able to leverage funding and emphasize synergies in capital projects. As a first step, they can explore the opportunity to leverage climate change mitigation funding for public buildings to simultaneously improve resilience at its assets.

## LEVEL OF SERVICE AND REPLACEMENT

The project team considered useful service life to correlate with deterioration. However, assets that no longer deliver the expected level of service may be replaced before the end of their USL. This issue is particularly pronounced for linear assets relating to stormwater and wastewater. For example, if a culvert no longer prevents recurrent overflowing, it will likely be replaced early. For stormwater and wastewater systems, it is also likely that renewal will be passed over in favour of replacing a combined system with a separated system. For water infrastructure, the O&M climate change climate-cost elasticity coefficient is applied until they get retrofit or replaced. Once they cross the state of good repair threshold, the retrofit climate-cost elasticity coefficient is applied additionally to the normal rehabilitation cost. Once they cross the failure threshold or once they reach twice their useful service life, they are replaced completely, where the renewal climate-cost elasticity coefficient is applied. It is not likely for water assets to be replaced at their current replacement value, without any additional capacity consideration. WSP considers that, overall, they are also not likely to be repaired without being retrofitted. As discussed, even though physical failure is not as likely as capacity failure to motivate the replacement of assets, it is the opinion of the project team that integrating the efforts to increase capacity to maintain the historical level of service remains a potential improvement to the model. As discussed in the previous section, this situation also highlights the limitation of using only an asset deterioration model, without considering wider economics impacts (pollution, damage to nearby buildings, health issues, etc.) when assessing the return-on-investment for certain climate change adaptation measures.

# 5 FUTURE IMPROVEMENTS

Overall, the deterioration model used by the FAO (based on modelling techniques developed by the Ontario Ministry of Infrastructure – MOI), combined with Provincial and municipal infrastructure, provided the required flexibility to incorporate future climate hazards impacts projected from the current IPCC RCP greenhouse gas emissions scenarios. The nature of the assessment (i.e., a novel, landmark project with a brand-new methodology), and the complexity of the potential climate impacts on the service life of assets or components, the costs to operate and maintain the assets to provide the expected levels of service, and the retrofit or renewal investments needed, resulted in valuable lessons learned by the project team (WSP and FAO) which could be applied to future refinements and research.

The deterioration model is robust for financial projections at the portfolio level and based on the team's experience to incorporate climate impacts could be adapted to project impacts at the local level, for sub-asset classes (for example, buildings of the same type built within a given time period), and inform asset management plans. Although the model currently only focuses on the condition of assets or components and considering that assets may be retrofitted or renewed due to other performance considerations (e.g., capacity to meet demand or functionality), the model could be adapted to include these criteria – provided the data is available.

In the discussions with the subject matter experts regarding changes in service life and costs (O&M, retrofit and renewal) due to climate impacts, it was clear that some assets/components may undergo retrofits or renewal when even the majority of the elements are in a state of good repair. For example, an asset owner is unlikely to do many spot repairs on a kilometer of water pipes and may choose to do the entire length of pipe replacement, since mobilisation and service disruption costs would be significantly higher for many interventions and would leave potentially weak asset components that may fail in a near future.

Further to the above observation, it is common practice when renewing or retrofitting deep buried infrastructure (e.g., wastewater pipes), to plan for interventions on other assets within the right of way since surface assets (e.g., road pavement) will be disrupted. This impact on the assumptions of unit costs, but also implies that some assets will be replaced before the end of their useful life and can be difficult to capture in the financial model.

In general, as observed in many (if not all) climate risk assessments conducted by the team, language and technical terminology is extremely important to ensure the coherence of the input, analysis and results. The necessity of a multi-discipline team to perform such an assignment, also means that the professionals – finance and economics, climate science, and engineering, bring their own understanding of terms. For example, being "conservative" for a climate scientist may mean having a bias towards underestimating the change in a climate indicator in the future, while for an engineer it would lead to adding a factor of safety (e.g., increase capacity or strength) and adopt upper bound risk ratings.

Although refinements were made in the definition of the climate indicators, particularly freeze-thaw cycles, and new projections in future climate were generated, similar refinements could not be made to the asset data; it was not possible, for example, to collect additional data on the condition of sewer pipes or bridges to refine the projected climate impacts. In the future, it may be valuable to conduct a sensitivity analysis of the benefits of improving one data set (either climate or assets) over the other to optimize the level of effort.

Finally, although the subject matter experts input involved in several instances iterations with the core project team to ensure clear understanding of the climate indicators considered in the assessment, future work with more complex climate variables (for example, combined events) may require additional upstream work to translate climate indicators into engineering terms and variable designers and asset managers commonly use.

## 5.1 OBSERVATIONS REGARDING THE CLIMATE INDICATORS

Extreme climate events, with the exception of some such as widespread ice storms, are often located and difficult to integrate into a regional, portfolio-level assessment. For example, when considering flooding, there are significant differences in the climate events that will produce riverine flooding versus overland or sewer backups. Proxies can be used in those instances, but this introduces additional uncertainties without a rigorous analysis of the sensitivity of the results.

Climate events that cause disruptions in services and physical damages to assets usually comprise several meteorological phenomena, for example wind and rain, freezing rain or snow, or extreme high temperatures accompanied with high levels of humidity. In many instances it is the combination of these phenomena that will result in the most acute impacts but are also the most difficult to project in the future. In the second phase of the project, the team tested and adopted a “hybrid” model for certain climate indicators to better represent the mechanisms leading to the deterioration and/or additional costs for road pavements. By combining the impacts of freeze-thaw cycles with those of winter rain intensity, the subject matter experts were more comfortable in estimating the effects of this climate parameter on the assets. Further refinements in regard to this approach may be useful in the future.

The complexity of the performance of assets or components in a portfolio which are at various stages of deterioration and built to different standards make it difficult to select the predominant climate indicators that will create the most significant impacts. For example, changes in design standards or industry practices may accommodate higher intensity rainfall events than in the past. The climate event intensity threshold selection is therefore critical since the subject matter experts rating the changes in USL and costs will base their recommendations on their understanding of these parameters.

## 5.2 OBSERVATIONS REGARDING THE ASSETS

The climate impacts on tangible capital assets vary depending on a wide range of factors and asset attributes, including age, condition, design standards at the time of construction, maintenance practices, etc. The model, and the subject matter experts input on their optimistic, most likely and pessimistic projections of impacts somewhat captures these differences. Refinements could be made to the financial impacts of climate change on the public assets considered by performing the analysis by sub-asset classes (for example, masonry building constructed over a given decade).

Assets are likely to be impacted by a wide range of climate events, and in some cases the impacts of these events may be cumulative. For instance, extreme heat may deteriorate windows’ sealant which, during a rainfall accompanied by strong winds may cause water infiltration into walls and interior. In other instances, climate events may cause damages that will not contribute to increased deterioration from different events. Considering whether the impacts are cumulative or independent will need further study in the next generation of the model. It will also be important to explore the benefits the rehabilitation or retrofit to address a climate hazard may (or not) have in mitigating the impacts of other events.

Adaptation or retrofit to account for climate impacts may, in some cases, be necessary due to externalities to the assets or components that do not exist but will be necessary. For example, climate changes may affect the quantity or quality of the raw water source for a potable water system. This may require modifications to the water treatment plant even though the asset itself is not affected from a physical point of view. Another example is the need to add cooling systems in buildings (e.g., schools) that currently do not have air conditioning but, in the future, may require it. This could be an area of refinement for the financial forecast.

Unit costs, in some instances, may be difficult to assess accurately since what is included in the work can vary depending on the project and procurement. For example, if the project involves the replacement of buried infrastructure, the unit costs may include pavement reinstatement. It is also possible for some agencies to have access to trenchless technologies contractors that can avoid open-cut construction in busy and dense urban areas and install structural liners that will reinstate the useful life of the asset. It would be possible, in the same way that the subject matter experts defined the range of impacts (optimistic, most likely and pessimistic) that upper- and lower-bound unit costs of renewal and retrofit could be defined and used.

# 6 ACRONYMS

| | |
|---|---|
| CIPI | Costing the Impacts of Climate Change to Public Infrastructure in Ontario |
| CRV | Current replacement value |
| FAO | Financial Accountability Office of Ontario |
| GHG | Greenhouse gas |
| IDF | Intensity-duration-frequency curve |
| IPCC | Intergovernmental Panel on Climate Change |
| LPA | Linear Pool Analysis |
| MOI | Ministry of Infrastructure of Ontario |
| NRC | National Research Council Canada |
| O&M | Operations and maintenance |
| PAID | Provincial Asset Inventory Deterioration |
| PERT | Project evaluation and review techniques |
| RCP | Representative Concentration Pathways |
| SCC | Standards Council of Canada |
| SME | Subject matter expert |
| SOGR | State of good repair |
| TPP | Transfer payment partners |
| USL | Useful service life |

# 7 GLOSSARY

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|---|---|
| 2.5% July daily maximum temperature | 97.5th percentile of the distribution of daily maximum temperature in July. |
| Adaptation | In human systems, the process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities (IPCC, 2018). |
| Alpha (α) coefficient | Relative variation in a cost parameter of an asset for a given change in a climate indicator. |
| Annual highest temperature | The highest temperature reached within a year (corresponds to the annual maximum of the daily maximum temperature). |
| Annual number of cooling degree-days | Annual sum of daily degrees above 18°C, based on daily mean temperature, directly linked to cooling demand to maintain average air conditions in the building interior. Example: if the daily average temperature is 30°C on each day of July, and below 18°C for the rest of the year, the annual number of cooling degree-days will be 31*(30-18) = 372. |
| Annual number of deep freeze-thaw cycles | A deep freeze-thaw cycle is defined by a cycle occurring within a day when the mean daily temperature is below 0°C. Depending on the infrastructure type under study, this type of cycle can have a greater impact than a "mild" freeze-thaw cycle. They are more likely to occur during winter months. The annual number of cycles is then the number of days with a cycle considering all month in the calculation. |
| Annual number of freeze-thaw cycles | A freeze-thaw cycle happens when the daily maximum temperature is above 0°C and the daily minimum temperature is below 0°C. Under these conditions, it is likely that some water at the surface is both liquid and solid at some point during the day. The annual number of cycles is then the number of days with a cycle considering all month in the calculation. |
| Annual number of hot days | The number of days within a year when the maximum temperature reaches 30°C or more. |
| Asset-hazard interaction | Relation between an asset and the potential occurrence of a natural physical event or trend that may pact impact the level of service provision. |
| Average annual precipitation | Total amount of precipitation received in one year. |
| Climate cost elasticity coefficients (α) | See *Alpha coefficients* |
| Climate hazard | The potential occurrence of a natural physical event or trend that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems and environmental resources (IPCC,2018) |
| Climate variation ($\Delta c$) | Change rate of a climate indicator $c$ between the historical period (1981–2005) and the future period (2051–2080) |
| Cost parameter variation ($\Delta p$) | Expected financial impacts given RCP 8.5 |

| | |
|---|---|
| Damage function | A simplified expression of economic costs or benefits, as a function of climate inputs, such as changes in average precipitation or temperature. The term climate-cost elasticity is preferred in the report. |
| Deep freeze-thaw cycle | A freeze-thaw cycle happens when the daily maximum temperature is above 0°C and the daily minimum temperature is below 0°C. Under these conditions, it is likely that some water at the surface is both liquid and solid at some point during the day. A deep freeze-thaw cycle is a freeze-thaw cycle occurring on a day that the average temperature is below 0°C. |
| Delphi method | The Delphi method is a common process used in economics and asset management to arrive at a common decision by surveying a panel of experts and aggregating their answers. Experts are surveyed multiple times and answers are shared between rounds. The goal is to reduce the range of responses and arrive at something closer to expert consensus. |
| Deterioration | Reduction process of the state and/or the financial condition index (FCI) of an asset between two periods. The deteriorate rate is expressed by the Beta coefficient within the PAID Model. |
| Elasticity | Elasticity measures the relative change of one economic variable in response to a change in another. |
| IDF x-hr 1:y | Maximum rainfall event of the duration of x hours with a return period of y years. |
| Maximum 5-day precipitation | The maximum amount of precipitation within a year received during five consecutive days. This metric can be used to assess the impacts on hydraulics of the channel infrastructure. |
| Mean July daily maximum temperature | Monthly average of daily maximum temperature in July. |
| Most-likely scenario | Scenario representative of the overall portfolio of public infrastructure assets. |
| Optimistic scenario | Scenario assigned to less vulnerable assets, i.e., designed with more recent standards, well maintained components and recent repairs. |
| PERT distribution | The PERT distribution is a family of continuous probability distributions defined by the minimum, most likely and maximum values that a variable can take. |
| Pessimistic scenario | Scenario assigned to more vulnerable assets, i.e., designed with older standards, poorly maintained components and significant repair backlog. |
| Rehabilitation | Intervention in order to bring back the asset to its state of good repair (SOGR). The rehabilitation costs are expressed by the product of the asset current replacement value and the magnitude of the rehabilitation work, expressed by the financial condition index delta. |
| Renewal | Total replacement of a failed asset by an asset delivering an equivalent level of service than the previous one. |
| Retrofit | Asset intervention in order to furnish with new or modified components to ensure an improved, or at least equivalent, level of service than its previous state, under future climate condition. |

| | |
|---|---|
| Sensitivity | Vulnerability or the propensity or predisposition to be adversely affected. |
| Unweighted | Results expressed are weighted by their assumed CRV share. Stormwater and Wastewater are weighted coefficients. |
| Tipping Point | Refers to the economic consequences of irreversibility and non-linearity. A level of change in system properties beyond which a system reorganizes, often abruptly, and does not return to the initial state even if the drivers of the change are abated. For the climate system, it refers to a critical threshold when global or regional climate changes from one stable state to another stable state (IPCC, 2018) |
| Weighted | Results expressed are weighted by their assumed CRV share. Buildings, Roads, Bridges and Transit are weighted coefficients. |
| Winter Rain Intensity | Total amount of liquid precipitation averaged daily on the length of winter, defined as the period between the first day of frost and the last day of frost. A day of frost is defined by a negative daily minimum temperature. |

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# APPENDIX

## A

## COMPLETE ASSUMPTIONS AND RATIONALES

### WORD OF CAUTION

The results presented below are a summary of the rationales of the SMEs to explain their appreciation of changes in cost due to climate change. The SMEs were asked to provide an optimistic, most likely and pessimistic percent change in the four types of cost based on a set of climate projections that was provided. These climate projections were extracted from three localities in Ontario for RCP8.5 90th percentile scenario, which could be considered as the worst-case scenario in terms of magnitude of change in climate.

As the FAO will use the full regional climate projections provided by ECCC under different climate change scenarios, **it is expected that the FAO's result will differ from the results from the SME consultation developed below**.

# A. BUILDINGS

## CIVIL INFRASTRUCTURE AND LANDSCAPING

### USEFUL SERVICE LIFE

- **Extreme heat**: Degradation of surface features will likely increase, leading to an increase in cracking and maintenance operations. Severity is low as bitumen generally resists to temperatures between -28°C and 52°C. Functionality of parking lots and access to buildings (sidewalks, ramps) would not be affected, and buried infrastructure would not be affected as well. Vegetation impacts could occur depending on the nature of plants and grass used; no significant impacts are expected on rehabilitation costs for landscaping as the life cycle of these elements is generally short; trees may require replacement with species more tolerant to higher temperatures in some areas.
- **Extreme rainfall**: Civil infrastructure will likely be affected when ineffective site drainage (due to low design capacity or reduced capacity due to blockages) is in place. When drainage systems are operating correctly, little or no damage or reduction of USL would be expected. However, considering the range of age and design standards used for the portfolio considered in this analysis, it is reasonable to expect that some overall reductions in USL will occur. For subcomponents vulnerable to high precipitation, USL should not directly be reduced. However, capacity may be exceeded before the end of life, then requiring 100% replacement (for instance, roof drainage and storm water). Considering civil infrastructure systems with a USL matching the service life of the building, with a USL of 50 years, the likely reduction of USL due to this climate hazard would be approximately six months.

  Water services are designed for proper depth of bury, thus a negligible impact is expected regarding drinking and sanitary water subcomponents. As for concrete walkways, deterioration is site dependent - a range has been provided based on full requirement of full replacement (refer to Portland Cement Information (2002) for more information). Asphalt paving and surfacing values were given according to Ouiao et al. (2013); surface infrastructure may be affected if improper or inefficient onsite stormwater drainage cause pounding and soil saturation resulting in loss of bearing capacity. Winter and spring extreme rainfall followed by sub-zero temperatures may induce damages in landscaping elements due to ice build-up and cracking, resulting in accelerated deterioration and need for early replacement of elements.

  Landscaping is expected to be adversely affected by increases in short duration/high intensity rainfalls due to potential local flooding and erosion. However, the USL of this element is much shorter than the building USL. It is also likely that changes in landscaping will occur due to temperature variations (e.g., potential changes in plant hardiness) and in drainage configurations. If the USL of these elements is in the order of 10 years, the expected reduction in USL due to this climate indicator will be low (several months), which may be incorporated in annual or regular landscaping planning and activities.

- **Freeze-thaw cycles**: Increased deep freeze-thaw cycles may lead to heaving or increased degradation of pavement resulting in increased renewal cycles. This shift can induce premature deterioration of surface element of civil infrastructure (e.g., concrete and asphalt). This shift may also impact the vegetation. An increase in freeze-thaw cycles is expected to accelerate the deterioration of exposed elements of the civil infrastructure (asphalt concrete and PCC surfaces, joints and mortar) due to penetration of water and subsequent freezing. The increase use of aggressive de-icing products may also increase the rate of deterioration. The projected decrease in the number of freeze-thaw cycles will therefore be beneficial for buildings.

### O&M COSTS

- **Extreme heat**: Increased temperature could impact watering requirements to maintain plant health. In the event of accelerated degradation, repair and maintain will be required more frequently. No financially significant O&M impacts on civil infrastructure are however considered for this climate hazard.

- **Extreme rainfall**: Extreme rainfall is expected to be the main driver marginally amongst all hazards for civil infrastructure. Storm sewer and roof drainage are expected to require 10% more O&M shares, for instance. Concrete walkways and pavement are also expected to be impacted by erosion. Small but expected impacts on vegetation due to destruction/erosion need to be considered.

- **Freeze-thaw cycles**: Increased freeze-thaw cycles may lead to heaving or increased degradation of pavement resulting in increased maintenance requirements or road renewal. The projected decrease in the number of freeze-thaw cycles will therefore be beneficial for buildings.

### RENEWAL COSTS

- **Extreme heat**: Design soft- and hardscaped areas would help to mitigate heat island effect (more vegetated area, white concrete, trees providing shade, asphalt coatings to reflect long wave UV). Civil infrastructure is expected to require low additional retrofit costs due to changes in this climate hazard in the future. Landscaping retrofit options can include elements that will reduce the overall heat impacts on the building and reduce heat island effect.

- **Extreme rainfall**: A low-carbon resilience option would be to reduce hardscaping to encourage infiltration of rainfall and adoption of nature-based solutions to manage rainwater. Civil infrastructure and landscaping may require stormwater ponds, infiltration galleries, and retention or detention tanks to slow and minimize runoff rates and quantity. Stormwater management systems may also need to be designed to meet updated local regulations regarding effluent release in the environment or receiving municipal system. Site constraints may limit upsizing drainage systems and other options may have to be envisaged at greater costs.

- **Freeze-thaw cycles**: The projected decrease in the number of freeze-thaw cycles will be beneficial for buildings.

### RETROFIT COSTS

- **Extreme heat**: Design soft- and hardscaped areas to mitigate heat island effect (more vegetated area, white concrete, trees providing shade, asphalt coatings to reflect long wave UV). Civil infrastructure is expected to require low additional retrofit costs due to changes in this climate hazard in the future.

- **Extreme rainfall**: For sewers, upsized capacity would be needed to meet future rainfall events. Alternatives may include source control and local retention. Civil infrastructure and landscaping may require stormwater ponds, infiltration galleries, retention or detention tanks to slow and minimize runoff rate and quantity.

- **Freeze-thaw cycles**: The projected decrease in the number of freeze-thaw cycles will be beneficial for buildings.

## STRUCTURE

### USEFUL SERVICE LIFE

Structure accounts for approximately 6.2% of the reduction of USL of the entire building (i.e., smallest portion compared to other components). The reduction of service life attributed to structure should not exceed 2%. Structural components of buildings are not expected to be impacted by temperature parameters selected for this assessment.

- **Extreme rainfall**: Given an expected 31%-increase in average extreme rainfall (according to the high range of RCP8.5 projections), the impact on the USL of a typical building structure (independent of location) can be between 0.2% and 0.5% with a most likely value of 0.4%. However, structure represents only 5% of the expected reduction in USL associated with extreme rainfall. The cumulative effects of the increase in annual precipitation may result in higher groundwater table conditions that can affect the foundation drainage systems and waterproofing membranes in foundation walls, increasing the potential for moisture and water infiltration. Roof structure and substructure materials are equally affected, followed by the superstructure. Based on Ontario locations selected in this analysis and comparing two different standards (National Building Code of 1960 and Ontario Building Code of 2012), the rain load has mostly not been governing structural design. The two codes mentioned reflect an increase in rain load and a decrease in snow load. However, the increase in rain load remains below the critical threshold defined in design standards for the time horizon selected. The combination of the evolution of average precipitation and annual freeze-thaw cycles best represents the influence of climate change to the structure components. Only horizontal structure components (substructure, foundations, and roof structure, where water accumulation is most likely) is considered vulnerable. For instance, design data (Ministry of Municipal Affairs and Housing, 2014) for Kitchener considered average annual precipitation of 780 mm while a 22.2% increase in annual rain is projected for this region by the end of the century under RCP8.5 scenario (Cannon et al., 2020).

- **Freeze-thaw cycles**: An increase in freeze-thaw cycles would accelerate the deterioration of exposed elements of the structure (concrete surface, joints, and mortar) due to penetration of water and subsequent freezing. The increase use of aggressive de-icing products may also increase the rate of deterioration. Given the projected decrease in freeze-thaw cycle, a small increase in USL is likely to occur at the portfolio level.

### O&M COSTS

- **Extreme rainfall**: O&M shares are and will mostly be related to increased monitoring. O&M spending attributed to structure is expected to be the lowest among all building components.

- **Freeze-thaw cycles**: Decreases in O&M costs will be mostly due to less frequent repairs (e.g., sprawling concrete in sidewalks, entrances, and access ramps). Impacts of climate change on O&M costs will only affect exposed elements of the structure.

### RENEWAL COSTS

- **Extreme rainfall**: Shifts in precipitation patterns (e.g., rain episodes in winter) may have greater impacts on the structural capacity than the average annual precipitation. This is consistent with current changes and updates in applicable building codes.

- **Freeze-thaw cycles**: Climate projections show an overall decrease in the annual number of freeze-thaw cycles which will be beneficial for the structure

### RETROFIT COSTS

Structural components of buildings are not expected to be significantly impacted by the temperature parameters selected for this assessment and therefore impacts on retrofit costs are unlikely to occur.

- **Extreme rainfall**: Structure could need to handle greater loading on the roof due to stormwater detention, but this impact alone should be negligible (without consideration of snowfall precipitation). Rainfall resilience of the structure will not represent the lion share of the building retrofits costs.

- **Freeze-thaw cycles**: As the total number of cycles is projected to decrease on an annual basis, retrofit costs will most likely decrease.

## ENVELOPE

### USEFUL SERVICE LIFE

- **Extreme heat**: A significant increase in July daily maximum temperatures are expected to occur in the near future, with higher increases in the medium- and long-term. For example, using the Kitchener projection data (one of the references in this study), the historical number of days with a daily maximum temperature above 32°C is 0 to 8 days. Future projections (RCP8.5) shows this will increase to a projected 5 to 39 days in the 2050s and 40 to 93 days at the end of the 21st century. Even a greater increase in daily maximum temperature is expected in the North of the province. Extreme heat could increase the range of operative temperatures for brick walls, increasing thermal expansion beyond its historic range. Extreme heat could increase the operative temperatures for metal panels, increasing thermal expansion beyond its historic range. This could result in chalking of non-metallic window framing. As windows also protect the indoor environment, aged windows with poorer heat rejection / thermal performance could result in suboptimal operations (HVAC, comfort). An increase in deterioration of PVC membrane systems and associated sealants remains likely. Finally, extreme heat could increase the operative temperatures for copper panels, increasing thermal expansion beyond its historic range.

- **Extreme rainfall**: Given a significant increase in the IDF 15-min 1:10 (according to high-range projections of the RCP8.5 scenario), the impact on USL on the typical building envelope could be between 1.0 and 2.3%. Impacts will likely be more pronounced for:

    - sealants in flat or low slope openings (e.g., skylights) or, if accompanied with wind, to windows;
    - ineffective roof drainage systems (designed with older standards, damaged or poorly maintained);
    - masonry walls (mortar deterioration, penetration of moisture leading to future damage); and
    - damage to exterior elements due to winter rain followed by sub-zero temperatures.

    It is therefore realistic to expect that impacts from extreme rainfall will reduce the USL of building envelopes for the portfolio by approximately 2% (i.e., reduction of less than one year of USL of the envelope for a building with an average 50-year USL). Extreme rainfall could negatively affect sealants, overload internal drainage channels, contributing to leakage and failure (fogging) of the insulated glass units (IGUs). As for roof PVC, extreme rainfall could overwhelm drainage systems leading to pounding or structural overloading, which is not membrane system specific. It could also exploit existing breaches in the roof system contributing to insulation wetting or leakage. Regarding copper, extreme rainfall could negatively affect sealants and contribute to leakage. When combined with wind, extreme rainfall can produce damages to sealants in openings (doors, windows, skylights) and allow water infiltration in walls and interior (for instance: Public Works and Government Services Canada and Engineers Canada, 2008). Damage may also occur in masonry walls (mortar deterioration) or moisture accumulation if weep holes are plugged. If rainfall occurs in winter or spring and is followed by sub-zero temperatures, ice formation will accelerate the deterioration of sealants and other envelope elements that will reduce their service life.

- **Freeze-thaw cycles**: Freeze-thaw cycles are expected to decrease, which will result in less severe triggering of defects within brick and stone walls, leading to slower deterioration. Freeze-thaw cycles will increase the rapid cyclic temperature range, potentially increasing “pumping” of insulating glazing units (IGUs) and reduce their service life. Decreased exposure to freeze-thaw cycles may induce less damage window materials. Since subcomponents of the envelope have varying service lives, the overall increase in USL of the envelope remains low.

### O&M COSTS

- **Extreme heat**: For suboptimal operations (HVAC, comfort), more frequent usage is expected to increase the cost of operations. Higher temperature peaks make the system more vulnerable to frequent maintenance. Building envelopes are not designed for such high temperatures will also have impacts on the indoor environment, which may result in higher overall building operational costs (energy consumption) due to increased cooling. Roofing materials are likely to be more affected by increases in daily maximum temperature than other envelope components, and therefore will require more frequent inspections and possibly maintenance and repairs as well. Productivity of staff working outdoors will also be impacted during high temperature events, thus potentially increasing maintenance and repair time (and costs) and possibly delaying other maintenance activities or requiring additional staff hours (e.g., overtime or additional resources). Additional costs may be incurred when temporary AC units (windows, portable) are used to maintain acceptable indoor temperature in buildings with deficient or no AC capabilities.

- **Extreme rainfall**: Extreme rainfall will lead to an increase in monitoring of the leaks. WSP considers that PVC and bitumen of the roof envelope could require up to respectively 20% and 15% more maintenance costs in the worst-case scenario (90% of all buildings in Ontario are affected). Increased inspection activities (sealants of openings, drains) and clear-out (debris from drains) will be required (see Golder Associates (2012) for examples).

- **Freeze-thaw cycles**: When it comes to O&M costs, bricks, a porous building material, are the most vulnerable to climate change type of cladding (between 5 and 25% of attributed O&M increase expected for this type of material). It is assumed they represent the most common type of cladding (approx. 35%). Envelope is particularly sensitive to this hazard, as doors and windows can require more annual maintenance. The decrease in the frequency of freeze-thaw cycles should therefore lead to fewer repairs.

### RENEWAL COSTS

- **Extreme heat**: Finishes on the exterior need to more sustainable to withstand heat. For instance, analysis conducted to assess the influence of cool painting on the thermal response of an Italian residential building concluded that cooling energy consumption was reduced by 10%-20%, and peak operative temperature was reduced by a range of 0.5°C to 1.6°C (Zinzi, 2016).

- **Extreme rainfall**: In the renewal process, roof drainage needs to be sized for future rainfall projections and sufficiently graded to limit pounding. Overall, this climate hazard will have a small impact on renewal costs to consider future climate impacts on this building component.

- **Freeze-thaw cycles**: The renewal cost of envelope materials should be lower, given the expected decrease in the frequency of freeze-thaw cycles.

### RETROFIT COSTS

- **Extreme heat**: Driven mostly by retrofits needed to copper roofs and curtain walls, to make the envelope resilient to extreme heat could represent a fair share of the total CRV of the building.

- **Extreme rainfall**: Basement window openings need to be sealed to ensure perimeter drains and sump pumps will provide adequate protection to avoid seepage into the basement. Cladding and roof retrofit could represent respectively up to 30% and 60% of retrofit costs as a share of the CRV. When extreme rainfall occurs in winter, rain-on-snow may increase the load on some components requiring additional protection measures (e.g., drainage systems, increased load-bearing capacity).

- **Freeze-thaw cycles**: The retrofit cost of envelope materials should be lower, given the expected decrease in the frequency of freeze-thaw cycles.

# MECHANICAL AND ELECTRICAL SYSTEMS

## USEFUL SERVICE LIFE

The reduction of service life attributed to M&E subcomponents is approximately 3.9% in future climate conditions. It is not considered to be the main contributor of the decrease in the total building USL. The analysis considers that the machinery and equipment (also referred in facilities management and building breakdown structures as mechanical and electrical systems) is located inside the building, and therefore not affected by this climate indicator. It is possible, however, that some equipment may remain outside the building envelope (for example, roof-mounted HVAC equipment) that may be affected by extreme rainfall.

- **Extreme heat**: HVAC systems will be the most impacted M&E components in the buildings due to the significant increase in cooling degree-days requirements, but also in the cooling needs in the shoulder seasons (end of spring, early autumn). Increases in temperature could overwhelm capacity of cooling system if the system is designed for historical climate. Heat waves (increasing annual frequency or intensity) are the most problematic hazards regarding reduction of USL. In some cases, it could represent a third of the expected USL reduction that could be attributed to this group component. Possible changes in relative humidity will increase the requirements for dehumidification as well. Finally, buildings where cooling towers are used will be significantly affected during more intense and longer heat waves. In those cases, the system is not capable of recovering. Cooling equipment that will be required to operate at maximum capacity more frequently, and during longer periods of time, will deteriorate faster and thus require repairs and replacements earlier. Typical USL for components of HVAC systems vary from 15 years (e.g., pumps) to 30 years (e.g., boilers, ductwork). Although more impacts are expected on the O&M costs for HVAC systems (more frequent maintenance due to increase use), the USL of components is likely to also be shortened.

## O&M COSTS

- **Extreme heat**: Sub-optimal operations (HVAC, comfort) and more frequent usage is expected to increase the cost of operations. Higher temperature peaks make the system more vulnerable to frequent maintenance. More directly, higher temperature will result in higher costs of operating HVAC. Additional costs may be incurred when temporary AC units (windows, portables) are used to maintain acceptable indoor temperature in buildings with deficient or no AC capabilities. The increase in cooling degree-days will be significant across the province and current HVAC equipment may be required to operate at maximum loads for longer periods resulting in additional maintenance costs and higher operational costs. In buildings where the capacity of the AC system is insufficient or non-existent, additional operational costs (material and human resources) will occur to maintain an acceptable indoor air quality. Furthermore, the shift in seasonal high temperature events, and the increase variability (i.e., temperature swings) - particularly in winter, creates challenges in balancing HVAC systems' operations which demand more staff interventions.

  On another note, there might be less wear-and-tear in heating systems due to a decrease in the number of heating degree-days. But this decrease is relatively much lower than the increase in cooling degree-days by close to an order of magnitude. Benefits of reduced heating are difficult to estimate. From an O&M perspective, balancing HVAC systems during the shoulder seasons will also require increased staff interventions (more operational costs). From a risk management perspective, it is therefore sensible to ignore this beneficial impact.

## RENEWAL COSTS

- **Extreme heat**: Possible renewal cost estimate ranges from low to moderate. A portion of the costs to upgrade cooling equipment may be offset by lower costs of heating equipment. In new construction projects, it would be relevant to leave space for cooling capacity upgrades over time, or to design for easy integration of increased capacity. Energy modelling projects could ensure to optimize the design that should incorporate future cooling degree-days. Such M&E considerations are considered as costly as envelope improvements. Electrical equipment that is not sensitive to heat and humidity is unlikely to lead to additional renewal costs.

### RETROFIT COSTS

- **Extreme heat**: New or added cooling capacity will be required to maintain comfort conditions indoors. Recommendations will be implemented to improve energy efficiency of the building. An increase in the cooling capacity and consideration of innovative options for replacement would be beneficial. M&E systems are expected to be the main driver of costs regarding resilient retrofits related to extreme heat.

## EQUIPMENT AND FINISHING

### USEFUL SERVICE LIFE

The USL of exterior finishing is highly vulnerable to climate change, making this component counting for the highest contributor in terms of reduction of service life.

- **Extreme rainfall**: Exterior finish selections may need to be modified sooner than expected, especially for components installed before 1993 (Day et al., 2002). Roof mounted equipment may be susceptible to damage from rainfall when drainage systems are inefficient (damaged or clogged) and when water accumulation occurs. When extreme rainfall occurs in winter, rain-on-snow may increase the load on some components resulting in damages and need to replace. The service life of equipment and finishes is shorter than for the building structure and envelope. These elements are expected (equipment) to be replaced or renewed (finishes) once or more during the USL of the entire building. It is expected that the equipment/materials used when replacements/renewals take place will consider the “new climate normals” and therefore would be adapted to the future precipitation patterns (frequency and intensity of events).

  If the USL of these elements is in the order of 10 to 20 years, the expected reduction in USL due to this climate hazard will be low (several months), which may be less than the timing of planning and implementing corrective measures for all “wear and tear” interventions.

### O&M SHARES

- **Extreme rainfall**: Outdoor finishing are expected to be significantly impacted (+15% in O&M costs). Roof mounted equipment may be susceptible to damage from rainfall when drainage systems are inefficient (damaged or clogged) and when water accumulation occurs, requiring more frequent inspections and clean outs. Elements already deteriorated would likely reach a stage where additional inspections and maintenance are necessary. When rainfall occurs in winter, rain-on-snow may increase the load on some components resulting in the need to increase snow removal operations.

### RENEWAL COSTS

Renewal costs are expected to represent approximately 25% of the total CRV for a resilient building increase compared to a standard renewal.

- **Extreme rainfall**: The selection of exterior finishes selection may need to be changed to withstand more extreme rainfall intensity/duration/frequency. Exterior equipment is likely to sustain little or no impacts from this climate indicator at the projected future intensity. The impact on renewal costs linked to finishing from this climate hazard is expected to be low.

### RETROFIT COSTS

Retrofit costs should be relatively lower comparatively to other components.

- **Extreme rainfall**: The selections of exterior finishes may need to be modified to withstand more extreme rainfall intensity/duration/frequency. Older exterior equipment may have to be relocated outside of potentially flooding areas due to increase in frequency and intensity of short duration / high intensity rainfall events.

## B. ROADS

## PAVEMENT

### USEFUL SERVICE LIFE

The estimated impact of extreme heat and extreme rainfall on the USL of roads from the CIPI project are slightly less than the 32% by 2040 estimated by Ouranos for the Ministère des Transports du Quebec projections (Ouranos, 2015).

- **Extreme heat:** Pavement materials, especially asphalt, are significantly affected by high temperatures. Asphalt is more vulnerable to extremely high temperatures than concrete and gravel due to its viscosity and plasticity. At the same time, higher and more frequent high-temperature days may impact the curing of concrete pavement if there is a smaller optimal temperature window for proper curing, which may affect USL. Therefore, WSP expects that asphalt's useful service life will most likely decrease by 10% to 20%, whereas concrete should only decrease by 0 to 5 %. The USL of gravel roads will likely remain the same. Extremely high temperatures (over 30°C) can reduce heat dissipation efficiency, which can cause asphalt pavement to soften. This softening occurs because asphalt temperature design criteria are typically 59°C or 64°C, and asphalt temperatures are often more than 20°C to 25°C higher than outside temperature due to low albedo. Extreme heat increases the risk of cracks forming through thermal weathering, leading to water infiltration that weakens the base/subbase. A weak base/subbase can lead to surface issues such as potholes.

  At higher temperatures, asphalt binders are more prone to permanent deformation. Using a higher temperature grade asphalt binder can help to alleviate this issue. For concrete pavement, high temperatures can cause more frequently warping/curling and blow-up due to slab expansion. Mitigative measures may include shortening joint spacing, installing high-quality expansion joints, and checking that expansion joints are functioning correctly. Maintenance for distressed concrete pavement may consist of edge grinding, while rehabilitation may include slap replacement and retrofitting with load-transfer devices.

- **Extreme rainfall**: Typically, there is a target of 20 years of useful service life for asphalt roads before planning significant repairs, with no material distinction made between granular material for the base and subbase. Bitumen is blended with asphalt due to similarity in terms of climate-related considerations. Cured asphalt and concrete surfaces are not vulnerable to extreme rainfall. Gravel surfaced roads are vulnerable because increased rainfall can increase erosion of the granular materials and washout of finer fill materials (sand). This increased rate of deterioration will most likely reduce service life by 20 to 25%. WSP assumes that gravel roads represent 37% of all total road length. However, their attributed share of the current replacement value should be lower due to their smaller unit costs.

  Extreme rainfall may cause washout of sand materials that fill voids between gravel, as well as increased upward fine migration from subgrade soil and contaminate base/subbase, further reducing drainage. It may also reduce base/subbase strength supporting the road surface layers and reduce overall service life of the pavement by 25% or more. WSP assumes that approximately 59% of road length in Ontario is paved. Before it is fully cured (~< six months) asphalt is more vulnerable to damage from heavy rainfall, particularly if the road surface is not properly drained. Most of the damage will occur if water can accumulate in cracks. Note that no material distinction is made between granular material for the base and subbase. Bitumen is blended with asphalt due to similarity in terms of climate-related considerations.

- **Freeze-thaw cycles:** While future climate projections suggest fewer freeze-thaw cycles over time, WSP is concerned that winter liquid precipitation will increase. The negative impact on deterioration should exceed the possible USL benefit caused by the reduction of winter freeze-thaw cycles. These processes present the possibility for "negative" trends in the data. In Eastern Ontario, pothole patrols are increasing throughout the winter, and pavement degradation is happening earlier in the season, lowering USL. Deep freeze-thaw cycles will have more impact on the surface. WSP has entered values for conservative assumptions about USL reductions due to larger and longer temperature swings. However, the FAO decided not to apply these results as climate projections diverged.

### O&M COSTS

- **Extreme heat:** O&M cost shares expected to increase for asphalt pavements (which represent approximately 60% of all Ontario roads) due to noted sensitivities. Increase in extreme heat will cause more cracking and will result in more crack sealing effort to prevent water infiltration until the surface is rehabilitated or replaced. Asphalt pavement materials are significantly affected by high temperature. At higher temperature, the asphalt binder becomes more viscous and more prone to permanent deformation (rutting) thus requiring increased maintenance.

  Concrete and gravel road O&M will likely remain similar with only marginal increases in the worse-case scenarios.

- **Extreme rainfall**: WSP expects that operations and maintenance costs will remain relatively consistent but that but that the need for some maintenance activities (e.g., crack-sealing and patching) may increase as extreme rainfall speeds up the development of distress in pavement. O&M costs for base/subbase should remain the same because most maintenance activities only apply to the surface layer. Water can cause loss of aggregates, which can be fixed by localized O&M or more substantial rehab/reconstruction, depending on the scale. If not adequately constructed initially, increased extreme rainfall may trigger the need for local repairs to improve camber. Local washing of material on the edge of roads may also require minor repairs to the surface.

- **Freeze-thaw cycles:** Increased deterioration due to freeze-thaw cycles in saturated conditions may require additional inspection and preventive maintenance, increasing O&M costs. This is consistent with WSP professional judgements and experiences in Ontario. Therefore, it is unlikely that climate change will alleviate the costs of road maintenance in Ontario due to pavement failures resulting from freeze-thaw cycles. However, the FAO decided not to apply these results as climate projections diverged.

### RENEWAL/RETROFIT COSTS

- **Extreme heat:** Asphalt mixes will need to use a higher Performance Graded Asphalt Cement (PGAC) additive to accommodate higher temperatures and more high temperature days, at a 5% to 10% construction premium. As noted, higher temperatures and more high temperature days may result in additional measures required to keep concrete curing conditions optimal, or concrete slabs will have to be constructed off-site and transported to the worksite with anticipated construction cost premiums of around 10% or more. Extreme heat increase for surface will result in possibly more cracking. When the surface is ready for resurfacing, a bitumen that can resist better to higher temperature can be used to lessen the probability of cracking. No anticipated change in CRV for gravel road.

- **Extreme rainfall**: Specialized asphalt mixes such as Stone Mastic Asphalt (SMA) may be utilized to improve asphalt drainage to improve road safety, with a 15% to 20% cost premium. Gravel surfaced roads may require higher quality materials or micro-surfacing with cost premiums of 50% or more to mitigate drainage or erosion issues caused by extreme rainfall. Higher quality granules in the base/subbase layers, or increased base/subbase layers, or usage of geogrids and subdrains may be required at additional costs at 40% to 80% premium or higher, to facilitate improved drainage to accommodate extreme rainfall and mitigate erosion and deterioration of the base/subbase layer. The increase in CRV for surface will be due to using materials with better permeability to prevent damage caused by rainfall to the surface but mostly to protect the base and subbase better. In the case of gravel, it might mean coarser material.

  **Freeze-thaw cycles**: To reduce cracking in asphalt and concrete, using a binder more resistant to lower temperature and significant winter rain might be helpful but this improvement is not dictated by impacts of climate changes. For gravel roads improvements would involve more strengthening in the gravel layer, often by adding more material or installing geotextiles; note that this is not an improvement required by climate changes alone. However, the FAO decided not to apply these results as climate projections diverged.

## ROAD ASSOCIATED STRUCTURES

### USEFUL SERVICE LIFE

- **Extreme heat:** At higher temperature, there is an increased potential of bonding failure between the paint and the pavement surface. Aging of pavement marking is therefore accelerated and requires more frequent reapplication. Extreme heat will have a marginal impact on pavement marking USL, as it would be replaced in conjunction with the asphalt below. WSP considers their likely be a different formulation in paint in the future that would better “stick” to the asphalt as it softens - there would be a premium for this paint in a replacement/maintenance scenario.

- **Extreme rainfall**: The most significant impact of extreme rainfall is expected to be erosion, reducing service life by approximately 10%. Extreme rainfall increases the likelihood of erosion and washouts due to the volume of water, overwhelming of existing drainage features (curbs, gutters, subdrains, etc.) that are above/below retaining walls and embankments.

  Increased precipitation intensity will also shorten USL as water penetrates the base and subbase materials, reducing their bearing capacity, and increasing the potential for differential settlement. Increase potential for shrinking/swelling due to moisture changes is also a concern with extreme rainfall events occurring after drought periods. Extreme rainfall impacts may be more pronounced in embankments.

- **Freeze-thaw cycles:** Freeze-thaw cycles may affect the footing of barriers or destabilize posts. However, in view of some reduction in the number of FTCs, very minor impacts are expected to either pavement markings or barriers. Again, liquid winter precipitation remains a concern given the role of ground saturation in the effectiveness of frost weathering.

  Pavement markings would need to be maintained/replaced in the same cycle as the asphalt. It would need a pretty significant freeze thaw to cause issues for barriers. Very little positive change/impact there.

### O&M COSTS

- **Extreme heat:** Minimal to no impact expected on marking due to increase in maximum temperature and higher number of warm days.
- **Extreme rainfall**: O&M activities should remain fairly similar. Additional inspection and intervention may be required to monitor deterioration from erosion caused by extreme rainfall.
- **Freeze-thaw cycles:** No significant change in O&M would be expected as a result of changes in the frequency of freeze-thaw cycles.

### RENEWAL COSTS

- **Extreme heat:** Application of paint that has a higher tolerance for heat and sun exposure would likely slightly increase CRV for road associated structure by, in particular in warmer areas of Ontario.
- **Extreme rainfall**: To account for additional extreme rainfall, increased strengthening for material retention will be required which is likely to increase CRV. Additional premium costs of 10 to 15% anticipated for usage of more geotextiles and fewer erodible materials to improve erosion protection and control. Additional cost can be expected from adding strengthening measures or reinforcement during reconstruction. The damage from additional rainfall would likely create more loss of material than expected.
- **Freeze-thaw cycles:** No expected change to pavement markings or barriers’ CRV.

### RETROFIT COSTS

- **Extreme heat:** Extreme heat will not have a high impact on pavement marking rehab. Rehab costs for pavement marking is same as CRV as markings will have to be repainted. Heat will likely cause more cracking in the asphalt. When rehabbing, the contractor will be looking at an asphalt mix that is more resistant to heat than what was previously installed.
- **Extreme rainfall**: Retrofit costs expected to increase by 20 to 25% due to increased erosion and deterioration from greater rainfall. Retrofit costs of embankments should remain similar as embankments have either failed or not failed. In case of failure embankments would generally need to be reconstructed to have its condition

restored. Retrofitting embankments in increased extreme rainfall events is likely to require additional material and some additional stabilizing measure.

- **Freeze-thaw cycles:** Pavement markings do not typically get rehabilitated; they are simply repainted.

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## C. TRANSIT ALIGNMENTS

### USEFUL SERVICE LIFE

- **Extreme heat:** The stress of high temperature on track and all components like rail brace, tie plates, insulated joints is major. We can consider between -30% and -40%. Dilatation of rail pushes on everything on what it sits. Plastics, electronics, moving machinery and asphalt are more vulnerable to extreme heat than concrete and gravel due to the UV degradation of molecular bonds and loss of plasticity properties of plastics, and reducing viscosity of asphalt in high temperatures, which results in higher friction and erosion. With respect to steel, higher temperature increase friction between train wheels and tracks, which is costly because potentially resulting in buckling of tracks. Thus, considering the fact that the extreme heat is expected to exceed 40 degrees and based on experience, the useful service life (USL) of level crossings will most-likely decrease by 9 to 19%, whereas tracks should only decrease by 2–5%. As a crossing surface, asphalt and rubber are more venerable to extreme heat than wood or concrete due to their physical attributes. Therefore, as the temperature and number of hot days are expected to increase, the USL shall decrease by up to 20%, whereas the USL of concrete or wood will likely only decrease by 5%. The electrical components of an active crossing are most likely to be affected by extreme heat, whereas there is likely to be little to no impact on a passive crossing. Therefore, impact on an active crossing is likely to be up to 15%, whereas the impact on a passive crossing likely will not exceed 2%. These projections are based upon current observations of rail and transit operations in hotter climates.

  Higher occurrence of rail buckling due to extreme heat will result in an overall reduced USL of less than 10% for rails. The buckling probability become exponential once the temperature exceeds 32 to 35 degrees (Chinowski, 2017).

### O&M COSTS

- **Extreme heat:** Considering extreme temperatures exceeding 40 degrees in Southern Ontario in 2051–2080 climate conditions, the cost of operation and maintenance (O&M) of existing assets is expected to increase, particularly for components made of plastics, hydrocarbons, asphalt, and wood, which are commonly used in level crossings. Less affected are O&M activities related to steel and concrete. Thus, considering the expected extreme heat estimates, the O&M cost of level crossings will most likely increase to approximately 1% for the most parts. As the current level of operation and maintenance required for crossing surfaces and passive crossings is negligible as the assets typically are not maintained throughout their USL and instead replaced, there is expected to be little impact of the O&M effect.

  Of the crossing surface types, there likely will be more of an increase to wood and asphalt, with a greater delta for asphalt. In an extreme case, the increase for asphalt will be 6%. An active warning system’s componentry currently requires maintenance and can be affected by heat. We estimate there likely will be a 5% to 10% increase on the annual cost of maintenance as a share of the CRV based on current observations of rail and transit operations in hotter climates. As the current level of operation and maintenance required for rail ties is negligible since the assets typically are not maintained throughout their USL but instead replaced, there is expected to be little impact of the O&M effect. More movement of the track means more maintenance for active crossings and more periodic inspections. For passive crossing it is a bit more for material and part of the periodic inspections that will be increased.

  There are relatively high maintenance costs associated with track buckling prevention because even greater costs can result from derailments.

## RENEWAL COSTS

- **Extreme heat:** Renewals are expected to require increased stability of rail (type of anchorage on and beside crossing). Rubber will be used more frequently compared to asphalt on active crossings so the cost will be higher. Adequate tie plates and anchors to accommodate the dilatation of the rail are also expected to be required. Temperatures will vary from very low to very high and likely need to increase the level of stability and the level of flexibility, which is challenging when dealing with extreme values. For passive crossing, the impact should be minor since mainly wood is required and rail is freer than active crossings.

  The CRV of level crossings will most-likely increase to 110% to ensure material used in moving components are tolerant to higher operating temperatures. The use of rubber, concrete and asphalt CRV is likely to increase more than wood as they are "designed" materials; hence there is a greater possibility for innovation (new mix designs, etc.), which could increase the cost share of the current CRV up to 130%. The 5% to 10% increase on wood accounts for the potential of alternate sourcing and treating of the material.

  Due to the complex nature of active warning systems, and current observation of the perpetual innovation and upgrades that are implemented in active warning systems, we believe that there is likely to be a 120% to 150% increase of the current CRV, just due to the influence of extreme heat. Since passive crossings are very simplistic by nature (generally only 2 to 4 signs required), there is very little room for redesigning the asset. There might be changes to the materials used, which accounts for our 105% increase. These projections are based upon current observation of rail and transit operations in hotter climates.

  As for tracks, concrete, and steel CRV are likely to increase more than wood as they are "designed" materials which could increase the cost share of the current CRV up to 125%. The 5% to 10% increase on wood accounts for the potential of alternate sourcing and treating of the material. These projections are based upon current observation of rail and transit operations in hotter climates.

  Resilient structural adaptation will include changing rail distressing temperatures to reduce likelihood of rail buckling.

## RETROFIT COSTS

- **Extreme heat:** Typically, there is little to no retrofit done on crossing surface (i.e., wood, concrete, asphalt & rubber). In general, the whole crossing surface is replaced. However, retrofits can be completed on wood and asphalt crossing surfaces by such measures as replacing wooden planks or mending cracked asphalt. Therefore, there is no impact on the retrofit costs for rubber or concrete surfaces, and a projection of up to 30% for asphalt and wood crossing surfaces. Likewise, there is typically very little retrofits done to a passive crossing. However there is a slight chance of estimated 10% of the cost to retrofit for passive crossing signs that would require to be rehabbed/retrofitted to address the extreme heat.

  Due to the nature of an active crossing, the cost for retrofitting an active crossing warning system, without the impacts of climate change, could be up to 100% (or more, in extreme cases) of the cost of the CRV. Warning systems not only require the physical components (i.e., the lights, bells, gates, masts, etc.) but every warning system requires computer programing, testing, and commissioning to integrate the system into the track and roadway. These costs often outweigh the cost of the physical components. Therefore, the "Bad" case rehab cost will likely be 100%, as the cost for the physical components may increase slightly, but the bulk of the cost will remain with the integration of the warning system into the track systems.

  For all intents and purposes, there is no retrofit to ties. Broken or damaged ties will be replaced instead of repaired. Ties, regardless of their material type, are periodically replaced in specified intervals depending on, but not limited to, the material type, location of use and the weight and frequency of rail movements on the alignment. Therefore, there is a blanket 0% increase on the cost to retrofit. For the track, we might have to introduce new equipment for stabilization.

## RAIL ASSOCIATED STRUCTURES

### USEFUL SERVICE LIFE

- **Extreme heat:** Plastics and electronics are generally more vulnerable to extreme heat than concrete and gravel due to the degradation of molecular bonds and loss of plasticity properties of plastics (vinyl), and reducing viscosity of asphalt in high temperatures, which results in higher friction and erosion. Plants are extremely sensitive to extreme temperatures, and some noise walls are covered with creeping plants. Thus, considering the fact that noise walls have components made of plastic and potentially organic, and the extreme heat is expected to exceed 40 degrees, the useful service life (USL) of noise walls will most likely decrease by 20%, whereas concrete crash walls may not be affected by extreme heat and its USL should stay the same.

### O&M COSTS

- **Extreme heat:** O&M for the living wall may significantly increase due to increase plant care requirements for the living vegetation in extreme heat. Absolute value of this cost increase should, however, remain limited due to the small share of the total asset value that could be attributed to living wall. Probable limited physical impacts and even more limited when it comes to financial impacts.

### RENEWAL COSTS

- **Extreme heat:** Concrete and vinyl CRV are likely to increase as they are “designed” materials; hence there is a greater possibility for innovation (new mix designs, etc.), which could increase the cost share of the current CRV up to 130%. The CRV value for a living wall may lower to 80% or may increase to 130% as the change in temperature may allow for different vegetation options that previously would not have thrived in this application. Likewise, the increase in the CRV value may be due to the same factor. Living walls would not be the preferred options for noise walls.

### RETROFIT COSTS

- **Extreme heat:** As there is a chance the extreme heat could be high enough to kill all the vegetation on the living wall which would increase the rehab value to 100%. Retrofitting of concrete and vinyl will likely include structural considerations which could increase the value up to 50%. Likely, though, the work would not include major structural work and would only be about 15%.

## EQUIPMENT AND FINISHING

### USEFUL SERVICE LIFE

- **Extreme heat:** Plastics, electronics, moving machinery and asphalt are more vulnerable to extreme heat than concrete and gravel due to the degradation of molecular bonds and loss of plasticity properties of plastics, and reducing viscosity of asphalt in high temperatures, which results in higher friction and erosion. Thus, considering the fact that communication devices have components made of plastic, and the extreme heat is expected to exceed 40 degrees in Southern Ontario, the useful service life (USL) of communication devices will most likely decrease by 20%. Similarly, power supply transformers and rooms storing communication devices have cooling devices that are sensitive to extreme heat exceeding 40 degrees.

### O&M COSTS

- **Extreme heat:** For power supply, O&M will be higher due to increased energy costs. There might be a need to remotely monitor or to conduct more periodic on-site visits which could represent approximately 20% more maintenance.

### RENEWAL COSTS

- **Extreme heat:** Increases in power supply needs and higher operating temperature requirements are likely to result in higher costs of equipment, including signals and control equipment. WSP considers that approximately 60% of the total value could be affected. Cost is also likely to be higher because all equipment will be designed to meet new (climate) standards.

### RETROFIT COSTS

- **Extreme heat:** If resilience work is required due to this climate indicator on power supply equipment, it will be more expensive because of the need for higher temperature extremes operating parts. WSP assumes that 60% of the power supply equipment value could be subject to resilience work. As for signals, cost will be higher since existing equipment will have to be rebuilt more often and reconsider what must be used and reused. Ten percent more for rebuilding, approximately.

## ROLLING STOCKS

### USEFUL SERVICE LIFE

- **Extreme heat:** Plastics, electronics, moving machinery are more vulnerable to extreme heat than steel due to the degradation of molecular bonds and loss of plasticity properties of plastics. Considering the fact that locomotives are primarily made of steel and have a lot of steel wheels, the only impact of extreme heat would be higher friction between locomotive wheels and steel tracks. Considering that the extreme heat is expected to exceed 40 degrees in Southern Ontario, the useful service life (USL) of locomotives could decrease down between 0 or 10%. However, Class 1 railroads, such as Canadian Pacific and Canadian National operations span both Canada and the US. Their locomotives currently operate throughout all of Canada and down to the southern states. Therefore, based on current operations of railroads, the impact of extreme heat on the USL could be negligible. Considering the fact that passenger cars these days have many plastic components under the hood, body parts and electronics, the useful service life (USL) of passenger cars will most likely decrease by 5% due to higher deterioration. Rail maintenance equipment is primarily made of steel, their useful service life (USL) will most likely decrease by 5% due to additional maintenance needed to be performed, which results in faster degradation of maintenance equipment. Maintenance equipment currently already operates in climates akin to that of the highest annual temperature due to extreme heat. Ultimately, there is likely to be no change to the USL of the maintenance equipment with an extreme change of -2%. Operations with the same, or very similar maintenance equipment currently operate all over Canada and the US, therefore, based on current operations, the impact on of extreme heat on the USL is going to be negligible.

### O&M COSTS

- **Extreme heat:** Plastics, electronics, moving machinery are more vulnerable to extreme heat than steel due to the degradation of molecular bonds and loss of plasticity properties of plastics. Considering the fact that locomotives are primarily made of steel and have a lot of steel wheels the only impact of extreme heat would be higher friction between locomotive wheels and steel tracks, with means higher fuel and maintenance cost. Locomotives currently already operate in climates akin to that of the highest annual temperature due to extreme heat. Ultimately, there is likely to be very little change to the O&M of the locomotive with an extreme change of 5%. Class 1 railroads, such as Canadian Pacific and Canadian National operations span both Canada and the US. Their locomotives currently operate throughout all of Canada and down to the southern states. Therefore, based on current operations of railroads, the impact on of extreme heat on the O&M may be a slight increase to the current operating and maintenance the locomotives require.

  Passenger cars currently already operate in climates akin to that extreme heat. Ultimately, there is likely to be no change to the O&M of the passengers' cars with an extreme change of 5%. Operations with the same, or very similar passenger cars currently operate all over Canada and the US, therefore, based on current operations of passenger cars, the impact on of extreme heat on the O&M may be a slight increase to the current operating and maintenance the passenger cars require. Ultimately, there is likely to be no change to the O&M of the maintenance equipment with an extreme change of 5%. Operations with the same, or very similar maintenance equipment currently operate all over Canada and the US, therefore, based on current operations, the impact on of extreme heat on the O&M may be a slight increase to the current operating and maintenance the maintenance equipment requires.

### RENEWAL COSTS

- **Extreme heat:** Locomotives, maintenance & passenger cars currently already operate in climates akin to that of the highest annual temperature due to extreme heat. Ultimately, there is likely to be no change to the CRV of the locomotive with an absolute change of 1%. Class 1 railroads, such as Canadian Pacific and Canadian National operations span both Canada and the US. Their locomotives currently operate throughout all of Canada and down to the southern states. Therefore, based on current operations of railroads, the impact on of extreme heat on the CRV is negligible.

### RETROFIT COSTS

- **Extreme heat:** Locomotives currently already operate in climates akin to that of the highest annual temperature due to extreme heat. Ultimately, there is likely to be no need for Rehab/Retrofitting of the locomotive with an extreme change of 1%. Class 1 railroads, such as Canadian Pacific and Canadian National's operations span both Canada and the US. Their locomotives currently operate throughout all of Canada and down to the southern states. Therefore, based on current operations of railroads, the impact on of extreme heat on the need for rehab/retrofitting is negligible.

## *D. BRIDGES AND CULVERTS*

## BRIDGES

### USEFUL SERVICE LIFE

- **Extreme rainfall:** The main anticipated effect of extreme rainfall on embankments and approaches is erosion. This will result in a need to reconstruct approaches or add heavy rock protection to embankments earlier than before. Ancillary represents a very small share of the total asset and based on an approximate increase in rainfall of approximately 50%, the expected reduction of USL attributed to this component is negligible. The main anticipated effect of extreme rainfall on foundation is scouring and erosion. This will result in a need to replace some shallow foundations, which we estimate to represent approximately the most common type of foundations, since they tend to be used on smaller projects. 29% of Ontario's bridges are locals. WSP anticipates that extreme rainfall will have an almost negligible effect on deep foundations as these are not subject to negative effects from scour and erosion. Thus, based on engineering judgment and on a potential increase in rainfall of 55%, bridges USL should be reduced by approximately 7%, due essentially to shallow foundations bridges. Limited deterioration to the substructure. The main anticipated effect of extreme rainfall on substructure elements scours and erosion, which will reduce marginally the asset's USL.
- **Freeze-thaw cycles:** Freeze-thaw cycles contribute to concreting cracking and the vast majority of these components are made of concrete. Thus, reducing the number of freeze-thaw cycles will increase the service life of concrete. Therefore, the values estimated are positive values. Because of reduced freeze-thaw cycles, deck and barriers are expected to perform better than before. It shall be noted that timber deck and metallic barriers are not sensitive to freeze-thaw cycles, but WSP assumed that approximately most of the bridges are made of concrete. This assumption is supported by the fact that overall, there are 1060 bridges across water, 286 over or carrying rail, and 1508 highway bridges in Ontario (Mermigas, 2018). WSP assumes highway bridges and those across water are at least partially made of concrete. The bridge superstructure & substructure are generally protected by the bridge deck and they are not directly exposed to freeze-thaw. Most approaches are asphalt, which heaves significantly in freeze/thaw.

### O&M COSTS

- **Extreme rainfall:** It is anticipated that climate change will increase the cost of maintenance associated with erosion of these components. The values estimated are based on engineering judgment and the current 0.7% share assumed by the model. There is no associated operation/maintenance, or standard upkeep repair cost associated with buried foundation elements. As such, these values have all been set to zero regardless of the impacts of climate change. It is anticipated that climate change will increase the maintenance and preventive small repairs associated with these components. Based on engineering judgment, WSP considers that the cost of such repairs is a large component of the 0.7% value. As such, values entered are greater than this level. The increase in extreme rainfall will have a significant impact on the peak flow volume and velocity of the river channel. Channel protection will be vulnerable to (a) wash out and (b) scour damages. This will significantly increase O&M costs.

- **Freeze-thaw cycles:** Similarly, to the decrease in the reduction of freeze-thaw cycles, there is a probable, but small expected reduction in the annual expenses of O&M.

### RENEWAL COSTS

- **Extreme rainfall:** About 50 percent of the replacement cost is associated with the substructure. Shallow foundations can generally be constructed for 50 to 65 percent of the cost for deep foundations (Briaud & Gibbens, 1995). Thus, shallow foundations resilient renewal is likely to increase the costs, especially if it renewed for a deeper foundation. Assumed added rip rap for foundations in watercourses. Increased rainfall will have a significant impact on reconstruction costs. Assumed 50% more for erosion protection and runoff control. Assumed increased drainage requirements resulting in higher cost.

- **Freeze-thaw cycles:** Decreasing freeze-thaw cycles will have minimal impact on asset resiliency for new bridges. Most of these components are concrete. Bridge concrete components requires air entraining the concrete to be resistant to freeze-thaw. This is current standard practice for all structural concrete. So, there is no significant cost difference between current practice and freeze-thaw resilient concrete.

### RETROFIT COSTS

- **Extreme rainfall:** Increase in drainage and erosion control will be required. On smaller bridges, this could be mostly for retrofitting costs. Retrofitting embankments and approaches would essentially be replacing them, thus the cost per unit is approximately the same. Shallow foundations are more vulnerable to extreme rainfall. WSP considers approximately a 10% cost increase for shallow foundations. Rehabilitating deep foundations would essentially be replacing them so the cost per unit is approximately the same. Minimal, if any, impact on substructure resilient retrofit costs. Rehabilitating substructure elements involves patches and general repairs so the cost as a percent of the asset is relatively low. These different values are based on engineering judgment. For the vast majority of these components, retrofit costs are expected to exceed the renewal cost.

- **Freeze-thaw cycles:** Freeze-thaw will have minimal impact on CRV. Building concrete components to be resistant to freeze thaw require air entraining the concrete. This is current standard practice for all structural concrete. So, there is no cost difference between current practice and freeze-thaw resilient concrete.

## LARGE STRUCTURAL CULVERTS

### USEFUL SERVICE LIFE

  - **Extreme rainfall:** A reduction in large structural culverts USL is expected. Similarly, to bridges, the main anticipated effect of extreme rainfall on bridges is scouring and erosion of embankments, approaches, and shallow foundations.

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### O&M

- **Extreme rainfall:** The increase in extreme rainfall will have a significant impact on the peak flow volume and velocity of the river channel. Channel protection will be vulnerable to (a) wash out and (b) scour damages. This will significantly increase O&M costs. We assume increased cleaning of debris requirements.

  Culverts will be vulnerable to (a) wash out and (b) scour damages. This will significantly increase operation and maintenance cost. Potential increase in operation and maintenance cost is associated with inspections (before and after extreme rainfall events), debris removal and scour hole filling.

### RENEWAL COSTS

- **Extreme rainfall:** The main drivers for channel protection replacement will be erosion due to extreme rainfall or the fact that they are undersized. A large proportion of this asset class will require earlier replacement. As such, values entered are significative. It is assumed that increased precipitation will require larger pipe / structure and associated excavations. The percentages entered here for CRV are representing percentage increases over the replacement cost of the original components. It is expected that most existing culverts are under capacity for the peak flow volume of projected extreme rainfalls and their replacement requires use of a larger size culvert or use of multiple culverts of same size. Similarly, it is expected that most of channel protection will be inadequate for the peak flow velocity of projected extreme rainfalls and their replacement will require using rocks of larger diameter for channel protection. Therefore, CRV will be significantly higher for these components, reflecting the need for increased capacity. It is assumed that increased precipitation will require larger pipe / structure and associated excavations.

The percentages entered here for CRV are representing percentage increases over the replacement cost of the original components. It is expected that most existing culverts are under capacity for the peak flow volume of projected extreme rainfalls and their replacement requires use of a larger size culvert or use of multiple culverts of same size. Similarly, it is expected that most of channel protection will be inadequate for the peak flow velocity of projected extreme rainfalls and their replacement will require using rocks of larger diameter for channel protection. Therefore, CRV will be significantly higher for these components, reflecting the need for increased capacity.

The main driver for wing wall and headwall replacement will be when the associated culverts are undersized. A large proportion of this asset class will require such replacement. Interdependencies with culverts will require upsize.  As such, values were tied to those entered for culverts.

### RETROFIT COSTS

- **Extreme rainfall:** Rehabilitation of channel protection will be costly due to environmental requirements for instream works. It will likely require extensive compensation for habitat losses due to rehabilitation. Rehabilitating channel protection to be resilient to extreme rainfall essentially requires replacing it. Assumed increased cost required to provide protection. Rehabilitation to culverts is restricted to installing additional culverts to increase their capacity.

  Rehabilitating a culvert to be resilient to extreme rainfall essentially requires replacing it. Rehabilitation to culverts is restricted to installing additional culverts to increase their capacity.

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## *E. STORMWATER AND WASTEWATER*

## PIPES

### USEFUL SERVICE LIFE

- **Extreme rainfall:** Pipes will most likely fail due to lack of capacity in extreme rainfall, not structurally. Failure rates will be the same for all pipe material types. Assuming higher intensity and volume approx. Fifty percent increase is likely to significantly reduce the effective lifespan. Performance failure will be due to increased flows and the three pipe types will respond similarly to increased flow volumes. Extreme rainfall events are expected to be stronger and/or more frequent and exceed the built-in margins of safety. Based on previous climate risks assessments (PIEVC, others), it can be expected the reduction of service life due to lack of capacity to be anywhere from 10–30%. However, capacity is not considered in the coefficient, thus the cost coefficients are assumed to be not significant.

  WSP considers that the USL of drainage pipes is relatively independent from other subcomponents of the drainage system (ditches, culverts) and they could represent a little bit less than half of the CRV of storm water linear infrastructure.

### O&M COSTS

- **Extreme rainfall:** Drainage infrastructure, depending on their condition and capacity will require more frequent and costly inspections. Intervention and preventive maintenance are expected to increase as more debris, sediment & vegetation are expected to flow from increased intense precipitation events. Most pipes are small, which justifies the interaction with the 2-year events. Corrosion risk must be monitored (Sustainable Solutions Corporation, 2017).

### RENEWAL/RETROFIT COSTS

- **Extreme rainfall:** The risk of flooding is real and justify greater capacity. Increase in terms of capacity will result in higher cost of replacement. The majority of drainage pipes are not sized to be able to capture these more frequent/intense rainfall events. There are likely going to have a cost increase to increase capacity (including the costs of deeper excavations if larger pipes are installed) and even if a certain part is a fixed cost (for instance, right of way restoration that is 30% to 40% of the total installation costs). The relation between the increase in rainfall patterns & the capacity requirement is not linear due to collecting/funnel proprieties of these assets. It is expressed as an increasing marginal cost whereas the cost increase is greater than the climate variation. Greater pipes are going to be buried deeper.

  Note that it is cheaper to replace completely than retrofit/rehab the existing assets and therefore the owner of the asset may decide to replace all together as opposed to retrofitting. Retrofitting stormwater assets to make it climate resilient would be either upgrading to a larger pipe, twining, or incorporating “green infrastructure” solutions to reduce and slow down stormwater. WSP considers that retrofitting drainage pipe has the potential of being more costly than renewing the assets completely. Note that combined systems are not considered under stormwater systems. However, due to similarity of engineering work to be conducted for renewal or retrofit, both cost elasticities were combined.

## DITCHES

### USEFUL SERVICE LIFE

- **Extreme rainfall:** Vegetated ditches may see some capacity issues from increased precipitation. This type of drainage infrastructure would be less sensitive than a piped system and so impact on the USL is expected to be less significant. Reinforced ditches will be more resistant to collapse but will perform the same as earth ditches regarding capacity. Unlike pipes, ditches tend to be constructed with more capacity. Ditches are highly common infrastructure in Ontario.

  WSP considers that the USL of ditches is relatively independent to other subcomponents (pipes, culverts) and they could represent half of the CRV of all storm water linear infrastructure in Ontario.

### O&M COSTS

- **Extreme rainfall:** Vegetated ditches may see some capacity issues from increased precipitation. Unlike pipes, ditches tend to be constructed with more capacity. Maintenance involves cleaning out, sectoral profiling & pruning. Sectoral profiling & cleaning out will be more frequent, thus more costly, with climate change.

### RENEWAL/RETROFIT COSTS

- **Extreme rainfall:** Vegetated ditches may see some capacity issues from increased precipitation. Making this asset more resilient and less sensitive than a piped system and so impact on the CRV is expected to be less significant. The costs if mostly driven by more reinforced ditches that will be more resistant to collapse but will perform the same as earth ditches regarding capacity. Unlike pipes, ditches tend to be constructed with more capacity.

- Note that it is often less costly to renew ditches that retrofitting since the ditch drainage system is gravity-based and requires continuity in slopes to adequately operate. Vegetated ditch replacement would include digging out the ditch. Concrete or geotextile used in a reinforced ditch would represent higher cost. To retrofit increased capacity for ditches would be similar to the construct new except possibly for reduced excavation. The cost of retrofits will be higher because the efficiency is reduced compared than renewal and the additional works required to maintain the gradient of the system for proper water evacuation, with possibly the installation of additional elements to the system.

## SMALL NON-STRUCTURAL CULVERTS

### USEFUL SERVICE LIFE

- **Extreme rainfall:** The primary mode of failure for wingwalls and headwalls in extreme rainfall will be insufficient capacity and a secondary less likely mode of failure will be damaging structure from the event either by debris or scour, which should not significantly affect the costs. Gabion baskets would also be minimally impacted by increasing rainfall. Expect riprap/stones and concrete to perform similarly under increasing rainfall. Earth fill would see the largest drop in USL as it would be subject to significant erosion. Performance failure will be due to increased flows.

  WSP considers that the USL of small culverts is relatively independent to other subcomponents and they could represent a very small share of stormwater linear infrastructure in Ontario, with only 5% of the total CRV of stormwater linear infrastructure.

### O&M COSTS

- **Extreme rainfall:** Small non-structural culverts are going to require more maintenance. More frequent scouring due to increasing presence of debris and larger volume of sediments. Without adaptation measure, cleaning will be more frequent. Ideally, culverts are inspected and cleared before and after significant rainfall events to ensure they have the intended capacity.

### RENEWAL/RETROFIT COSTS

- **Extreme rainfall:** Culverts and their complementary components will have an increase in cost. In the best scenario, the existing size of culvert had some extra capacity in the design because not everything is sized to minimum standards. The cost increase is expected to be a little bit smaller than for drainage pipes due to its additional capacity, but, however, is not insignificant. Small non-structural culverts are also often installed in areas where there are few limitations to upsizing; the increase in cost is mainly due to the costs of the culvert - installation is considered fixed costs. Retrofit capacity for extreme rainfall will require additional excavation and reinforcement. Retrofit for wingwalls and headwalls will require an additional unit for a second culvert will require the installation of a duplicate/twin culvert. Retrofit should incorporate other onsite retention solutions, not only focus on the specific asset. Rehab due to extreme rainfall will likely be focused on soil erosion and piping around the headwall. Renewal and retrofit essentially use the same solutions: bigger pipes, twinned pipes, or source control. It would therefore be expected that the cost increases would be in the same range.

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## GRAVITY SEWER

### USEFUL SERVICE LIFE

- **Extreme rainfall:** Higher rainfall infiltration into wastewater mains is expected, especially for older assets. Inflow contribution is going to be problematic, especially for combined sewer systems. More intense rainfall events are expected to produce infiltration spikes. However, similar to stormwater systems, the major risk remains capacity concern. For separated systems, which is assumed to represent the greater share of wastewater systems in Ontario, increased flows due to infiltration only will likely cause a performance failure due to capacity rather than a material or structural failure. Inflows and infiltration are mostly caused by rainfall events and less frequently by snow melt of fluctuating water tables..Therefore, the impact on useful service life was assumed to be zero.

### O&M COSTS

- **Extreme rainfall:** Similarly, to drainage pipes, gravity sewers, depending on their condition and capacity will require more frequent and costly inspections. Interventions and preventive maintenance are expected to increase as more debris, sediment & vegetation are expected to flow from increased intense precipitation events, specifically for combined sewer systems. Most pipes are relatively small, which justifies the interaction with the 2-year events.

### RENEWAL/RETROFIT COSTS

- **Extreme rainfall:** For combined system, performance failure will be due to increased flows. The three pipe material types will respond similarly. As for separated systems, increased flows due to infiltration only will likely cause a performance failure due to capacity issues rather than a material or structural failure. Inflows and infiltration are mostly caused by rainfall events and less frequently by snow melt of fluctuating water tables. It is often very difficult to differentiate the contribution of inflows versus infiltration to excessive wastewater flows beyond the rates predicted at the design phase, but WSP considers that separating system that is currently combined is going to be an operation significantly more costly (approx. Forty percent, according to one of our SMEs), explaining the high-cost increase predicted even if replacing serrated systems is going to be less costly than for drainage pipes.

  Making resilient a combined sewer to make it resilient to extreme rainfall will either require an uprising of the pipe or implementing a green infrastructure solution to reduce stormwater or I&I in the combined sewer. It is normally very challenging to upsize pipes in urban settings due to density of other utilities, narrow rights-of-way, and sequencing of infrastructure replacement while maintaining service, therefore additional costs are related to these project requirements. Separating systems can be an option as well.

  Retrofitting a sanitary sewer to make it resilient to extreme rainfall will require either an uprising of the pipe, or sewer upgrades to reduce I&I into the system. It is normally challenging to upsize pipes in urban settings due to the same factors listed above for combined sewers, therefore additional costs are related to these project requirements. The combined sewer will be more sensitive to the rainfall and stormwater contribution and therefore rehab efforts should be focused on the storm/sani separation projects vs. rehab. The difference of cost between renewing and retrofitting gravity sewer is smaller than for drainage pipes, due to the higher complexity of transforming a combined system into a separated system.

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## SANITARY FORCE MAINS

### USEFUL SERVICE LIFE

- **Extreme rainfall:** Force main pipes are relatively reliable and could have a slightly reduced service life (Metro Vancouver, 2008). Service life reduction will be more related to wet well size in the buildings which is not captured accurately by this model. A ~50% increase in rainfall will cause significantly more I&I into the sewer system and increasing pumping costs through force mains due to increased friction in the pipe. Greater corrosion will also increase friction. A ductile / cast-iron pipe may fail sooner due to increased stress on joints from increased pumping. An HDPE or PVC pipe are more flexible and may better handle the increased flow.

### O&M COSTS

- **Extreme rainfall:** Force main pipes are relatively reliable and could have a slightly reduced service life (City of Vancouver, 2018). Increases in O&M will be more related to wet well size in the buildings which is not captured accurately by this model. Although an approximately 50% increase in rainfall will cause significantly more I&I into the sewer system and increasing pumping costs through force mains due to increased friction in the pipe, it is not expected that O&M will be increased by this type of climate event occurrence.

### RENEWAL COSTS

- **Extreme rainfall:** Inflow from gravity system could increase the load downstream of pump stations; force mains were sized at double future capacity required. The cost is expected to follow relatively the capacity increase, which is something we cross-validated with the US force main construction costs data (EPA, 2000).

  Incremental renewal costs are likely to occur in components other than the piping system.

## RETROFIT COSTS

- **Extreme rainfall:** Renewal and retrofit costs, which use similar solutions, would have similar cost increases. Retrofitting a force main to make it resilient to extreme rainfall will most likely require upsizing the pipe. It is normally very challenging to upsize pipes in urban settings due to density of other utilities, narrow rights-of-way, and sequencing of infrastructure replacement while maintaining service, therefore additional costs are related to these project requirements.

  Force mains are more reliable than gravity systems and rehab costs may increase slightly due to increased cleaning of pipes, or CIPP relining costs.

# APPENDIX

# B

## FINAL CLIMATE-COST ELASTICITIES

## WEIGHTED VS. UNWEIGHTED

The climate-cost elasticities, or alphas, can be interpreted as a direct relationship between the evolution of a climate indicator under climate change and the projected changes (increase or decrease) in useful service life and costs for a given asset or component. In this framework, the relative variation in a cost parameter is derived from a bottom-up approach (starting with the impacts on the asset components) on how a climate hazard interacts with a given asset. In other words, the variation in a cost parameter at the asset level is the cumulative variation in cost of its components.

Deconstructing assets into component was considered a necessary step because the component's vulnerability and exposure to climate variation are unequal. However, the public infrastructure inventory does not necessarily collect information at the component level. Therefore, assumption had to be made on the relative contribution of each component, at the asset level (e.g., if component X represents 50% of the CRV, and we expected a 50% renewal costs increase for this component, then the cost for this asset is 50%*50%=25%). This process is called weighting.

**Weighted coefficients:** Results expressed are weighted by their assumed CRV share. Buildings, Roads, Bridges and Transit are weighted coefficients.

**Unweighted coefficients**: Results expressed are weighted by their assumed CRV share. Stormwater and wastewater are weighted coefficients.

In the following tables, the relative shares of the CRV are added in the table. Dividing a weighted climate-cost elasticity, or alpha, by its relative CRV will give its unweighted version.

See Table 13 for more details.

## A. BUILDINGS

### Final climate-cost elasticities for buildings, weighted by the relative share of CRV of each component in the average building structure

| Climate Hazard | Building Component | **Climate Indicator** | **Relative CRV** | USL | | | O&M Costs | | | Renewal Costs | | | Retrofit Costs | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | **Optimistic** | **Most likely** | **Pessimistic** | **Optimistic** | **Most likely** | **Pessimistic** | **Optimistic** | **Most likely** | **Pessimistic** | **Optimistic** | **Most likely** | **Pessimistic** |
| **Extreme heat** | Civil and Landscaping | Mean July daily maximum temperature | 5% | -0.001 | -0.001 | -0.002 | 0.000 | 0.000 | 0.000 | 0.002 | 0.002 | 0.003 | 0.003 | 0.003 | 0.004 |
| | Structure | N/A | 35% | | | | | | | | | | | | |
| | Envelope | 2.5% July daily maximum temperature | 20% | -0.001 | -0.002 | -0.002 | 0.000 | 0.000 | 0.000 | 0.004 | 0.004 | 0.004 | 0.004 | 0.005 | 0.006 |
| | Mechanical and Electrical | Annual amount of cooling degree days | 35% | -0.002 | -0.004 | -0.006 | 0.000 | 0.000 | 0.000 | 0.007 | 0.007 | 0.007 | 0.012 | 0.014 | 0.017 |
| | Equipment and Finishing | N/A | 10% | Negligible climate impact | | | | | | | | | | | |
| **Extreme rainfall** | Civil | IDF 24-hr 1:5<br>IDF 24-hr 1:100 | 5% | -0.013 | -0.023 | -0.034 | 0.002 | 0.003 | 0.003 | 0.023 | 0.024 | 0.024 | 0.041 | 0.046 | 0.051 |
| | Landscaping | IDF 15-min 1:10 | 5% | -0.015 | -0.026 | -0.038 | 0.003 | 0.003 | 0.003 | 0.027 | 0.027 | 0.027 | 0.047 | 0.052 | 0.058 |
| | Structure | Average annual precipitation | 35% | -0.007 | -0.012 | -0.015 | 0.002 | 0.002 | 0.002 | 0.076 | 0.077 | 0.077 | 0.127 | 0.133 | 0.141 |
| | Envelope | IDF 15-min 1:10 | 20% | -0.032 | -0.053 | -0.070 | 0.005 | 0.005 | 0.006 | 0.071 | 0.072 | 0.073 | 0.106 | 0.118 | 0.131 |
| | Mechanical and Electrical | N/A | 30% | Negligible climate impact | | | | | | | | | | | |
| | Equipment and Finishing | IDF 15-min 1:10 | 10% | -0.028 | -0.047 | -0.064 | 0.003 | 0.003 | 0.004 | 0.029 | 0.029 | 0.029 | 0.062 | 0.071 | 0.081 |
| **Freeze-thaw cycles** | Civil and Landscaping | Number of deep freeze-thaw cycles | 10% | -0.007 | -0.012 | -0.017 | 0.000 | 0.000 | 0.000 | 0.016 | 0.016 | 0.016 | 0.031 | 0.035 | 0.039 |
| | Structure | Number of deep freeze-thaw cycles | 35% | -0.005 | -0.008 | -0.011 | 0.000 | 0.001 | 0.001 | 0.046 | 0.047 | 0.048 | 0.068 | 0.073 | 0.079 |
| | Envelope | Number of deep freeze-thaw cycles | 20% | -0.011 | -0.018 | -0.024 | 0.001 | 0.001 | 0.001 | 0.043 | 0.044 | 0.045 | 0.055 | 0.062 | 0.069 |
| | Mechanical and Electrical | N/A | 30% | Negligible climate impact | | | | | | | | | | | |

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Equipment and Finishing | Annual number of freeze-thaw cycles | 10% | -0.029 | -0.045 | -0.063 | 0.002 | 0.002 | 0.002 | 0.031 | 0.032 | 0.032 | 0.082 | 0.095 | 0.110 |

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## B. ROADS

### Final climate-cost elasticities for roads, weighted by the relative share of CRV of each component in the average road structure

| Climate Hazard | Road Component | **Climate Indicator** | **Relative CRV** | USL | | | O&M Costs | | | Renewal Costs | | | Retrofit Costs | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | **Optimistic** | **Most likely** | **Pessimistic** | **Optimistic** | **Most likely** | **Pessimistic** | **Optimistic** | **Most likely** | **Pessimistic** | **Optimistic** | **Most likely** | **Pessimistic** |
| **Extreme heat** | Pavement | Annual number of hot days (>30 °C) | 85% | -0.011 | -0.015 | -0.019 | 0.001 | 0.001 | 0.001 | 0.007 | 0.010 | 0.013 | 0.007 | 0.010 | 0.013 |
| | Road Associated Structures | Annual number of hot days (>30 °C) | 13% | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.001 | 0.001 | 0.001 |
| **Extreme rainfall** | Pavement | IDF 24-hr 1:100 | 85% | -0.205 | -0.268 | -0.332 | 0.011 | 0.012 | 0.014 | 0.153 | 0.217 | 0.307 | 0.153 | 0.217 | 0.307 |
| | Road Associated Structures | IDF 24-hr 1:100 | 13% | -0.016 | -0.023 | -0.029 | 0.002 | 0.002 | 0.002 | 0.022 | 0.031 | 0.041 | 0.033 | 0.047 | 0.068 |

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## C. TRANSIT

### Final climate-cost elasticities for transit, weighted by the relative share of CRV of each component

| **Climate Hazard** | **Transit Component** | **Climate Indicator** | Relative CRV | **USL** | | | **O&M Costs** | | | **Renewal Costs** | | | **Retrofit Costs** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | **Optimistic** | **Most likely** | **Pessimistic** | **Optimistic** | **Most likely** | **Pessimistic** | **Optimistic** | **Most likely** | **Pessimistic** | **Optimistic** | **Most likely** | **Pessimistic** |
| **Extreme heat** | Alignments | Annual number of hot days (>30 °C) | 35% | -0.006 | -0.009 | -0.012 | 0.001 | 0.001 | 0.002 | 0.004 | 0.007 | 0.010 | 0.018 | 0.020 | 0.023 |
| | Rail Associated Structures | Mean July daily maximum temperature | 10% | -0.001 | -0.002 | -0.004 | 0.001 | 0.002 | 0.002 | 0.002 | 0.004 | 0.006 | 0.003 | 0.005 | 0.007 |
| | Equipment and Finishing | Annual highest temperature (°C) | 20% | -0.005 | -0.007 | -0.010 | 0.002 | 0.004 | 0.005 | 0.005 | 0.008 | 0.010 | 0.003 | 0.006 | 0.009 |

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Rolling Stocks | Annual number of cooling degree days (°C*days) | 35% | -0.003 | -0.009 | -0.015 | 0.000 | 0.003 | 0.006 | 0.000 | 0.027 | 0.041 | 0.003 | 0.006 | 0.012 |

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## D. BRIDGES AND CULVERTS

### Final climate-cost elasticities for bridges and culverts, unweighted

| Climate Hazard | Bridge / Culvert Component | Climate Indicator | Relative CRV | USL | | | O&M Costs | | | Renewal Costs | | | Retrofit Costs | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Optimistic | Most likely | Pessimistic | Optimistic | Most likely | Pessimistic | Optimistic | Most likely | Pessimistic | Optimistic | Most likely | Pessimistic |
| Extreme rainfall | Bridges | IDF 24-hr 1:100 | 100% | -0.102 | -0.143 | -0.205 | 0.020 | 0.020 | 0.020 | 0.017 | 0.110 | 0.260 | 0.082 | 0.123 | 0.164 |
| | Large Structural Culverts | IDF 24-hr 1:100 | 100% | -0.369 | -0.512 | -0.676 | 0.020 | 0.041 | 0.041 | 0.307 | 0.410 | 0.553 | 0.779 | 0.963 | 1.147 |
| Freeze-thaw cycles | Bridges | Annual number of freeze-thaw cycles | 100% | -0.384 | -0.177 | -0.035 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| | Large Structural Culverts | N/A | 100% | Negligible climate impact | | | | | | | | | | | |

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## E. STORMWATER AND WASTEWATER

### Final climate-cost elasticities for stormwater and wastewater, unweighted

| Climate Hazard | Stormwater / Wastewater Component | Climate Indicator | Relative CRV | USL | | | O&M Costs | | | Renewal Costs | | | Retrofit Costs | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Optimistic | Most likely | Pessimistic | Optimistic | Most likely | Pessimistic | Optimistic | Most likely | Pessimistic | Optimistic | Most likely | Pessimistic |
| Extreme rainfall | Pipes | IDF 24-hr 1:2 | 45% | 0.000 | 0.000 | 0.000 | 0.042 | 0.083 | 0.104 | 1.022 | 1.230 | 1.543 | 1.022 | 1.230 | 1.543 |
| | Ditches | IDF 24-hr 1:100 | 50% | 0.000 | 0.000 | 0.000 | 0.020 | 0.041 | 0.041 | 0.983 | 1.209 | 1.537 | 0.983 | 1.209 | 1.537 |
| | Small Non-structural Culverts | IDF 24-hr 1:10 | 5% | 0.000 | 0.000 | 0.000 | 0.041 | 0.041 | 0.061 | 1.222 | 1.385 | 1.569 | 1.222 | 1.385 | 1.569 |

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Gravity Sewer | 0.5*IDF 24-hour 1:2 + 0.5* | 95% | 0.000 | 0.000 | 0.000 | 0.038 | 0.038 | 0.057 | 0.955 | 1.165 | 1.528 | 0.955 | 1.165 | 1.528 |
| | Sanitary Force Mains | Maximum 5-day precipitation | 5% | -0.123 | -0.225 | -0.348 | 0.020 | 0.041 | 0.061 | 0.799 | 1.065 | 1.393 | 0.799 | 1.065 | 1.393 |