Pavement Flooding Risk Assessment and Management in the Changing Climate

by

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Author's Declaration

This thesis consists of material all of which I authored or co-authored: see Statement of Contributions. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Statement of Contributions

Chapter 2 section 2.7 of this thesis contains parts of a paper co-authored by myself, and my supervisors Dr. Tighe and Dr. Xie. I wrote the paper based on the review of infrastructure adaptation framework and methodology in the climate change, all with input from Dr. Tighe and Dr. Xie.

Donghui Lu, Susan L. Tighe, and Wei-Chau Xie. (2018). Adapting Pavement Infrastructure to Flood Risk under Climate Change — A Review of Adaptation Strategies. CSCE 2018 Annual Conference (Paper no. DM7), June 13-16, 2018. Fredericton, NB, Canada.

Chapter 3 and Chapter 6 of this thesis contains parts of a paper co-authored by myself, and my supervisor my supervisors Dr. Tighe and Dr. Xie. I developed the methodology and research design of the paper, with input from Dr. Tighe and Dr. Xie.

Donghui Lu, Susan L. Tighe, and Wei-Chau Xie. (2018). Pavement Risk Assessment for Future Extreme Precipitations under Climate Change. Transportation Research Record, 2672(40), pp.122-131

Chapter 4 of this thesis contains parts of a paper co-authored by myself, and my supervisors Dr. Tighe and Dr. Xie. I developed the methodology for the analysis, and wrote the paper based on the findings, all with input from Dr. Tighe and Dr. Xie.

Donghui Lu, Susan L. Tighe and Wei-Chau Xie. (2018). Impact of Flood Hazards on Pavement Performance. International Journal of Pavement Engineering, pp.1-7

Chapter 5 of this thesis contains parts of a paper co-authored by myself, and my supervisors Dr. Tighe and Dr. Xie. I developed the methodology for the analysis, and wrote the paper based on the findings, all with input from Dr. Tighe and Dr. Xie.

Donghui Lu, Susan L. Tighe, and Wei-Chau Xie. (2017). Pavement Fragility Modelling Framework and Build-in Resilience Strategies for Flood Hazard. Transportation Research Board (TRB) Annual Meeting (No. 17-01735), January 2017, Washington DC.

Donghui Lu, Susan L. Tighe, and Wei-Chau Xie. (2017). Impacts of flooding on Asphalt Pavements under Climate Change. 2017 Canadian Technical Asphalt Association (CTAA) Annual Conference, November 12-15, Halifax, Canada.

Abstract

Flooding, which can cause substantial infrastructure damages resulting in adverse social, environmental, and economical consequences, is a rising concern in the changing climate. Road networks consisting of interconnected links designed to accommodate transportation needs of the public and can be affected by flood hazards. In road pavement design and management, historical climate design data are becoming less representative of the future climate resulting in unexpected risks. Road pavement damage caused by expected intensification of flood events under climate change can lead to safety, mobility, comfort, functionality, and accessibility concerns. In order to mitigate the risk of flooding on pavements, this research develops risk quantification methodology and implementation guidelines, which enable informed pavement management and adaptation leading to increased resilience of pavement networks in the changing climate.

The risk assessment methodology includes project level risk assessment and network level risk assessment. The key components of project level risk assessment include flood hazard assessment, flooded pavement performance analysis, quantification of pavement fragility, and consequence analysis. The network level risk assessment is an extension of the project level risk assessment. It involves an eight-step approach including mapping the flood hazards, mapping the road exposure and characteristics, matching fragility models, calculating risk for a range of events, and summing up the risks. The risk estimation can be used to inform and initiate the adaptation planning and programming at the prioritized sections of pavement networks. Case studies have been conducted to illustrate the implementation of the risk assessment methodology. Based on the research findings, pavement flooding risk assessment and management implementation guidelines and procedures are developed. The outcome of the research helps the advancement of pavement design and management practices for addressing flood hazards.

The results in the flood hazard analysis indicate that the probabilistic flood hazard analysis method provides a quantitative estimation of flood hazard for various climate change scenarios. Road pavement infrastructure can be subjected to more frequent and intense extreme precipitation events causing more pavement flooding in the case study area. The new extremes should be incorporated in pavement design and management practices. Regarding pavement damage, a comprehensive analysis summarizes the pavement damage processes, causes, components, damage patterns, impact factors, and temporal and spatial characteristics. Probabilistic pavement flooding damage analysis is illustrated by fragility models, which provide estimations of conditional probability of exceeding certain pavement damage given a flood event. Pavement mechanistic-empirical (ME) design method is utilized to simulate the impact of extreme precipitations on pavement performance of typical arterial and collector flexible pavements in Toronto, Canada. Fragility models and curves are generated based on the performance simulation results. In the case study, the pavement roughness degradation is accelerated post-flooding during the life cycle, which is assessed as the jump & delayed effect damage pattern. The extreme events can lead to the loss of pavement life up to 303 days, approximately more than 4% of a pavement's life. More flood cycles lead to shorter pavement life, which is caused by the accelerated deterioration after the flood cycles. The increase of precipitation levels under climate change increases the probability of pavement damage in each damage state for different designs. The incorporation of ME performance simulation and experimental testing allows obtaining the damage data from aged pavements for fragility analysis.

The quantitative pavement flooding risk assessment at the project level integrates the findings of the flood hazard analysis, fragility, and vulnerability. Considering the climate from 2017 to 2100, the extreme precipitations from representative concentration pathway (RCP) 8.5 climate scenario results in asset value losses as high as CAD$112,471 and CAD$46,487 per kilometer for arterial and collector pavements, respectively for moderate damage. The risk of major damage is not the highest when compared to the risks of minor and moderate damage, which is because the major damage has a lower occurrence resulting in lower asset value losses in the case study. The network spatial risks are analyzed and visualized through risk mapping. The results indicate the length of flooded pavements for each functional class increases as the magnitude of flooding increases. As the damage state threshold value increases, the percentage of road sections with high risk decreases and that with low risk increases. The risk of climate-change-induced flooding is sensitive to the range of flood events included in the risk assessment. When include the climate change scenario in a full range of flood hazard, the percentage of road network with low risk is increased from 12.1% to 45.7%, and the percentage of high-risk sections is increased from 46.0% to 79.9% for pavement damage over 1.5%.

Adaptation strategies that have been established are reducing hazard exposure, reducing fragility of pavement structures, and reducing the cost of certain damage. The implementation guidelines are introduced according to the time horizon: pre-event, during-event, and post-event. Pre-event, probabilistic risk assessment and risk matrix approach are both included in the risk assessment guide. The general principles, key activities, and procedures introduced in the guide enable researchers, practitioners, and stakeholders to apply the research findings.

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I would like to acknowledge and express my deep gratitude to the many people who have supported me during the completion of this research. Firstly, to my supervisors Dr. Susan Tighe, her support, encouragement, and the opportunities she provided have been exceptional. Dr. Wei-Chau Xie's mentorship, support and patience are irreplaceable, and his impact is on all aspects of my life. Secondly, I would like to thank Yang Zhou for his tireless support and patience. Thirdly, thanks to my family, for every type of support they provide me.

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Dedication

This thesis is dedicated to my husband, baby Skye and family,
whose support, patience, and love have made this a possibility.

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Nomenclature

AASHTO	The American Association of State Highway and Transportation Officials
AADTT	Average annual daily truck traffic
AC	Asphalt Cement
AEP	Annual Exceedance Probability
AMP	Annual Maximum Precipitation
AR5	IPCC Fifth Assessment Report
CBR	California Bearing Ratio
CDF	Cumulative Distribution Function
DDF	Depth-Duration-Frequency
ECIM	Enhanced Integrated Climate Model
FOD	Foreign Object Damage
FWD	Falling Weight Deflectometer
GCM	General Circulation Model
GEV	Generalized Extreme Value Distribution
GIS	Geographic Information System
HMA	Hot Mix Asphalt
IDF	Intensity-Duration-Frequency
IPCC	Intergovernmental Panel on Climate Change
IRI	International Roughness Index
MEPDG	Mechanistic Empirical Pavement Design Guide
MSA	Multi Stripe Analysis
PCC	Portland Cement Concrete
PCI	Pavement Condition Index

PG	Performance Grading
PMF	Probable Maximum Flood
RCM	Regional Climate Model
RCP	Representative Concentration Pathway
SPSS	Statistical Product and Service Solutions software
SP	SuperPave
SN	Structure Number

Chapter 1 Introduction

Climate change displays widespread influence on road transportation systems (Humphrey, 2008). Flood hazards and the exposure of people and economic assets have increased (Jongman et al., 2012; Jongman et al., 2015) in the context of climate change. Road networks, consisting of interconnected links designed to accommodate the transportation needs of the public, are affected by flood hazards. The expected intensification of flood events caused by climate change (Prein et al., 2017) can lead to traffic disruptions, accidents, and road closures. The loss of structural integrity of pavements in a part of the network may cause long-term loss of access for that part of the network from the remainder of the network system (Eleutério et al., 2013). In the events of natural disaster, other sectors also depend on the road transportation systems to carry the workforce to sites, access to raw materials, and for food and product distribution. Damage of road infrastructure can jeopardize safety, mobility, comfort, functionality, and accessibility resulting in adverse social and economic implications.

Canada has a road network of over 1,000,000 kilometers. Road pavement is an important asset to Canada's economy given that a huge amount of goods and services are transported by trucks and the dependence on car transportation. Flooding poses threat to pavements as it can exacerbate pavement distress, such as cracking, rutting, and fatigue of pavements. In Canada, the average temperatures are expected to rise by an additional 1.5°C to 4.5°C by 2070 (Environment and Climate Change Canada, 2016). The average national precipitation amounts indicate a wetter climate in recent years (Environment and Climate Change Canada, 2017). Designed based on historical climate, pavement structures can be vulnerable and subjected to unanticipated risk from future extreme weather events. Climate events in Canada in recent years have provided insight into how the potential impact of climate change affects pavement design, construction, maintenance, and management practice.

Climate change will continue for many decades, and even centuries, regardless of the success of global initiatives to reduce greenhouse gas emissions (Furgal & Prowse, 2008). Therefore, adapting pavement infrastructure to climate change due to the past emissions is unavoidable. The adverse effects of flood hazards on economic development are complex, and often there is a lack of observations or experiences for achieving comprehensive understanding. Having a better understanding of the pavement flooding damage and risk is imperative for determining the adaptation actions and building resilient infrastructure. However, there is a lack of a comprehensive method to address the potential flood threats and associated potential damage. This research aims to establish the risk assessment framework and methodology to facilitate a smooth transition into informed pavement adaptation for flooding risk in the changing climate.

1.1 Research Hypothesis

The main hypotheses for this research are as follows:

- There is unanticipated risk of pavement damage due to more intensive and frequent flooding in specific regions under climate change. The pavement design that is based on previous climate information is inadequate for dealing with the future climate;
- The prediction of flood events at a regional level can be updated by considering the changing climate;
- Pavement structural damage and performance deterioration due to flooding can be quantified by pavement fragility analysis;
- The risk of flooding on pavements can be identified and assessed quantitatively by integrating flood hazards and pavement vulnerability;
- The risk of flooding on pavements can be extended from the project level to the network level. The flooding risk assessment for pavement networks can be achieved by spatial analysis at a specific location.

1.2 Scope

Risks of flooding for pavements involve social aspects, economical aspects, and environmental aspects. This research focuses mainly on assessing economy-related risk of flooding of physical pavement assets in the scope of the pavement asset management system, such as pavement deterioration, possibility of pavement physical damage, and asset value loss. The outcome of the risk assessment framework and methodology may be used to evaluate other aspects of the consequences in future work. In terms of the flooding type, the case studies in this research involve urban flooding in Southern Ontario, Canada. In addition, the generation of flood maps is not in the scope of this research.

1.3 Objectives

In order to increase the resilience of pavement assets under climate change, it is important to analyze pavement flooding damage, assess the risk, and develop adaptation strategies. The research is focused on establishing a novel framework and methodology for assessing pavement fragility and risk for flooding at both project level and network level in the changing climate. The risk information is useful for supporting the decision making of climate change adaptation and advancing pavement design and management technologies for dealing with flood hazards. The main objectives of this research are:

- To generate a framework for pavement flooding risk assessment and adaptation;
- To analyze pavement flooding damages;
- To develop pavement fragility modelling methods;
- To establish methods for quantifying pavement flooding risk under climate change;
- To perform risk assessment for pavement networks and conduct spatial risk analysis;
- To provide climate change adaptation strategies and implementation guidelines.

1.4 Methodology

The flow of this research is illustrated schematically in Figure 1.1. Flooding risk analysis for road pavements is a broad and complex process, involving a number of science and engineering disciplines. Followed by a comprehensive literature review, methods for flood hazard analysis under climate change are proposed. Fragility analysis involves pavement flooding response and damage analysis, and a probabilistic approach to generate fragility models. Based on the results of fragility analysis and hazard analysis, with the estimation of associated cost, pavement vulnerability and risk can be determined and assessed. The models can be extended to network level, and pavement network risk maps can be developed for prioritizing adaptation decisions. Adaptation strategies and implementation guidelines are developed based on the research findings. The guidelines provide principles and key activities to build climate change resilient pavement concerning flood hazards.

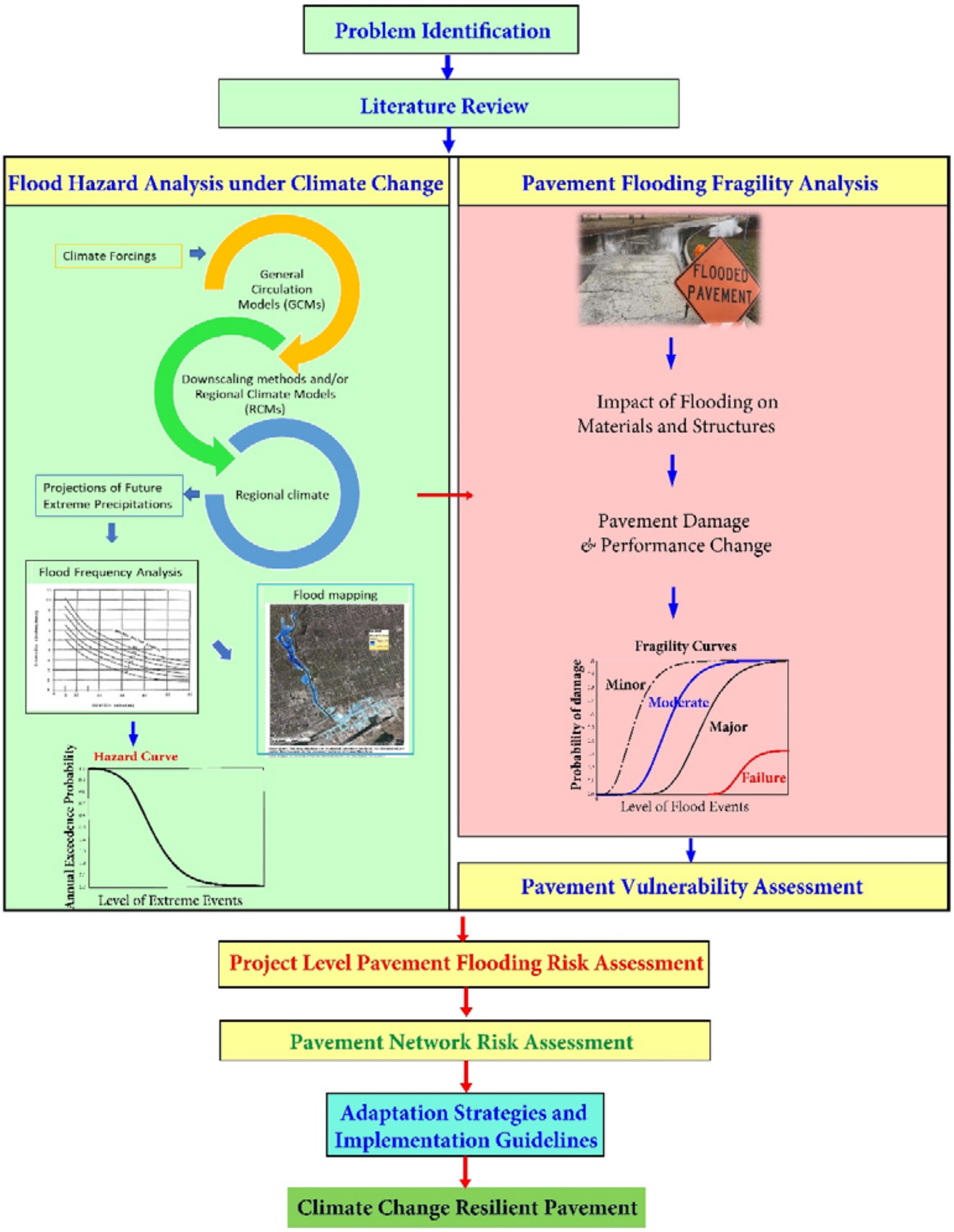


Figure 1.1 Research Flow

The key research work ultimately focuses on establishing a risk analysis approach for flooding of pavements and developing the adaptation implementation guidelines in the changing climate. The flood risk analysis methodology involving Project Level Risk Assessment (Figure 1.2 Part (i)); Network Level Risk Assessment (Figure 1.2 Part (ii)); and Adaptation (Figure 1.2 Part (iii)) is illustrated in detail in Figure 1.2.

The project level risk assessment includes five areas: flood hazard assessment, flooded pavement performance analysis, quantification of flood fragility of pavement, consequence analysis, and flooding risk quantification.

The network level risk assessment is an extension of the project level risk assessment. It involves an eight-step approach. The process of estimating network risk includes mapping the flood hazards, mapping the road exposure and characteristics, matching fragility models, calculating risk for a range of events, and summing up the risks.

Part (iii) discusses adaptation strategies, procedures, and implementation guidelines.

The key components are described in detail in the following sections.

1.4.1 Flood Hazard Assessment in the Changing Climate

The objective of flood hazard assessment is to determine the flood hazard curves and flood input at the site of interest in terms of flood depth, duration, and other characteristics that can be used for pavement performance analysis. To achieve this objective, it is essential to understand pavement flood hazards, flood frequency analysis, engineering design flood, and methods for incorporating climate change in flood hazard modelling.

Flood hazard analysis gives a quantitative estimation of flood hazard for various climate change scenarios. Flood hazard analysis involves the estimation of the occurrence of future hazards, flood extent, and the hazard exposure of road pavements. Probabilistic flood hazard analysis provides the flood hazard curves, which are the annual probabilities of exceedance versus flood magnitude parameter.

1.4.2 Flooded Pavement Performance Analysis

The aim of the flooded pavement performance analysis is to determine the potential pavement performance change and damage caused by potential flood hazards. It is essential to understand the damage processes, potential structural damage components, damage patterns, damage impact factors, the temporal and spatial characteristics, and life cycle pavement deterioration for pavement flooding events. All the elements involved in characterizing pavement susceptibility to flood damage are highlighted throughout the analysis.

1.4.3 Quantification of Flood Fragility of Pavement

The objective of fragility analysis is to determine the fragility curves. Fragility is the conditional probability that the damage of a pavement exceeds a specified limit state for a given level of flood hazard. Pavement fragility analysis, as one of the key parts for the vulnerability and risk assessment, connects flood hazard and pavement physical damage. Modelling the fragility involves the quantitative analysis of probabilistic damage for various designs and pavements conditions. The integration of fragility models and consequence is the pavement vulnerability. Risk can be quantified by incorporating flood hazard and fragility or vulnerability, and the consequences.

1.4.4 Flood Risk Assessment of Pavement at the Project Level

The objective of conducting a flooding risk analysis for a pavement is to determine the occurrence of adverse consequences due to the potential effects of flooding. In pavement management, project level and network level are two important levels for managing pavements. Flood risk assessment of pavement performed at the project level involves identifying the risk for individual pavement section. This is a fundamental step for assessing pavement risk at the network level.

Pavement flooding risk assessment contains the information of occurrence of certain hazard and pavement responses to the hazard, which provides the probability of occurrence and costs for a certain damage state of the individual section. It allows for identifying the potential of pavement damage and providing a reference to make management decisions.

1.4.5 Flood Risk Assessment of Pavement on the Network Level

The purpose of flood risk assessment across pavement networks is to identify the distribution of the risk and to prioritize adaptation actions. The process of estimating network risk includes mapping the flood hazards, mapping the road exposure and characteristics, matching fragility models, calculating risk for a range of events, and summing up the risks. Network risk assessment is made possible by extending the project level risk estimation method based on a geospatial information system. The analysis of network risk can guide the efficient allocation of funds to increase the resilience of an existing pavement network.

1.4.6 Adaptation Strategies and Guidelines for Managing Pavement Flood Risk

The objective of generating strategies for adapting to the increased flooding risk is to capture the key elements for reducing pavement flooding risk. Climate change adaptation decisions can be made strategically based on the risk assessed for achieving cost effective pavement asset management and building resilient pavement infrastructure.

An implementation guideline is also developed to provide answers to the questions of how to address climate change related flooding risk and what to do pre-event, during-event, and post-event. A procedure is identified regarding the application of the research findings in practice.

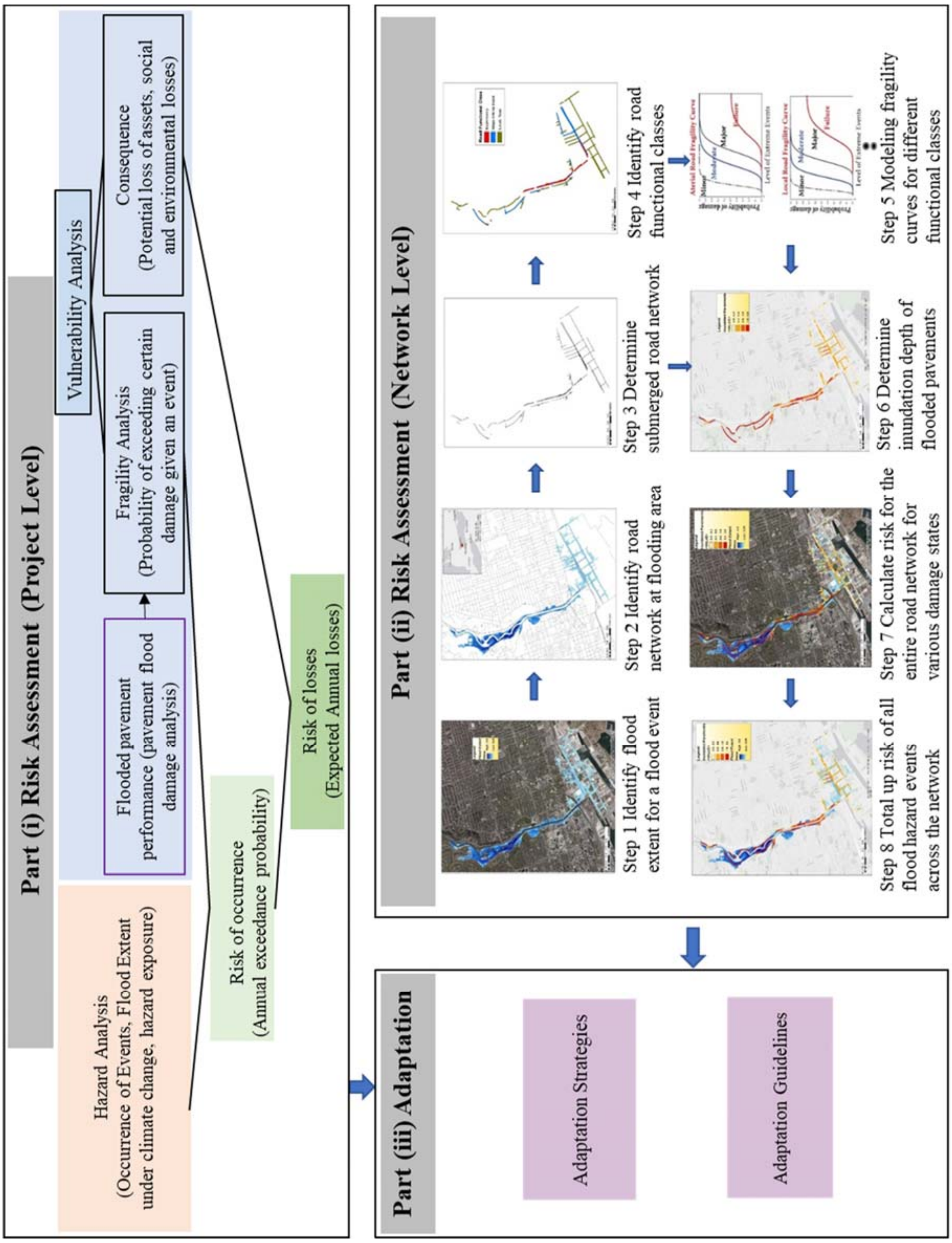


Figure 1.2 Flooding Risk Analysis Methodology

1.5 Thesis Organization

The thesis is divided into nine chapters.

Chapter One introduces the research, and outlines the scope, objective, and research methodology.

Chapter Two summarizes the literature review that was conducted on the current state of the practice and identifies the current gaps and how the research will address these gaps.

Chapter Three describes the flood hazards in the context of climate change and pavement management. A case study is conducted to illustrate the incorporation of climate change in flood hazard prediction.

Chapter Four discusses the processes, components, patterns, impact factors, the temporal and spatial characteristics, and life cycle deterioration of pavement flooding damage.

Chapter Five describes the development of the pavement fragility modelling methods and vulnerability estimations. Case studies are conducted to illustrate the fragility analysis methods.

Chapter Six outlines the pavement flooding risk quantification methods. A case study is presented to demonstrate the estimation process.

Chapter Seven extends the risk estimation to the pavement network level. The methodologies for developing flood risk maps of pavement networks and spatial analysis are described. A case study is presented to demonstrate the application of the methods.

Chapter Eight outlines pavement flooding risk adaptation strategies, framework and implementation guidelines in the changing climate.

Chapter Nine summarizes the conclusions and recommendations and identifies areas of future work.

1.6 Data Source

Data used in the case studies are from various sources. The sources and usage are introduced at the beginning of each case study. In this section, a summary of the data and usage is provided.

Case Study for Flood Hazard Analysis

The input future climate scenarios are representative concentration pathway (RCP) 2.6, RCP 4, and RCP 8.5. The climate-change-induced future extreme precipitation data are generated by IDF-CC tool version 3 (Simonovic et al., 2016) based on the future scenarios. The output of the IDF-CC tool is the updated depth-duration-frequency (DDF) curves considering the changing climate. Then, the DDF curves are converted to flood hazard curves.

Cast Studies for Fragility Analysis

In the Mechanistic-Empirical pavement performance simulation, the thickness designs of arterial and collector pavement designs in Southern Ontario, Canada are adopted from the report "Methodology for the Development of Equivalent Pavement Structural Design Matrix for Municipal Roadways: Including Maintenance and Rehabilitation Schedules and Life Cycle Cost Analysis" (Applied Research Associates, 2011). The traffic data in terms of annual average daily truck traffic (AADTT) is also from the report. The historical climate data in the case study area are from the AASHTOWare Pavement ME Design tool. Other pavement design input data are from "Ontario's Default Parameters for AASHTOWare Pavement ME Design" (Ontario Ministry of Transportation, 2014).

In the fragility modelling, the pavement damage data are from the output of the Mechanistic-Empirical pavement performance simulation.

Case Study for Project Level Risk Assessment

The risk of occurrence is calculated by using the flood hazard curves from the flood hazard analysis case study and the fragility curves from the fragility analysis case study. The cost data for estimating risk of loss are the initial construction costs per kilometer and the salvage values for the typical design of arterial and collector pavement in Southern Ontario, Canada from the report “Methodology for the Development of Equivalent Pavement Structural Design Matrix for Municipal Roadways: Including Maintenance and Rehabilitation Schedules and Life Cycle Cost Analysis” (Applied Research Associates, 2011).

Case Study for Network Level Risk Assessment

Flood map data. Toronto and Region Conservation Authority (TRCA) took the effort in generating the regulatory engineered flooding mapping for the Lower Don River providing flood characterization maps and visual tools for communicating the potential flooding issues. Flood hazard data are provided by the TRCA in terms of flood plain maps of return periods of 2, 5, 10, 25, 50, 100, and 350 years for Lower Don Area in ASCII format. The resolution is 2 meters × 2 meters cell.

Pavement network data and other data. Pavement network data are collected from City of Toronto and Applied Research Associates, Inc. including pavement network information and map. The detailed information mostly includes pavement functional class across the network, street names and locations of the pavement assets. The spatial reference in the pavement flooding risk mapping used is NAD 1983 UTM Zone 17N. For mapping the pavement network flooding risk, a rectangular boundary is clipped based on the world map in ArcGIS platform to cover the pavement network and flooded area in the case study. All data used are either already in, or converted to, raster format.

Chapter 2 Literature Review

This chapter reviews the background of climate change and flood hazards, pavement design and management, climate change adaptation and resilience, risk assessment and management, and literatures on pavement damage analysis and models related to flooding in the context of climate change.

2.1 Flooding

A flood is a natural phenomenon, which occurs when a body of water rises to overflow normally dry land. Flooding is often caused by the overflow of inland waters or tidal waters. Flood waters can lead to massive amounts of erosion. Such erosion can weaken and undermine the pavement structures.

Sources of flooding are illustrated in Figure 2.1. An increase in water levels greater than that normally associated with tides causes Storm Surge, which occurs typically associated with a hurricane. Dam Failure results in the release of the reservoir water. Heavy rainfall leads to the concentration of water at a drainage area causing flooding. Tsunami caused by the sudden displacement of a body of water (e.g. from earthquake) generates large waves to coastal land. Seiche effect is created by wind-action. The water surface oscillates leading to rise in water levels. Ice jam floods are usually caused by ice blockage on a river when floating ice accumulates. Ice jams can significantly reduce the flow of a river causing upstream flooding. Also, downstream flooding can occur when ice jam releases an outburst flood. Ice jam floods may also occur during freezing weather and may leave large pieces of ice behind, but they are much more localized than open-water floods.

Flooding can also be categorized as: fluvial (river) flooding, pluvial (surface water) flooding, coastal flooding, reservoir flooding, ground water flooding, and ice jam flooding. When it refers to fluvial flooding, the events are caused by sustained and intense rainfall leading to rivers or streams to burst. Pluvial flooding, also named surface water flooding, occurs when there is an extreme heavy downpour of rain such that the excessive water cannot be absorbed by drainage systems. Coastal flooding is caused by high water levels including tides, storm surges, and tsunamis, which can lead to overtopping of coastal defenses and inundation of low-lying coastal areas. Reservoir flooding happens when there is dam failure. Ground water flooding occurs when the underground aquifers overflow onto the surface and stop water from draining.

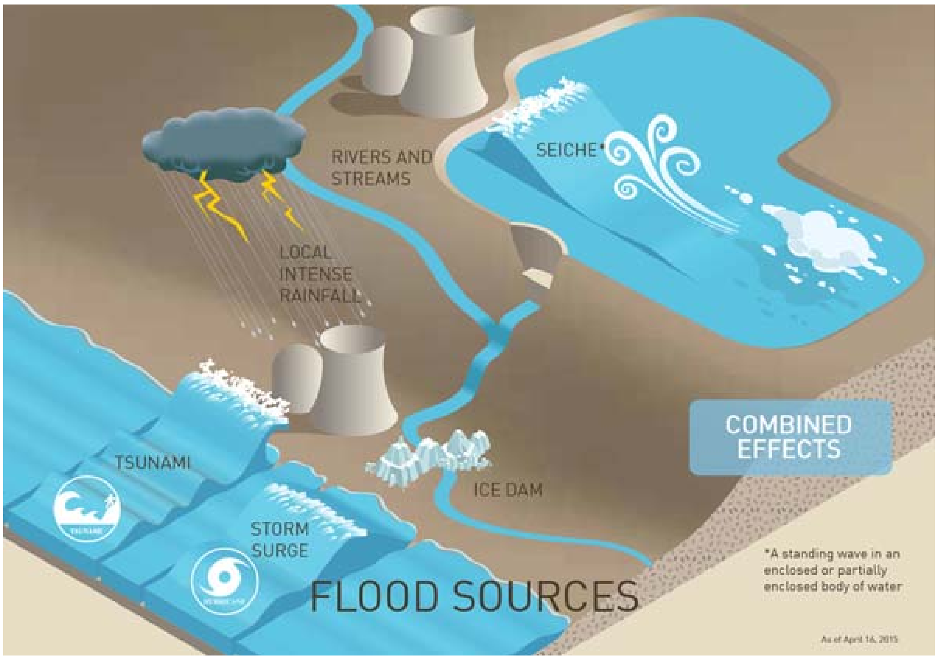


Figure 2.1 Flood Sources (USNRC, 2015)

Some of the recent flood events are shown in Figure 2.2. Flooding can cause significant social, environmental and economic consequences. The flood events can lead to traffic disruptions, accidents, road closures, and the loss of structural integrity of infrastructure. In the events of natural disaster, other sectors would depend on road transportation systems for carrying workforce to sites and for food distribution. Flooding of road infrastructure can jeopardize safety, mobility, comfort, functionality, and accessibility, resulting in adverse social and economic implications.

Credit: Ville de Gatineau
Floods in Gatineau, Quebec
Canada, April 2019.

Credit: Hydro Ottawa
Riverside Drive area in Ottawa,
ON, Canada, October 30, 2017.

Credit: Mark Blinch
A car is stuck during a flood on the Don Valley Parkway, a major highway, during a heavy rainstorm in Toronto, July 8, 2013.

Credit: Nickolay Lamm/StorageFront interpretation of Climate Central data
Hurricane Sandy struck New York City on October 29, 2012; LaGuardia Airport, flooding parts of east-west runway.

Credit: AAP Image
A vehicle drives down the flooded runway at Rockhampton Airport, Australia, January 1, 2011.

Credit: AFP, BBC NEWS
India's Chennai Airport hit by flooding, December 3, 2015.

Credit: U.S. Coast Guard Photo by Lt. John Geary
Hurricane Dorian: The aircrew was taking medical personnel to the island due to the fact that it is not accessible by car. North Carolina, Sept. 6, 2019

Credit: U.S. Coast Guard photograph
Hurricane Florence, Sept. 16, 2018.

Credit: AP photo/David J. Phillip
Hurricane Harvey struck Houston, August 27, 2017; Heavy rains wallop Houston area, causing widespread 1 in 500-year flooding.

Figure 2.2 Recent Pavement Flooding Events

2.1.1 Flood Mapping

Flood hazard mapping is a process to define the areas that are at risk of flooding under extreme conditions with the primary objective to reduce the impact of flood hazards. The hazard maps as an information system enable a better understanding and awareness of flood hazard. The visualized flood hazard provides easily read and rapidly accessible features, which facilitate the identification of risky areas and helps prioritise adaptation strategies. It is imperative to note that, in the context of climate change, flood hazard maps require periodic updates to reflect the changed flooding hazard. By identifying flood hazard across road networks, areas with high risk can draw more attention for risk reduction. The raised awareness could promote the implementation of flood risk management, climate change adaptation measures, and sustainable development.

The process of generating flood hazard maps in river domains can be divided into hydrological analysis and hydraulic analysis.

A hydrology model simulates the effect of an amount of rainfall as if it were over each watershed, considering the topography, soil type, land-use, and other characteristics to determine how much water would end up in the rivers and streams. The hydrological analysis enables a better understanding of the characteristics of rainfall and the responses of the watershed given certain rainfall event. An example of hydrologic procedures (Nature Resource Canada, 2019) is shown in Figure 2.3.

Based on hydrological modelling output and other data, a hydraulic model focusses on where this water would go, what areas would be inundated, and what is the physical properties of the flood such as depth and velocity. It can inform the design and operation of structures to control the runoff and produce flood maps. An example of hydraulic procedures (Nature Resource Canada, 2019) is shown in Figure 2.4.

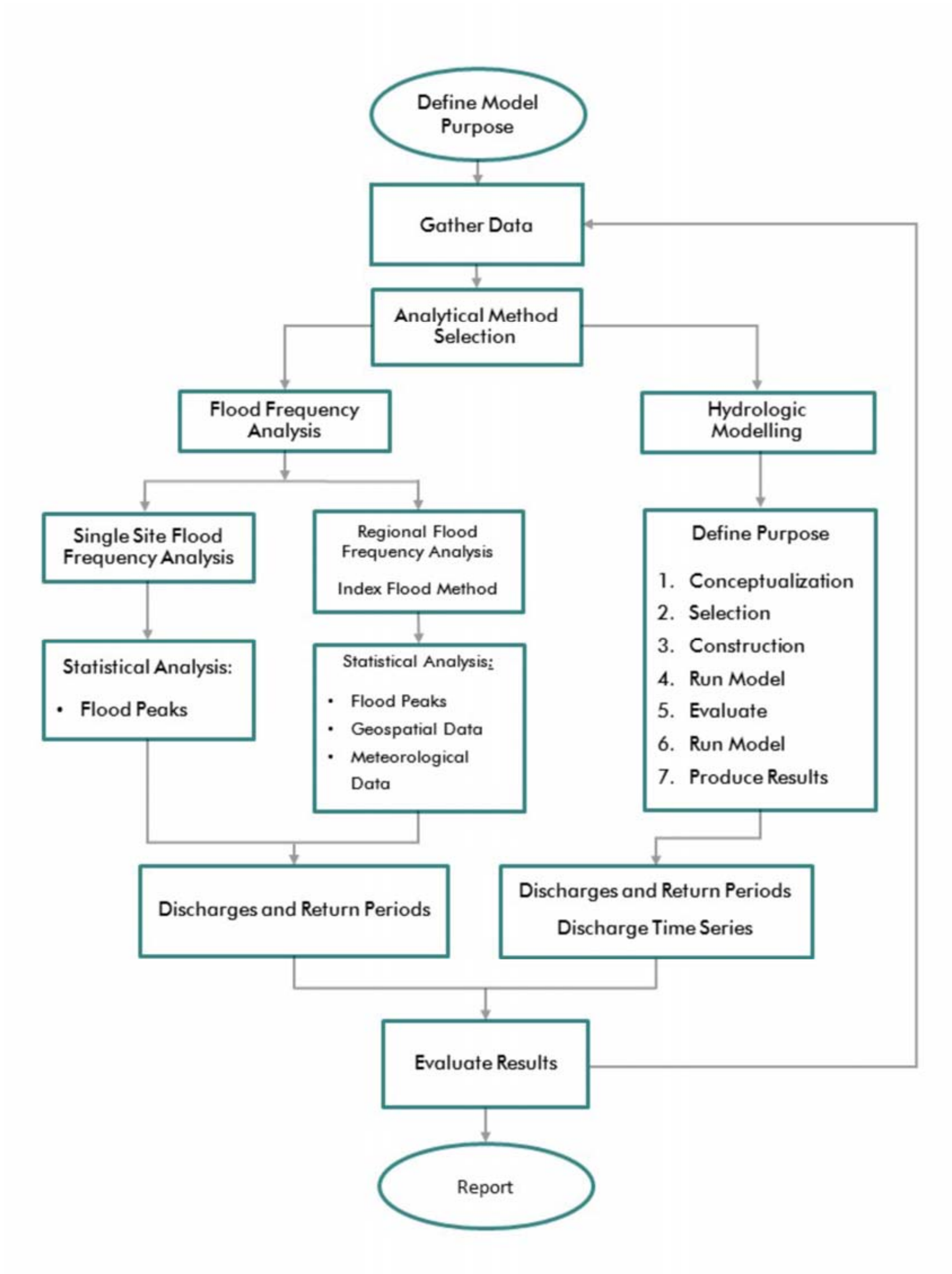


Figure 2.3 Canadian Federal Hydrologic Procedures for Flood Hazard Delineation (Nature Resource Canada, 2019)

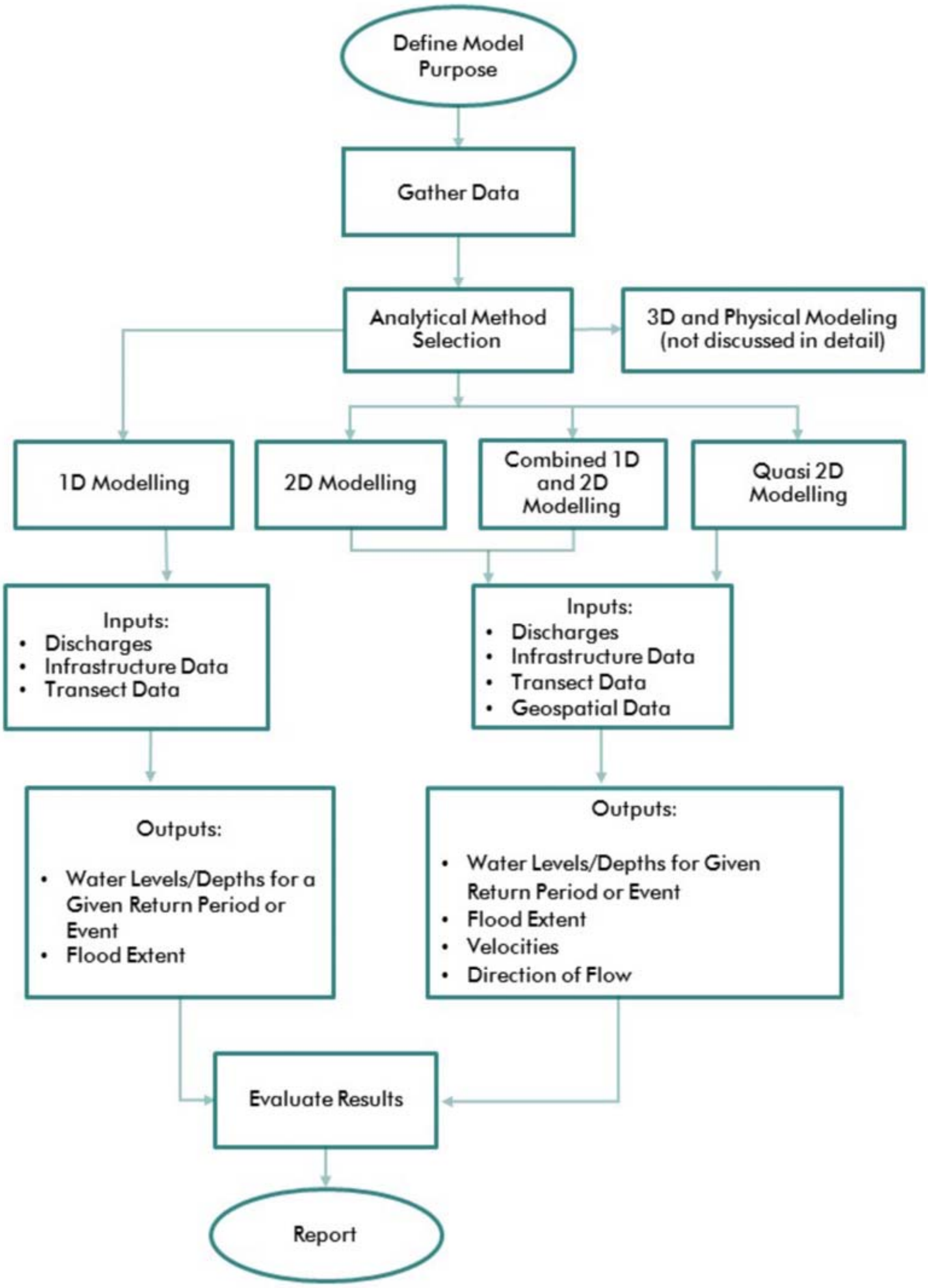


Figure 2.4 Canadian Federal Hydraulic Procedures for Flood Hazard Delineation (Nature Resource Canada, 2019)

2.2 Climate Change and Flood Hazards

The change in climate is impacting on human and natural systems (IPCC, 2014). Anthropogenic greenhouse gas emissions lead to the atmospheric concentrations of carbon dioxide, methane, and nitrous oxide, and these are extremely likely to have been the dominant cause of the global warming since the mid-20th century (IPCC, 2014). In the changing climate, it is predicted that it is very likely that the frequency and intensity of extreme precipitation will increase in mid-latitude mass land regions (IPCC, 2014), as shown in Figure 2.5, where majority of the world's population resides, and large cities were built. The evidence indicates the potential and uncertainty of flooding. Extreme weather events, such as floods, are increasing and damage costs are likely to increase over time (IPCC, 2007). For example, return periods for one-in-20-year extreme daily precipitation events would become a one-in-10-year event for mid to high latitude regions under moderate to high emission scenarios (Kharin et al., 2007). Another climate change implication is the rise of sea level leading to more coastal flooding. The case studies in this thesis focuses on mainly urban flooding and its impacts on pavement infrastructure.

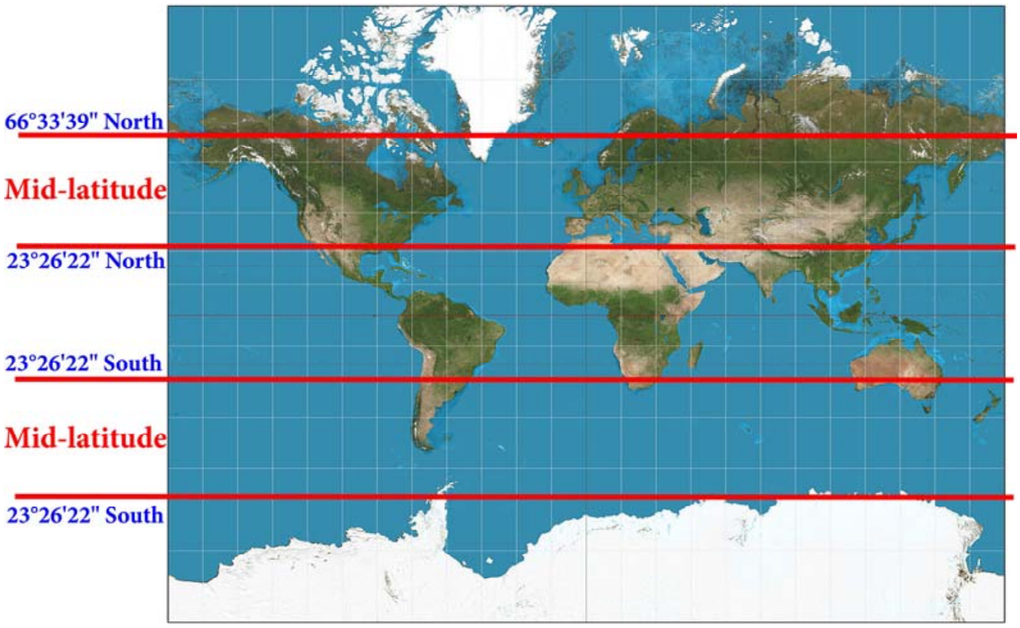


Figure 2.5 Global Map Showing Mid-Latitude Area Impacts

In Canada, the national average land temperature for the year 2014 was 0.5°C above the reference value. Since 1950, the annual average surface air temperature over Canada's landmass has warmed by 1.7°C, and average temperatures in Canada are expected to rise by an additional 1.5 °C to 4.5°C by 2070 (Environment and Climate Change Canada, 2016). The precipitation data indicates that, when averaged across the nation, precipitation amounts have tended to be wetter than the 1961–1990 average since the beginning of the 1970s for winter, spring, and summer, respectively (Environment and Climate Change Canada, 2017). More extreme events, such as heavy rain, floods, would damage road infrastructure assets, which is a critical infrastructure asset to sustain the national economy.

In Ontario, climate change, rapid urbanization, aging infrastructure, and under-resourced flood management continue to challenge communities (Conservation Ontario, 2013). Ontario's communities are at the front lines of climate change (NMAP, 2014). Ontario's climate has warmed up, temperature and precipitation are projected to increase over the next century (Colombo et al., 2007). By 2080, the overall precipitation is predicted to increase up to 240 mm annually (McDermid et al., 2015). Especially for small- and medium-sized communities in Ontario, flooding is a major source of socio-economic vulnerability (Moghal & Planner, 2016). Flooding caused the most expensive municipal natural disaster in Ontario's history; with 125 mm of rain in a few hours over some parts of Ontario in July 2013, it caused property damages in the estimated amount of 940 million dollars in the City of Toronto alone (Moghal & Planner, 2016). Ontario's infrastructure (roads, bridges, buildings, and sewer systems), with an average age of 15.4 years, would face the challenge of climate change (Ontario Ministry of Environment and Climate Change, 2011). A study was conducted recently, which investigated 33 municipalities, six First Nation communities, and 19 Conservation Authorities. The result shows that flooding poses a major risk for Ontario communities currently, as most interviewed have experienced urban and riverine flood events between 2005 and 2015, with 30% experiencing significant impacts from urban floods. Regarding future flood risk, 70% of communities believe they are at risk of a major flood event of urban flooding and riverine flooding in the next 30 years (Moghal & Planner, 2016). Climate change adaptation and action plan for critical infrastructures, including the understanding of the climate change risks to physical infrastructure, are one of the important strategies for dealing with climate change in Ontario (Ontario Ministry of Environment and Climate Change, 2011).

2.3 Pavement Design and Management

Pavements are designed to accommodate traffic wheel load and distribute them to the underlying subgrade. Pavement design is the process of selecting the pavement factors and input values that, when combined, will result in the most cost-effective pavement to meet the needs of users (TAC, 1999). This objective is achieved by specifying pavement layer thickness with proper materials based on the traffic and environmental conditions and by doing life-cycle cost analysis (Tighe et al., 2007). An example of pavement design input and output is illustrated in Figure 2.6.

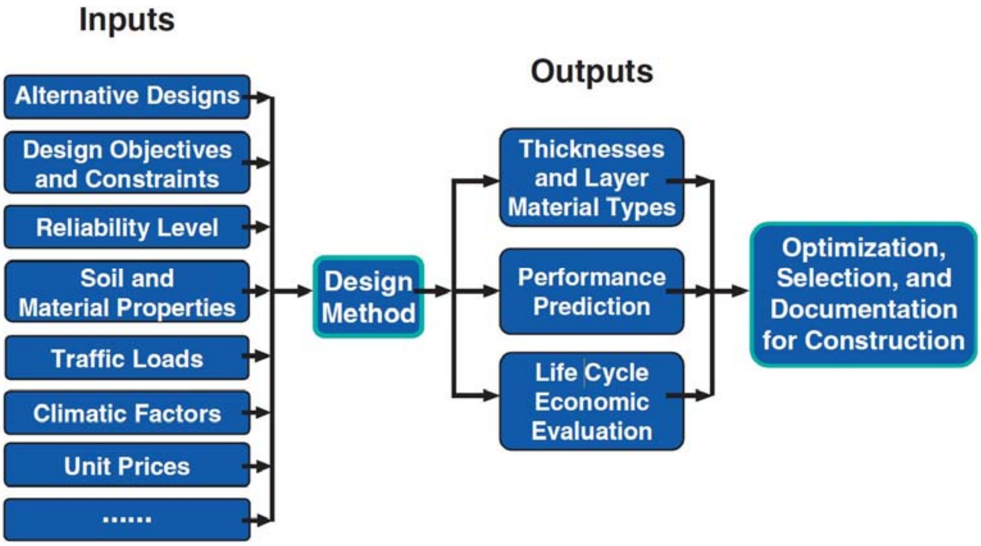


Figure 2.6 Pavement Design Framework (Tighe et al., 2007)

The major factors involved towards achieving the intended design life are illustrated in Figure 2.7. The factors including environment, structure, traffic, maintenance, and construction, interact with each other, and these interactions are often complex.

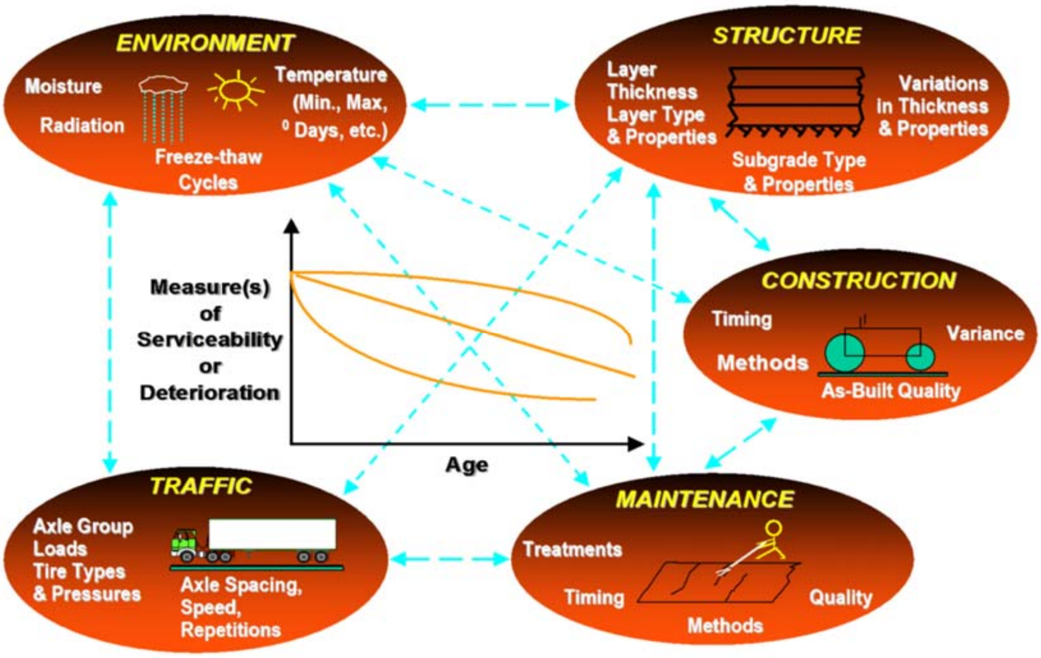


Figure 2.7 Factors Influencing Pavement Performance and Design Life (Tighe, 2007)

Pavement asset management system is a framework for making cost-effective resource allocation, programming and management decisions to provide safety, adequate level of service, preservation of investment, security and environmental stewardship considering financial, resource, and other constrains (TAC, 2013). The key activities (Figure 2.8) associated with pavement life cycle management include planning and programming, design, construction, maintenance, preservation and rehabilitation, in-service evaluation, and end of service life management (TAC, 2013).

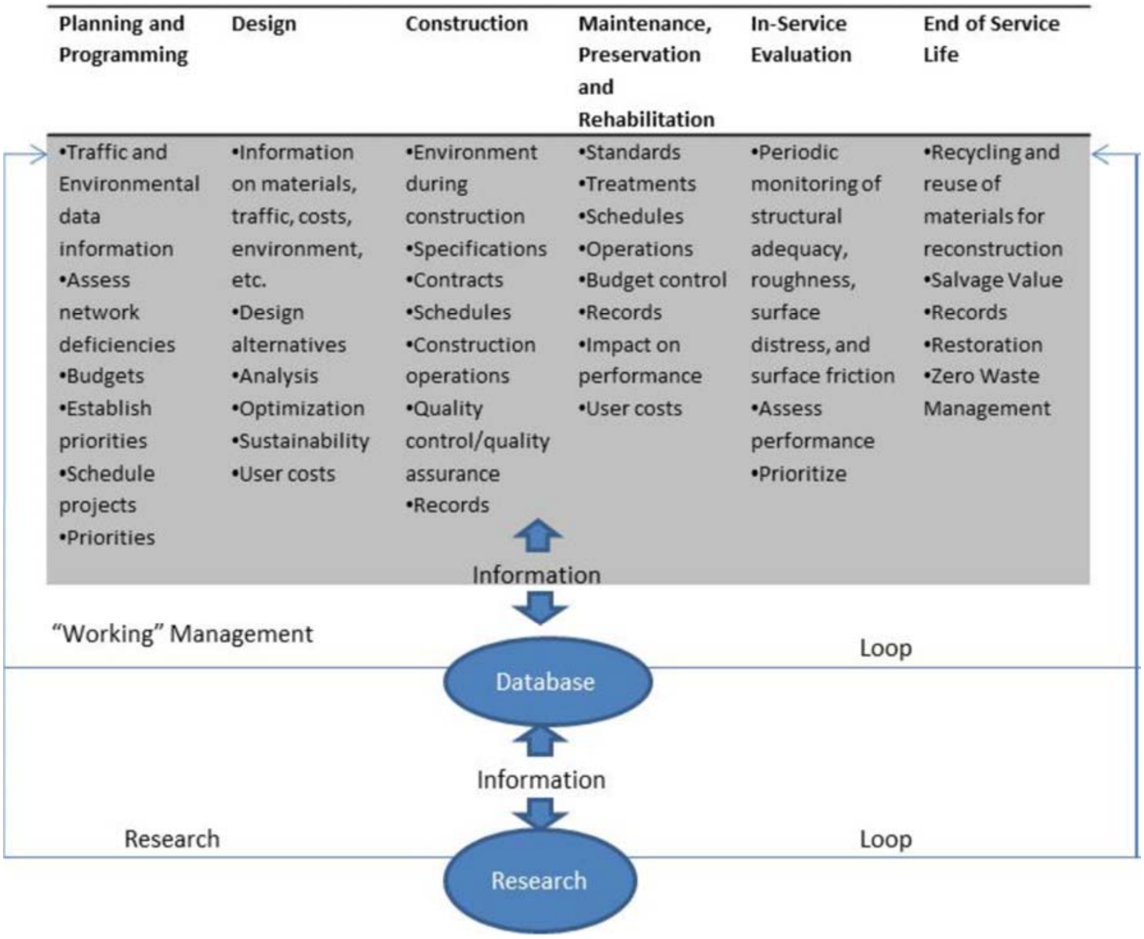


Figure 2.8 Life Cycle of Pavement Management (TAC, 2013)

The impact of climate change on pavement infrastructure has become a rising concern, because current road infrastructure was designed based on historical climate data, which does not adequately reflect current and future climate patterns. The concerns related to climate change in pavement design and management include reduced performance, loss of serviceability, shortened service life, long service disruption, high rehabilitation and replacement costs, and significant negative socio-economic impacts on communities. In the changing climate, using a static climate in the design and management practice is not a wise strategy for sustainability. After a flooding event, the existing pavement performance trend could be changed even if the flooding damage is not obvious immediately after flooding. The flooded pavement structure could lose its strength during flooding, and the degradation is amplified by the traffic loading after the flooding events. Identifying the potential pavement performance change under flooding condition enables the adjustment for developing optimal management decisions.

In order to achieve the objectives of pavement management listed in Table 2.1, (i.e., maintain a satisfactory level of service, safety, asset preservation, and sustainability), the risk of potential pavement damage should be assessed considering future climate. This requires a comprehensive understanding of the flood hazards, pavement structures, pavement in-service conditions, and other information involved. Upon the risk evaluation, adaptation actions can be taken to mitigate the risk. The decision should be aimed to build resilient pavement infrastructure through cost-effective pavement adaptation planning, design, construction, maintenance, preservation, and rehabilitation activities.

Table 2.1 Examples of Institutional Objective, KPIs and Implementation Targets (TAC, 2013)

Policy Objectives	Key Performance Indicators	Implementation Targets
Level of Service	• Network level of service (smoothness, functionality and utilization)- network condition • Provision of mobility (average travel speed by road class)	• Maintain 90% or greater of network in fair or better category (e.g. IRI≤2 m/km) • Rush hour traffic average speed minimum of 50% of posted speed limit
Safety	• Accident reductions (%) • Bridges (% of number with reduced load postings)	• Reductions of fatalities and injuries by 1% or great annually • Number of reduced load postings to less than 5% the network
Asset Preservation	• Asset value of road network ($)	• Annual increase in written down replacement cost by 0.5% or greater
Sustainability	• Recycling of reclaimed materials • Emission levels	• Maintain at 90% or greater • Maintain at levels <90% of standards

In Canada, the federal government has launched the National Disaster Mitigation Program (NDMP) (Public Safety Canada, 2016) to build knowledge of flood risks and reduce the impacts of flooding disaster. In 2018, Engineers Canada released the new climate change guidelines: Principles of Climate Adaptation and Mitigation for Engineers. Engineers should follow the eleven guides (EngineersCanada, 2018):

#1 integrate climate adaptation and resilience into practice;

#2 integrate climate mitigation into practice;

#3 review adequacy of current standards;

#4 exercise professional judgement;

#5 interpret climate information;

#6 emphasize innovation in mitigation and adaptation;

#7 work with specialists and stakeholders;

#8 use effective language;

#9 plan for service life and resilience;

#10 apply risk management principles for uncertainty;

#11 monitor legal liabilities.

The eleven guides are summarized in three categories: professional judgement (#1- #4), partnerships (#5- #8), and practice guidance (#9- #11).

Table 2.2 lists the principles and suggested implementation actions.

Table 2.2 Climate change guidelines for Canadian engineers (EngineersCanada, 2018)

Guides	The principle	Suggested implementing actions
Integrate Climate Adaptation and Resilience into Practice	*All engineers are responsible and need to be engaged*	• Listing the climate change predictions and potential impacts for the area where the project is located; • Discussing the aspects of the project the engineer believes could be impacted; • Detailing what has been done in the design to reduce those impacts; • Discussing the climate-relevant national, provincial, and municipal level codes, policies and bylaws establishing the level of acceptable risk, and identifying the client's level of risk tolerance; • Detailing what additional/revised operations and maintenance (O&M) and inspection procedures are recommended within the service life cycle of the project; and • Outlining policies and procedures to restore interruptions to service, loss of functionality or repair damages from extreme weather events.
Integrate Climate Mitigation into Practice	*All engineers have a responsibility to reduce GHG emissions*	• Identify all potential sources of GHGs related to the scope of the project; • Given the materials and processes on-site, quantify the potential releases of GHGs; • Seek opportunities to improve energy efficiency or reduced energy consumption as well as evaluate renewable energy options; • Compare the level of potential GHG emissions with alternative technologies and approaches; • Suggest the use of technologies that minimize the release of GHGs; • Examine options for controlling the GHGs if appropriate;
Review Adequacy of Current Standards	*Review applicable codes and standards and advise stakeholders on potential revisions or updates*	• Apply the most up-to-date revisions of relevant practice guidelines, codes and standards, as a baseline from which climate change adaptation or mitigation measures are applied. • Create a file of adjustments made to codes, standards and assumptions to accommodate changing climate or reflect improvements in technology.
Exercise Professional Judgement	*Evaluate and document the impact of climate and achieving resilience for engineering works, and consider opportunities for advancing climate change mitigation*	• Develop a checklist of climate parameters with potential to impact performance of design • Develop a checklist of climate parameters and operations/maintenance processes that may affect resilience to climate events • In the process of design, operation, procurement, management and maintenance activities, confirm applicability of climate information, policies/procedures, and assumptions about available technology that may be embedded in codes, standards, guidelines, etc. • In engineering working papers, spreadsheets and other documents, note that the review has been completed and prepare

		an accompanying memo to file that the review was completed. The engineer responsible for engineering activity should sign the accompanying memo.
Interpret Climate Information	*Consult with climate scientists and specialists*	• List climate information needs in terms of parameters that are listed in codes, standards, guidelines and "rules of thumb" as well as other information that is not formally codified within codes, standards, etc. but are nonetheless relevant to the professional work. • Develop the current climate profile based on analysis of historical weather data. Engineers should make sure that they are using data from the most current treatment of the subject. • Estimate the changes in frequency and extreme values of relevant climate parameters based on scientifically defensible methods of future climate projections over the service life of the engineered system. • Engage climate scientists and climate experts as appropriate to derive current and future extreme values and frequencies of relevant climate parameters.
Emphasize Innovation in Mitigation and Adaptation	*Seek collaborative, innovative strategies, technologies and/or new approaches*	• Identify known technologies and their status of development and implementation • Investigate areas of current research and their potential to deliver GHG reductions • Determine Canadian research expertise capabilities and its role in international endeavours • Research enabling and breakthrough or transformative technologies for the longer-term • Implement mechanisms for enhancing research and development of promising climate mitigation technologies that may have resilient co-benefits.
Work with Specialists and Stakeholders	*Work with multi-disciplinary and multi-stakeholder teams*	• During the formation of multi-disciplinary teams, review the overall service life and operability requirements of the engineered system and ensure that the entire range of skills necessary to assess climate implications of the work are covered. • In working papers and files maintain a written record of the team membership, skill sets, and training of each member of the multi-disciplinary team relative to the project/assignment
Use Effective Language	*Communicate effectively*	• Review each piece of professional writing with an eye to the intended audience for the piece • In aid of clearly communicating the primary message of the piece, apply common language and expressions more likely to be understood by the audience • As necessary, discuss suitable language with the intended audience and come to an agreement regarding the definition of terms used in the writing • In situations where common language may not suffice, ensure that the piece contains sufficient background information and definitions to promote the audience's understanding • Where the professional does not have the skills or expertise to simplify the writing, consult with or engage suitably qualified

		communications professionals to revise the piece for more general, broader understanding • Consider hiring a communications consultant to redraft the language to convince the necessary decision-making audience(s) • Assume that each piece of writing may be misunderstood and challenge the writing from different perspectives to identify areas where simplification or clarity may be necessary • Work with other members of the multi-disciplinary team and stakeholders engaged in the work for appropriate communication to different target audiences and stakeholders that will inform or trigger evidence-based decision-making with regards to climate change adaptation • It may be advisable to periodically remind the reader of the definition of terms that are not in common use and have the potential to be misunderstood.
Plan for Service Life and Resilience	*Consider the level of service and resilience over the entire operating life of the engineering work*	• During the design phase of a project, maintain a record of any reviews of climate and/or meteorological assessment conducted during the design of the engineered system • Identify any adjustments made to the design based on climate considerations • Identify the basis for any adjustments made to the design based on climate considerations • Identify the economic impact of changes made to design based on climate considerations • Identify how the adjustments address the full-service life cycle of the engineered system • During and after the construction phase provide as-built drawings to verify that the project was executed as designed to support ongoing operations and maintenance as well as for assessing the need for and planning of refurbishments later in the service cycle • During the operations and maintenance period of the project, maintain operating records of climate events that caused damage or interruption of service. • During refurbishment planning and design, maintain a record of any reviews of climate and/or meteorological assessment conducted during the design/plan of the refurbishment • Identify any adjustments made to the refurbishment design/plan based on climate considerations • Identify the basis for any adjustments made to the refurbishment design/plan based on climate considerations • Identify the economic impact of changes made to the refurbishment design/plan based on climate considerations • Identify how the adjustments address the full-service life cycle of the refurbishment design/plan • Ask the climate specialist to recommend a range of alternative methodologies for projecting climate information over the shorter timeframes used for refurbishment service cycles. • Develop, institute, review and/or revise operations and maintenance policies, standards, and procedures to better ensure the infrastructure asset functions at the capacity it was designed

		to perform, including ability to respond to loadings imposed by future changes in climate. • Good practices can extend service life beyond the design life, which means replacement or rehabilitation can be delayed, allowing re-allocation of human and financial resources to other priorities • Review and modify training and competency policies and standards on operations, maintenance, and emergency preparedness and response.
Apply Risk Management Principles for Uncertainty	*Use risk management to address uncertainties*	• First, develop competence in risk assessment • Establish awareness and knowledge of the range and applicability of risk assessment tools • Where appropriate, pursue professional development and training in risk assessment tools and approaches relevant to professional practice • Where the engineer does not have sufficient expertise in risk assessment, seek guidance from qualified professional practitioners that have such expertise • As appropriate, retain the services of professional practitioners with risk assessment expertise to advise and/or assist in the review of climate risks • Consider building risk assessment into all stages of the process – design, operation, maintenance, planning, procurement, management, etc. • Different tools will be applicable in different stages and the engineer should apprise themselves of the risk assessment approaches that are appropriate at each stage of a project or engineering task. • Consult with the broad range of stakeholders/users of the engineered system to assess their overall risk tolerance levels for the system.
Monitor Legal Liabilities	*Be aware of potential legal liability*	• Consult with the regulator on any applicable case law • Maintain a record of actions undertaken to address climate change issues within daily practice • Pursue enough additional professional training on climate change and meteorology • As appropriate, consult with climate and meteorological specialists to inform climate change adaptation measures • Maintain written documentation of training and consultation

Ministry of Infrastructure and Communities launched a program called Climate Lens (Infrastructure Canada, 2019) demonstrating the requirement in assessing the infrastructure locations, designs, and planned operations for climate change risk. In addition, the Disaster Mitigation and Adaptation Fund is designed for helping communities better withstand the risk of future nature hazards. These guidelines indicate that climate change is influencing engineering design and management practices, and actions need to be taken to address this problem. Risk assessment is identified as one of the important approaches in infrastructure design and management to address the impact of climate change.

However, most of the risk information available for informing policy is focused on the likelihood of the hazard in Canada (Jakob & Church, 2011). The responds of the infrastructure should be evaluated and incorporated in the risk assessment. Then, a more comprehensive profile of climate change risk can better inform management decisions.

2.4 Pavement Performance Simulation

There are many different design procedures in use around the world. A variety of different techniques exist, and they are generally categorized as: empirical, mechanistic, and mechanistic-empirical. Pavement structural mechanistic-empirical (M-E) analysis is the state-of-the-art method for designing and predicting pavement performance. In the M-E approach, the mechanistic analysis applies mathematical models to predict pavement structural responses (deflections, strains, and stresses) due to traffic loads and climate conditions based on mechanics of materials. Then, the empirically transfer functions are used to estimate distress initiation and development based on the responses.

Mechanistic Empirical Pavement Design Guide (MEPDG) is state-of-art systematic tool for pavement design and performance prediction for achieving pavement M-E analysis. MEPDG is widely used in pavement design and analysis practice in Ontario and some other provinces in Canada. It incorporates climate conditions and traffic conditions into pavement designs. Figure 2.9 shows the design system. The MEPDG performance predictions provide pavement performance indicators. For example, for asphalt concrete (AC) pavement, the following indicators are predicted during the design life: AC Bottom-Up Fatigue Cracking (%); Top-Down Fatigue Cracking (m/km); Total Cracking including Reflective and Alligator (%); AC Thermal Fracture (m/km); Permanent Deformation Total for AC only (mm); Terminal International Roughness Index (IRI) (m/km).

AC Bottom-Up/Alligator Fatigue Cracking is a form of fatigue or wheel load-related cracking that is initiated at the bottom of the AC layers due to tensile and shear stresses generated by repeated traffic loads. The cracks propagate with accumulative traffic loading.

AC Top-Down / Longitudinal Fatigue Cracking occurs within the wheel path parallel to the pavement centerline, and the cracks coalesce with continued truck loadings.

Thermal Fracture or Transverse cracking is usually perpendicular to the pavement centerline and is caused by changes in temperature.

Permanent Deformation (rutting) is a longitudinal surface depression in the wheel path. Under traffic and environmental loadings, the depression may occur in any pavement layers or subgrade due to consolidation or lateral movement of materials (AASHTO, 2008). This depression can also form due to poor compaction during the construction.

International Roughness Index (IRI) is an expression of irregularities in the pavement surface that adversely affect the ride quality. IRI indicates the characteristic of the longitudinal profile of pavements.

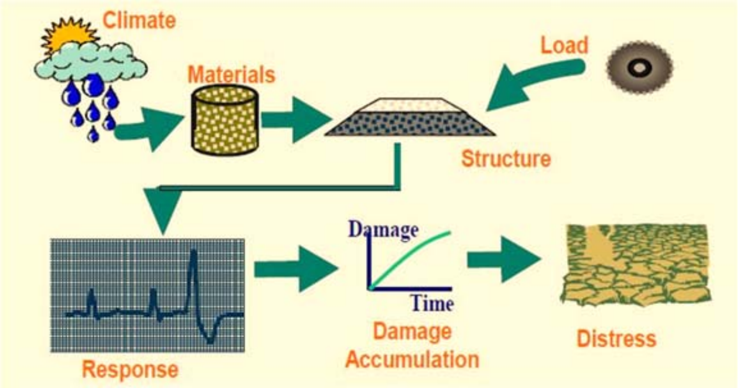


Figure 2.9 MEPDG Pavement Design System

In the MEPDG, Enhanced Integrated Climatic Model (EICM) is a one-dimensional coupled heat and moisture flow model that is used to analyze the impact of climate on pavement performance for pavement designs. The EICM is used to predict or simulate the changes in behavior and characteristics of pavement and unbound materials in conjunction with natural cycles of environmental conditions that occur over many years of service (NCHRP, 2008). The input parameters needed for pavement design include hourly air temperature, hourly precipitation, hourly wind speed, hourly percentage sunshine, hourly relative humidity, and ground water table depth (Figure 2.10). The air temperature is used to determine the long-wave radiation emitted by the air and the convective heat transfer from surface to air, and also to estimate the number and duration freeze–thaw cycle. The precipitation data are used for water infiltration and aging process (Hasan et al., 2016). The percentage of sunshine is used in calculating heat balance, and wind speed is for computing the convection heat transfer coefficient at the pavement surface. The relative humidity affects the long-term performance of pavements. Ground water table information is required for understanding the moisture contents and equilibrium modulus of underlaying layers (NCHRP, 2008).

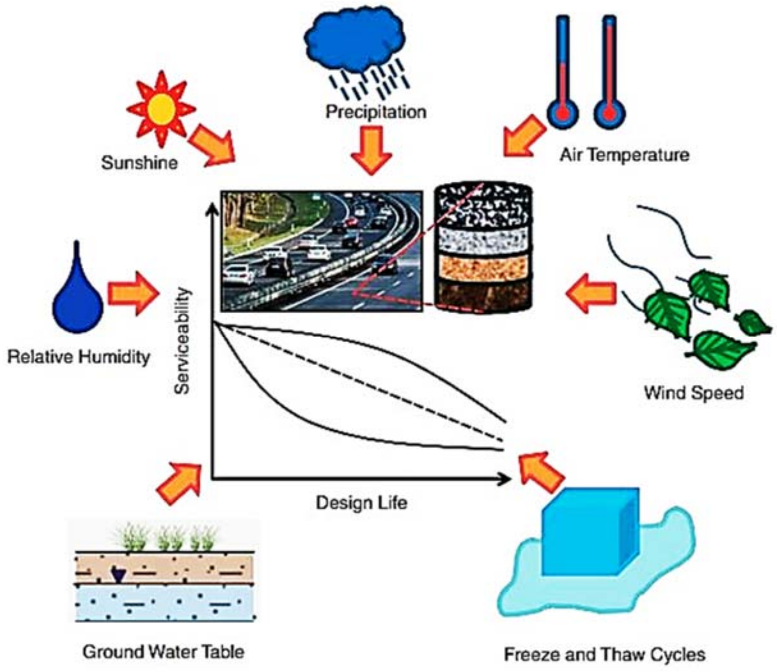


Figure 2.10 The Climate Inputs for Enhanced Integrated Climatic Model (Hasan et al, 2016)

2.5 Pavement Evaluation

Pavement evaluation refers to the procedure of field measurement and/or observing the current state of various pavement characteristics and documents them for future use (Ministry of Transportation Ontario, 2013). The observed performance data helps indicate the level of service, the pavement condition changes over time, and the need of repair for the pavement.

The pavement evaluation results are used for providing input for calculating the pavement performance, providing input for pavement design, ensuring the level of service and to trigger preventive and/or corrective treatments, providing input to calculate funding allocation, supporting the efforts of research and development (Ministry of Transportation Ontario, 2013).

There are typically four kinds of pavement evaluation surveys:

- Surface distress evaluation

  Surface distresses surveys involve the inspection and rating of irregularities and inspections and flows on the pavement surface (TAC, 2013). The methods are different from agency to agency, but the principles are the same. Most survey method include: type of distress (cracking, ravelling, rutting, scaling, faulting, etc.); area or extent of the distress; and severity of the distress (e.g. low, moderate, or high) (TAC, 2013). The causes can be determined based on the type and severity of the distresses. For example, alligator cracking or rutting indicate the traffic load related distress which could be from the inadequate structural capacity or uncorrected materials.

- Pavement roughness evaluation

  Roughness is defined as "*the deviation of a surface from a true planar surface with characteristic dimensions that affect vehicle dynamic and ride quality*" (ASTM, 2009b). Roughness as a measure of pavement serviceability can affect vehicle operating cost, which is an important measurement in pavement management decisions. Smooth pavement with low initial roughness can last longer and require less maintenance (Raymond, 2003). The distortion of pavement surface may be because of the poor quality of initial construction, and deterioration due to traffic and environmental factors. International Roughness Index (IRI) is a worldwide standard for roughness measurement. Typical Canadian highways have IRI value of 1 to 3 mm/m (TAC, 2013).

- Pavement strength evaluation

The structural or load carrying capacity of a pavement is an important component for pavement design and management. Investigations are divided into destructive and non-destructive method. Destructive techniques involve the measurement of the thickness of each pavement layer through coring, boreholes and test pits. Structure Number (SN) is often used to express the strength. Non-destructive techniques include the used of pavement deflection testing devices, which determines the structural adequacy of an existing pavement and assesses its capability of handling future traffic loadings. Falling Weight Deflectometer (FWD), Dynaflect, and Benkelman Beam are commonly used in Canada (TAC, 2013).

- Pavement safety evaluation

  Skid resistance and rut depth are typically the measurement of safety evaluation. Skid resistance is expressed as the frictional resistance between a wet pavement and the locked tires of a moving vehicle (Ministry of Transportation Ontario, 2013). It is largely determined by the macrotexture (its ability to channel water away from under the tire) of the surface (texture wavelength between 10^{-3} m and 10^{-2} m). The relative skid resistance of a pavement is expressed by a friction number (FN) ranging from 0 (worst) to 100 (best) by field measurement and correlation.

  Pavement surface ruts is another safety concern affecting the handling of a vehicle and hydroplaning property on wet pavements. Rut depth is defined as the depth of the depressions in the wheel path (Ministry of Transportation Ontario, 2013). Rutting issue can result from load associate deformation, quality of construction, and pavement deterioration.

Based on the evaluation and analysis of reasons, appropriate maintenance, preservation and rehabilitation treatment can be identified.

2.6 Pavement Maintenance, Preservation, and Rehabilitation

The life cycle of a pavement begins with initial construction and is followed by maintenance, preservation, and rehabilitation operations as it deteriorates. Maintenance occurs in the early service life before it has reached a limit of serviceability, while preservation aims to prevent distress and slow the speed of deterioration. Rehabilitation involves the enhancement of the structure to renew the service and improve its load carrying capacity (TAC, 2013). Treatments are selected based on the pavement type, condition, traffic, environment, available budget, and other constraint. Figure 2.11 illustrate the MTO Pavement Improvement Strategies and Related Schedule.

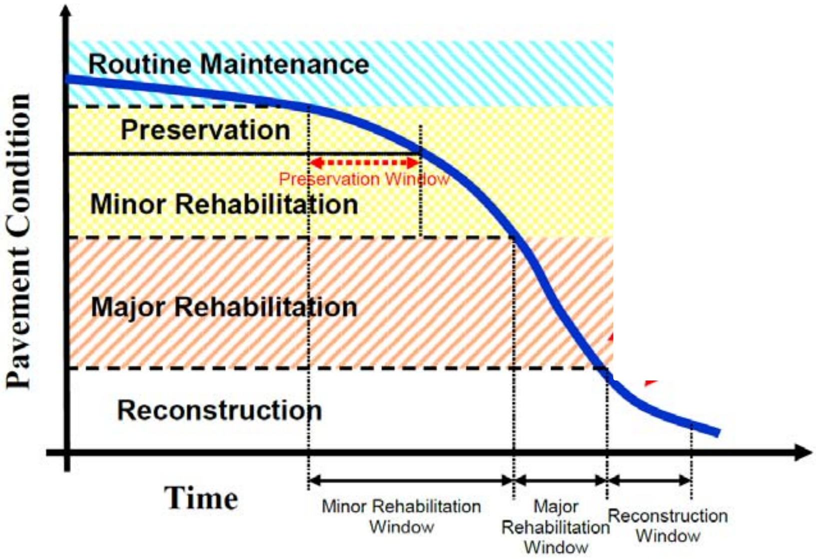


Figure 2.11 Pavement Improvement Strategies and Related Schedule (Ministry of Transportation Ontario, 2013)

2.7 The Impacts of Flooding on Pavement System

2.7.1 Impacts of Flooding on Pavements

When floods occur, there are both short- and long-term implications on pavements (Mallick et al., 2014; Willway et al., 2008). Damage can be caused by pavement water saturation, debris swept by flood flow and current, and potential wash-out. Regarding asphalt surface texture, it can be clogged with debris, which can cause difficulties in reinstating the surface to an adequate skid resistance and noise characteristics (Willway et al., 2008). The ingress of excessive moisture, especially with the presences of cracks and joints, can accelerate pavement degradation. There is a need to consider climate-change-induced precipitation regimes (Daniel, 2017) because moisture conditions can significantly affect the deterioration of road structures (Dawson, 2009).

Some researchers have investigated the effect of flooding on pavement structures after devastating flood events. Pavement structural damages caused by Hurricane Katrina (New Orleans and southeastern Louisiana on August 29, 2005) flooding were collected by FWD to calculate elastic moduli of pavement layers, and Dynaflect for determining the structural number and subgrade resilient modulus. The results indicate that flood weakens asphalt pavement through decreasing the stiffness of asphalt concrete layer and subgrade, while the effect on rigid pavement is much smaller (Zhang et al., 2008). Asphalt pavements at lower elevations were affected more than the ones at higher elevations by flooding (Zhang et al., 2008). After Hurricane Katrina and Rita, Helali et al. (2008) assessed pavements and roadways. The comparison between the flooded/non-flooded road section and historical and post analyses conditions indicated that the pavements submerged in flood water achieved significant damages. The damage is equivalent to the loss of 2.3 inches of asphalt concrete material. Average pavement performance and structural condition of the flooded sections are significantly worse than those of the control sections, and flexible pavement is more vulnerable than rigid pavement (Helali et al., 2008). In addition, following Hurricanes Katrina and Rita in 2005, highway damage increased as a result of the heavy trucking or vehicle loading required for transporting the vast amounts of debris (Chen and Zhang, 2014). The study also found that an escalation in deterioration occurred as subgrade components was not designed to sustain the vehicle loads and weakened by the submergence in water for extended periods of time (Chen and Zhang, 2014).

For the January 2011 flood in Queensland, pavement damage was evaluated post-flood using FWD deflection data on flood affected roads; the results indicate a consistent trend of decrease in strength due to the sustained flood water submergence. Condric and Stephenson (2013) indicated that after the January 2011 flooding, there was a significant reduction in pavement strength due to the ingress of water, which damaged and weakened supporting subgrade layers. Visual inspections showed that pavement failures occurred. The accelerated deterioration and loss of pavement life due to the inundation were identified. The roughness and rutting values of the flood affected sections had significantly increased following the heavy rainfall and flooding event from 2010 to 2014 (Sultana et al., 2016). The deterioration of the surface roughness and rutting may not always be visible immediately after flooding, but the flood-affected pavement sections had a rapid reduction in the structural and subgrade strength. Furthermore, pavements with weakened subgrade condition deteriorate rapidly when traffic starts to use the road again (Sultana et al., 2016). Results of flood impact on pavement in Australia illustrate that pavements deteriorate rapidly rather than gradually when subject to flooding for a certain inundation period. Furthermore, there is an increase in roughness, rutting, and cracking in some sections of flooded pavement, and the reduction of subgrade California bearing ratio (CBR) value and structural number can be up to 67% and 50%, respectively (Sultana et al., 2016).

After the 2011 Missouri River flooding in western Iowa, Vennapusa et al. (2013) used visual, destructive and nondestructive methods to evaluate levees, bridge abutments/foundations, paved and unpaved roadways, culverts, and embankment slopes. The primary modes of failure for pavements included voids at shallow and deeper depths due to the failure of underlying base materials and erosion of shoulders close to the water line in paved roadways and rutting and erosion of materials in unpaved roadways.

Models and estimation methods for flooding damage is emerging. The effect of flooding on pavement roughness is significantly correlated to initial pavement roughness, traffic, flood depth, and duration (Tari et al., 2015). A modelling framework for assessing flood-induced damages through introducing the critical time for saturation was developed (Mallick et al., 2015). Khan et al. (2014) proposed IRI and rutting-based road deterioration models to address flood hazard and derived post-flood optimal maintenance and rehabilitation strategies for the advancement of pavement management system. Khan et al. (2016) derived a pre-flood road maintenance strategy. The results of the case study in Queensland, Australia indicated pre-flood maintenance strategy is more effective than post-flood maintenance strategy. Wang et al. (2015) developed an estimation method for the loss of flexible pavement life due to flooding by considering a reduction in subgrade resilient modulus due to saturation. The transfer functions in M-E pavement design method were used to estimate the reduction of allowable traffic under saturated subgrade conditions. The results indicate significant reduction of allowable traffic at post-flooded pavement. Mallick et al. (2018) combined results from the hydraulic and structural analysis. Surface deflections were estimated by using layered elastic analysis for pavement under different hydraulic conditions. Elshaer et al. (2018) applied layered elastic analysis to investigate the effect of various depths of the groundwater levels on pavement damage. The results demonstrated a significant decrease in the pavement structural capacity when the base and subgrade layers are fully saturated. Nivedya e.al. (2018) developed an approach for defining the resilience and loss of resilience of pavements to flooding by analyzing the flow of water through pavement layers based on unsaturated soil mechanics and finite elements method. The stiffness and structural condition were estimated and translated to a resilience index. The results indicated that base course materials with appropriate gradation, and/or thicker surface layer help avoid a reduction in service quality and loss of resilience for an extended period. The results also show that the significant impact of cracking in the surface layers can lead to a more rapid ingress of water.

In the long term, the effect of climate change on pavement seems to be significant. Researchers have used climate factors, including temperature and precipitation, to predict pavement performance. The impacts of high temperatures to roads was examined (Underwood et al., 2017) and the cost required to upgrade the asphalt cement materials were estimated across the United States. Mallick et al. (2014) employed the system dynamics method to predict the long-term impact of climate change on pavement performance and cost. The results show that there is an increase in pavement temperature, number of 100% saturation months, and number of inundations, along with the consequences of reductions of subgrade modulus, HMA modulus, and average pavement life. Mills et al. (2007) suggested that the global warming and associated precipitations bring challenges and raise the frequency, duration, and severity of flooding damage and thermal damage based on quantitative analysis of six sites in Canada. Meagher et al. (2012) found that the implications of climate change in asphalt concrete rutting warrant additional consideration of climate change and its future variability in pavement design and evaluation. FHWA (2015) summarized climate impacts and adaptation strategies for pavement system, and proposed some future research areas to be extensively investigated in the short-term and long-term.

Opening a flooded or post flooded road to traffic may lead to structural damage. It is sometimes economical to close the road and reopen it when its ready. However, it can be a difficult decision when road closure may lead to significant economic loss from traffic delays (Qiao et al., 2017).The factors affecting decision making to open or close a road after flooding include flooding magnitude, pavement structural strength, subgrade modulus, traffic volume, and truck percentage (White et al., 2013; Zhang et al., 2008). Qiao et al. (2017) used a Bayesian decision tree approach for highway emergency operations after flooding. Uncertainties in the structural state of the pavement after flooding and costs are addressed with Monte Carlo simulations. The recommendations on whether FWD testing is necessary on the flooded road once the water recedes can also be provided.

Research on the effects of flooding on pavement networks is majorly focused on the disruption of the link of the network, traffic disruption and its consequence (Chang et al., 2010; Dehghani et al., 2017; Jenelius & Mattsson, 2012; Matisziw et al., 2009; Sohn, 2006; Versini, Gaume, & Andrieu, 2010; Yin et al., 2016). Some methods (Bles et al., 2016) are developed to assess the risk of flooding to road networks in terms of traffic disruption and its consequences. However, this network analysis did not concern the risk of physical pavement assets damage or the susceptibility of pavement infrastructure to the impact of flooding.

2.7.2 Models for Estimating Pavement Structural Damages and Risk

Reliable damage estimates are not always available, but losses due to climate related hazards appear to become more expensive in recent decades (Smith, 2004). Currently, literature on risk of flooding on pavement structure is very rare. Models on estimating other civil structures are typically depth-damage functions.

Flood damage estimation to structures was commonly accomplished in previous studies by applying the method of depth-damage function (Davis, 2003; Smith, 1994). Depth-damage functions were used to characterize the direct damage in relation to the depth of flood, inundation or flood stage. According to the generation process of depth-damage functions, two main types of functions can be distinguished: empirical functions (which use damage data collected from historical observations), and synthetic functions (which employ theoretical damage data based on hypothetical analyses and expert judgment) (Pistrika et al., 2014). The estimation considers flood depth as a main determinant of direct damage in the depth-damage functions without considering other factors, such as flow velocity, duration of flooding, contamination, and adaptative capacity (Smith, 1994; Tsakiris, 2014), leading to the inaccurate prediction of the flood damage. However, most flood damage models rarely involve all factors, and the uncertainty involved when applying a site-specific depth-damage function to another region is still a research gap. The successful application of depth-damage function approach for direct damage estimation highly depends on the level of analysis and the availability of data (Messner et al., 2007).

2.8 Risk Assessment and Management

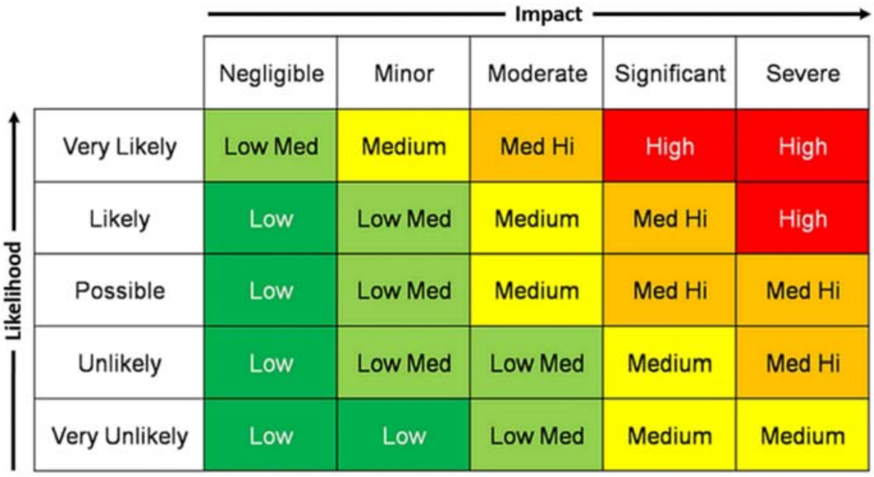
Risk is the effect of uncertainty on objectives (ISO, 2009). There are various definitions when systemizing hazards, exposure, vulnerability, risk, and adaptation in the context of climate change (IPCC, 2014). Risk can be qualitative or quantitative. For a specific risk, it is a description of a specific event, which may or may not occur, along with hazard and consequences. Climate change is not a risk per se; rather the interaction between climate changes related hazards and the vulnerability and exposure of systems together determine level of risk (IPCC, 2014). General factors of vulnerability identified, in both the disaster risk management and climate change adaptation communities (Cardona, 2011; Carreño et al., 2007; Gallopín, 2006; IPCC, 2007; Manyena, 2006) are: susceptibility/fragility or sensitivity; lack of resilience or lack of coping and adaptive capacities. Climate change risks involve people, societies, economic sectors, and ecosystems (IPCC, 2014). It is generally unevenly distributed and impacts communities at all levels of development.

Risk is a natural part of engineering system. Although the major objective of engineering design is to ensure system performance, there is still a chance for damage/failure leading to adverse consequences. Climate change risk analysis is the process of identifying and analyzing the dangers posed by climate change-caused adverse events and generating strategies to deal with them. Climate change risks on infrastructure result from the interaction of climate-related hazards with the exposure and vulnerability of infrastructure. Assessing risks of critical infrastructure is essential, especially when climate change hazards, such as flooding, anticipated in the future that may cause detrimental impact on the infrastructure system.

There are many ways of defining risk analysis. Generally, risk analysis involves risk assessment and risk management. Risk assessment is to identify, evaluate, and measure the risk; risk management is to develop strategies to mitigate and adapt to the risk based on risk assessment. Risk assessment is usually considered a part of risk management.

Risk assessment. Risk estimation can be qualitative or quantitative. Qualitative risk estimation uses descriptions by words, colours, and risk matrix, while quantitative risk analysis focuses on probabilistic risk assessment, including hazard and consequences analyses. Risk can be expressed in units such as probability of occurrence, costs, and time.

The risk matrix is a commonly used method in qualitative risk analysis; it is sometimes called a pseudo-quantitative method, because it may use numerical values to determine the risk. It would assign numbers to the likelihood and consequences for a risk without a mathematical model. The combination of the hazard likelihood and consequence categories corresponds to a risk level. Figure 2.12 shows an example of risk matrix. The severity levels are represented by different colors or descriptions. In the current climate risk analysis, a number of researches and practices are employing the matrix method (Amuzu et al., 2018), because risk assessment requires many engineering judgements.



	Negligible	Minor	Moderate	Significant	Severe
Very Likely	Low Med	Medium	Med Hi	High	High
Likely	Low	Low Med	Medium	Med Hi	High
Possible	Low	Low Med	Medium	Med Hi	Med Hi
Unlikely	Low	Low Med	Low Med	Medium	Med Hi
Very Unlikely	Low	Low	Low Med	Medium	Medium

Figure 2.12 Example of Risk Matrix

Quantitative Risk Analysis is a method for quantifying risks. This method can calculate the probability of a risk to be 0-100% instead of a scale of one to five. Then, the risk of consequence can be quantified as a number in dollars. It provides more detail about the risk and the interaction between the hazard and consequences.

Risk evaluation as the last step in risk assessment discusses what losses are acceptable and what are not. Then the intervention actions can be prioritized.

Risk management approaches often lead to no-regrets, low-regrets, or win-win options (UNFCCC, 2011). Risk management provides a science-based tool to support decision-makers. Risk management often starts by reviewing all data and information from the risk estimation and evaluation. The major goal of risk management is to reduce the disaster risk by mitigating the known threats. A risk management process is involved in climate change adaptation. The process includes identification and generation of options, assessment of the options, selection of optimized options, implementation, and monitoring and feedback to the whole process. Climate change risk management helps stakeholders identify and prioritize risks caused by climate- related hazard events, therefore, directing toward the optimum adaption actions.

2.9 Climate Change Adaptation and Resilient Infrastructure

Changes in extreme events are of concern for adaptation planning (Lemmen et al., 2008). Climate change impacts affect the operation and performance of a wide range of infrastructures leading to the need for new or modified designs, and adaptation in asset management system. Adaptation involves reducing risk and vulnerability, seeking opportunities, building capacity to cope with climate related hazards, and implementing decisions and actions (Tompkins et al., 2010).

Adaptation requires adequate information on risks for identifying needs and appropriate adaptation options (IPCC, 2014). Identifying adaptation needs requires an assessment of the factors that determine the climate risks, and the vulnerability, and an assessment of adaptation options to reduce risks. There are various frameworks for identifying the adaptation needs: risk-hazard framework and social vulnerability framework (IPCC, 2014). Risk-hazard framework focuses on the adverse effects of natural hazards and other climate impacts on physical and biological aspects of impacts and adaptation at a given location (Burton et al., 2002; Füssel & Klein, 2006). Social vulnerability framework focuses on the vulnerability of individuals, groups, and communities to climate impacts (IPCC, 2014) with the emphasize on how different factors shape the socioeconomic conditions that put humans at risk (Preston et al., 2011). There could be overlaps between the frameworks.

Adaptation measures are required to improve the resilience or robustness of a system exposed to climate change (Furgal & Prowse, 2008). The concept of resilience defined by Intergovernmental Panel on Climate Change (IPCC) is "*The ability of a social or ecological system to absorb disturbances while retaining the same basic structure and ways of functioning, the capacity for self-organization, and the capacity to adapt to stress and change*". Similarly, United Nations International Strategy for Disaster Reduction (UNISDR) defined it as "*The ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures* *and functions*." The ultimate adaptation strategies of road infrastructure should be directed towards a more resilient system to resist future climate-change-induced hazards.

2.9.1 Adaptation Framworks

Wall and Meyer (2013) presented a review of climate change adaptation strategies that focused on the transportation sector. Some of the important frameworks are listed in Table 2.3.

Table 2.3 Adaptation frameworks used in Canada and other countries

Framework	Country	Agency/Organization
Climate Risks and Adaptation Practices for The Canadian Transportation Sector 2016	Canada	Government of Canada (Palko and Lemmen, 2017)
Infrastructure Vulnerability Assessment and Adaptation to a Changing Climate	Canada	Public Infrastructure Engineering Vulnerability Committee (PIEVC) (Engineers Canada, 2015)
Federal Adaptation Policy Framework	Canada	Government of Canada (2011)
Adapting to Climate Change: A Risk Based Guide for Local Governments	Canada	Natural Resources Canada (Black et al., 2010)
Adapting to Climate Change: A Risk Based Guide for Ontario Municipalities	Canada	Ontario Ministry of Municipal Affairs and Housing (Bruce et al., 2006)
Risk Management for Roads in a Changing Climate: A Guidebook to the RIMAROCC Method	European Union	ERA-NET ROAD (Bles et al., 2010)
Climate Change Effects on the Land Transport Network Volume Two: Approach to Risk Management	New Zealand	NZ Transport Agency (Gardiner et al. 2009)
Climate Change Adaptation Strategy and Framework	United Kingdom	Highways Agency (2009)
Climate Change, Extreme Weather Events, and the Highway System Practitioner's Guide and Research Report	United States	National Cooperative Highway Research Program Report 750 (NCHRP, 2014)
Climate Change Risks for Coastal Buildings and Infrastructure: A Supplement to the First Pass National Assessment	Australia	Department of Climate Change and Energy Efficiency (2011)

2.9.1.1 Canada

Federal Adaptation Policy Framework was developed in 2011. It guides domestic actions by the Government of Canada to address adaptation to the impacts of climate variability and change. The framework sets out a vision of adaptation, objectives, roles of the federal government, and provides criteria for setting priorities for action. The document notes that the "*costs associated with future climate-related failures in infrastructure could potentially be avoided by changing current infrastructure design protocols to become more resilient to predicted future changes in climate*" (Government of Canada, 2011). An adaptation platform from Natural Resource Canada was launched in March 2012 bringing together key groups from government, industry, and professional organizations in Canada to collaborate on climate change adaptation priorities. The related investments to be made are to help Canadians adapt to climate change, including protecting the health of Canadians, assessing key vulnerabilities in Northern/Inuit populations, improving predictions of climate changes, and disseminating adaptation tools for regional adaptation.

Figure 2.13 shows the engineering protocol of climate change vulnerability assessment from Public Infrastructure Engineering Vulnerability Committee (PIEVC). PIEVC protocol is a major Canadian initiative examining the infrastructure vulnerability to climate change from an engineering perspective that provide amendments to existing codes, standards and practices for the design, operation, and maintenance of infrastructure (Engineers Canada, 2015).

Adaptation options for transportation sectors in Canada include engineering and technological solutions, as well as policy, planning, management, and maintenance approaches (Palko & Lemmen, 2017). The adaptation options can include (Palko & Lemmen, 2017):

- Changing pavement mixes for roads, for example using moisture susceptibility materials;
- Expanding drainage capacity for infrastructure;
- Increasing maintenance, including clearing debris from culverts to reduce flooding risks;
- Changing infrastructure design requirements to include climate change considerations or to introduce new flood event thresholds;

- Elevating or relocating new infrastructure where feasible;
- Increasing monitoring of weather events and infrastructure conditions;
- Implementing or enhancing travel advisories and alerts to communicate travel conditions and service delays during weather events.

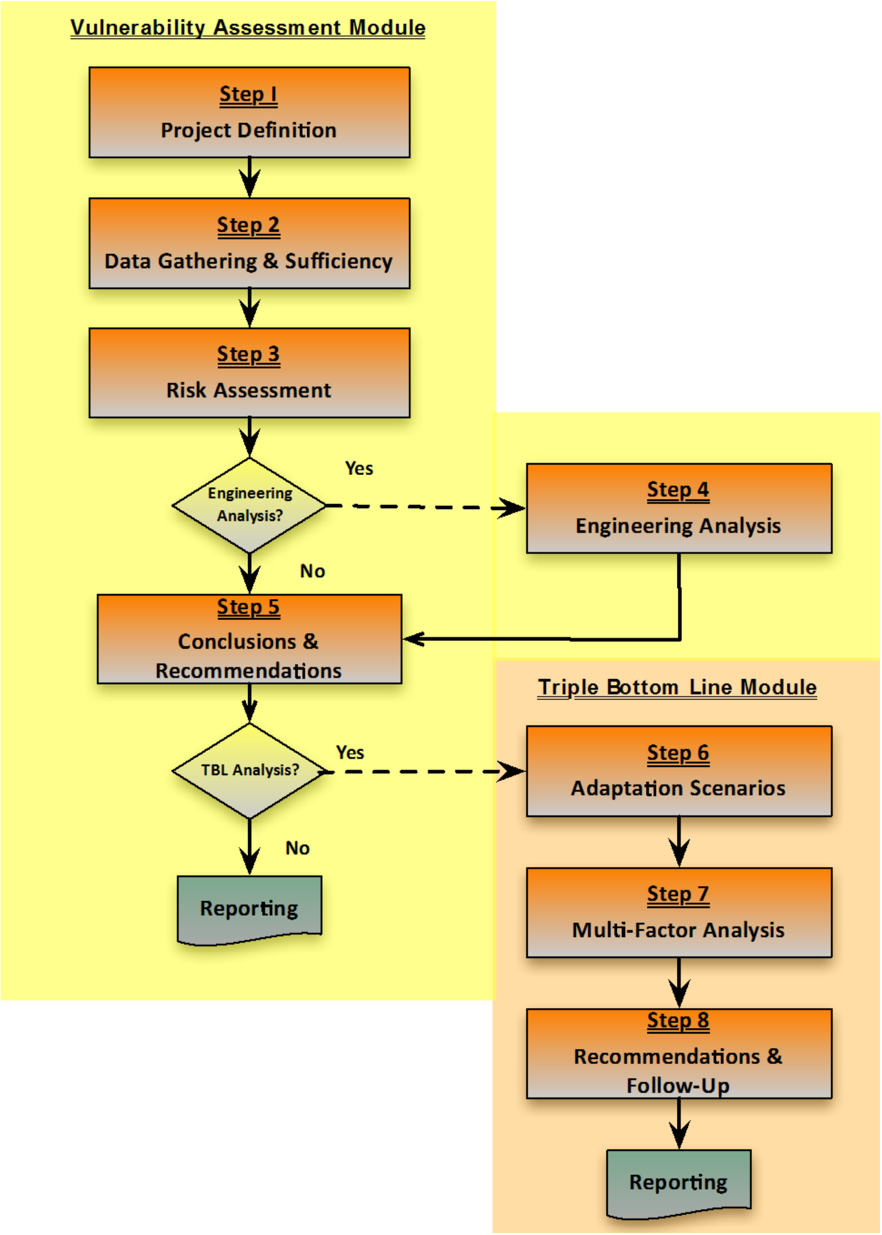


Figure 2.13 PIEVC Engineering Protocol (Engineers Canada, 2015)

2.9.1.2 United States

The Council on Environmental Quality (CEQ) issued “Instructions for Implementing Climate Change Adaptation Planning in Accordance with Executive Order 13514” in 2011. The Order requires US federal agencies to evaluate climate change risks and manage the risks. A climate change adaptation policy was adopted by the U.S. DOT in 2012. The policy also encourages state, regional, and local transportation agencies to consider climate change impacts in the decision-making process. In 2014, “Climate Change, Extreme Weather Events, and the Highway System: Practitioner’s Guide and Research Report” was released, which comprehensively addressed the strategic issues facing transportation. There are 8 steps in the US transportation adaptation framework (NCHRP, 2014):

(1) Identify key goals and performance measures;

(2) Define policies on assets, asset types, or locations that will receive adaptation consideration;

(3) Identify climate changes and effects on local environmental conditions;

(4) Identify the vulnerabilities of asset(s) to the changing environmental conditions;

(5) Conduct risk appraisal of asset(s) given vulnerabilities;

(6) Identify adaptation options for high-risk assets and assess feasibility, cost effectiveness, and defensibility of options;

(7) Coordinate agency functions for adaptation program implementation (and optionally identify agency/public risk tolerance and set trigger thresholds;

(8) Conduct site analysis or modify design standards, operating strategies, maintenance strategies, construction practices, etc.

Beside the framework, Hazus is a nationally applicable standardized methodology for estimating risk from earthquakes, floods, hurricanes, and tsunamis in the US. It graphically illustrates the limits of identified high-risk locations due to earthquakes, hurricanes, floods, and tsunamis.

2.9.1.3 European Union

Three topics together acting as a template for organizations to initiate, and develop climate change adaptation measures (Axelsen et al., 2016), was developed by Conference of European Directors of Roads (CEDR) group, on adapting to climate change: (1) Strategy and action plan; (2) Awareness; (3) Risk methodology approach. A range of tools and methodologies related to climate change adaptation have been developed within CEDR programs such as Risk Management for Roads in a Changing Climate (RIMAROCC), ROADAPT Roads for today adapted for tomorrow (Bles et al., 2016).

The framework is named “Risk Management for Roads in a Changing Climate (RIMAROCC)” (Figure 2.14). It is designed to meet the common needs of road owners and road administrators in Europe in risk management for roads regarding climate change. The tool highlighted out that identifying the climatic risks to implement optimal action plans can maximise the economic return to the road owners.

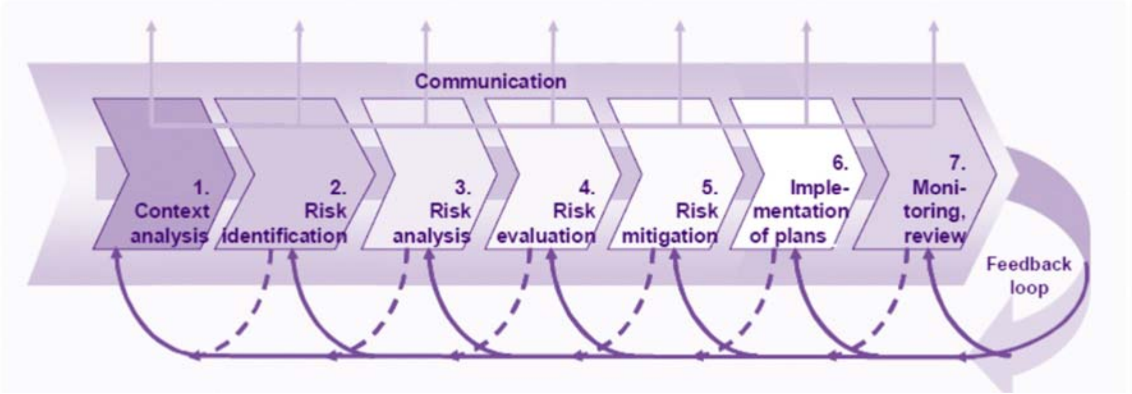


Figure 2.14 Framework of Risk Management for Roads in a Changing Climate (RIMAROCC) (Bles et al., 2010)

Quick Scan is a methodology developed to identify the major risks that can be associated with extreme weather conditions both in the current climate and in the future on roads in the ROADAPT project. The method is implemented through gathering knowledge of experts and practitioners to analyze road networks. Another model, entitled Blue Spot model, developed in the Danish Road Directorate, has a main purpose to identify road sections that are vulnerable to flooding events (Bles et al., 2016)

2.9.1.4 United Kingdom

The 2008 Climate Change Act in United Kingdom created a framework for building the ability to adapt to climate change. The United Kingdom has also developed the Climate Change Risk Assessment (CCRA) including analysis of climate hazard occurrence, the potential consequences, and prioritizations.

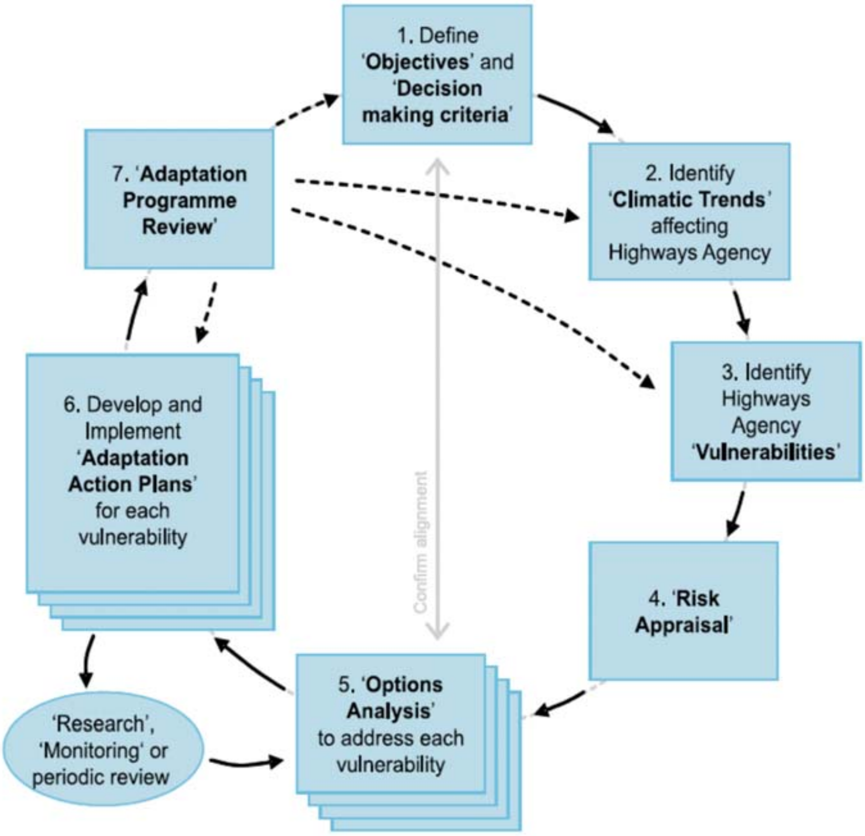


Figure 2.15 Highway Agency Adaptation Framework Model (Highways Agency, 2009)

England developed an adaptation framework named "Highway Agency's Climate Change Adaptation Strategy". The framework (Figure 2.15) includes seven steps for increasing the highway resilience including methods for prioritizing risk and implementation. These steps are summarized as:

(1) Define objectives and decision-making criteria;

(2) Identify climate trends that affect the highways agency;

(3) Identify highways agency vulnerabilities;

(4) Risk appraisal;

(5) Options analysis to address vulnerabilities;

(6) Develop and implement adaptation action plans;

(7) Adaptation program review.

2.9.1.5 Australia

In Australia, climate change adaption is managed under the Department of Climate Change and Energy Efficiency. The policy related to adaptation aims to adapt to the climate change that cannot be avoided. The key goal is to ensure that the infrastructure can provide continued and uninterrupted functioning of these assets, which are critical to support the economy (Commonwealth of Australia, 2010). The Australian Government released a *National Climate Resilience and Adaptation Strategy* in 2015, which outlines how Australia is managing its climate risks for the benefit of the community, economy and environment, now and into the future (Commonwealth of Australia, 2015).

2.10 Summary, Research Gaps, and Opportunities

The changing climate is already impacting the pavement infrastructure by the shifted temperature and precipitation patterns. Flooding is a rising concern, which can cause substantial road pavement infrastructure damage resulting in adverse social, environmental, and economic consequences. In the pavement design and management, historical climate design data are becoming less representative of the future climate. Future risk may be under-estimated.

Literature is now emerging on the impact of climate change on pavement systems and climate change adaptation strategies. However, they mostly focus on general observations on pavement performance and structural damage from certain flood hazards. The probabilistic pavement susceptibility to flooding damage needs to be accounted to get a better understanding of the uncertainty on how pavements respond to the extreme events. Studies conducted for pavement networks mainly focus on traffic disruptions and associated social economical consequences from only flooding information, not accounting for the information of pavement fragility and vulnerability. Most of the current climate change adaptation frameworks encourage the use of risk management approach to assess the impacts of changing climate on infrastructure systems. However, the research on the risk quantification of pavement asset flooding damage is scarce at both project level and network level.

Quantitative risk assessment is very challenging; great efforts are needed to understand more about future pavement flooding risk. Therefore, to bridge the research gap, conducting a study to comprehensively identify the pavement flooding damage, address probabilistic pavement damage, and develop a methodology to quantify the risk is of great importance. Risk assessment should be conducted by incorporating both climate-change-induced flooding and pavement fragility/vulnerability to inform the decisions in pavement planning and programming, design, construction, maintenance, preservation and rehabilitation. Then. maximization of life-cycle performance and cost-effectiveness can be achieved, and resilience can be built for road infrastructure systems.

Chapter 3 Flood Hazard Analysis

This chapter introduces flood hazard analysis method in the changing climate and performs a case study to illustrate the changed extreme precipitation magnitude in an urban setting.

3.1 Pavement Flood Hazards

Potential hazard posed by various flooding on pavements are described in Table 3.1.

Table 3.1 Pavement Flood Hazards Causes and Features

Types	**Causes**	**Features**
Pluvial flooding	Extreme heavy downpour of rain overwhelms drainage system	• Climate change and urbanization can increase the frequency of this type of pavement flooding. • Pavement can be subjected to frequent water saturation. • Pavement can be submerged in water for a long duration.
Fluvial flooding	Sustained and intense rainfall lead to rivers or streams to burst	• Climate change can increase the frequency of this type of pavement flooding. • Pavement can be submerged in water for a long duration. • Pavement erosion can occur as a result of more runoff from increased rainfall intensity.
Coastal flooding	High water levels including tides, storm surges, and tsunamis overtop coastal defenses and inundation of low-lying coastal areas	• Climate change can increase the frequency of this type of pavement flooding. • Large scale of pavement network damage is possible. • Post event debris on pavement may decrease surface textures leading to unsafe situations. • The force of flood water may impact the pavement structural integrity.
Reservoir flooding	Dam failure	• Climate change is not likely lead to this type of flooding.
Ground water flooding	Underground aquifers overflows onto the surface and stop water from draining	• The ground water level can be higher affecting the strength of underlaying layers and subgrade. • The pavement structural saturation can be severe resulting in pavement rapid deterioration post event.
Ice jam flooding	Blocked ice on river reduce the flow of a river causing upstream flooding, and downstream flooding can occur when ice jam releases an outburst flood	• Pavement damage is from flooding and freezing weather together. • A small network can be affected because it is more localized than open-water floods.

3.2 Flood Frequency Analysis

To reduce disaster risk and effectively protect people, goods, and infrastructures, it is essential to correctly assess and map the hazard. In hydrology, this topic is called Flood Frequency Analysis (FFA). It aims to associate stream flow or precipitation with its probability of exceedance. This kind of knowledge is essential for diverse operational applications such as flood prevention or civil engineering design.

Engineers analyze streamflow data for many purposes, including flood prediction, water management and allocation, design and operation of locks and dams, and recreational safety and enjoyment. Hydrographs and flood frequency analyses are ways that engineers determine the probability that a certain area will flood due to rainstorms, the expected response of a specific watershed region to a rainstorm, and annual/seasonal streamflow information. The return period of floods at a region has been widely used in engineering practice for analysis and design of structures. The Annual Exceedance Probability (AEP) is numerically the inverse of return period.

Rainfall Intensity-Duration-Frequency (IDF) curves are one of the most important tools for design, operation, and maintenance of a variety of water management infrastructures. IDF curves describe the relationship between rainfall intensity, rainfall duration, and return period. An equivalent procedure that differs only in using rainfall depth rather than intensities is called Depth-Duration-Frequency (DDF) curve. IDF curves provide precipitation accumulation depths for various return periods and different durations, usually, 5, 10, 15, 20, 30 minutes, 1, 2, 6, 12, 18, and 24 hours. Most of the current estimations of IDF and DDF curves are obtained through frequency analysis of historical rainfall observations with the assumption that the same underlying processes will govern future rainfall patterns. In the changing climate, the IDF and DDF curves should be updated for adapting engineering designs to climate change.

3.3 Design Flood for Roads

Standard engineering practice dictates the design flood with a specific return period appropriate for a given situation. In Ontario, Canada, for example (Table 3.2), waterway openings for culverts, bridge crossings, and other drainage facilities for freeway and urban arterial commonly use floods with 50- to 100-year return period for sizing bridges, culverts, storm drainage systems, and related stream channels (Ontario Ministry of Natural Resources, 2002). For rural arterial collector roads, the design flood is 25- to 50-year return period. However, these may not always be adequate in the changing climate. New protocols may need to be applied for new situations in the future to prevent potential loss of properties and assets.

Table 3.2 Design Flood for Road Crossings (Ontario Ministry of Natural Resources, 2002)

Road Classification	Design Flood	
	Total span up to 6.0 m	Total span over 6.0 m
Freeway, Urban Arterial	50 Year	100 Year
Rural Arterial Collector Road (paved)	25 Year	50 Year
Local (unpaved) Resource Access Road	10 Year	25 Year
Temporary Detours	1 to 5 Year	1 to 10 Year

3.4 Flood Hazards at the Project Level and Network Level

The flood exposure of pavement infrastructure and the vulnerability of the physical structure together determine the risk.

For project level risk assessment of pavement flooding, flood hazard is one of the important components in the risk estimation in this study. Flood hazards can be described by hazard functions/curves which indicate the relationship between flood level and annual exceedance probability (AEP) at a certain site.

In the network level risk analysis, project level risk estimation is extended to the network, and flood hazard maps are preferred to be examined and used for risk estimation across the pavement networks. Flood hazard maps are informative products indicating detailed flood information that can include types of flood, flood extent, water depths, flow velocity and so on for certain AEP cross the network.

3.5 Flood Hazard Analysis in the Changing Climate

3.5.1 Projection of Climate Futures

An understanding of future extreme projections is imperative for the adaptation design and maintenance of infrastructure, and for effective emergency responses. Climate change may increase the magnitudes and intensities of precipitations, which increase the flood potential in certain region. Predicting the characteristics of future precipitation can inform a future flood hazard prediction. Figure 3.1 illustrates the process for projecting the future extreme precipitation. This procedure follows the standard approach of climate change impact assessment described in IPCC (2013), which is a scenario-driven approach. The future climate is estimated under a given future climate-forcing scenario. Climate forcings are input in global climate models (GCM), and the output of GCMs is downscaled. Regional climate models (RCM) and or downscaling methods are used to study the local climate under climate change (IPCC, 2013).

Climate forcings or radiative forcing is the difference between insolation absorbed by earth and energy radiated back to space (in W m^{-2}) (Figure 3.2). Positive climate forcing produces warming, because the earth receives more insolation than the reflection to space leading to the net gain of energy. Conversely, negative radiative forcing results in earth cooling because the earth loses more energy than it receives.

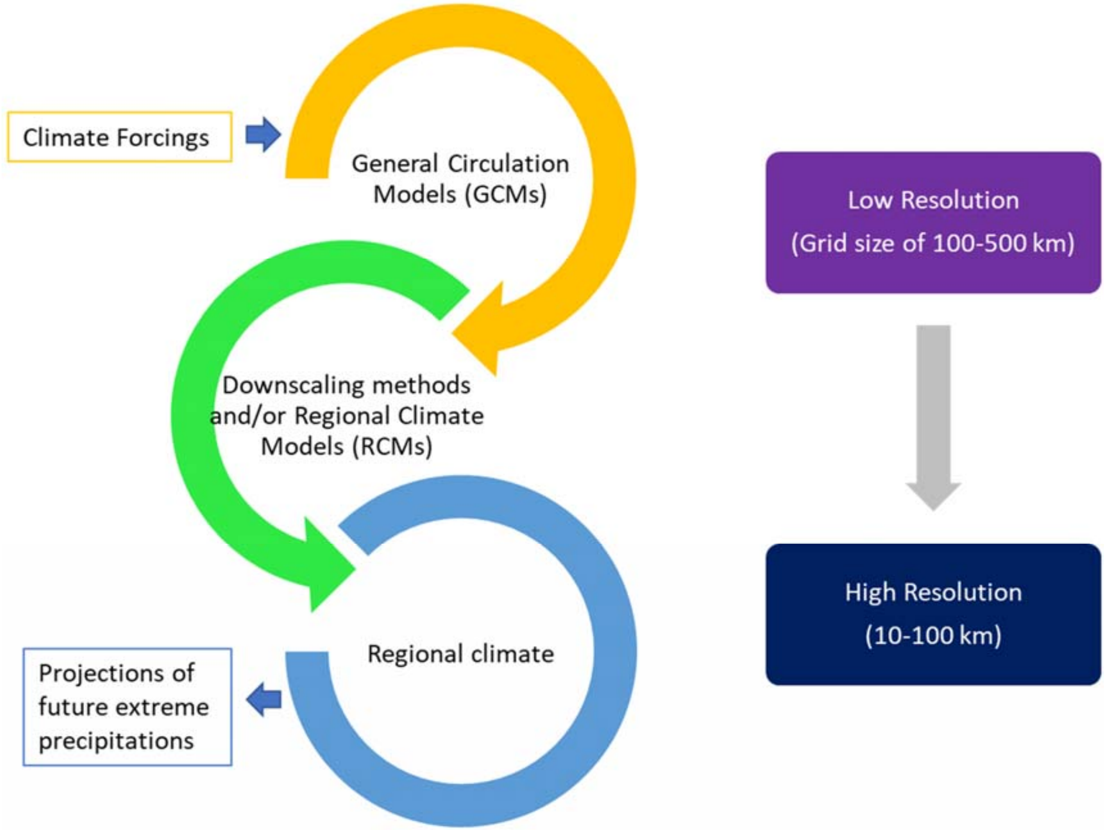


Figure 3.1 Processes for Projecting Future Extreme Precipitations under Climate Change

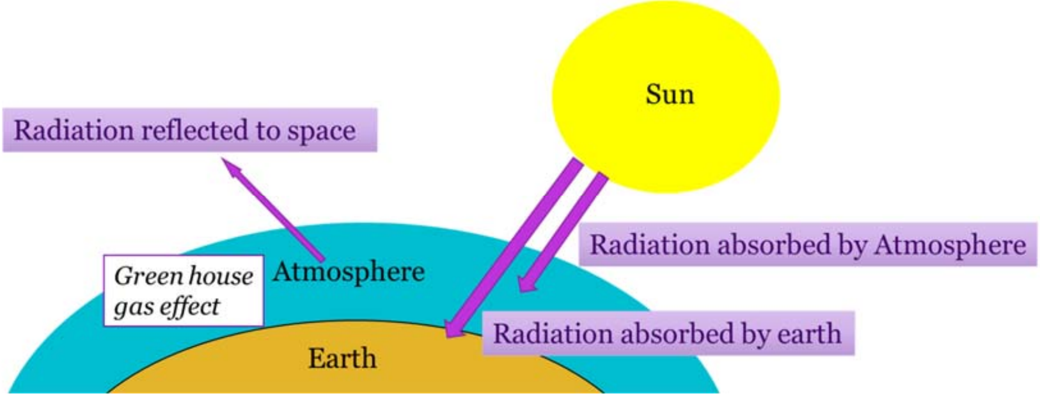


Figure 3.2 Climate Forcing

Climate-forcing scenarios are expressed by various Representative Concentration Pathways (RCPs). RCPs are greenhouse gas concentration trajectories adopted by the IPCC for its fifth

Assessment Report (AR5) (IPCC, 2014). Four RCPs, namely RCP2.6, RCP4.5, RCP6, and RCP8.5, have been selected for climate modelling and research, which describe different climate futures (IPCC, 2013). The four pathways are labelled after a possible range of radiative forcing values in the year 2100, which are 2.6, 4.5, 6.0, and 8.5 W/m^2, respectively. Table 3.3 shows the global temperature increase projections for these climate futures. RCP2.6 represents one pathway where radiative forcing peaks at approximately 3 W/m^2 before 2100 and then declines. RCP4.5 and RCP6.0 are two intermediate stabilization pathways in which radiative forcing is stabilized at approximately 4.5 W/m^2 and 6.0 W/m^2, respectively, after 2100. RCP8.5 is referred to as one high pathway for which radiative forcing exceeds 8.5 W/m^2 by 2100 and continues to rise after.

Table 3.3 Global Temperature Increase Projections for Various Climate Forcings (IPCC, 2013)

Years	2046–2065	2081–2100
Scenario	Mean and *likely* range (℃)	Mean and *likely* range (℃)
RCP2.6	1.0 (0.4 to 1.6)	1.0 (0.3 to 1.7)
RCP4.5	1.4 (0.9 to 2.0)	1.8 (1.1 to 2.6)
RCP6.0	1.3 (0.8 to 1.8)	2.2 (1.4 to 3.1)
RCP8.5	2.0 (1.4 to 2.6)	3.7 (2.6 to 4.8)

General Circulation Models (GCMs) are three-dimensional globe climate modelling tools for representing physical processes in the atmosphere, ocean, cryosphere, and land surface that can simulate the response of the global climate system to the increasing greenhouse gas concentrations. GCMs provide coarse horizontal resolution typically between 100 km and 500 km. For practical planning of local issues such as flood management, local scaled information is required. Downscaling methods and Regional Climate Models (RCMs) provide the solution to this problem.

Downscaling methods is the process of derivation of local to regional-scale (10-100 kilometers) information from larger scale modeled or observed data. There are dynamical downscaling, statistical downscaling, and dynamical-statistical downscaling approaches (Caffrey & Farmer, 2014).

Dynamical downscaling relies on the use of Regional Climate Models (RCMs), which are computer models that represent local features and provide higher resolution climate simulation results. RCMs take the large-scale atmospheric information supplied by GCM output at the lateral boundaries. Then, by incorporating the processes that control local climate such as topography, vegetation, hydrology, and detailed physical processes, climate information at specific areas can be generated.

Statistical downscaling involves the establishment of empirical relationships between historical large-scale climate and local climate. Then, future GCMs projections are used to predict future local climate using the empirical functions.

Dynamic-statistical downscaling first uses RCMs to downscale GCM output. Then, statistical downscaling methods are used to further downscale RCM output providing a finer resolution.

With the projection of future precipitations available, extreme events for different climate change scenarios can be input into the frequency analysis informing infrastructure design and analysis.

3.5.2 Future Rainfall Intensity Duration Frequency Analysis

Reliable rainfall intensity estimates are critical for infrastructure planning and drainage design. Thus, IDF curves need to be updated in the changing climate (Srivastav et al., 2014). The climate projections from GCMs and RCMs driven by RCPs provide a way to understand future climate and to update IDF and DDF curves under climate change. The hazard curves indicating the relationship between extreme precipitation levels and annual exceedance probability (AEP) can be obtained from the updated IDF curves for a certain duration. The updated IDF and DDF curves can also inform hydrology models for future flooding prediction. Furthermore, the extreme precipitations read from the updated curves can be used as input for pavement performance simulation in the changing climate.

Intensity duration frequency (IDF) curves are typically developed by fitting a theoretical probability distribution to an annual maximum precipitation (AMP) time series. Extreme value distributions, such as Gumbel, Generalized Extreme Value (GEV), Log Pearson, and Log Normal, are often used to fit AMP data.

In the following section, a case study is performed for project level hazard analysis. In Chapter 7, a case study on spatial risk analysis of the pavement networks will be presented to illustrate the incorporation of flood hazard maps into the road network risk estimation.

3.6 Case Study - Projection of Future Hazard Curves

This case study aims to incorporate various climate-forcing scenarios into the flood hazard analysis for future extreme precipitations events (Lu et al., 2018).

3.6.1 Case Study Area

Toronto Lester B. Pearson International Airport, Ontario, Canada (Figure 3.3) is selected as the case study area.

Figure 3.3 Case Study Area for Projection of Future Extreme Precipitation (Google map, 2019-10-10)

3.6.2 Data

The climate-change-induced future extreme precipitation data are generated by IDF-CC tool version 3 (Simonovic et al., 2016) and the updated IDF curves are created by the tool.

3.6.3 Climate Forcing Scenarios

The climate-forcing scenarios RCP 2.6 (lower bound), RCP 4.5 (intermediate level), and RCP 8.5 (higher bound) are used for predicting future extreme precipitations events in this study.

3.6.4 Local Climate Prediction Method

Selected Coupled Model Intercomparison Project Phase 5 (CMIP5) projection models are used as GCM models for future climate prediction. In this study, an ensemble of 24 GCMs and 9 bias-corrected GCMs downscaled using the Bias Correction/Constructed Analogues with Quantile mapping reordering (BCCAQ) (PCIC, 2016) are employed for predicting future precipitations events. The GCMs models are listed in Table 3.4. The output of GCMs has a grid size of 250 km and downscaled to about 10 km.

Table 3.4 Global Climate Models Used for Predicting Future Extreme Precipitation

Modelling Center	Model	Modelling Center	Model	Modelling Center	Model
CCCma	CanESM2	LASGCESS	FGOALS_g2	IPSL	IPSL-CM5A-MR
CCSM	CCSM4	EC-EARTH	EC-EARTH	MIROC	MIROC5
CNRM	CNRM-CM5	NOAA GFDL	GFDL-CM3	MIROC	MIROC-ESM
CSIRO	CSIRO-Mk3-6-0	NOAA GFDL	GFDL-ESM2G	MIROC	MIROC-ESM-CHEM
CESM	CESM1-CAM5	NOAA GFDL	GFDL-ESM2M	MPI-M	MPI-ESM-LR
MRI	MRI-CGCM3	MOHC	HadGEM2-AO	MPI-M	MPI-ESM-MR
BNU	BNU-ESM	MOHC	HadGEM2-ES	BCC	bcc_csm1_1 m
BCC	bcc_csm1_1	IPSL	IPSL-CM5A-LR	NOR	NorESM1-M

For temporal downscaling, Equidistant Quantile Matching (EQM) method (Srivastav et al., 2014) is used for capturing the distribution of changes between the projected time period and the baseline. For spatial downscaling, statistical downscale method was used for getting Canadian climate at a gridded resolution of roughly 10 km (PCIC, 2016).

For generating IDF curves, Gumbel distribution for fitting the historical AMP data and GEV distribution for fitting both historical and future precipitation data are used. The parameter estimation is carried out using the method of moments for Gumbel and L-moments for GEV. The process is implemented by using IDF-CC tool version 3 (Simonovic et al., 2016). The hazard curves are then converted from the IDF curves.

3.6.5 Future Hazard Curves and Uncertainty

The historical data are based on the precipitation data from 1950 to 2013 from Environment and Climate Change Canada. Future extreme precipitations (2017-2100) are estimated based on projected climate from RCP 2.6, RCP 4.5, and RCP 8.5 scenarios. The IDF curves are generated and converted to the depth-duration for various return periods. The historical precipitations and projected median future precipitation curves of 100-, 50-, 25-, 10-, 5-, and 2-year return period events for various climate change scenarios are illustrated in Figures 3.4-3.9. It indicates that climate change is predicted to increase the median precipitation magnitude for various events.

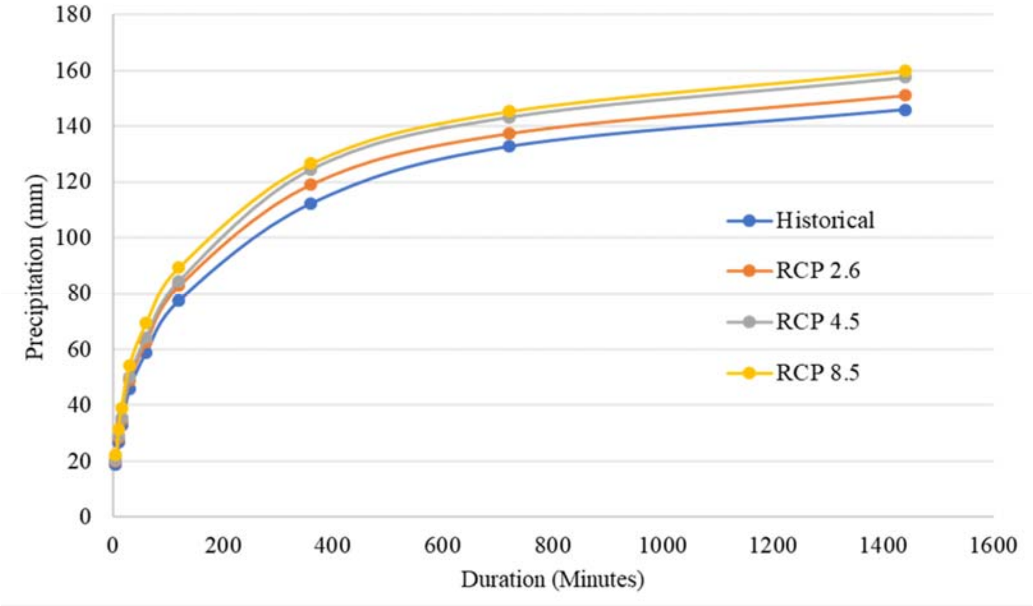


Figure 3.4 100-Year Return Period Precipitations under Various Climate Change Scenarios

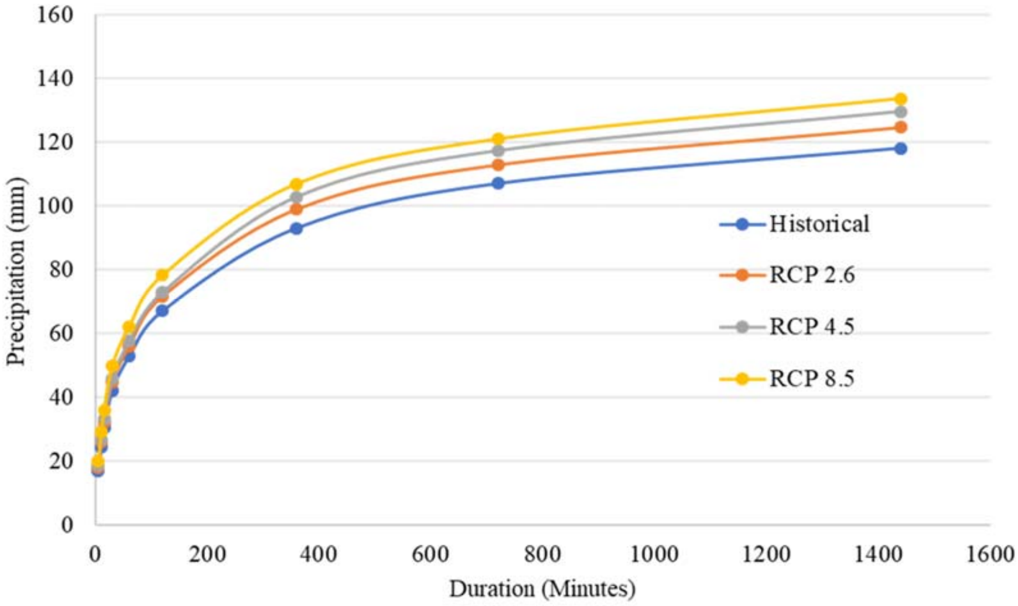


Figure 3.5 50-Year Return Period Precipitations under Various Climate Change Scenarios

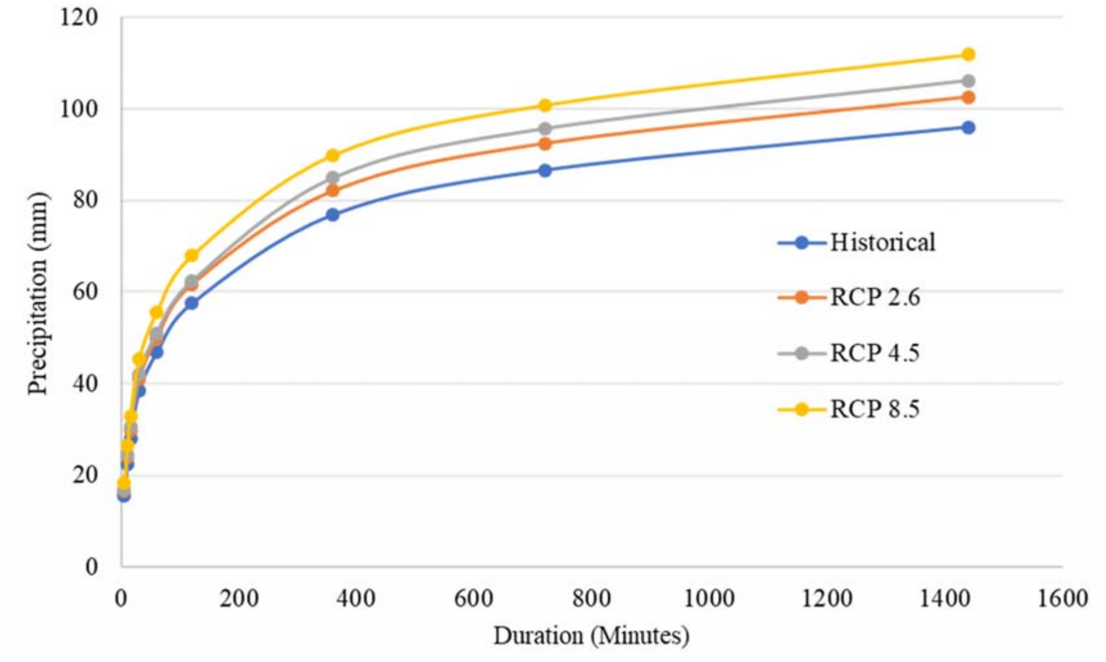


Figure 3.6 25-Year Return Period Precipitations under Various Climate Change Scenarios

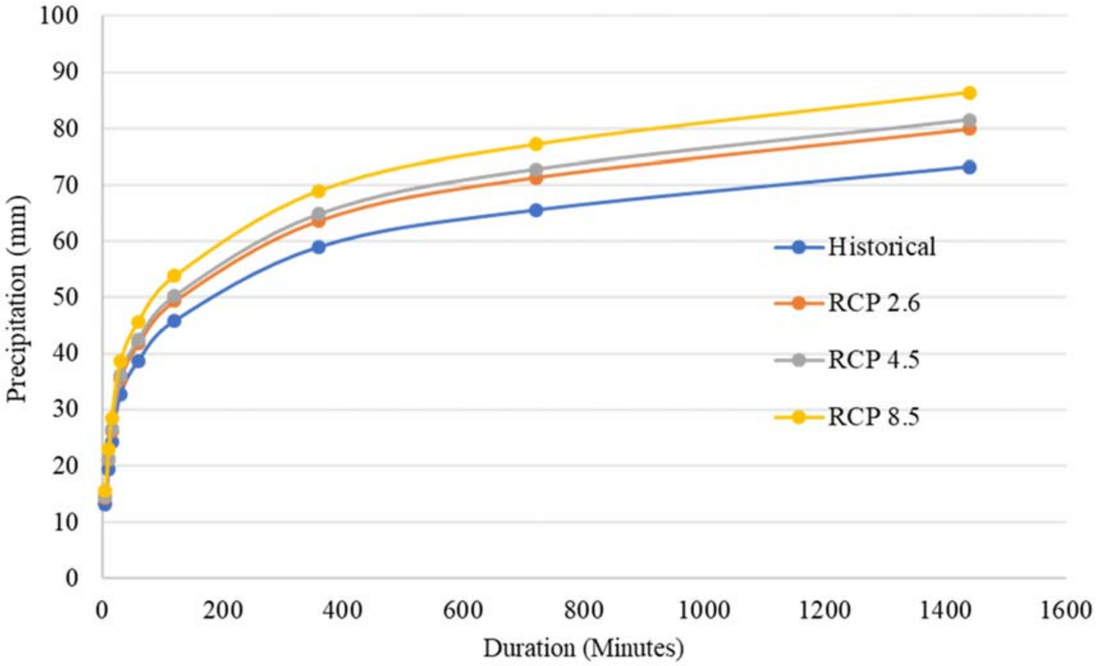


Figure 3.7 10-Year Return Period Precipitations under Various Climate Change Scenarios

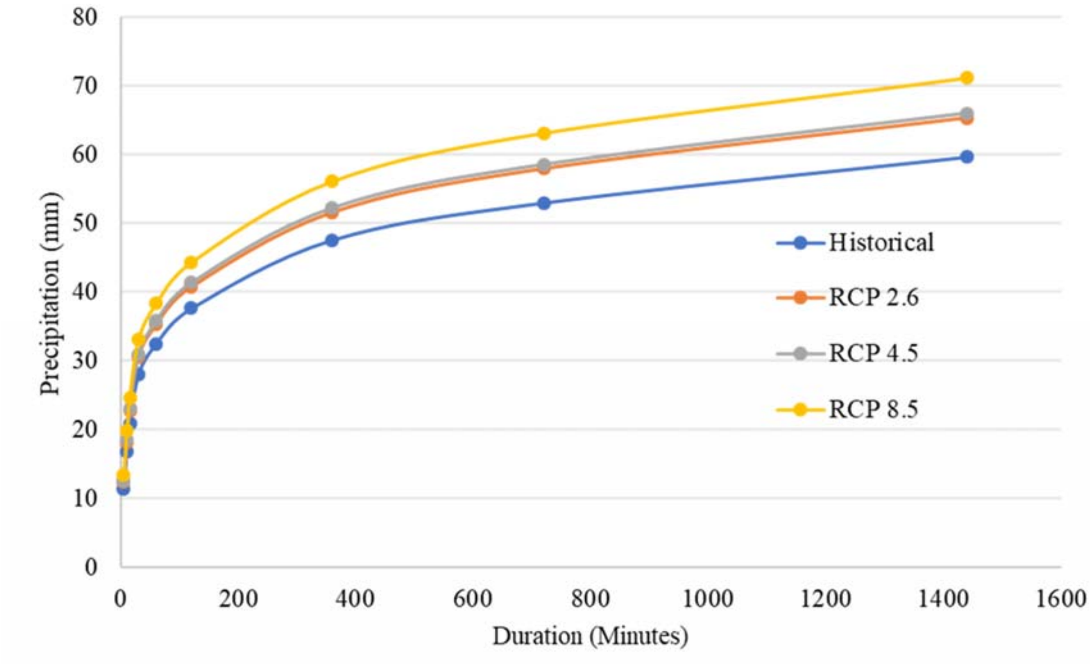


Figure 3.8 5-Year Return Period Precipitations under Various Climate Change Scenarios

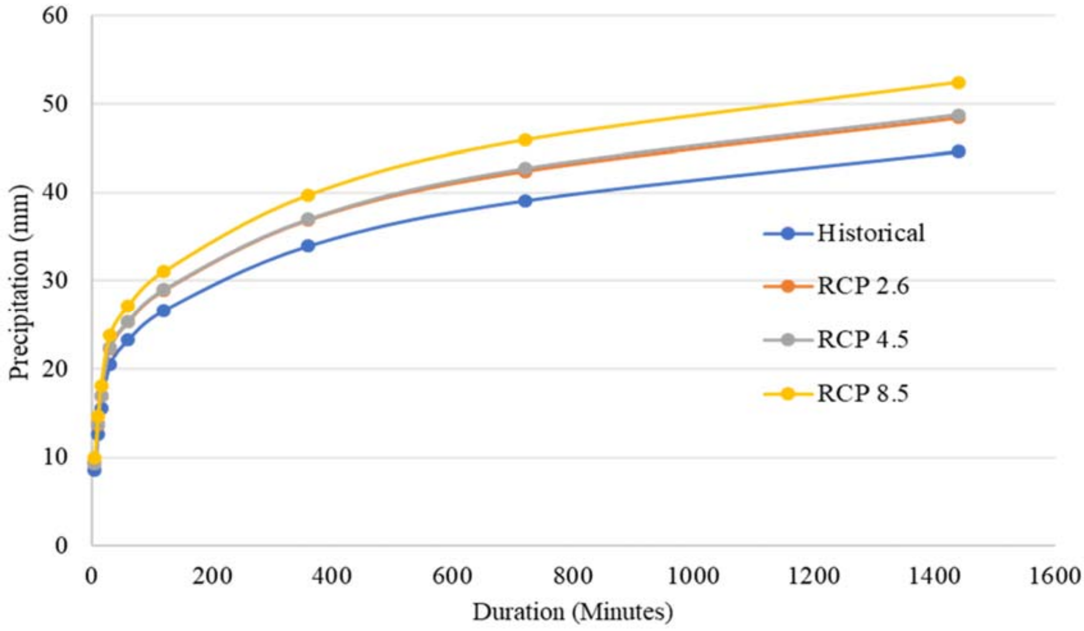


Figure 3.9 2-Year Return Period Precipitations under Various Climate Change Scenarios

Figure 3.10 demonstrates the change of precipitation patterns at Toronto Pearson Airport Station. The 5-year return period precipitation event is almost reaching to the magnitude of 20-year return period events under the worst climate change scenario (RCP 8.5).

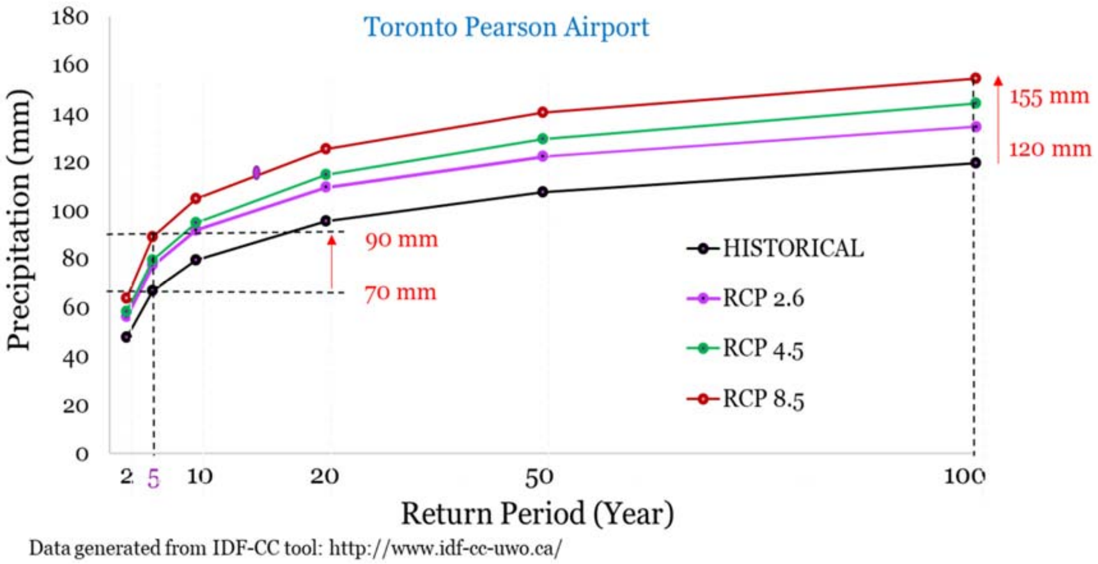


Figure 3.10 Precipitation Pattern changes at Toronto Pearson Airport Station, Ontario

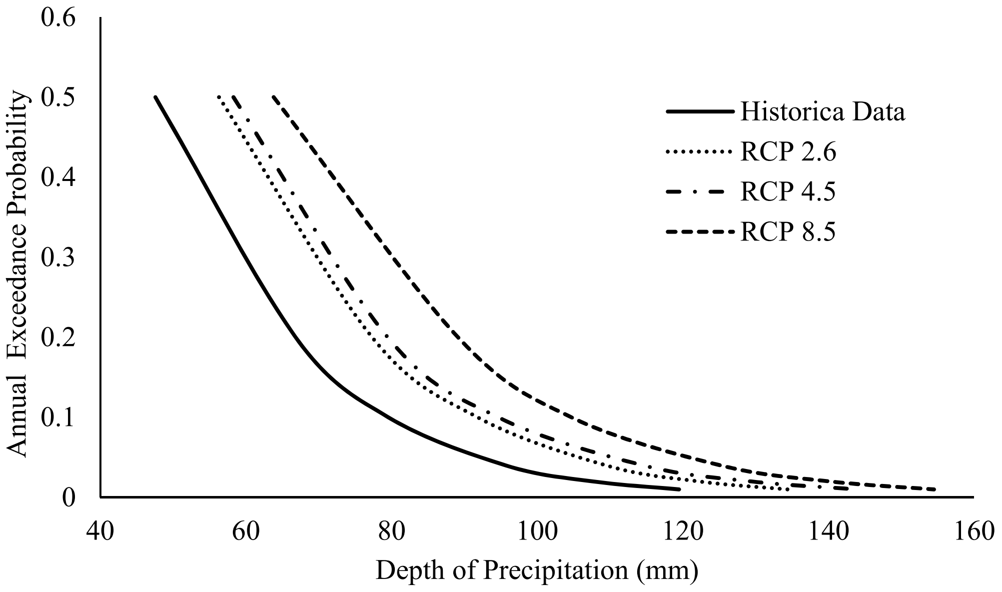


Figure 3.11 Hazard Curves for Future and Historical Extreme Precipitation

Figure 3.11 shows hazard curves indicating the relationship between annual exceedance probability (AEP) and extreme precipitation depths (24-hour duration) for 2-, 5-, 10-, 25-, 50-, and 100-year return periods under historical condition, RCP 2.6, RCP 4.5, and RCP 8.5 scenarios at the case study area. The vertical axis is annual exceedance probability, which is the reciprocal of the return period.

In the hazard analysis for risk estimation, the uncertainty should be considered for a more accurate prediction. Climate predictions often involve uncertainty, especially for precipitation predictions. There are variations in the predictions; the uncertainty of future the 100-year return period precipitation events for various climate scenarios and durations are presented in Figures 3.12 to 3.14 (generated from IDF-CC tool). The box plots show the upper bound, 75% quantile, median, 25% quantile, and lower bound predictions. The results of uncertainty indicate that there is high variability involved in the analysis.

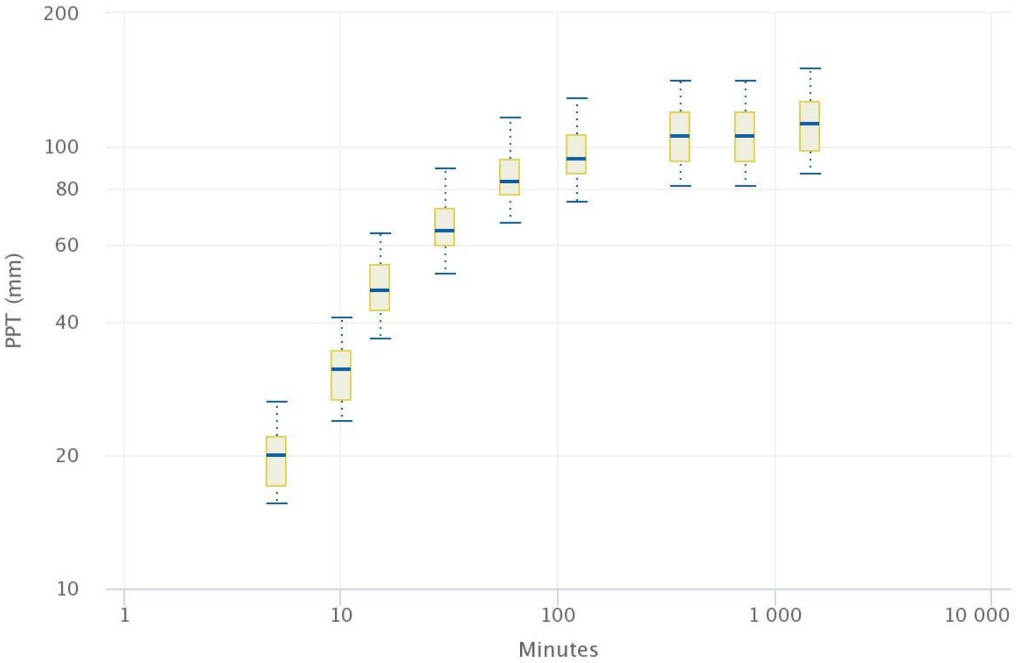


Figure 3.12 Uncertainty of 100-Year Return Period Precipitation under RCP 2.6

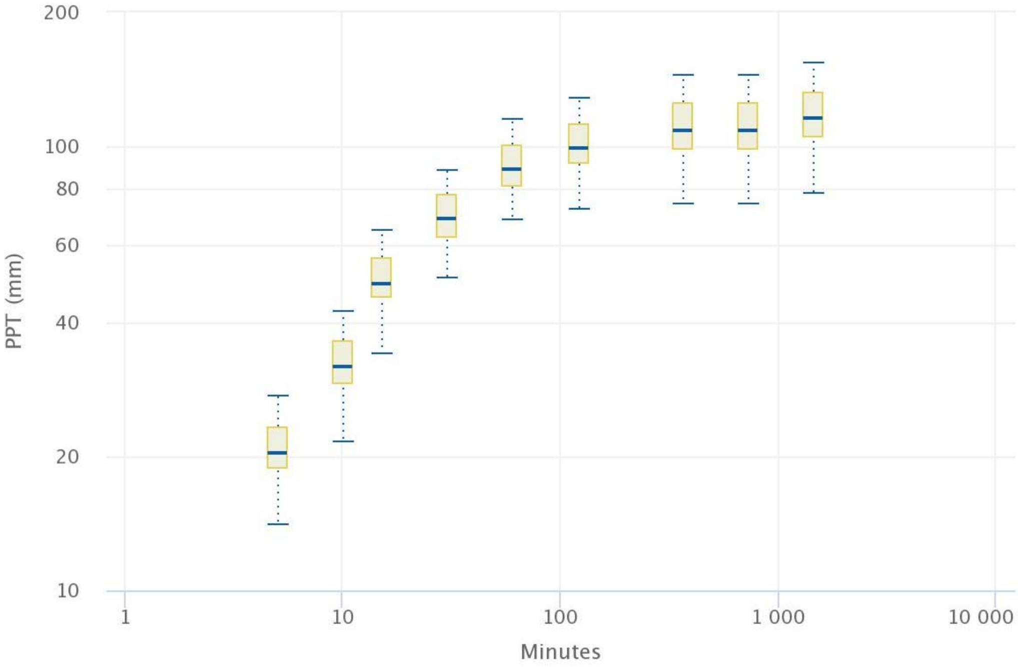


Figure 3.13 Uncertainty of 100-Year Return Period Precipitation under RCP 4.5

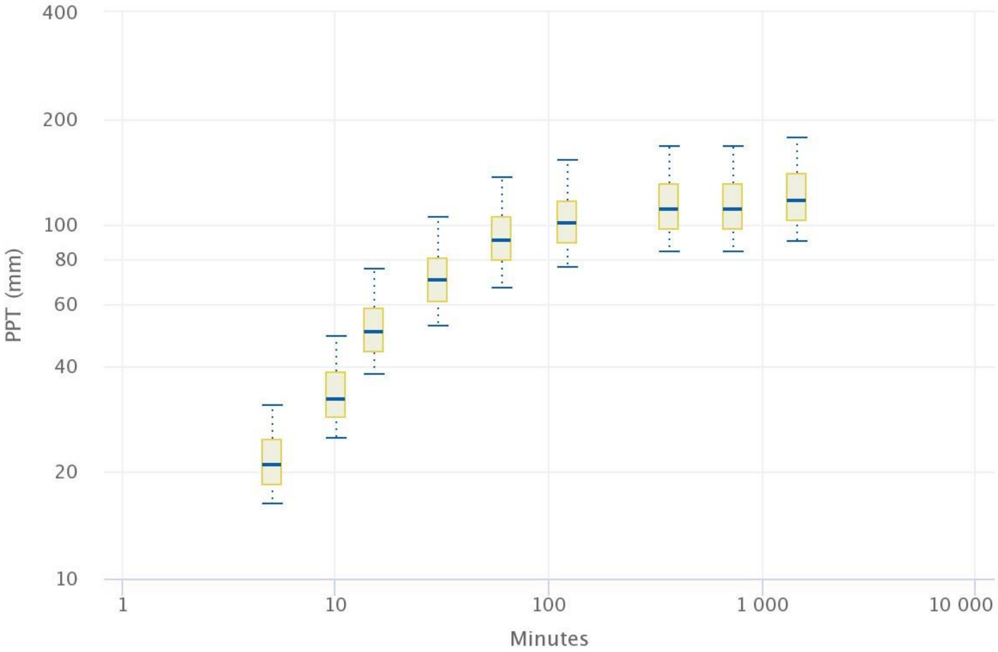


Figure 3.14 Uncertainty of 100-Year Return Period Precipitation under RCP 8.5

3.6.6 Discussion

The IDF curves can be updated, and they illustrate a new flooding potential under climate change. The results of the hazard analysis show that probabilities of occurrence of certain depths of precipitation under climate change are increased. The intensities of extreme precipitations are also increased. This indicates that high extreme precipitation events could happen more frequently and more intensity in the changing climate, which can lead to a higher damage risk for a pavement. There is large uncertainty involved due to the uncertainty in the GCMs and RCMs models. The uncertainties should be incorporated in the risk assessment to provide comprehensive risk results.

3.7 Summary

Flood hazard analysis is one of the essential steps for risk estimation. This chapter summaries the pavement flood hazard, flood frequency analysis, engineering design flood, and the methods for incorporating climate change in flood hazard modelling. A method is developed to establish flood hazard curves demonstrating annual exceeding probability of certain flood depth considering various climate change scenarios. A case study is conducted to illustrate the process and describe the flood hazards in a probabilistic manner in the changing climate. Uncertainties are also considered as the nature of climate predictions can be variable. The findings indicate that road pavement infrastructure may be subjected to more frequent and intense extreme precipitation events in the case study area causing more pavement flooding. The new extreme events should be incorporated in pavement design and management practices. To achieve risk management, it is imperative to further address pavement flooding damage and risk of flooding damage on road pavements.

Chapter 4 Flooded Pavement Performance Analysis

This chapter analyzes pavement performance change and damage from flood hazards qualitatively. The main content involves the processes, causes, components, patterns, life cycle management, impact factors, and the temporal and spatial characteristics of pavement flooding damage.

4.1 Pavement Flooding Damage Process

Figure 4.1 shows the pathway of pavement damage starting from the occurrence of flooding to pavement network performance change.

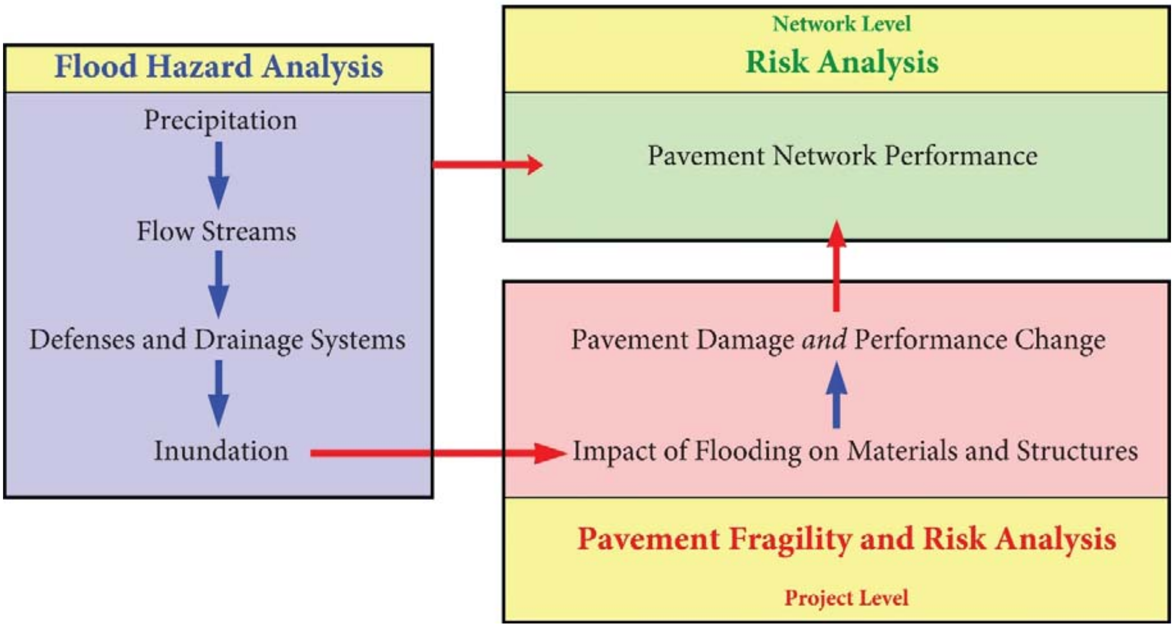


Figure 4.1 Pavement Flooding Damage Pathway

For flood hazard analysis, estimates of extreme values of precipitation are needed for the prediction of flood level (Dingman, 2015). The estimation of streamflow from precipitation and other water cycle elements in specific sites of interest can be used to predict floods. If a flood flow goes across inadequate defenses (such as dams) and drainage system, inundation is possible to occur on pavements. Pavement materials and structures would be impacted leading to pavement damage and performance change. As a result, there could be a change in the overall performance of pavement network system. Therefore, pavement management plans and operations should be adjusted to maintain a satisfactory level of service.

4.2 The Causes of Pavement Damage

Evidence of various pavement damages are shown in Figure 4.2. Flooding events can cause inaccessibility of road pavements, pavement structural saturation, loss of pavement integrity, debris on pavements, reduced safety, road pavement failure and other adverse social economical consequences.

Credit: AP
2013 Toronto Flood

Credit: Luke Hendry/The Intelligencer

Credit: AP
2013 Alberta Flood

Figure 4.2 Pavement Flooding Damage Pictures

There are various loads applied to pavements during flood events including depth, duration, velocity, debris, and contaminants (van de Lindt & Taggart, 2009). Potential reasons of the loads and the descriptions are listed in Table 4.1. The effect of flood depth and duration on pavement damage is due to absorption of flood water. The degree of damage would depend on the water infiltration, the drainage capacity, and the combination of pavement material saturation level with hydrostatic pressure (Setiadji et al., 2015). Damage caused by flood velocity is due to the force of water and its effect combined with saturation level. Flood water can also deposit debris on pavements and slowly washout the area resulting in inaccessibility of the road and safety issue posed by clogged pavement texture. Certain contaminants carried by flood may damage pavements depending on the reaction of the chemical composition of the contaminants with the pavement materials.

Table 4.1 Pavement Damage Reasons Caused by Flood

Load type	Description of pavement damage causes	Unit of measure	Comments
Flood depth	Absorption of water	Height (mm)	Depend on the water infiltration, the ability to drain, and the degree of material saturation combined with water pressure
Flood duration	Absorption of water	Time (hr)	Depend on the water infiltration, the ability to drain, and the degree of material saturation
Flood velocity	Force of water	Speed (m/s)	Depend on the force of water, and its effect combined with saturation level
Flood debris	Debris carried by water	Quantitative measure (m^3/m)	Depend on the flood water deposition or the blockage potential of the pavement surface texture
Flood contaminants	Absorption or adhesion of contaminants	Chemical and physical testing	Depend on the reaction of chemical compounds with pavement materials

When floods inundate pavements, flood water exerts load on pavement structures. Figure 4.3 illustrates the overtopping of flood water on concrete and asphalt pavements. There is a certain depth of water sitting on the pavement surface resulting in water saturation of the pavement materials. The saturation degree depends on the duration of water standing on the pavement structure and the pavement condition (e.g. cracks). As the depth of water increases, the static water pressure can also increase resulting in higher levels of saturation and potentially increase the probability of material degradation. Debris can be carried by the flow of water on to the pavement surface leading to the loss of surface texture, which can decrease the skid resistant leading to safety issues. Furthermore, debris carried by flood water with a certain velocity could cause scouring of the pavement materials. During flooding events, the level of water table can be high, and this will result in the degradation of the subgrade materials leading to unstable subgrade conditions. As flood water induced loads remain on pavement structure, the whole pavement structure deteriorates gradually. If there are cracks and other distresses on the pavement surface and the underlaying layers, the process can be accelerated. Because the pavement materials are different for concrete and asphalt pavement, the moisture susceptibility of the mix is another factor affecting the pavement deterioration process during flooding.

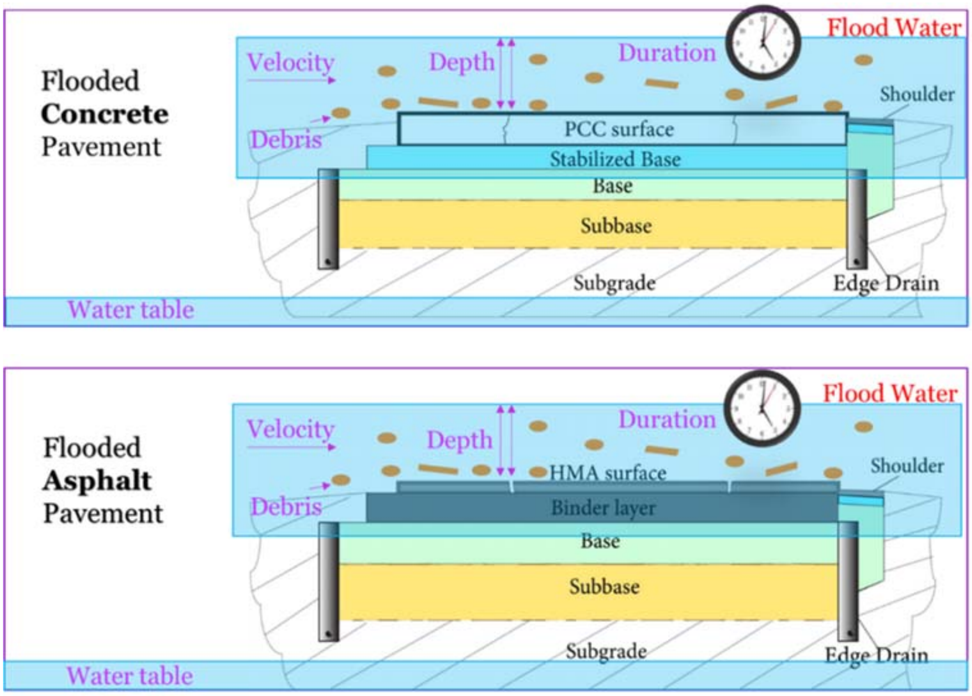


Figure 4.3 Loads of Flood Water Overtopping on Pavements

Figure 4.4 and Figure 4.5 demonstrates how water typically moves through asphalt and concrete pavement structures when there is a rainfall event. Pavement structures could expect water input (red arrow) and water discharge (blue arrow). Water input includes rainfall water seepage from surface discontinuities, seepage from high ground, edge seepage, capillary suction, vapor from the underneath, and rising water table. Water discharge involves runoff from the pavement cross section slope, evaporation effects, and subsurface drainage through edge drains. The inundation characteristics of pavement structures will depend on the total water input and total water discharge during a certain time period.

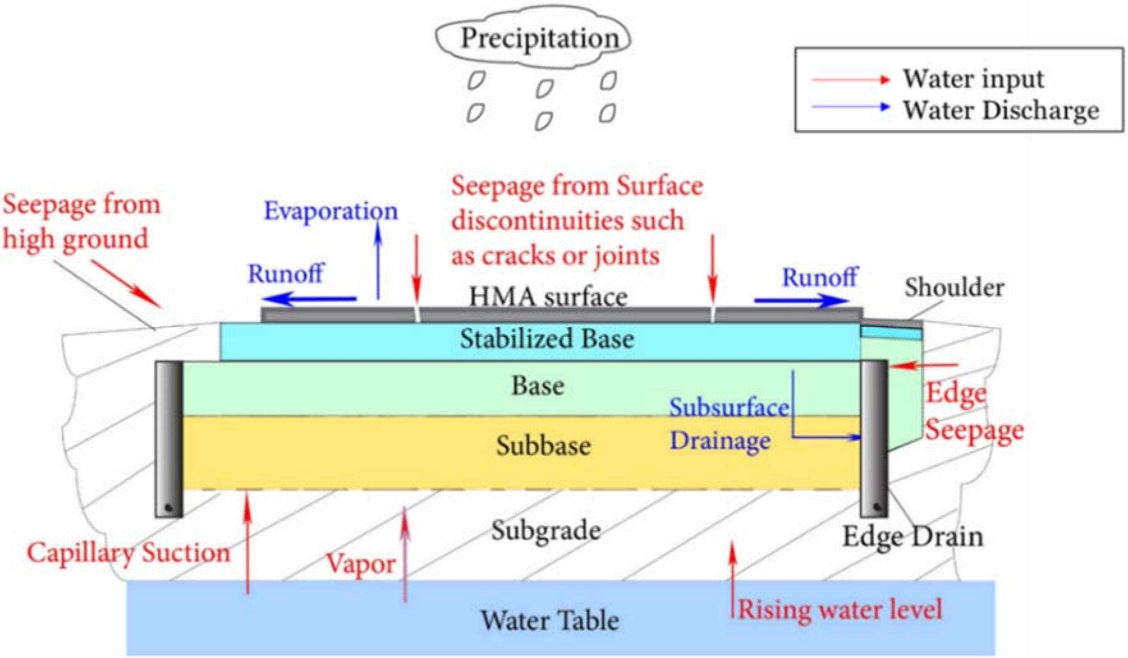


Figure 4.4 Movement of Water on Asphalt Pavement

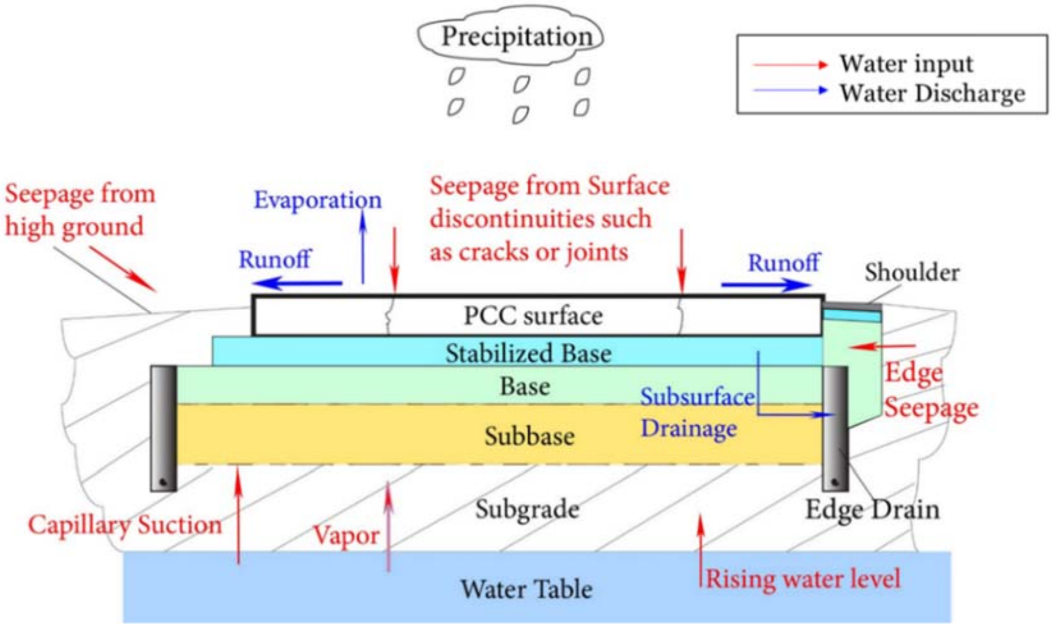


Figure 4.5 Movement of Water on Concrete Pavement

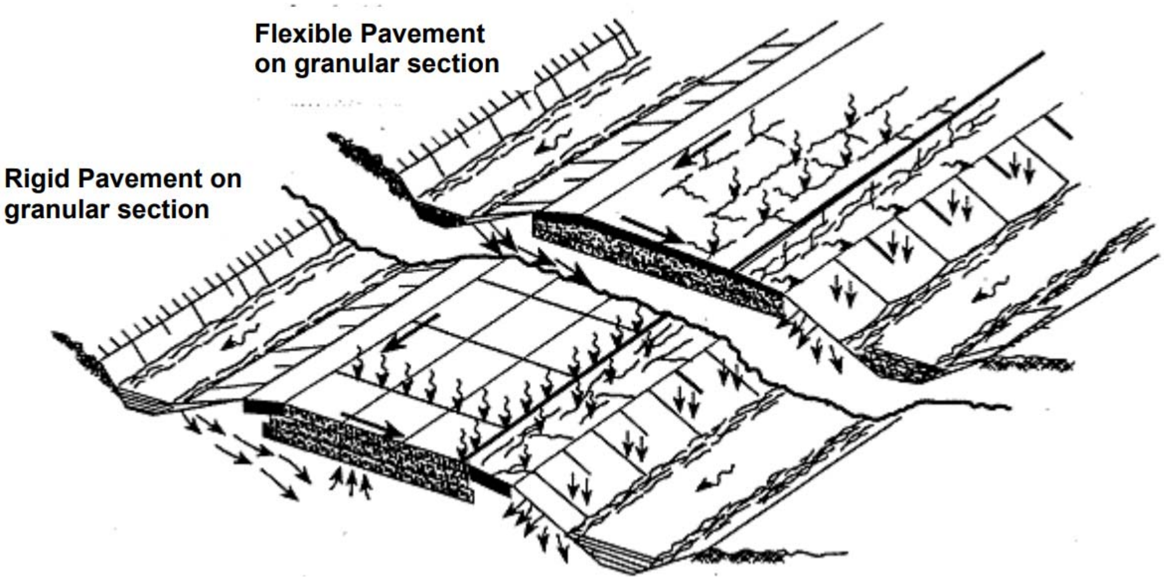


Figure 4.6 Water Infiltration into Flexible and Rigid Pavement Sections (Ministry of Transportation of Ontario, 2013)

Figure 4.7 Example of Side Ditch and Edge Drain of Pavement

Figure 4.6 provides an illustration of the water infiltration into pavement sections from the top view of pavements. Figure 4.7 shows examples of typical side ditched and edge drains of pavements. The ditch system is commonly used in rural areas because there are usually no space constraints of storm sewer systems. In urban areas, pavement edge drainage system consisting of curbs and catch basins with subdrains is often used (Ministry of Transportation of Ontario, 2013).

The differences and similarities of water movement related damages in flexible pavement with Hot Mix Asphalt (HMA) materials and rigid pavement with Portland Cement Concrete (PCC) materials are described as follows.

HMA is more moisture sensitive compared to PCC. Water penetrates in HMA layer through cracks, while PCC designed with joints may experience water penetration through poorly maintained joints. The ingress of excessive moisture, especially with the presence of cracks and joints, can accelerate pavement degradation, especially with the combination of traffic after flooding.

Debris causes problems including inaccessibility of road pavements, loss of skid resistance, foreign object debris (FOD) for airfield pavements, and clogged drainage system for both type of designs. Furthermore, the accumulation of debris at the joint gap can impair the thermal movement of the joint leading to compression failure and blow-up problems for PCC pavements.

Regarding impacts on lower laying layer, the saturation of the lower layer can cause premature failure. After flooding, if water is trapped in the interlaying layers, the traffic loads can cause erosion of unbounded subbase or subgrade leading to pumping and unstable support for rigid pavement. The same situation can result in the rapid deterioration of flexible pavement structure. More pavement investigation and preventative maintenance are required for both design types to resist rapid degradation of pavement structures concerning flood events.

4.3 Damage Components of Flooded Pavement

Pavement performance changes caused by flooding is composed of different damage components as shown in Figure 4.8. Layer material degradation, surface texture loss, interlayer bonding loss, and layer movement are the major sources of pavement damage. The synthesis of these damage components contributes to pavement performance change and serviceability change.

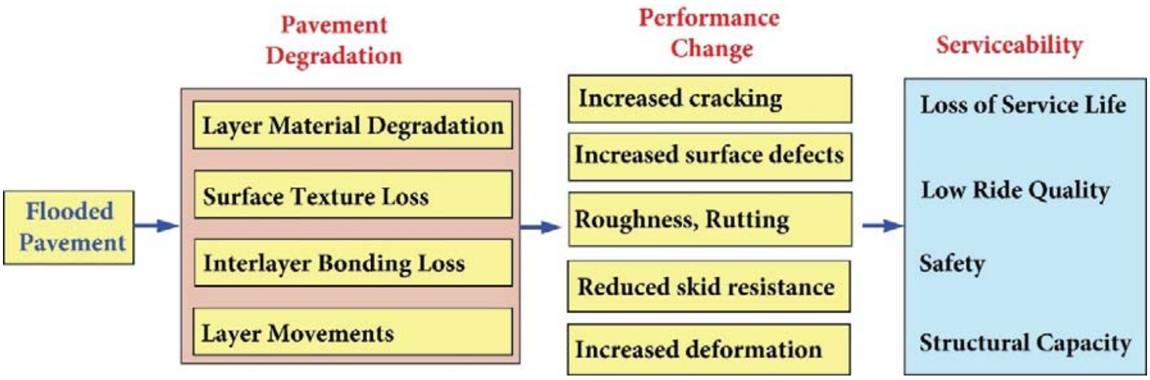


Figure 4.8 Damage Components of a Flooded Pavement

Pavement saturation during flooding is one of the key deterioration processes resulting in degradation of pavement materials. When flexible pavement layers are saturated, the adhesive and cohesive forces between asphalt and aggregate, and between asphalt and asphalt can be weakened (Little et al., 2003). Saturation can reduce the stiffness for unbounded pavement layers as well. Resilient behavior of the unbound pavement layer can also be affected significantly when full saturation is approached (Vuong, 1992).

Debris carried by flood water can clog pavement surface. Surface texture loss may lead to a reduction of surface skid resistance, which poses a safety issue.

Pavement is a multi-layered composite system that transfers and distributes traffic loads; for a flexible pavement, these loads are transferred to the lower layers as shown in Figure 4.9. A saturated pavement may lose interlayer bonding resulting in a low capability for transferring traffic loads which may cause pavement distresses including rutting, slippage cracking, and pothole (Leng et al., 2008).

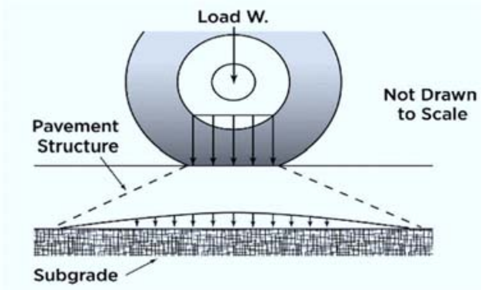


Figure 4.9 Load Transfer in Flexible Pavement (TAC, 2013)

Flow velocity is another factor affecting flood damage of pavement structures (Kreibich et al., 2009). An entire layer may achieve vertical or horizontal movement during flooding. In addition, a pavement can be broken down into pieces and gain movement as a result of the washing effect of the floods.

The pavement performance change can be summarized from the aspect of level of service, comfort or ride quality, safety, and structural capacity. In order to prevent pavement deterioration, the pavement condition should be investigated pre-event. Thus, actions can be taken to prevent pavements from damages of flooding in the changing climate.

4.4 Pavement Damage Patterns

Pavement damage patterns caused by flood hazards are illustrated in Figure 4.10. These damage patterns are summarized from different flood events assuming there is no human interventions after flood events. The four patterns are described as below (Lu et al., 2017):

- Delayed effect: There is no significant immediate performance decrease at the time of flooding, but pavement performance deterioration is accelerated after flooding.
- Jump effect: Pavement performance experiences a significant drop after flooding. The degradation of pavement performance may remain the same as before flooding.
- Jump & delayed effect: Pavement performance experiences a quick drop after flooding. In addition, the degradation of pavement is accelerated after flooding.
- Direct failure effect: The pavement structure is disrupted. Pavement performance experience sharp decreases to relatively low values. This very severe damage is usually observed in flash flood or flood disasters.

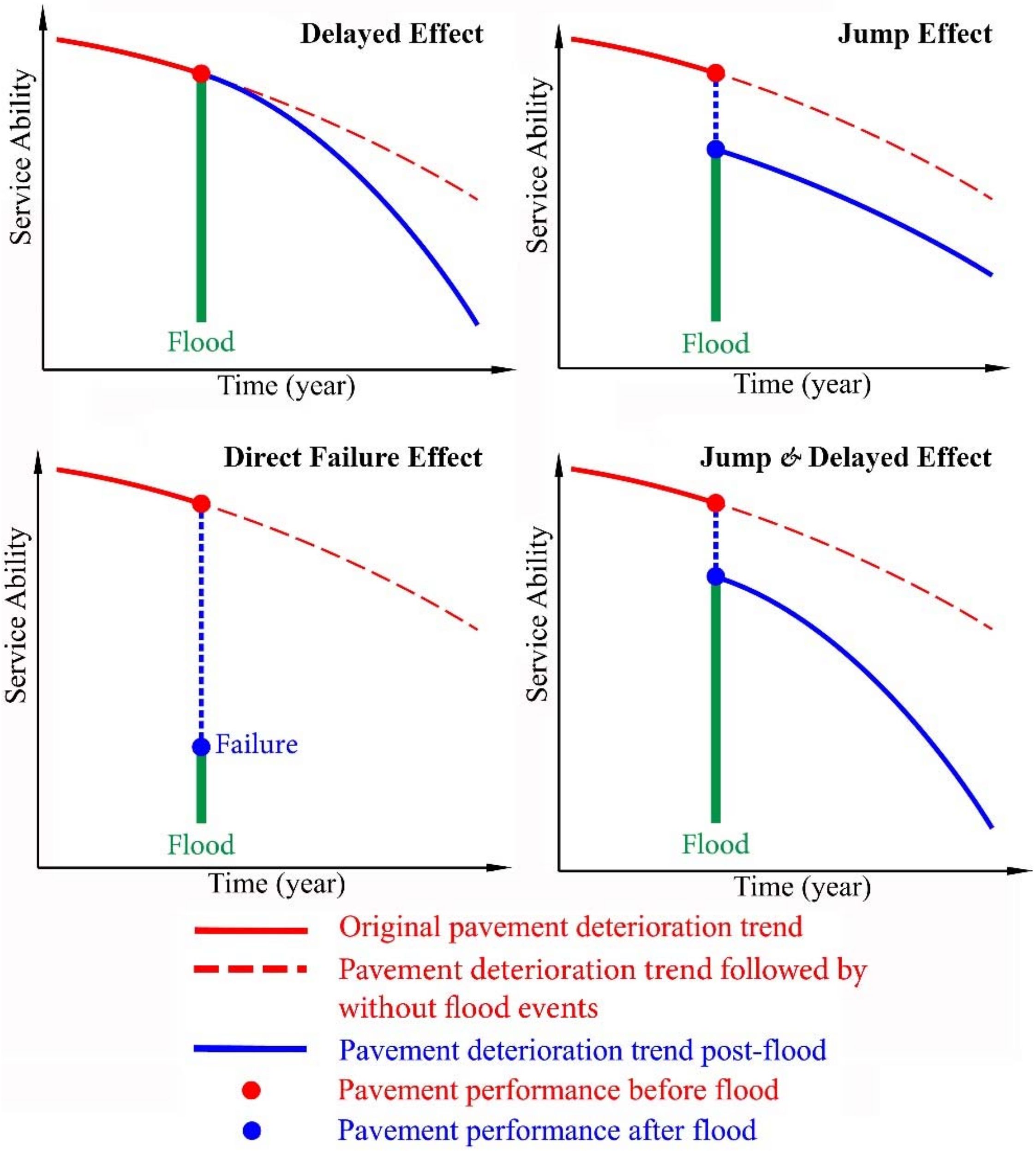


Figure 4.10 Pavement Damage Patterns for Flood Hazard

Pavement flood damage can also be categorized into two basic patterns: short-term damage and long-term damage. Short-term damage refers to pavement performance changes right after flood events, while long-term pavement damage refers to the implications of flood hazard on long-term pavement performance.

4.5 Analysis of Impact Factors for Pavement Flooding Damage

Table 4.2 summarizes the factors affecting pavement flooding damage. There are short-term damage and long-term damage impact factors.

Table 4.2 Impact Factors for Pavement Flooding Damage

Possibility of Damage	**Performance Change Factors**	**Input Parameters**
Short Term	Pavement Flood Loads and Pavement Conditions	Flood Characteristics: flood depth, duration, velocity, debris and contaminants;
		Pavement Condition: structure design, structural capacity, history maintenance, age, cracks and joints, etc.
Long Term	Human Interferences after Flooding	• Road Open Time Decision: Before or after flood is drained out to a proper stage from saturation; • Traffic characteristics; • Conducting maintenance & Rehabilitation activities for flood damages? • Adaptation designs considering climate change?
	Climate Condition after the Flood Event	Weather Condition after flood events: number of flood cycles, post flood dry weather.

For short-term damage, flood loads and pavement conditions are the major factors affecting pavement performance change. Pavement condition factors include age, structural design, structural capacity, maintenance and rehabilitation history, and pavement distresses (crack, joint condition, etc.).

Long-term pavement performance change is not only affected by flood loads but also human interferences and climate behavior after flooding. Regarding human interferences after flooding, road open time decision, traffic characteristics, and maintenance and rehabilitation activity arrangement for flood damage are major considerations. A major challenge posed is related to determining when the road should be opened. This decision of timing can have a huge impact on how the road deteriorates over time. For example, if the road is opened before the flood water has drained out of the pavement structure or if it is still saturated, this will directly impact the post flooding pavement deterioration trend. Excessive traffic load on pavements after flooding can exacerbate the flooding damage causing rapid deterioration. In terms of climate condition after floods, research indicated that flooded pavement sections can continue to regain strength after flooding because of the dry period or both rehabilitation and dry period (Sultana et al., 2016). If more flood events occur after a flooding event, the number of flood cycles in analysis period could affect the long-term pavement performance change.

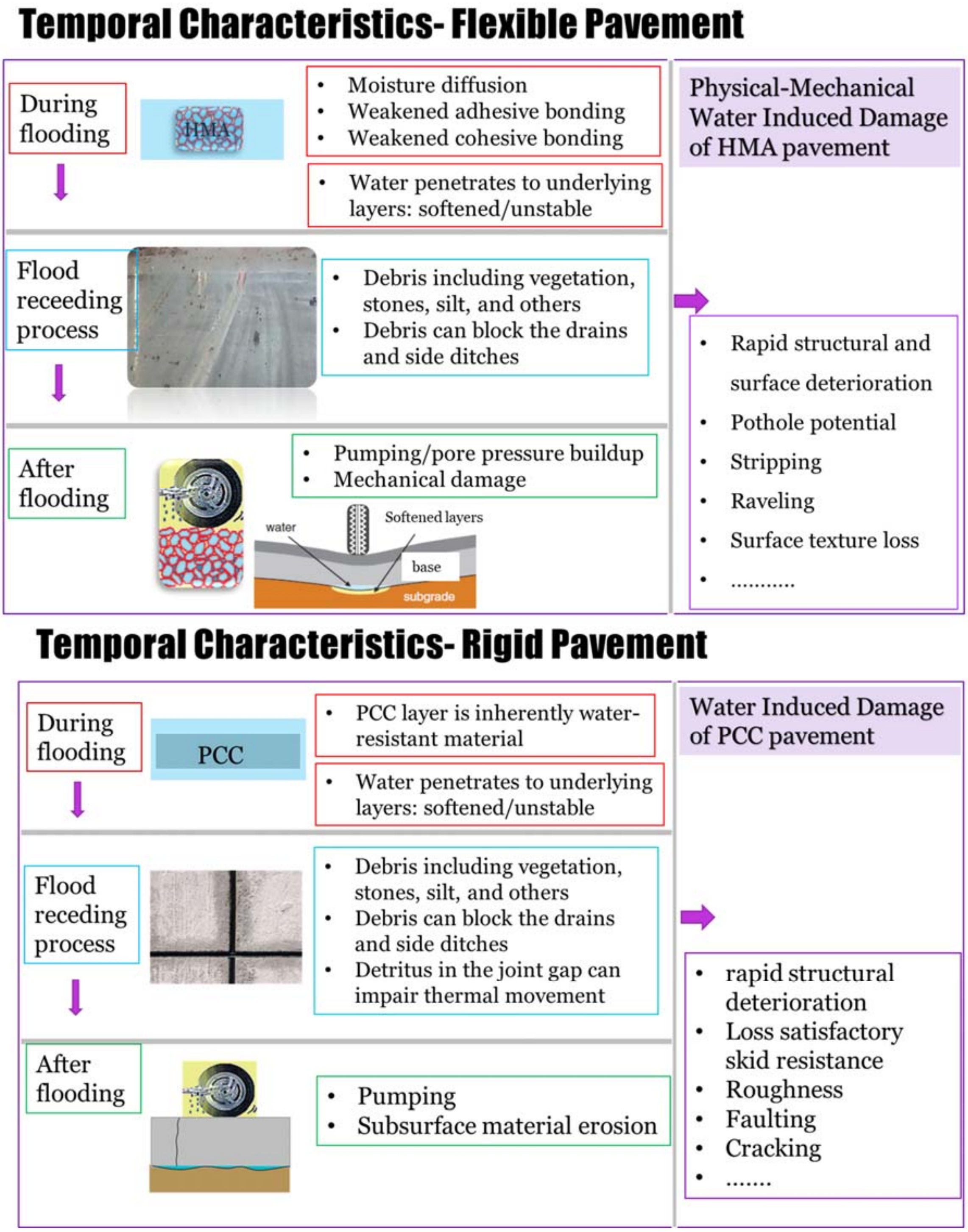
4.6 Temporal and Spatial Analysis of Pavement Flooding Damage

For physical infrastructure networks, vulnerability varies across temporal and spatial scales. Temporal characteristics indicate the damage changes from time to time, while spatial characteristics illustrate the distribution of the damages from location to location. This section introduces the temporal and spatial characteristics of pavement damages for flood hazards.

4.6.1 Temporal Characteristics of Pavement Damage from Flooding

Three stages of temporal characteristics can be considered in pavement flood damage analysis: a) during flooding, b) when flood recedes, and c) post flooding (the interaction between traffic, micro structural damage and moisture saturation). Figure 4.11 demonstrates the temporal characteristics for rigid pavement (Figure 4.11a) and flexible pavement (Figure 4.11b). Pavement flooding related damages is not only occur during flooding but also at the times when flood recedes and after flooding. Sometimes, the damages of pavement infrastructure are not obvious, and the deterioration can be accelerated due to post-event traffic and environmental stressors (Lu et al., 2018; Sultana et al., 2016). For instance, pavement surface textures can be restored by cleaning debris, but a weakened pavement structure could be unnoticed and ignored. In that case, accelerated deterioration may occur in the long-term due to the interaction of traffic and weakened structure.

Water induced rigid pavement damage. During flooding, as concrete layers consist of inherently water-resistant materials, pavement damage is majorly from the penetration of water to the underlaying layers.



Temporal Characteristics- Flexible Pavement

During flooding
- Moisture diffusion
- Weakened adhesive bonding
- Weakened cohesive bonding
- Water penetrates to underlying layers: softened/unstable

Flood receeding process
- Debris including vegetation, stones, silt, and others
- Debris can block the drains and side ditches

After flooding
- Pumping/pore pressure buildup
- Mechanical damage

Physical-Mechanical Water Induced Damage of HMA pavement
- Rapid structural and surface deterioration
- Pothole potential
- Stripping
- Raveling
- Surface texture loss
- ....

Temporal Characteristics- Rigid Pavement

During flooding
- PCC layer is inherently water-resistant material
- Water penetrates to underlying layers: softened/unstable

Flood receding process
- Debris including vegetation, stones, silt, and others
- Debris can block the drains and side ditches
- Detritus in the joint gap can impair thermal movement

After flooding
- Pumping
- Subsurface material erosion

Water Induced Damage of PCC pavement
- rapid structural deterioration
- Loss satisfactory skid resistance
- Roughness
- Faulting
- Cracking
- ....

Figure 4.11 Temporal Characteristics of Pavement Flooding Damage for Rigid and Flexible Pavements

Seepage of water into the underlaying layers results in unstable base, subbase or subgrade. When flood recedes, debris, such as vegetation, stones, and silt, can deposit on pavement surface leading to blocked drains and side ditches. Debris in joint gaps can impair thermal movement. After flooding, if water is trapped in between pavement layers, there could be pumping effects and subsurface material erosion due to traffic loads. These time to time-dependent damaging processes will lead to rapid structural deterioration, loss of satisfactory skid resistance and noise characteristics, roughness change, faulting and cracking issues.

Water induced flexible pavement damage. During flooding, asphalt pavement material as a relatively moisture susceptible material could degrade due to weakened adhesive bonding and cohesive bonding. Flood water can also infiltrate to underlaying layers resulting in saturation of the lower layers. This situation reduces the strength of the granular layers and the subgrade, resulting in a lack of support of the pavement. When flood recedes, debris can be deposited on the pavement surface, and block drains and side diches. After flooding, trapped water between the layers and saturated layer conditions can increase the pumping and pore pressure build-up potential under wheel loads. In addition, the accelerated deterioration may occur in the long-term due to the interaction of traffic and micro cracks. These damaging processes will result in performance change in terms of rapid surface and structural deterioration, pothole potential, stripping, raveling, surface texture losses, and so on.

4.6.2 Spatial Characteristics of Pavement Damage from Flooding

The characteristics of pavement and flood hazard are different across a network, which means that responses of pavements to flood hazards vary spatially. Consequently, risk varies across the network. Spatial analysis is crucial for characterizing risks across a pavement network.

In a certain road network, the functional classes, pavement types, pavement conditions and soil conditions are distributed spatially. Table 4.3 lists the factors affecting spatial characteristics of road networks and an example of categorization.

Table 4.3 Spatial Factors Affecting Pavement Flooding Damage

Factors	Category
Soil Type	Weak
	Moderate
	Strong
Pavement Type	Flexible pavement
	Rigid pavement
	Composite pavement
Pavement Overall Condition	Very good
	Good
	Fair
	Poor
	Very poor
Road Functional Class	Expressway
	Major Arterial
	Minor Arterial
	Collector
	Local

Soil types distribute across a road network, and so do the engineering properties of them. During flooding, the potential loss of subgrade support determines the post flooding pavement deterioration trend. Understanding soil characteristics under inundation situations is critical for proactive design considering potential flooding under climate change.

Pavement conditions for the sections of a road network are an important information for risk estimation. Figure 4.12 illustrates different responses of a pavement as its condition/age changes. Pavement condition evaluations regarding flooding damage potential can include water infiltration potential (cracking, surface defects, and drainage condition), pavement structural strength (deflection and thickness), debris deposition potential (surrounding environment, IRI, and rutting), and pavement integrity loss potential (raveling, striping, and unstable surface and layers). For example, if a pavement has a number of cracks, flood water can easily get into the pavement structure leading to more damage compared to a well-sealed pavement.

Pavement type as a factor varies spatially in a network; flexible pavement and rigid pavement have different responses to flooding events as demonstrated in Figure 4.11.

The road functional classes (Table 4.4) are described using an example of the road classification system from the City of Toronto. As can be seen in the figure, functional classes determine the traffic, speed, maintenance priority. Different levels of traffic require different design of the pavement structures. The functional class also indicates the different requirement of level of service for a pavement network. Table 4.5 describes an example of levels of service for different functional classes. Target level of service is the level that should be met or exceeded, and often expressed as the average condition of all pavements for a network, while the minimum acceptable means the level must be met (Tighe, 2013).

Table 4.4 Example of Levels of Service for a Pavement Network (Tighe, 2013)

Functional class	Target (Average PCI* for all sections)	Minimum Acceptable (Average PCI* for all sections)	Minimum Acceptable (PCI* for individual sections)
Arterial	80	65	55
Collector	70	60	45
Local	60	55	40

* Pavement Condition Index (PCI) is a numerical index (0-100) that is used for indicating the general condition of a pavement.

The intersection of the road pavement spatial characteristics and flood hazard extend results in the spatial distribution of risk. This risk distribution in a road network provides the key information for asset investment prioritization and social-environmental-economical consequence estimation. Spatial analysis provides a means for incorporation of project level pavement flooding risk management into network level asset management.

Table 4.5 The Description of Road Functional Classes (City of Toronto, 2018)

Road functional class	Description
Expressway	• Traffic movement is a primary function; • No property accesses; • Speed limits 80 to 100 km/h; • Greater than 40,000 vehicles per day; • No local transit services; Pedestrians and cyclists prohibited; • Grade-separated intersections (no traffic signals); • Highest priority of winter maintenance
Major Arterial	• Traffic movement is a primary function; • Subject to access controls; • Greater than 20,000 vehicles per day; • Greater than 5,000 bus passengers per day; • Speed limits 50 to 60 km/h; • Cyclists – special facilities desirable; • Sidewalks on both sides; • High priority of winter maintenance
Minor Arterial	• Traffic movement is a primary function; • Some property access control; • 8,000 to 20,000 vehicles per day; • 1,500 to 5,000 bus passenger per day; • Speed limits 40 to 60 km/h; No “Stop” signs; • Main intersections controlled by traffic signals; • No truck restrictions; • Sidewalks on both sides; • High priority of winter maintenance
Collector	• Provide access to property and traffic movement; • 2,500 to 8,000 vehicles per day; • Less than 1,500 bus (or streetcar) passenger per day; • Signalized intersections at arterial roads; Truck restrictions permitted; • Cyclists – special facilities as required; • Sidewalks on both sides of the road; • Medium priority for winter maintenance
Local	• Provide access to property; • Less than 2,500 vehicles per day; • Low traffic speed; • Generally no bus routes; • Cyclists – special facilities as required; • Sidewalks on at least one side of road; • Truck restrictions preferred; • Low priority for winter maintenance

4.7 Pavement Life Cycle Deterioration and Incorporating Flooding Events in Pavement Asset Management System

As a pavement ages, pavement performance decreases because of traffic loads, environmental factors, material aging, and other damaging processes. Planning maintenance, preservation, and rehabilitation during the pavement life cycle helps maintain a satisfactory serviceability with the optimized life cycle costs. However, when flooding occurs, pavement serviceability can decrease in both short-term and long-term.

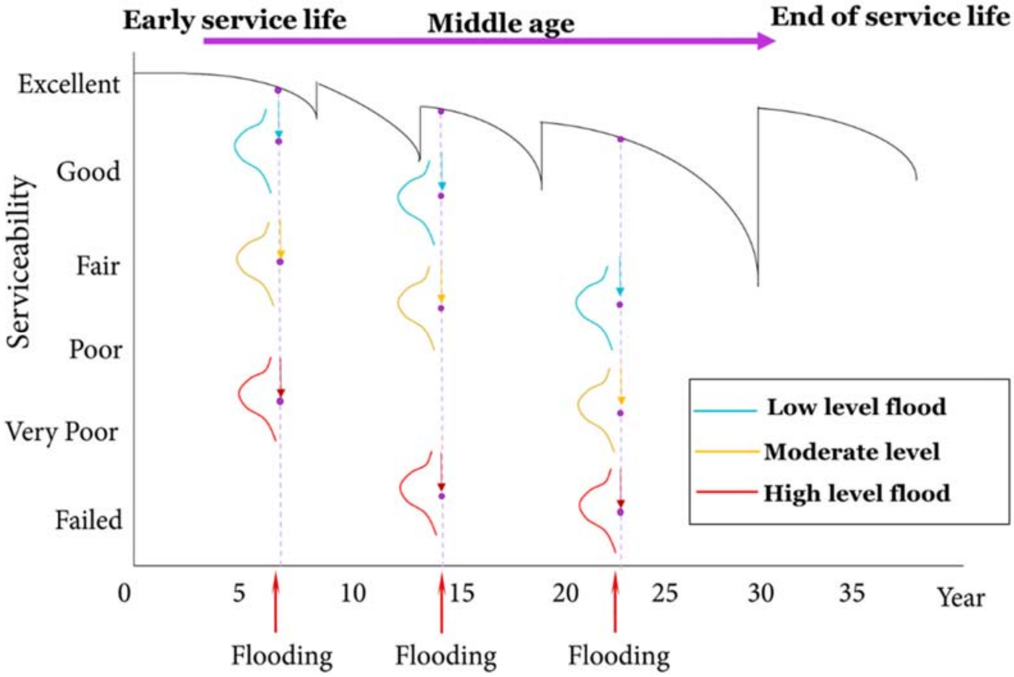


Figure 4.12 Pavement Deterioration Caused by Various Flooding Events

Figure 4.12 illustrates pavement deterioration with the occurrence of flooding events during a life cycle. The changes in pavement serviceability can be different according to the level of floods and pavement conditions. For example, if a flood event occurs at the early service life, low-level floods can result in an insignificant drop of the pavement performance, while high-level floods can result in a significant decrease of the pavement performance. As pavement ages, they may become increasingly vulnerable to flood hazards. When pavements get older or in a relatively lower condition, low-level flood may cause a significant decrease of pavement performance, and high-level flood could lead to a sharp performance drop.

The incorporation of flood hazard into pavement asset management system is critical for better decision making in asset management processes. The altered pavement deterioration trend due to flooding indicates the requirement of shifted plans for maintenance, preservation and rehabilitation operations, because agencies need to maintain pavements at a satisfactory serviceability level. Early maintenance is often necessary because the pavement performance curve will cross the maintenance criteria early. As shown in Figure 4.13, there can be a gap (ΔT) between the maintenance time before (T_{adjust}) and after ($T_{optimum}$) the occurrence of flooding.

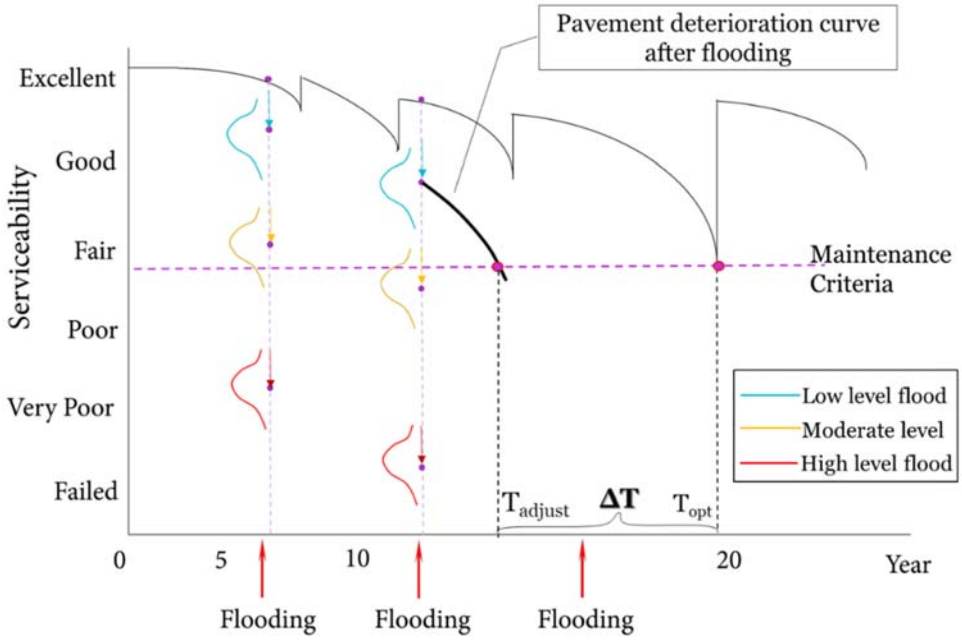


Figure 4.13 Gap of the Maintenance Timing for Flood Interrupted Pavements

4.8 Summary

Chapter 4 provides a comprehensive overview of pavement flooding damage and associated factors and characteristics, and the elements identified provide a foundation for fragility analysis and risk quantifications in the latter chapters. This study covers the processes, causes, components, patterns, life cycle management, impact factors, and the temporal and spatial characteristics of pavement flooding damage. Flooded pavement damage reasons include flood depth, flood duration, flood velocity, flood debris, and flood contaminants, and their interactions. Flooded pavement damage component can include layer material degradation, surface texture loss, interlayer bonding loss, and layer movement resulting in increased cracking/surface defects, structural deformation, reduced safety, decreased riding quality and loss of service life. Pavement flooding damage can follow four patterns: delayed effect, jump effect, jump & delayed effect, and direct failure. Impact factors of the flooded pavement damage include flood loads, pavement design and conditions, human interferences after flooding, and climate patterns after the flooding event. The findings provide the key activities and elements to guide pavement flooding risk assessment and management. Based on the findings, a risk matrix approach for managing the pavement flooding risk in the changing climate is developed in Chapter 8.

Chapter 5 Pavement Fragility and Vulnerability Analysis

This chapter develops methods for fragility analysis, which is one of the key components for risk assessment. The concepts of fragility and vulnerability are introduced to provide a holistic understanding of the necessary elements in a pavement flooding risk analysis. Then, three pavement fragility analysis methodologies are developed, and case studies are conducted to illustrate how to apply the proposed methods to assess pavement fragility for flood hazards. Finally, vulnerability and cost estimations are discussed.

5.1 Pavement Fragility and Vulnerability

Fragility analysis has been used in seismic risk assessment and is starting to gain momentum for application in flooding risk analysis. Figure 5.1 shows the role of fragility analysis in the pavement risk assessment framework. Pavement fragility models describe the susceptibility of physical pavement structure to hazards. Fragility of pavements for flooding can be defined as the conditional probability of certain damage given a level of flood hazard. Pavement damage analysis provides the parameters that can be considered in fragility modelling. Fragility analysis provides a way to determine the uncertainty in pavement damage. The outcomes of fragility modelling are Fragility Functions and Fragility Curves. By integrating the results of flood hazard analysis with fragility analysis, the risk of damage can be quantified.

Vulnerability in this framework is quantified as fragility combined with cost associated damage. The economic consequence related to pavement asset physical damage given hazard demonstrates the vulnerable of the infrastructure. By integrating the flood hazard with vulnerability, the risk of losses can be quantified.

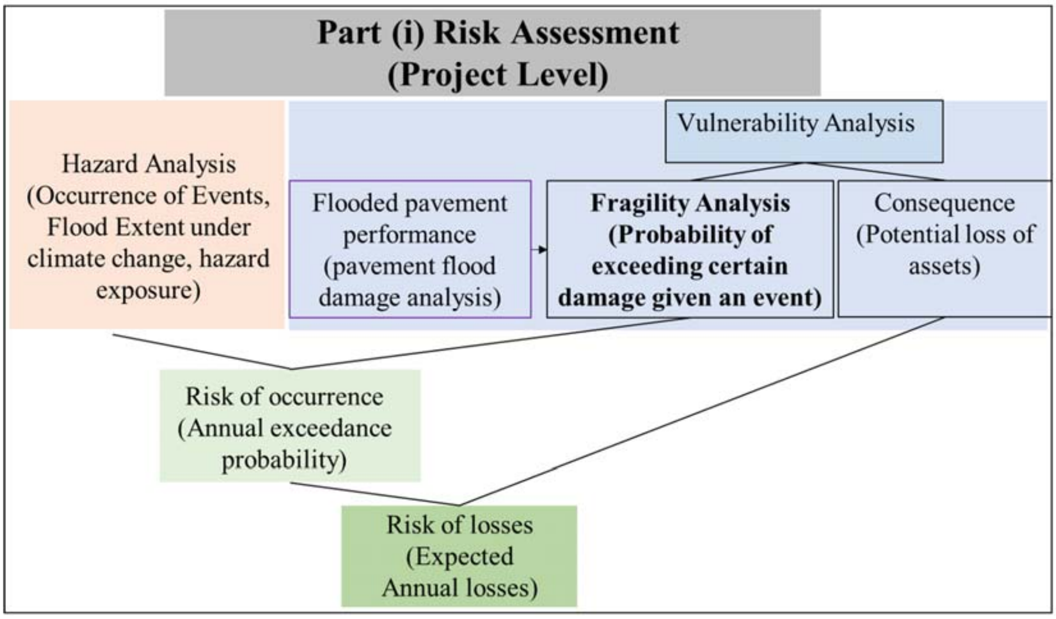


Figure 5.1 Risk Assessment Framework at the Project Level

5.2 Pavement Flooding Fragility Analysis and Modelling

5.2.1 Methodology

The probabilistic fragility modelling involves four processes: pavement performance analysis for various flood events in the analysis period; calculation of pavement damage; defining threshold values for damage states; parameter estimations for fragility functions for different damage states.

Pavement performance analysis for flood hazards. In the context of climate change, future extreme weather potential should be considered in pavement life cycle performance analysis to determine the susceptibility of a pavement to future climate change. However, observations of pavement flooding damage are often not available. As mentioned earlier, the state-of-art mechanistic and empirical model system can help simulate the pavement performance throughout the life cycle. By using pavement performance simulation system and tools such as MEPDG, the pavement performance with and without flooding can be determined in the analysis period for a certain pavement design. The performance data generated at this stage will be used in the damage estimation and fragility modelling in next steps.

Damage calculation. The damage is the pavement performance change post a flood event. In this study, pavement damages due to extreme precipitations are described by damage ratio. The damage ratio in percentage is calculated by using the change of the terminal (the end of the analysis period) performance indicator with and without the occurrence of extreme flood events divided by the terminal performance indicator without extreme flood events. The equation for calculating damage ratio by using International Roughness Index (IRI) for example is:

$$\kappa = \frac{\left(\mathrm{IRI}_t - \mathrm{IRI}_i\right)}{\mathrm{IRI}_i} \tag{5-1}$$

where

κ is damage ratio;

IRI_t is terminal international roughness value with the occurrence of extreme precipitations (m/km);

IRI_i is initial international roughness value without the occurrence of extreme precipitations (m/km).

Pavement damage can be determined using other key performance indicators such as loss of service life, safety, rutting, fatigue cracking, costs, and so on.

Definition of thresholds for damage states. Different levels of pavement damage can be defined by damage states (Table 5.1). Descriptions of damage states are related to pavement structural damage or performance change. In this study, the damages are illustrated according to pavement performance change. Damage states can be categorized based on damage level such as collapse, major damage, moderate damage and minor damage. The threshold values according to the damage levels can be determined by expert opinions based on experiences and observations. The measures in Table 5.1 are an example of threshold values for various pavement damage states.

Pavement damage states can be expanded to other indicators such as loss of service life, safety, and cost, where the threshold values need to be determined for each indicator.

Table 5.1 Damage States for Pavements

Damage	Damage level	Description	Measure
PDS0	Insignificant	Insignificant pavement performance change	0~5%
PDS1	Minor	Very slight pavement performance change	5%~30%
PDS2	Moderate	Medium pavement performance change	30%~60%
PDS3	Major	Severe pavement performance change	60%~90%
PDS4	Collapse	Totally damage and pavement replacement required	90%~100%

Generation of fragility functions. Fragility functions provide the probabilities that pavement structure will reach or exceed certain level of damage. A lognormal cumulative distribution function is often used to define a fragility function. There is nothing fundamental about the lognormal distribution that makes it ideal or exact or universal for the applications. At least four reasons justify its use in this situation:

1. Simplicity. It has a simple, parametric form for approximating an uncertainty quantity that must take on a positive value, using only an estimate of central value and uncertainty;
2. Precedent. It has been widely used for several decades in natural disaster engineering.
3. Principle of maximum entropy. It is the distribution that assumes the maximum entropy if one knows only that the variable is positively valued with specified median and logarithmic standard deviation.
4. Fit data. It often reasonably fits observed distributions.

Lognormal cumulative distribution function for generating fragility function:

$$P_{\text{Fragility}} = P(\text{DS} \mid \text{FH} = x) = \Phi\left(\frac{\ln x - \alpha}{\beta}\right) \tag{5-2}$$

where

DS is certain damage state;

FH = x is the level of flood hazard (m);

$\Phi()$ is the cumulative distribution function of standard normal distribution;

α and β are logarithmic mean and logarithmic standard deviation.

The maximum likelihood method is employed to estimate the optimum α and β by using pavement damage data. Assuming that observation of exceeding the damage state or not from each flood level is independent of the observations from other flood hazards, the probability of observing k_i damages that exceed certain damage state out of n_i observations for a certain flood level can be given by binomial distribution:

$$P_{k_i} = C_{n_i}^{k_i} p_i^{k_i} \left(1 - p_i\right)^{n_i - k_i} \tag{5-3}$$

where

p_i is the probability that $FH = x_i$ causes certain pavement damage;

n is the number of observations;

i is certain damage state;

$C_{n_i}^{k_i}$ is the binomial coefficient.

The maximum likelihood approach identifies the optimum α and β, which provides the highest probability of having the observed pavement damage data. Hence, the likelihood function is the product of the binomial probabilities at each flood level for the entire data set:

$$L = \prod_{i=1}^{m} C_{n_i}^{k_i} p_i^{k_i} \left(1 - p_i\right)^{n_i - k_i} \tag{5-4}$$

where

L is the likelihood function; for $k = 0, 1, 2, ..., n$,

m is the number of flood events.

Then, by substituting Eq. (5-2), the likelihood function for the parameter estimation becomes

$$L=\prod_{i=1}^{m} C_{n_i}^{k_i}\left\{\Phi\left(\frac{\ln x_i-\alpha}{\beta}\right)\right\}^{k_i}\left\{1-\Phi\left(\frac{\ln x_i-\alpha}{\beta}\right)\right\}^{n_i-k_i} \quad (5\text{-}5)$$

The fragility curves for each damage state can be generated according to the threshold values defined for each damage level. Two case studies are presented in the following sections to demonstrate the implementation of the fragility modelling methods.

5.2.2 Fragility Analysis and Modelling using Various Characteristics of Extreme Rainfall Events - Case Study 1

This case study illustrates the process of fragility analysis and modelling by using various characteristics of extreme precipitation events in the pavement life cycle. This case study employs extreme precipitation depths, various durations, and event cycles during the life cycle as climate variables to investigate the pavement performance changes and generate the fragility models.

Figure 5.2 show the approach of incorporating MEPDG pavement performance simulation in the risk estimation. The climate variables related to precipitation are input in the climate modulus in MEPDG, and the pavement performance change with and without these extreme events are simulated and used for the generation of fragility curves.

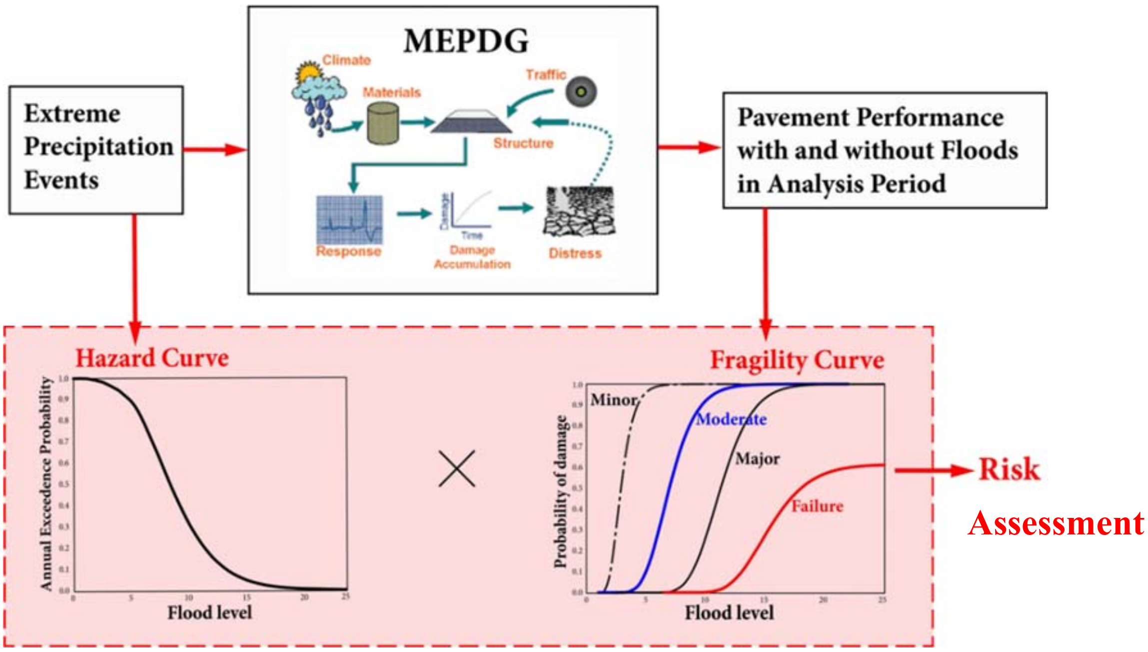


Figure 5.2 Pavement Performance Fragility Modelling Methodology

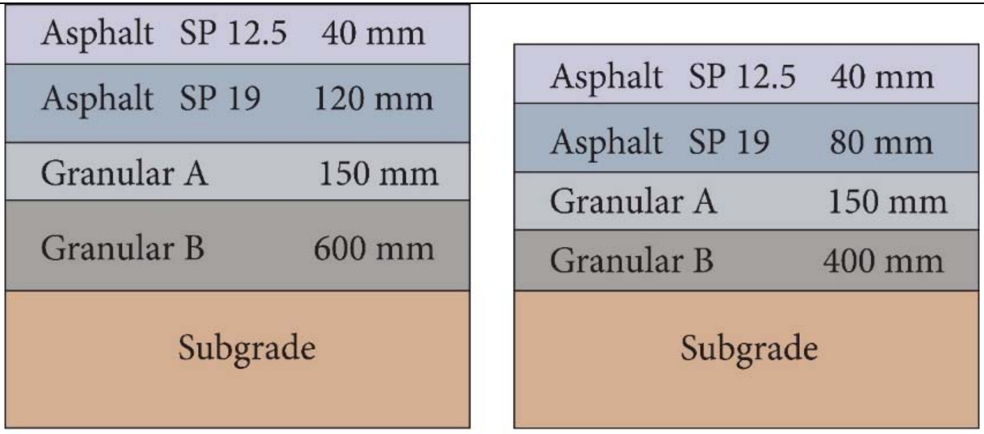
5.2.2.1 Pavement Designs

Commonly used in Ontario, Canada, MEPDG methodology is employed in pavement design and performance analysis in this case study. As the state-of-the-art pavement design system, MEPDG incorporates environment and traffic conditions over the design life.

Table 5.2 lists site characteristics and traffic assumptions. The two-way Average Annual Daily Truck Traffic (AADTT) is 2800 for cross section (a), and 400 for (b); the truck traffics in the design lane are 80% and 100% for sections (a) and (b), respectively. The materials and thickness of two pavement structures are shown in Figure 5.3. These designs are typical arterial and collector pavement designs in Southern Ontario, Canada (Applied Research Associates, 2011). The asphalt layer contains performance grading (PG) 64-28 with unit weight of 2,460 kg/m^3 for the asphalt mix with SP 12.5. The SuperPave (SP) 12.5 indicate the maximum Nominal Maximum Aggregate Size is 12.5 mm. For the asphalt mix with SP 19, the unit weight is 2,460 kg/m^3, and PG 58-28 is the grade of the asphalt cement. Similarly, 19 means the Nominal Maximum Aggregate Size for the mix is 19 mm. Granular A and Granular B indicate quarried bedrock or boulders, cobbles, gravel, sand, and fines from naturally formed deposits, while ML indicates silts, sandy silts, or diatomaceous soils. A new pavement is typically designed for a 20-year service life based on the environment and expected traffic loading. The performance threshold values (International Roughness Index (IRI) (2.7 m/km), asphalt concrete (AC) top-down cracking (380 m/km), AC bottom-up cracking (20%), AC thermal cracking (190 m/km), total permanent deformation (19.1 mm), and AC deformation (6.4 mm) are assumed to be triggers for pavement maintenance and rehabilitation decisions. Reliability levels for collector and urban arterial pavement designs are 80% and 90%, respectively. AASHTOWare Pavement ME Design version 2.3 is used to implement the MEPDG analysis.

Table 5.2 MEPDG Analysis Input: Climate region and Traffic data

Input Items	**Urban Arterial**	**Collector**
Climate Region		
Latitude/longitude (degree)	43.7/-79.6	43.7/-79.6
Elevation (m)	173.4	173.4
Climate station reference	6158733 (Lester B. Pearson International Airport, Toronto, Ontario)	
Traffic		
Two-way AADTT [a]	2800	400
Truck traffic in design lane (%)	80	100
[a] Average Annual Daily Truck Traffic.		



(a) Arterial Pavement (b) Collector Pavement

Figure 5.3 Pavement Cross Sections

5.2.2.2 Climate Input

The climate data are from Toronto Lester B. Pearson Airport climate station. This case study focuses on the impact of the flood depth, flood duration, and number of flood cycles on pavement life cycle performance.

Based on DDF curve from Engineering Climate Datasets (Government of Canada 2016), the 24-hour precipitation values at this site for return period of 50, 100, 200 years are selected as the precipitation magnitudes, which are 102 mm, 114 mm, and 125 mm, respectively. Based on the record between 1916 and 2016 in Canadian Disaster Database (Government of Canada 2016), floods occurred often during April and May. The duration is from 1 day to 61 days with an average of 4 days, and the second longest flood is 22 days. Extreme event cycles (1-, 2-, and 3-cycle) are also considered. The flood events were introduced at the 5th year, 10th year, and 15th year for 3-cycle event, 5th year and 10th year for 2-cycle event, and 5th year for 1-cycle event. Table 5.3 shows the climate input for pavement performance simulation. The climate file is prepared by changing the precipitation data.

Table 5.3 Climate Variables for the Case Study

Road Classification	Extreme precipitation event (return period)	Duration (day)	Event cycles
Urban Arterial	50, 100, 200-year	1, 4, 22, 61	1, 2, 3
Collector	50, 100, 200-year	1, 4, 22, 61	1, 2, 3

5.2.2.3 Pavement Performance Simulation Results

Table 5.4 shows the MEPDG runs and damage ratios (calculated from Eq. 5-1) results for the arterial and collector pavement. One-day duration events do not lead to any change in pavement performance in all scenarios. Extreme precipitation contributes only to IRI change in MEPDG performance simulation. In the 4-day duration simulation, IRI is changed by 0.39% and 0.46% for arterial and collector pavements, respectively, for all cycles.

Table 5.4 Arterial and Collector Pavement MEPDG Runs and Pavement Damage Results

Run	**Climate Input**	**Damage Ratio (%)**		**Run**	**Climate Input**	**Damage Ratio (%)**	
		Arterial	**Collector**			**Arterial**	**Collector**
1	102 mm, 1-day, 1-cycle	0.00	0.00	19	114 mm, 22- day, 2-cycle	0.78	0.46
2	102 mm, 4-day, 1-cycle	0.39	0.46	20	114 mm, 61- day, 2-cycle	1.57	1.37
3	102 mm, 22- day, 1-cycle	0.39	0.46	21	114 mm, 1-day, 3-cycle	0.00	0.00
4	102 mm, 61- day, 1-cycle	0.78	0.91	22	114 mm, 4-day, 3-cycle	0.39	0.46
5	102 mm, 1-day, 2-cycle	0.00	0.00	23	114 mm, 22- day, 3-cycle	0.78	0.91
6	102 mm, 4-day, 2-cycle	0.39	0.46	24	114 mm, 61- day, 3-cycle	1.96	1.83
7	102mm, 22- day, 2-cycle	0.78	0.46	25	125 mm, 1-day, 1-cycle	0.00	0.00
8	102 mm, 61- day, 2-cycle	1.18	1.37	26	125 mm, 4-day, 1-cycle	0.39	0.46
9	102 mm, 1-day, 3-cycle	0.00	0.00	27	125mm, 22- day, 1-cycle	0.39	0.46
10	102 mm, 4-day, 3-cycle	0.39	0.46	28	125 mm, 61- day, 1-cycle	0.78	0.91
11	102mm, 22- day, 3-cycle	0.78	0.91	29	125 mm, 1-day, 2-cycle	0.00	0.00
12	102 mm, 61- day, 3-cycle	1.57	1.83	30	125 mm, 4-day, 2-cycle	0.39	0.46
13	114 mm, 1-day, 1-cycle	0.00	0.00	31	125mm, 22- day, 2- cycle	0.78	0.46
14	114 mm, 4-day, 1-cycle	0.39	0.46	32	125 mm, 61- day, 2-cycle	1.57	1.37
15	114 mm, 22- day, 1-cycle	0.39	0.46	33	125 mm, 1-day, 3-cycle	0.00	0.00
16	114 mm, 61- day, 1-cycle	0.78	0.91	34	125 mm, 4-day, 3-cycle	0.39	0.46
17	114 mm, 1-day, 2-cycle	0.00	0.00	35	125mm, 22- day, 3-cycle	1.17	0.91
18	114 mm, 4-day, 2-cycle	0.39	0.46	36	125 mm, 61- day, 3-cycle	1.96	1.83

During the 22-day duration events (Figure 5.4), the pavement damage ratio ranges from 0.39% to 1.17% and more extreme precipitation event cycles result in a higher damage ratio. The higher damage ratio is observed from more cycles of extreme precipitation events. The damage behaviour of collector pavements is different from arterial pavements.

For the 61-day duration extreme precipitation events, the pavement damage ratio range jumps to from 0.78% to 1.96%. It is obvious that a higher number of cycles leads to higher damage ratio. In 50-year return period events, collector pavements are more fragile for the same flood cycle. For 100-year and 200-year return period events, the damage ratio for arterial pavements can go up to 1.96% which is the highest damage ratio throughout the simulations.

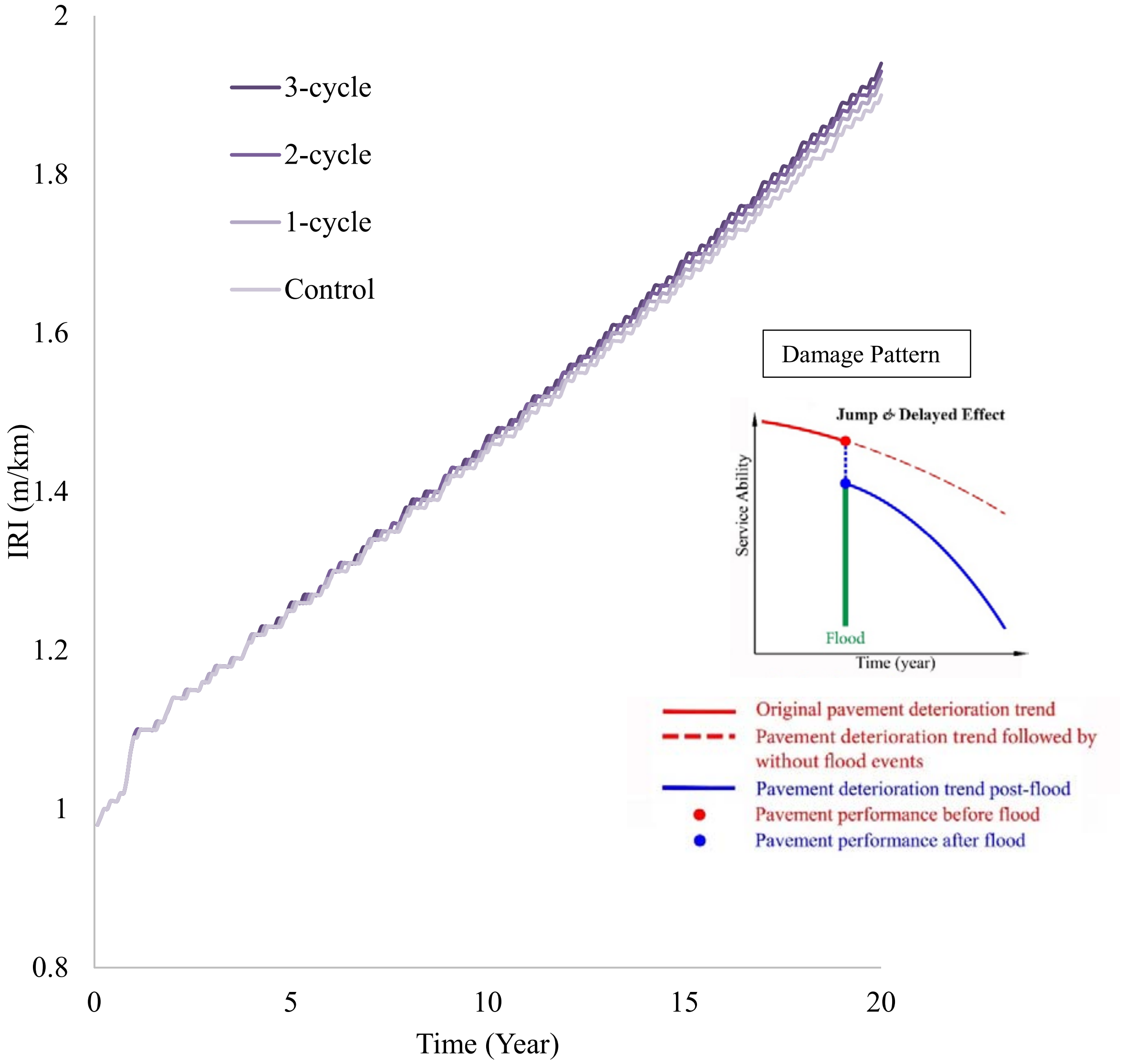


Figure 5.4 IRI Trends in The Design Life for 125 mm 61-day Duration Extreme Events

Figure 5.4 shows the performance curve indicated by IRI for various event cycles in the design life for 125 mm and 61-day duration events. It can be seen that the IRI trends (deterioration trend) are the same at the beginning and are accelerated after the each of the cycle of the flood events (5th year, 10th year, and 15th year) leading to the separation of terminal IRI values. After flooding events, the pavement IRI experiences a decrease, and the deterioration is accelerated. This trend can be assessed as the jump & delayed effect as described in Section 4.4. In practice, if there are pavement maintenance interventions after flooding events, the damage pattern can be changed to jump effect, i.e. the performance trend after flooding could follow the same rate as that without flooding events.

Figures 5.5 and 5.6 show the estimation of the loss of pavement life due to extreme precipitations. The loss of collector pavement life is generally more than that of arterial pavement. The loss of pavement life can be up to 303 days considering the analysis period is 20-year, that is, more than 4% of a pavements' life. Event cycles is an important factor that more cycles lead to shorter pavement life. In addition, it is noticeable that as the event duration goes longer, there is an obvious additional loss of pavement life.

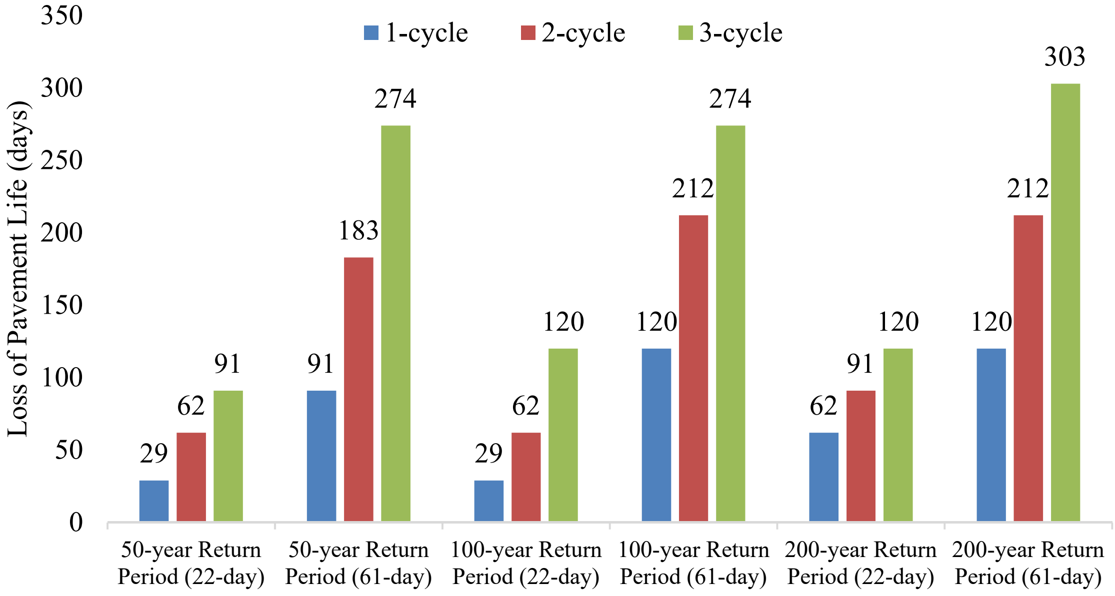


Figure 5.5 Loss of Pavement Life for Arterial Road

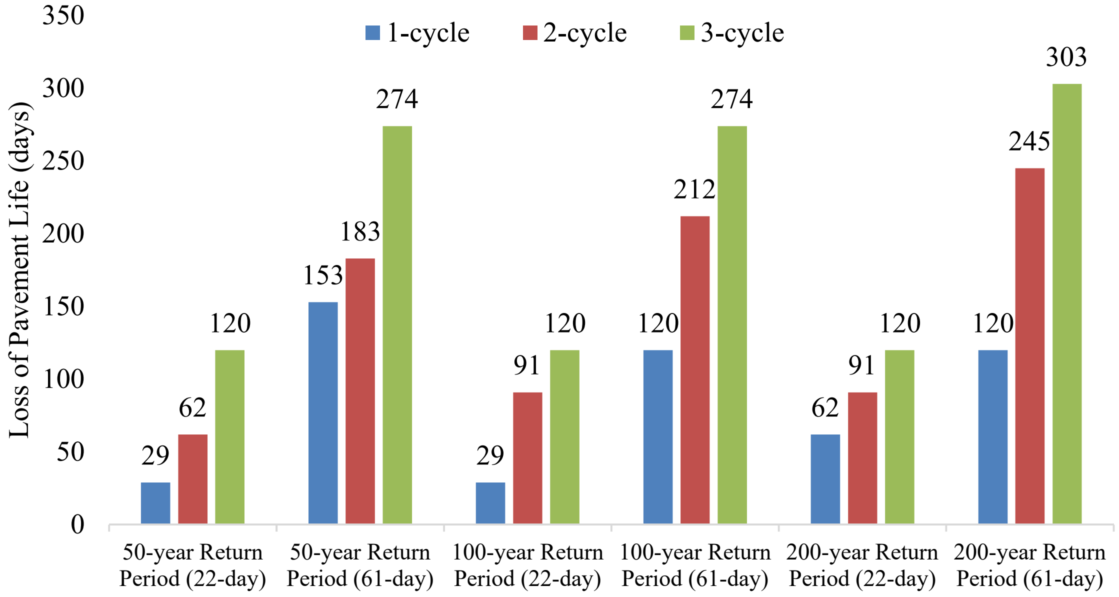


Figure 5.6 Loss of Pavement Life for Collector Road

In summary, the performance simulation results demonstrate the differences in performance change affected by different functional classes and extreme events during the pavement life cycle. It should be noted that the extreme event in this simulation does not contribute to other types of the damage pattern through the MEPDG analysis. The damage ratio results are small in value, although the extreme precipitation is designed to be relatively severe. This indicates the limitations of the MEPDG analysis on extreme precipitation or flooding events.

5.2.2.4 Generation of Fragility Curves

Factor analysis is applied to determine the main factors that affect pavement damage. SPSS software is used to conduct the factor analysis using the data from Table 5.4. The results show that durations and cycles of extreme event are the major contributors to pavement damage in this case study. Thus, based on duration and number of cycles, 12 flood levels are defined (Table 5.5). The mean value of the damage results of each level is calculated and taken as the mean for Monte Carlo simulation of lognormal distribution. The standard deviation is assumed to be 0.2% for each level.

The mean and standard deviation are converted to the parameters for the lognormal distribution. Monte Carlo simulation is used to generate 1000 events following the lognormal distribution. Multi stripe analysis (MSA) often used in seismic analysis is applied (Baker, 2015) to process the discrete set of flood hazard data. Figure 5.7 shows the distribution of arterial pavement damage at each flood level after applying Monte Carlo simulation and MSA. The fraction of each damage state for each flood level is calculated based on the simulated data. The parameters for the fragility functions are estimated using the maximum likelihood method to produce the optimized curves fitting the results.

The thresholds of the damage states for generating fragility curves are assumed to be damage ratios of 0.3%, 0.7% and 1% for pavement damage state PSD 1, PSD 2, and PSD 3, respectively, in this case study.

Table 5.5 Flood Levels and Damage Ratios

Flood level	Duration (day)	Flood cycle	Arterial damage ratio (%)	Collector damage ratio (%)
1	1	1	0	0
2	1	2	0	0
3	1	3	0	0
4	4	1	0.39	0.46
5	4	2	0.39	0.46
6	4	3	0.39	0.46
7	22	1	0.39	0.46
8	22	2	0.78	0.46
9	22	3	0.91	0.91
10	61	1	0.78	0.91
11	61	2	1.44	1.37
12	61	3	1.83	1.83

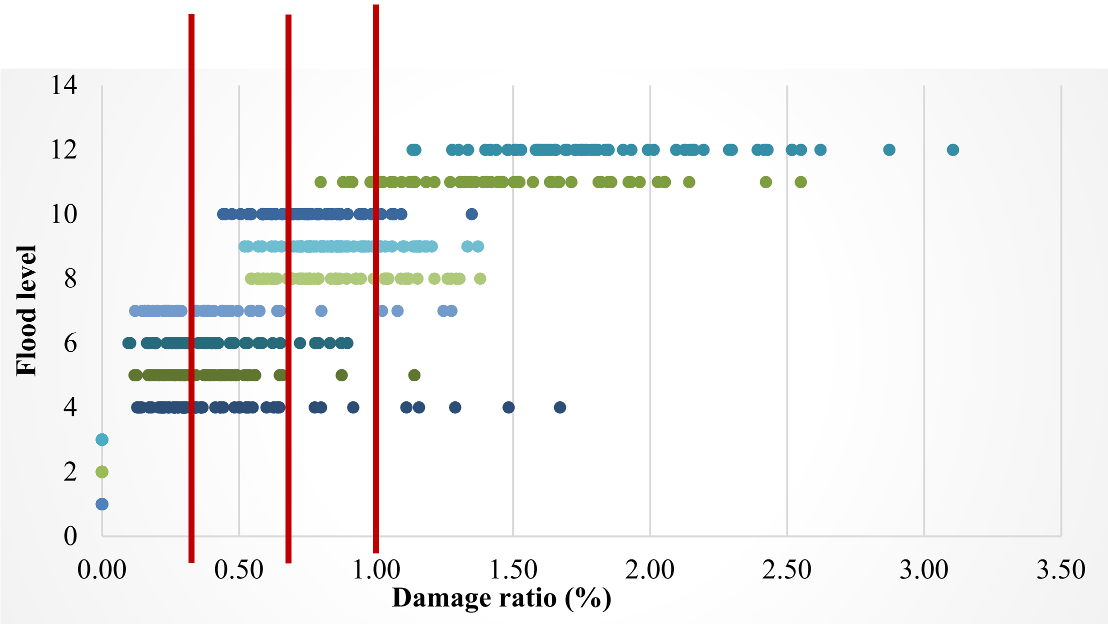


Figure 5.7 Multi Strip Analysis

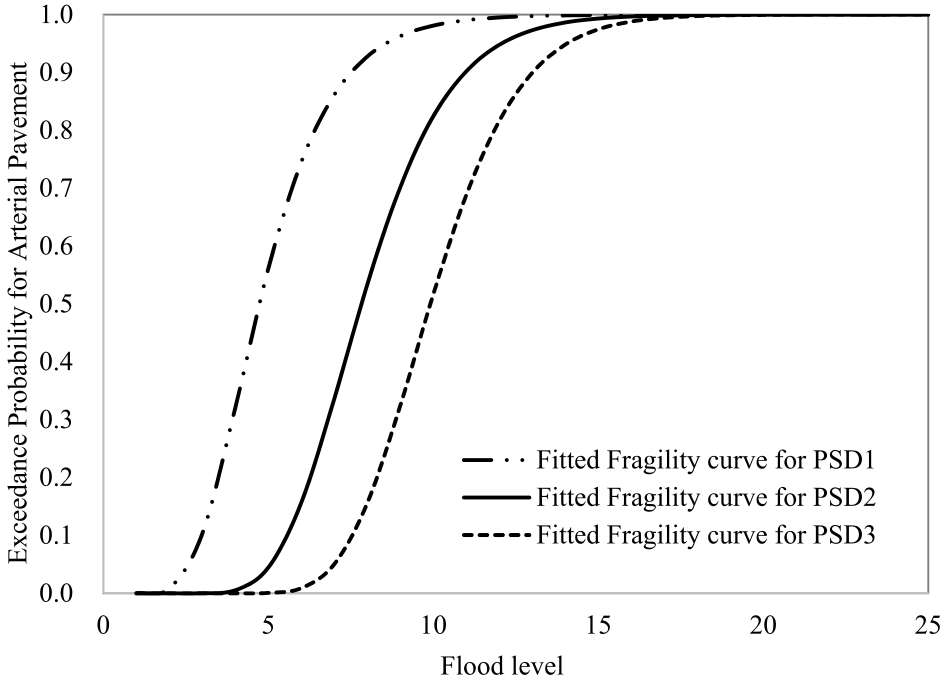


Figure 5.8 Flood Fragility Curves of Various Damage States for Arterial Pavement

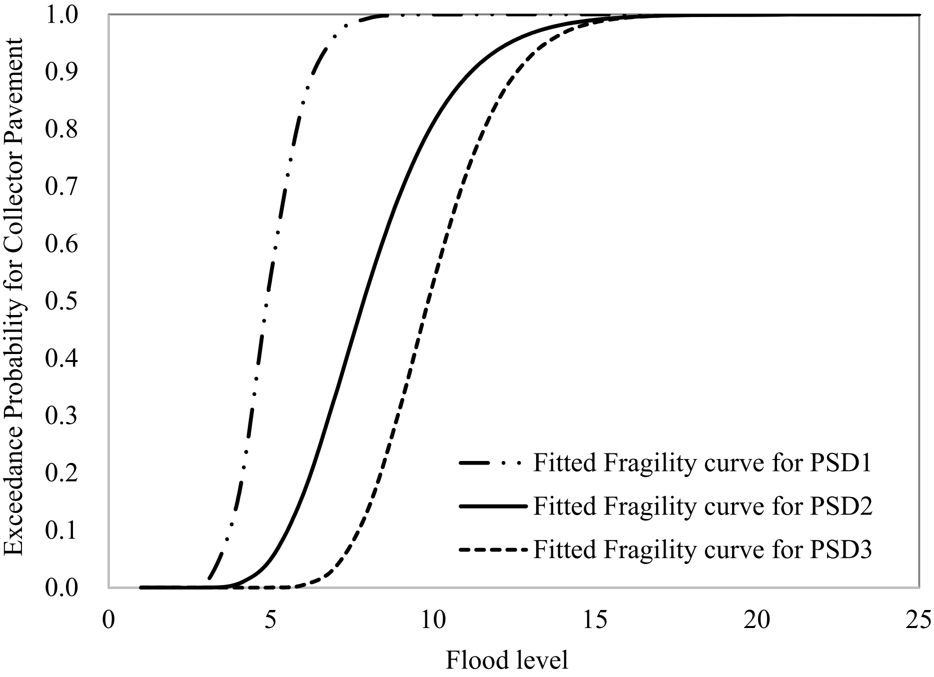


Figure 5.9 Flood Fragility Curves of Various Damage States for Collector Pavement

Figures 5.8 and 5.9 show the fragility curves in terms of annual exceedance probability of arterial pavement and collector pavement with pavement damage states PSD1, PSD2, and PSD3. It is obvious that the probability of pavement damages increases as flood level increase, and the probability of exceeding PDS1 is higher compared to PDS2 and PDS3 at the same flood level. From fragility models for all damage, the exceedance probability of pavement damage increases with the increase of flood level.

The pavement fragility curves indicate the uncertainty of pavement damage at various flood levels for various damage states. When the definition/description of damage states are related to other key performance indicators, such as loss of service life, safety, and costs, fragility curves can be generated accordingly. In applications, the curves can be used as an engineering property of a specific pavement or a type of pavement design and condition. A pavement flooding fragility curve database can be built for various pavement designs and conditions. The database of the curves enables the prediction the potential of pavement damage for a specified flood event.

The research findings regarding the method of probabilistic fragility analysis provide a tool for pre-event pavement flooding damage potential assessment. Based on the analysis results, if a pavement section is identified to have high fragility for certain future extreme events, actions can be taken to decrease the fragility of the pavement. This adaptation decision can help to increase pavement resilience for flood hazards.

5.2.2.5 Discussions

In this case study, the effect of extreme precipitation events on typical Ontario urban arterial and collector pavements is investigated by performing seventy-two simulations using MEPDG. Extreme precipitation level, number of cycles of extreme precipitation events, and pavement structural design are the input climate variables for simulating pavement performance change. The MEPDG simulation and Monte Carlo simulation data set are used as a baseline. Fragility curves were generated using the simulated pavement damage data. The results indicate that the extreme events can potentially lead to the loss of pavement life. More accurate fragility models would require to be calibrated for different pavement structure when actual damage data are collected. The successful application of this method is highly dependent on the availability of pavement data before and after flooding events. Nevertheless, the probability-based fragility analysis and modelling method is an approach that can illustrate the uncertainty of pavement damage given flood levels. It provides a way to investigate the interaction between flood characteristics and exceedance probability of pavement damage for various pavement designs.

5.2.3 Fragility Analysis and Modelling using a Range of Rainfall Events- Case Study 2

In a sense, pavement fragility for a specific pavement section is a physical property of the pavement structure given a condition. Therefore, obtaining the responses of the performance change given a wide range of desired levels of flood hazard could provide a comprehensive understanding of pavement susceptibility/fragility. The difference between this case study and Case Study 1 is the climate input. Case study 1 emphasizes the fragility analysis by using more climate variables for investigating the effect of different combination of extreme variables on pavement damage, while case study 2 focuses more on generation of fragility models in order to reveal the effect of a wide range of flood depth on certain pavement design and condition.

For flood damage analysis, depth is often used for developing deterministic depth damage curves in the current practices. In this study, the flood depth is used as flood level indicator for simplifying the fragility modelling, and the fragility models developed in this case study will then be used in the case studies for the risk assessment at the project level and network level in the following chapters.

5.2.3.1 Pavement Design

This case study utilizes the MEPDG for performance simulation to investigate pavement performance change due to a series of extreme precipitation events in intervals. The typical designs of arterial and collector pavement, traffic information, and site characteristics in case study 1 were used for the performance modelling. The change of performance (International roughness index (IRI)) resulting from the variation of flood events is selected for measuring pavement structural damage for the fragility analysis.

5.2.3.2 Climate Input

This study assumes that a 7-day precipitation event would occur each year in May based on the situation in Ontario. The input 24-hour precipitation values are 0, 20, 40, 60, 80, 100, 120, and 150 mm.

5.2.3.3 Results

Pavement damage for various depths of precipitations is shown in Table 5.6. These results will be used for generating fragility curves.

Table 5.6 Damage Ratio Results from Pavement Performance Simulation

Precipitation Scenarios (mm)	Arterial Pavement Damage	Collector Pavement Damage
20	0.80%	0.47%
40	0.80%	0.93%
60	1.20%	1.40%
80	1.60%	1.86%
100	2.00%	1.86%
120	2.00%	1.86%
150	2.40%	2.79%

5.2.3.4 Generation of Fragility Curves

The damage ratios are taken as the mean values for Monte Carlo simulation with a lognormal distribution. The standard deviation is assumed to be 0.2% for each level. Monte Carlo simulation is used to generate 1000 events following the lognormal distribution. Using equations (5-2) to (5-5) in section 5.2.1, the fragility curves are generated (Figures 5.10 and 5.11). In this case, the damage state thresholds are assumed to be damage ratios of 1%, 1.5%, and 2.5% for minor, moderate, and major damage, respectively for both arterial and collector pavements. Damage states could be defined differently, and verified by expert opinion. It can be seen from the fragility curves that the probability of exceeding certain pavement damages increases with increase of precipitation depth level, and the probability of minor damage is higher than that of major damage at a given depth level for each pavement type. For damage ratios 1.5% and 2.5%, the exceedance probability of the arterial pavement is lower than that of the collector pavement.

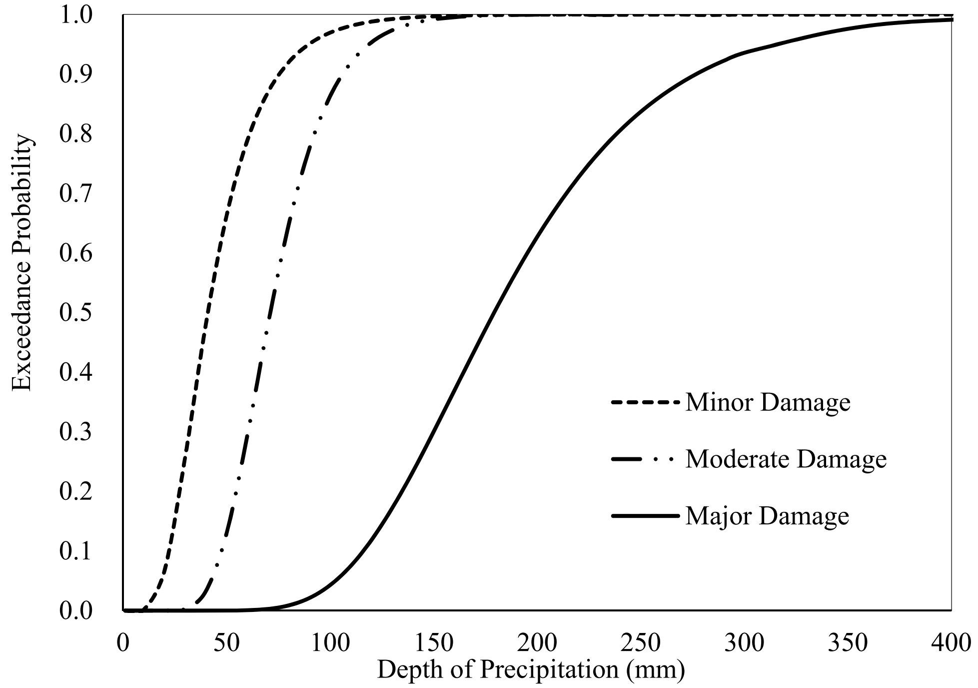


Figure 5.10 Fragility Curves for Arterial Pavement

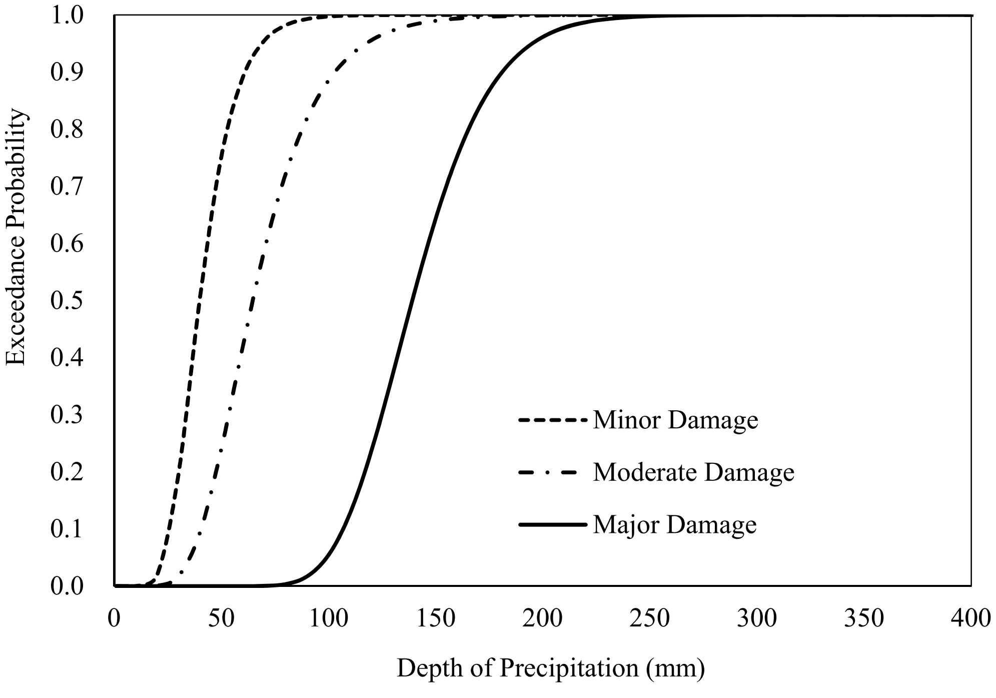


Figure 5.11 Fragility Curves for Collector Pavement

5.2.3.5 Discussions

This section presents a case study using a range of precipitation depth levels to generate fragility curves. These curves represent the physical properties of pavement damage related to flooding damage for specific designs and conditions. In the changing climate, the range of precipitations for the performance simulation can be adjusted to cover the climate change extremes so that the fragility curves would be able to predict climate change related damage.

In the future work, more dimensions of flood characteristics (velocity, duration) and various pavement conditions should be integrated in the fragility modelling to provide more accurate predictions.

Pre-event, the pavement damage potential evaluation can apply the fragility analysis method to address the uncertainty of the pavement damage potential. Based on future climate, relatively high fragility pavement sections can be prioritized for planning pavement maintenance, preservation, and rehabilitation activities to increase of the pavement resilience for flooding. For post-event management, the damage data collected can be used to verify and improve the fragility models and curves for future usage. The pavement flooding risk assessment and management guidelines in Chapter 8 describes the application of the fragility analysis method in terms of how to incorporate the outcome into adaptation and management.

5.2.4 Generation of Fragility Models by Integrating Experimental Testing and Performance Simulation

There are some limitations in the MEPDG simulation, although it is state-of-the-art method. For example, the moisture damage models assume that water would not infiltrate in asphalt pavement materials because the HMA is intact. The performance simulations in case studies 1 and 2 are performed based on new pavement designs. In the case of pavement with cracks, flood water can infiltrate in the layers causing damages. In addition, as pavement infrastructure ages, the pavements may become increasingly fragile to extreme events. Therefore, pavement condition should be considered when determining fragility and risk. Hence, a method that can obtain damage data to address the effects of water penetration and the influence of flood hazard on aged pavement is of great interest due to limit availability of damage data.

In this section, a method of integrating experimental testing and mechanistic-empirical pavement performance simulation is proposed, as shown in Figure 5.12. The material properties of the non-flooded and flooded pavement could be tested. Then, the properties of the flooded materials can be input in the MEPDG creating the updated material information for the performance simulation. The method is described in detail as follows.

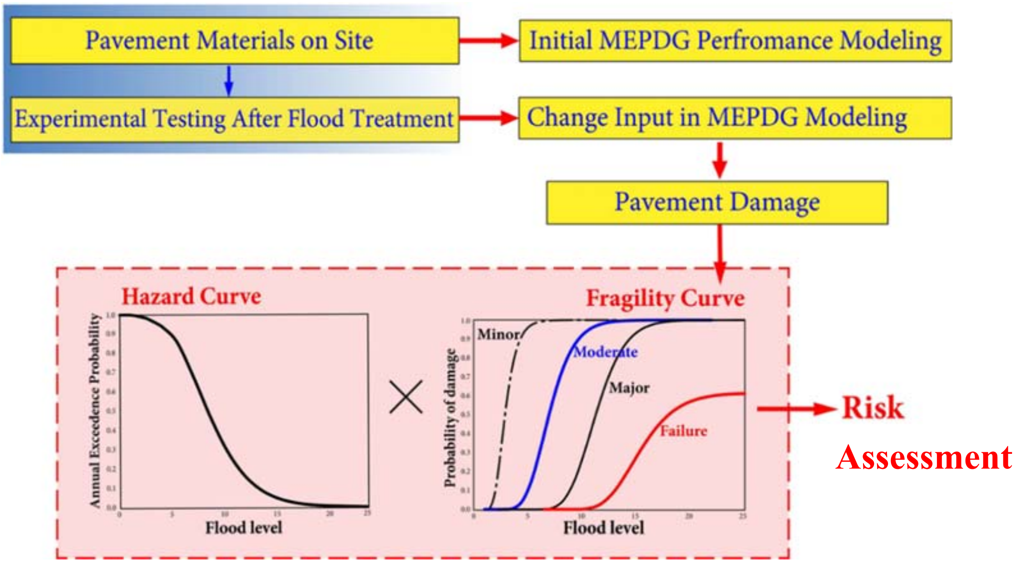


Figure 5.12 Fragility Modelling Procedures for Integration of Experimental Testing and Performance Simulation

Pavement samples are collected on site, and then critical physical properties are tested. The test results are the material input for the non-flooded pavement performance simulation. The samples are then subjected to certain flooding conditions, and the critical physical properties are tested again. The test results from the flood treated pavement samples are input for pavement performance simulation in the life cycle. The pavement performance change after flood events during the analysis period can be determined. By investigating the material properties with and without flooding, the pavement damage can be estimated by the mechanistic empirical pavement performance simulation method. Thus, the damage data can be used for fragility and risk modelling. This method analyzes the pavement damage due to flooding by carrying out experimental testing, which also facilitates the estimation of flooding damage for pavements at any conditions.

The major parameters connecting experimental testing results and performance prediction is the required MEPDG input that each layer of pavement materials. For example, for asphalt concrete layer, the parameters need to be tested are effective binder content, air voids, dynamic modulus for the mix, and asphalt cement characteristics, such as G* and phase angle. Case study for this method is not performed in this thesis.

5.3 Vulnerability and Damage Cost Estimation

Pavement vulnerability is quantified as pavement damage associated cost. In the proposed framework, cost estimation is one of the components for estimating vulnerability and risk. The cost can be estimated from social, economic and environmental aspects depending on the scope. This study focuses on mainly the economic aspect of vulnerability of the pavement assets. Vulnerability is determined as:

$$Vulnerability = P_{\mathrm{Fragiliy}} \times Cost \tag{5-6}$$

Costs can be generally categorized into two groups: direct cost and indirect cost. Table 5.7 listed the sources of direct and indirect costs from pavement damage, and the items included in each category are also presented. The following sections describe the costs in detail.

Table 5.7 Components of Flood Damage Cost for Pavements

Category	Cost Items	
Direct cost	Pavement Infrastructure damage cost	• Asset value loss: loss of infrastructure asset value • Additional life cycle cost: maintenance cost, preservation cost and rehabilitation cost
Indirect cost	Costs related to pavement damage	• Time delay costs • User costs at work zones • Discomfort costs • Vehicle operating costs • Collision costs • Environmental cost • Emergency response costs

5.3.1 Direct Costs

5.3.1.1 Asset Value Loss

Roads and pavements, as one of the transportation assets, are tangible capital assets in the municipal sector as defined by The Canadian Institute of Chartered Accountants (CICA).

Value at Risk is designed as an indicator to measure the risk of tangible capital asset losses from pavement flooding damage. It is correlated to pavement asset value estimation methods.

There are many ways to calculate asset value (Tighe, 2013). The asset valuation methods include book-value, written down replacement cost, replacement cost, and market value (Table 5.8).

Table 5.8 Definitions of Asset Valuation Methods (Falls et al., 2001)

Asset Valuation Methods	Definitions
Book value	Current value based on historical cost adjusted for depreciation (commonly used for financial accounting purposes)
Written down replacement cost	Current value based on replacement cost depreciated to current condition of the asset (commonly used for management accounting purposes)
Replacement Value	Current value based on cost of replacing/rebuilding the asset
Market Value	Price buyer is willing to pay

Book-value method is commonly used for financial accounting purposes. The current asset value is calculated based on historical cost (as-built cost) adjusted for depreciation. The estimation requires data of initial construction cost, pavement age, maintenance activity record (cost and year), and rehabilitation activity record (cost and year).

Written down replacement cost employs replacement cost depreciated to current condition of the asset to estimate asset value. In order to estimate this value, pavement type information, current pavement performance, and current construction costs are needed.

Replacement cost. The current value is estimated based on cost of rebuilding the asset. It requires pavement type information and current construction costs information.

Market value. Value of the asset is based on the price agreed in an open and unrestricted market. Pavement type, pavement age, current pavement performance and current construction costs are needed.

In the vulnerability assessment, asset value at risk is the potential loss of asset value given flood events. This loss is calculated by identifying the original asset value and the asset value with flood damage.

5.3.1.2 Additional Life Cycle Cost

Life cycle cost analysis is for evaluating the overall economics between competing alternative investment options (Tighe, 2013). Pavement flooding is a special event during pavement's life, and the associated costs are not counted in the initial life cycle cost analysis. **Additional life cycle cost** reflects the added cost to restore or prevent the damage from pavement flooding concerning the entire life cycle. The estimating of the additional life cycle cost requires the evaluation of the overall costs for competing various adaptation investment options in the context of climate change adaptation. The comparison of adaptation options could not only be between feasible maintenance, preservation, and rehabilitation plans but also different types (reconstruction projects) of pavement.

The pavement vulnerability considering additional life cycle cost demonstrates the added pavement maintenance, rehabilitation, and reconstruction costs if certain pavement damage occurs or is expected.

5.3.2 Indirect Costs

Indirect costs are the costs related to the event of pavement flooding. It is basically the user costs considering flooding conditions within the pavement life cycle cost analysis framework. It includes time delay costs, user costs at work zones, discomfort costs, vehicle operating and damage costs, collision costs, environmental costs, and emergency response costs. The importance of indirect cost is highlighted for high volume traffic roads where the interruptions caused by delay, closure, and restoration are large. However, these costs can be difficult to quantify. Descriptions of each of the item are presented as follows.

- Time delay costs

Flooding events cause traffic interruptions. The additional time spent for traveling due to congestion, road closure, and work zones incurred opportunity costs are a type of indirect cost for pavement flooding events. This cost can be significant for high volume roads.

During extreme rainfall and flooding events, excessive rainfall can cause the speed reduction and queuing because of slippery roads and insufficient sights. Under certain flooding conditions, road may not be accessible leading to closure; detours or rerouting are required. Therefore, the additional distances travelled result in time delays.

This quantification of the cost is typically determined by vehicle hours and a rate to represent the value associated with other activities that cannot be completed because of the extra time required for travel. Vehicle delays are estimated using traffic forecasting, and the delays are given a user rate to evaluate the financial cost (Tighe, 2013).

- User costs at work zones

A work zone affects the number of lanes available to the traffic and the operational characteristics of traffic flowing at the area (Tighe, 2013). After flooding, pavement restoration actions for flood hazard such as surface cleaning, maintenance, preservation, and rehabilitation activities can occur, and hence the work zones could impact on user costs due to the lane closures or, in some circumstances, road closure. Work zones can cause time delay costs, and the collision rates inside work zones can be higher. Different lane configurations, frequency of treatments, and slower construction options can lead to longer delays. Similar to the time delay cost, the user costs at work zones are often evaluated by vehicle hours and a rate.

- Discomfort costs

The comfort of passengers spend in a vehicle as a human factor is not easily quantifiable. Extreme rain fall events could result in slow-moving and congested traffic.

- Vehicle operating and damage costs;

Fuel efficiency and pavement conditions affect vehicle operating costs of individual vehicles. Flooding condition can alter the vehicle operating cost-effectiveness. Under the flooding condition, vehicles can also be inundated in flood water leading to vehicle damage and repair costs.

- Collision costs

Flooding conditions and extreme rainfall events are a safety factor. Interventions, such as road closure and construction activities pose a collision risk. There are costs associated with additional incidents resulting from slippery roads, insufficient sights, and work zones. The quantification of collision costs are mainly the costs of human fatalities, non-fatal injuries, and accompanying property damage (Lemke 2000).

- Environmental costs

The importance of climate change and sustainable developments for Canadian infrastructure is increasing. Other resource usage, greenhouse gas emissions, noise of traffic, and construction activities affect the environment. For example, the additional gas consumption in traffic congestion would contribute to the greenhouse gas emissions.

- Emergency response costs

In emergency, the responses need to be timely to save lives and properties. The cost associated with emergency responses demonstrates this cost item. It could include the costs of setting up signs and barricades, detours, maintaining a real time public alert travel information system, and so on.

5.4 Summary

Chapter 5 employs the theory of fragility analysis in probabilistic pavement damage modelling. As a key component in pavement flooding vulnerability and risk assessment, fragility models are developed to quantify the conditional probability of exceeding certain damage state given a level of flood hazard. The methods for estimating pavement vulnerability for flood hazards are discussed. Pavement damage data are crucial for generating accurate fragility models. Three methods for collecting pavement damage data for fragility analysis are proposed and illustrated in the case studies. Pavement mechanistic-empirical (ME) design method is utilized to simulate the impact of extreme precipitations on pavement performance of typical arterial and collector flexible pavements in Toronto, Canada. Fragility models and curves are generated based on the performance simulation results.

Case study 1 investigated the effect of extreme precipitation depth, number of cycles, and event durations on the performance of arterial and collector pavement designs. The results of IRI trends are the same at the beginning and are accelerated after the time points introducing cycles of flood events leading to the separation of terminal IRI values. This trend can be assessed as the jump & delayed effect as described as described in Chapter 4. The extreme events can potentially lead to the loss of pavement life up to 303 days. Considering that the analysis period is 20 years, the loss is more than 4% of a pavement's life. More flood cycles lead to shorter pavement life, which is cause by the accelerated deterioration after the flood cycles.

In the changing climate, the range of precipitations for the performance simulation can be adjusted to cover the extreme events. Case study 2 employed a range of precipitation depth levels to simulate the influence of precipitation depth on pavement performance.

The proposed method three is designed to address the effect of water penetration and the influence of flood hazard on aged pavement in the context of limit availability of damage data.

The research findings indicate that fragility analysis provides a practical tool for evaluating the uncertainty of pavement flooding damage. The process of fragility analysis helps to understand the relationships among exceedance probability of pavement damage, flood hazards, pavement structural designs, pavement conditions, and damage states, which allows to make the adaption decisions in reducing fragility of pavement infrastructure.

For pavement flooding risk assessment and management, at the point of pre-event, the pavement damage potential evaluation can apply the fragility analysis method to address the uncertainty of the pavement damage. Based on future climate, high fragility and important pavement sections can be prioritized for planning pavement maintenance, preservation, and rehabilitation activities to increase of the pavement resilience for flooding. For post-event management, the damage data collected can be used to verify and improve the fragility models and curves preparing the database for future usage. The pavement flooding risk assessment and management guidelines in Chapter 8 describe the application of the fragility analysis methods in terms of how to incorporate the outcomes into adaptation and management.

Chapter 6 Pavement Flooding Risk Assessment

Assessing pavement risk for extreme events is essential for prioritizing high risk infrastructure and developing adaptation strategies. Risk assessments provide information of potential adverse events enabling agencies or stakeholders to take actions proactively, thereby reducing losses. A robust risk assessment could empower management to better identify, evaluate, and exploit the risks maintaining efficient pavement management operations. This chapter aims to develop a quantitative risk assessment methodology for pavement flooding events considering future climate at the project level. The risk assessment integrates the three major components introduced in the previous chapters: flood hazard analysis, fragility modelling, and cost estimation. A case study is conducted to illustrate the application of the proposed method.

6.1 Pavement Flooding Risk Assessment Framework

6.1.1 General Risk Quantification Method

Risk is often quantified by integrating hazard exposure and vulnerability. In this study, vulnerability is obtained using fragility multiplied by costs. The simplified expressions are:

$$\text{Risk of Loss} = \text{Hazard} \times \text{Vulnerability}, \tag{6-1}$$

$$\text{Vulnerability} = \text{Fragility} \times \text{Costs}, \tag{6-2}$$

$$\text{Risk of Occurrence} = \text{Hazard} \times \text{Fragility} \tag{6-3}$$

where:

Hazard: characteristic of extreme events;

Vulnerability: cost of a certain level of damage given occurrence of a certain extreme event;

Fragility: probability of a certain level of damage given occurrence of a certain extreme event;

Costs: economic consequences given certain damage;

Risk of Loss: cost of a certain level of damage;

Risk of Occurrence: probability of a certain level of damage.

6.1.2 Pavement Flooding Risk Assessment Framework

The framework of pavement flooding risk assessment method is presented in Figure 6.1. Project level risk assessment involves hazard analysis, fragility analysis, and consequence analysis to estimate risk of occurrence and risk of losses. The analysis of pavement flooding risk includes: (i) the flood hazard – annual exceedance probability of certain flood level under climate change; (ii) the fragility characteristics – probability of exceeding certain damage given an event; and (iii) vulnerability – the cost of a certain level of damage caused by certain hazard. the levels of damage are defined by damage states in the previous chapter.

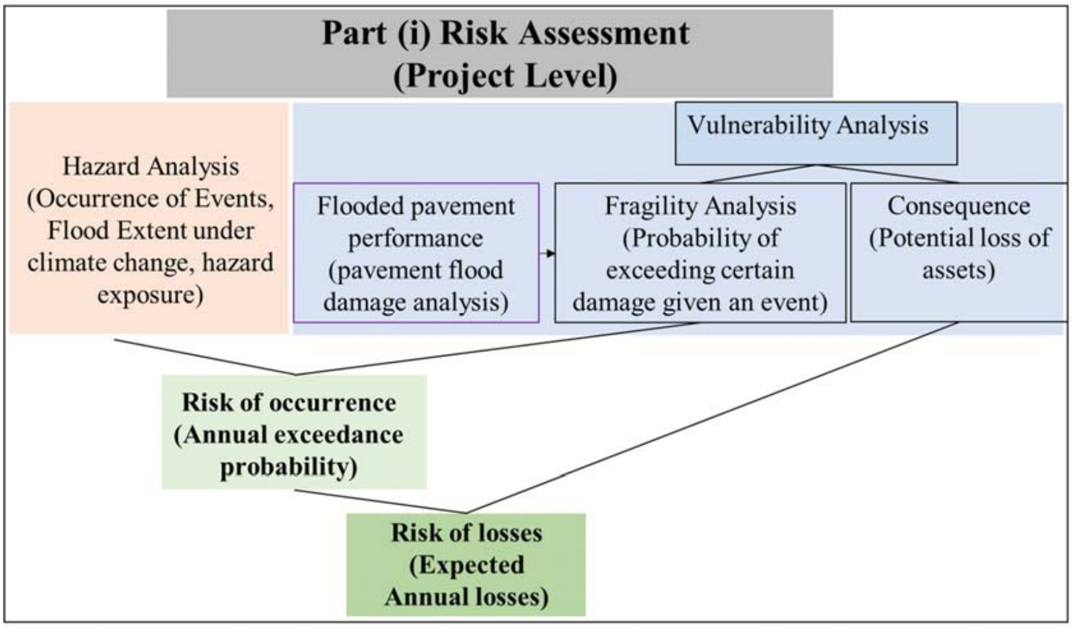


Figure 6.1 Risk Assessment Framework at the Project Level

6.1.3 Application of Pavement Flooding Risk Assessment Framework

The potential application and characteristics of the framework is described as below.

1. The framework is systematic, comprehensive, and universal. It addresses the risk comprehensively and systemically though incorporating all relevant elements in the assessment.

2. The framework is capable of providing a complete picture of risk of flooding on pavement sections and the extension to road networks.

3. Better results can be obtained with more information and better models (for each component including climate, flood, pavement, and road network).

4. Pavement flooding probabilistic risk assessment is the process in which the randomness and uncertainty in climate models, precipitation projections and floods on pavement sections, pavement structures and structural responses, and road networks variables are propagated through engineering modelling to determine a probability distribution of damage risks or the associated adverse consequences due to floods.

6.1.4 Uncertainty

Uncertainty include aleatory uncertainty and epistemic uncertainty. Aleatory uncertainty indicates the statistical uncertainty; the uncertainty due to variation in professional knowledge is known as epistemic uncertainty. On the other hand, the intrinsic randomness described by models is known as the aleatory randomness. In the risk assessment in this study, uncertainty arise from a variety of factors, including uncertainty associated with models, complex linkages, changing external factors.

Uncertainty is associated with the components of the risk estimation models including hazard prediction, fragility analysis, and consequence estimations. There is high uncertainty in climate change estimations such that the climate projections will have a wide range from the results of an ensemble of climate projection models. The estimation of fragility also bears uncertainty because the pavement and the damage data or observations have randomness and uncertainties. In practice, engineers are adjusting the maintenance practices and other operation methods to adapt to the potential future change, which alter the adaptive capacity of the infrastructure. Therefore, the risk modelling should be an iterative process and adjusted periodically to be more reliable as new information/knowledge becomes available.

The case studies in this research employ specific values for each component to illustrate the framework, but it is not the limitation of the framework. When there is more information or data available, the framework is able to provide a distribution. A logic tree is used to shown in Figure 6.2 to characteristic the uncertainty of the risk assessment process. Providing the limitation in the length of the thesis and data availability, the case studies in this research does not illustrate all these aspects.

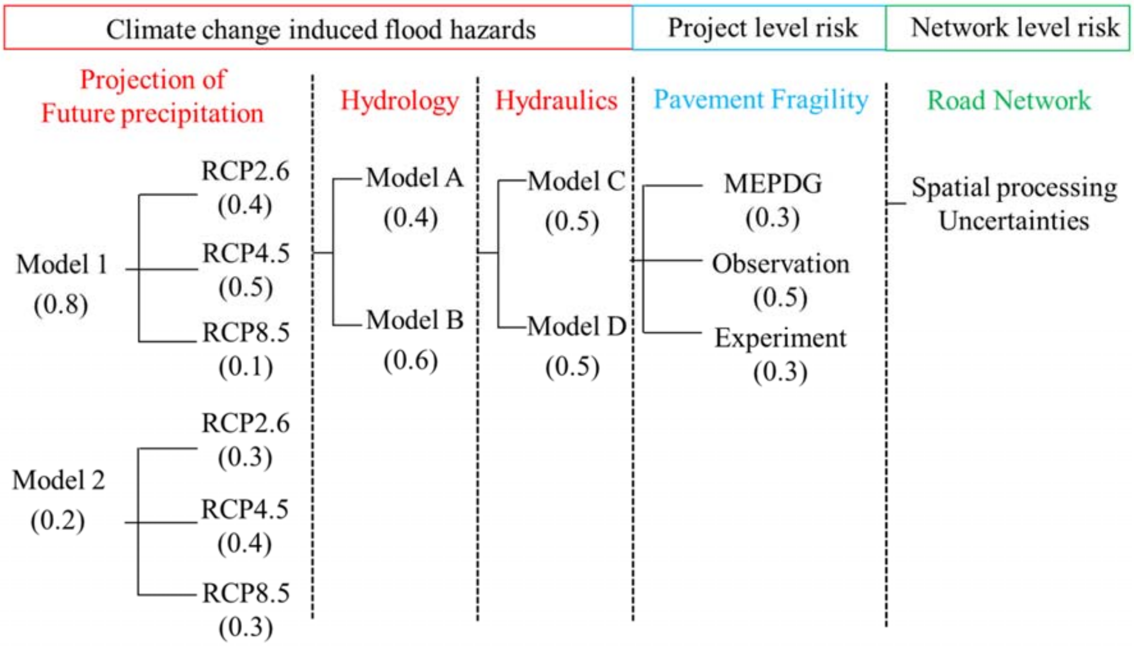


Figure 6.2 Logic Tree for Characterizing Epistemic Uncertainty of Pavement Flooding Risk Assessment under Climate Change

6.2 Pavement Flooding Risk Quantification Methodology

Figure 6.3 shows the process for estimating the risk in this study. Climate-change-induced extreme precipitation and flooding can be predicted. The extreme precipitation data are used for generating hazard curves and as input in the pavement performance simulations. The performance change with and without the occurrence of extreme events is used for generating the fragility curves. The integration of hazard curve, fragility curve, and cost gives the risk.

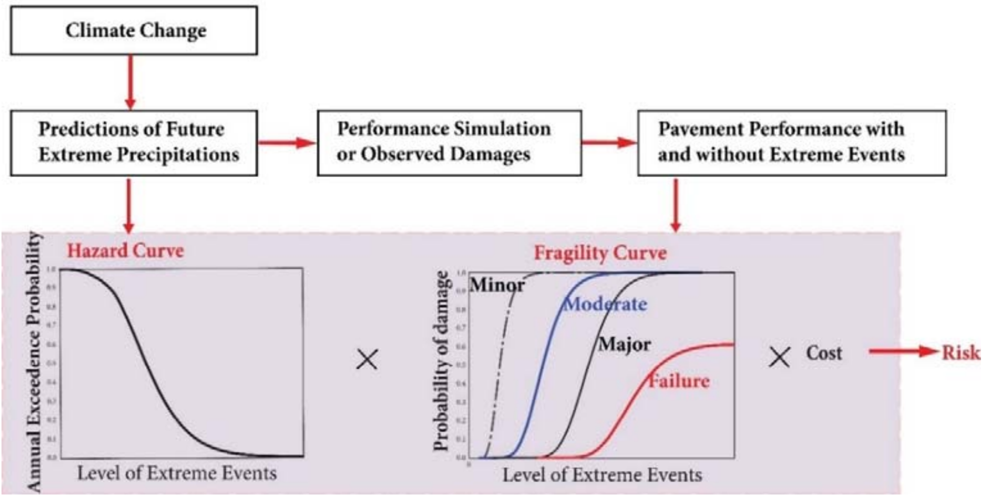


Figure 6.3 Pavement Risk Quantification Process under Climate Change

6.2.1 Estimation of Risk of Occurrence

Total probability theorem is applied to the risk estimation. High risk can result not only from frequent occurrences but also from low probability of occurrences with very severe consequences. In this study, the risk assessment covering a full range (for instance, 2, 5, 10, 25, 50,100-year) of hazards is evaluated to represent the risk from all possible events. Thus, the pavement asset risk estimation in terms of annual exceedance of probability for exceeding certain pavement damage state is expressed as Eq. (6-4),

$$\gamma = -\int_{0}^{\infty} P_{Fragility}(\mathrm{DP})\frac{dH(\mathrm{DP})}{d(\mathrm{DP})}d(\mathrm{DP}) \tag{6-4}$$

where

γ represents flooding risk for a flood event, i.e., annual exceedance probability of certain pavement damage;

DP is depth of flood;

$P_{\mathrm{Fragility}}$ (DP) is the probability of exceedance for certain damage state at DP

H is flood hazard function.

The flood hazard curves from the flood hazard functions (*H*) are shown in Figure 3.11

A numerical method is usually applied to evaluate the integral in equation (6-5),

$$\gamma = -\sum_{i=1}^{N} P_{\text{Fragility}}\left(\text{DP}^{(i)}\right)\, \Delta H\left(\text{DP}^{(i)}\right) \tag{6-5}$$

where N is the number of intervals for DP;

i indicate the i th interval;

$\text{DP}^{(i)}$ is the discretization of depth of flood at flood level DP;

$\Delta H(\text{DP}^{(i)})$ is the annual exceedance probability for DP at the i th interval.

The discretization of depth of flood is 0.5 for the case study as follows.

6.2.2 Estimation of Risk of Losses

The cost associate with certain pavement damage can be complex and include a variety of cost items. In this research, an example is used for demonstrating the estimation of risk of losses regarding the asset value loss. In future work, more items of cost can be defined and incorporated in the vulnerability assessment.

Value at risk is the potential loss of asset value due to certain damage from extreme events in analysis periods. To achieve the value at risk estimation, a method is developed to reflect the loss of the pavement asset value for flooding damage. The extreme events cause the reduction of the pavement asset value because of the decrease in pavement performance. Thus, the percentage of damage is assumed to reflect the percentage of the loss of asset value. The written down replacement cost method is employed to evaluate the asset value in the following case study. The current value of the asset is estimated based on replacement cost depreciated to current condition. If the straight-line method is used for evaluating depreciation. The depreciation expense is recognized evenly over the estimated useful life of an asset. The procedure for calculating the depreciation expense is as follows.

1. Determine the initial cost of the asset;

2. Subtract the estimated salvage value of the asset;

3. Determine the estimated useful life of the asset;

4. Calculate the straight-line depreciation rate by dividing the estimated useful life into 1;

5. Multiply the depreciation rate by (initial cost − salvage value) to get the depreciation expense.

The asset value in each year in the analysis period can be calculated. For pavement flooding occurring at a certain year of pavement life, by using the asset value in the year multiplied by the damage ratio, one can estimate the asset value loss.

The asset value for each year in the analysis period can be calculated using Eq. (6-6),

$$V_n = \text{ICC} - n(\text{ICC} - \text{Sal})\zeta \tag{6-6}$$

where

V_n is the asset value at year n;

ICC is the initial construction cost;

Sal is the salvage value at the end of the 20-year design life;

n is year number;

ζ is the depreciation rate.

Assuming there is a maximum one-time extreme event per year, the risk of asset value loss in the analysis period is determined:

$$R_{\text{total}} = \sum_{j=1}^{\infty} \sum_{m=1}^{q} \gamma_j R_j{}^m \tag{6-7}$$

$$R_j{}^m = \sum_{n=1}^{20} N_n^m V_n \, \kappa \tag{6-8}$$

$$\gamma_j = \gamma^j \times (1 - \gamma)^{20-j} \tag{6-9}$$

where

R_{total} is the total risk of asset value loss for any number of occurrences of extreme events in specified analysis periods;

R_j^m is the risk of asset value loss for the m^{th} case for j times of occurrences of extreme events in the analysis period (20 years);

j is the total times of occurrence of flooding in the analysis period;

m is the number of cases for j, m = 1, 2 ,3…, 20;

q is the total number of cases;

γ_j is the pavement flooding risk of for j times of occurrence of extreme events in the analysis period;

N_n^m is the number of occurrences of extreme events in the n^{th} year for the m^{th} case;

κ is the damage ratio from Eq. (5-1).

For example, when j = 1, it means a flood may occur in any year within the 20 years analysis period, i.e. q = 20. Assuming there is a maximum one-time extreme event per year, when m = 3, $N_3^3 = 1$, for n ≠ 3, $N_n^3 = 0$.

6.3 Case Studies

6.3.1 Future Flood Hazard Analysis in the Changing Climate

The process of generating the hazard curves for this case study is described in Chapter 3.

6.3.2 Pavement Design and Pavement Fragility Models

Pavement design and the fragility modelling follow the case study in Section 5.2.3 Case study 2. The fragility models are adopted in the risk assessment in this case study. The fragility curves are shown in Figures 5.10 and 5.11.

6.3.3 Data for Estimating Risk of Annual Asset Value Loss

For estimating value at risk, the method in Section 6.2.2 is used. Typical initial construction costs per kilometer for the arterial and collector pavement in Southern Ontario, Canada, are CAD$1,065,744 and CAD$430,236, respectively, and the salvage values at the end of the 20th year are CAD$646,135.6 and CAD$260,721.2, respectively (Applied Research Associates, 2011). The depreciation rate ζ is 0.05. By using Eqs. (6-7) to (6-9), the risk of occurrence for extreme events in the design life can be calculated. For this case study, the risks of asset value loss are calculated based on the assumption that there is a maximum one-time extreme event per year.

6.3.4 Results and Discussion

The risks of occurrence in terms of the median annual exceedance probability of arterial and collector pavements for different pavement damage states under various climate change scenarios are estimated (Table 6.1).

Table 6.1 Annual Exceedance Probability for Different Pavement Damage States under Various Climate Change Scenarios

	Arterial Pavement		
Scenarios	**Major**	**Moderate**	**Minor**
Historical data	0.0036	0.1978	0.3989
RCP 2.6	0.0086 (-0.0066, +0.0144)	0.2757 (-0.1057, + 0.0889)	0.4331 (-0.0484, +0.0273)
RCP 4.5	0.0109 (-0.0082, +0.0166)	**0.2917 (-0.0924, +0.0852)**	**0.4385 (-0.0372, +0.0248)**
RCP 8.5	0.0184 (-0.0167, +0.0431)	0.3432 (-0.1492, +0.0895)	**0.4543 (-0.0517, +0.0222)**
	Collector Pavement		
Scenarios	**Major**	**Moderate**	**Minor**
Historical data	0.0041	0.2481	0.4403
RCP 2.6	0.0125 (−0.0108, +0.0278)	0.3182 (−0.0960, +0.0724)	0.4682 (−0.0411, +0.0152)
RCP 4.5	0.0173 (−0.0149, +0.0320)	**0.3317 (−0.0810, +0.0684)**	**0.4718 (−0.0285, +0.0125)**
RCP 8.5	0.0313 (−0.0304, +0.0821)	**0.3735 (−0.1254, +0.0696)**	**0.4804 (−0.0337, +0.0078)**

The median, upper bound, and lower bound values are also presented to show the uncertainties. Compared to the historical condition, climate change causes an increased occurrence of damage from the median precipitation estimations. It can also be seen from the results that with the increase in climate forcing, the values of annual exceedance probability for all damage states and pavement designs are increasing. However, high uncertainty is evident as shown from the upper and lower bound result, which is due to the variation of future climate predictions.

The median value at risk per kilometer for arterial and collector pavements with upper and lower bounds are presented in Figure 6.4. Range of risk varies by damage state and RCP scenario considered. The bars represent the upper bound and lower bound risk. For all climate scenarios, the median risk for arterial pavements is higher than that for collector pavements, which may be because of the high asset value of arterial pavements. As the climate forces increase, the median risk increases. Decision makers should not neglect the consequences of minor hazards. Although minor damage is relatively small, the high occurrence of minor damage can lead to a high potential of asset value loss across the road network. On the other hand, it is noticeable that the occurrence of major pavement damage does not necessarily mean the highest risk in terms of asset value loss because the probability of occurrence of major damage can be relatively low. There is no large gap between moderate and minor damage risk within each pavement type. This indicates that the difference between moderate and minor damage is not significant regarding the risk of asset value losses based on the damage state threshold values. In addition, there is significant difference of risk of loss under future climate compared to the historical case for RCP4.5 and RCP8.5 with minor damage and RCP8.5 with moderate damage for both arterial and collector roads.

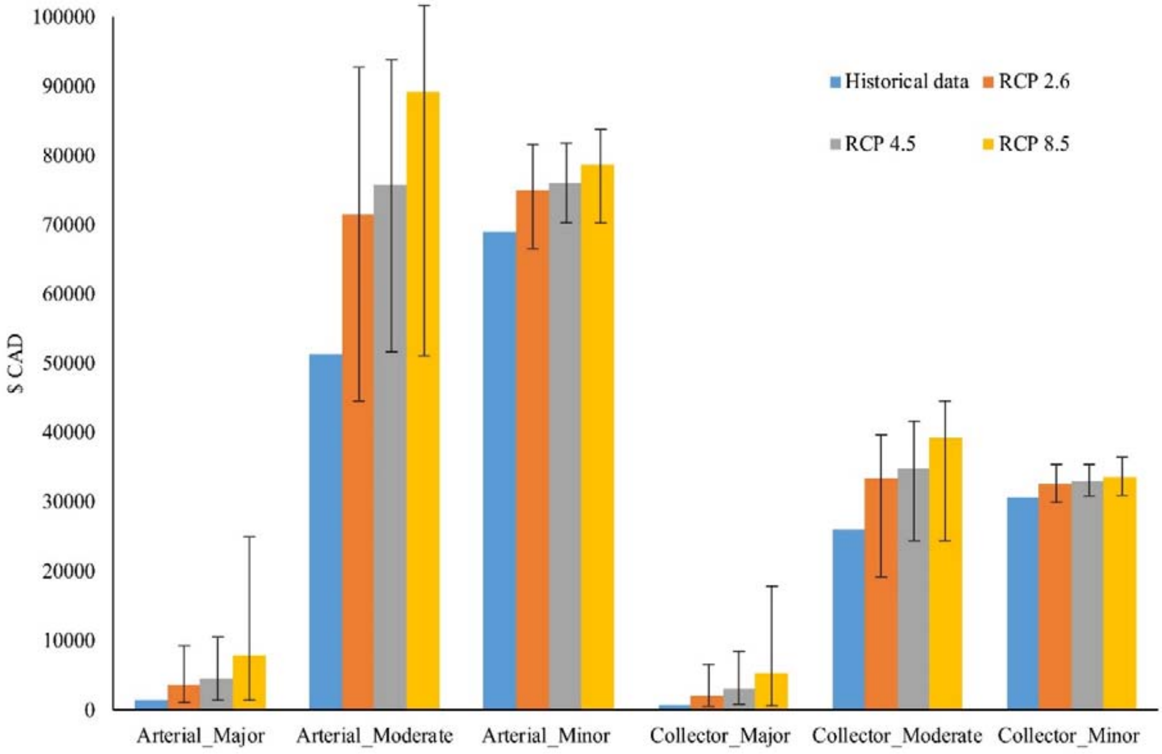


Figure 6.4 Value at Risk per kilometer for Arterial and Collector Pavements

From the median value, it is estimated that the risk of increased intensity of extreme precipitation is approximately as high as CAD$112,471.28, and CAD$46,487.81 per kilometer for moderate damage of arterial and collector pavements, respectively, with respect to the predicted worst climate scenario over the 2017 to 2100 period.

This risk assessment methodology determines the impact of a full range of hazards on pavement asset value at risk over the analysis period for different damage states. In the future, more meaningful threshold values should be determined when more observations of damage data can be collected. In addition, large uncertainty exists in the climate projection models and fragility models. Value at risk is determined based on the potential asset value losses in this study, while risk from the aspect of additional life cycle costs (including maintenance, preservation, and rehabilitation costs) and other costs should also be evaluated for informing the adaptation decision making in the future work. Nevertheless, the proposed risk assessment framework and methods can quantify the risk of asset value loss, and indicate the interaction between value at risk, probability of occurrence, damage states, and extreme events for different types of pavements.

6.4 Summary

Chapter 6 introduces flooding risk estimation methods for pavements. The research develops a quantitative risk assessment methodology for pavement flooding events considering future climate in the project level. The analysis of pavement flooding risk includes: (i) the flood hazard – annual exceedance probability of certain flood level under climate change; (ii) the fragility characteristics – probability of exceeding certain damage given an event; and (iii) vulnerability – the consequences of certain pavement damage. A case study is conducted to illustrate the application of the proposed methods. An ensemble of 24 global climate models is utilized for predicting future (2017-2100) hazard curves for various climate-forcing scenarios. Fragility models are developed based on the typical design for arterial and collector asphalt pavements in Toronto. The damage associated asset value losses are estimated based on the typical initial construction costs, 0.05 depreciation rate, and salvage values. Risk assessment covering a full range of hazards is performed. The probability of occurrence and risk of asset value loss per kilometer are discussed for different climate scenarios, damage states, and functionality of pavements. The results show that considering the climate from 2017 to 2100, the extreme precipitations from representative concentration pathway (RCP) 8.5 climate scenario results in asset value losses as high as CAD$112,471.28 and CAD$46,487.81 per kilometer for arterial and collector pavements, respectively. The risk of asset value losses is approximately 10% of the initial construction cost for both types of pavements. It is noted that the risk of major damage is not the highest when compared to the risks of minor and moderate damage, because the major damage has a lower occurrence resulting in lower asset value losses. The findings indicate that the risk assessment framework provide a tool to analyze the interactions among flood levels, pavement structural designs, damage states, risk of occurrence, and risk of asset value losses. Pre-event risk should be assessed by incorporating potential future hazard and pavement fragility/vulnerability. Thus, adaptation decisions can be made based on the assessment.

Chapter 7 Flooding Risk Assessment for Pavement Networks

Road network is crucial to economic development and social benefits. Climate-change-induced extreme precipitations and floods pose a risk of damage on road pavement structures resulting in reduced road network serviceability. This chapter develops a methodology for spatial risk assessment of flood hazards on road pavement networks. The spatial risk assessment enables the prioritization of pavement sections in a network considering the changing climate. The cost-effective flooding risk management and adaptation decision can then be achieved.

7.1 Pavement Network Flooding Risk

Pavement asset management aims to make cost-effective resource allocation, programming and management decisions for performing a function to an appropriate level of service (Tighe, 2013). Risk information can be used to identify the needs for the pavement network management. In the context of climate change, risk assessment and mitigation should be emphasized in the asset management process concerning potential future nature hazards. Pavement management decisions should be assisted by risk data to achieve cost-effective outcome. Incorporating pavement flooding risk assessment at the project level and network level into pavement asset management help facilitate a better pavement management and flooding hazard risk management as well as increase human security, well-being, quality of life, and sustainable development.

In the context of flood risk management, visualizations represent a powerful tool for decision making (Burch et al., 2010). Pavement network flood risk maps visualize the spatial distribution of the risk making the decision making more user friendly. The risk mapping processes provide a platform for spatial risk analysis. Through risk mapping, adaptation needs can be identified, effectively determining where adaptation resources are spent most efficiently. Pre-event, the maps can be a visual tool for decision makers to identify, evaluate, and respond to the risk. A pavement network flood risk map can include information of hazard type, hazard extent, exposure, and risk of occurrence, risk of loss, and basic information such as pavement asset inventory.

The maps can be used as a fundamental tool for many purposes:

- raising awareness;
- providing information for road pavement infrastructure development, and adaptation investment planning and prioritization determination;
- serving as a reference for adapting pavement design codes and standards considering further extreme events;
- helping with determination of pavement infrastructure flood risk insurance premiums; and
- allowing pre-event disaster preparation.

Risk maps can be generated by integrating flood hazard analysis and fragility analysis across specific pavement network based on Geographic Information Systems (GIS). The detailed methodology is described in the following sections.

7.2 Pavement Network Risk Assessment Methodology

An eight-step approach is established to conduct the pavement network risk assessment and mapping.

7.2.1 Eight-step Approach for Analyzing Spatial Risk of Pavement Networks

- Step 1: Identify flood extent of a flood event. The flood extent map should be generated at this stage by flood hazard mapping methods. The flood map can be collected from related institutions. All representative flood events considered in a local region should go through the mapping process. This helps understand the spatial distribution and identify the flooding area due to the storm events. The flood extent maps can include the flood characteristics such as flood depth and velocity.

- Step 2: Identify road network at the flooding area. The spatial road network map for the area should be collected. The road network should cover the entire flooded area determined in Step 1. Road network information should include the elevation, street name, road functional class, pavement structural information, asset value information, and so on.

- Step 3: Determine the submerged road network. By using spatial analysis techniques from geographic information system (GIS) tools, the road sections inundated by flood water can be extracted. Spatial distribution, the number and length of the affected road sections in the inundated network can be investigated. The list of the road sections affected by flooding can be generated along with the length information.

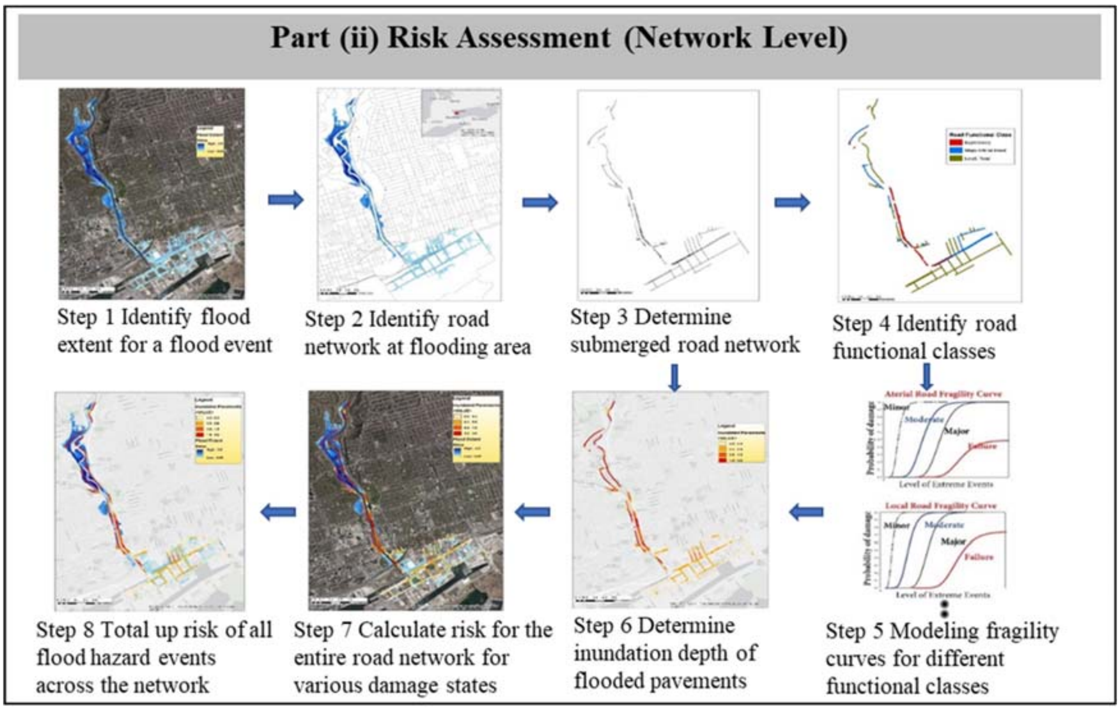


Figure 7.1 An 8-Step Approach for Pavement Network Flooding Risk Assessment

- Step 4: Identify road functional classes. The functional class of each inundated section can be highlighted out across the network within the submerged road sections from Step 3.

- Step 5: Modelling fragility curves for different functional classes. The fragility functions can be generated for various road functional classes and structural designs according to the method developed in Chapter 5. The fragility models can be used for matching each pavement sections identified by Step 4. This step is described in detail in Section 7.2.2.
- Step 6: Determine inundation depth of flooded pavements. The depth of pavement submergence can be calculated by the GIS system tools.
- Step 7: Calculate risk for the entire road network for various damage states. Using the flood depth (Step 6) as input in fragility models (Step 5) for each road section, risk of annual exceedance probability can be estimated across the network. The risk for 2-year, 5-year, 10-year, 50-year, 100-year, and more return period events can be determined individually.
- Step 8: Summing up risks of all flood events across the network. Sensitivity study can be conducted by taking different upper bound events in the total risk estimation. The risk can be calculated for various damage states as needed. The flooding risk maps across the road network can be created for individual event risk and sum up risks for visualization and spatial analysis purposes.

The key outcomes from this framework can include:

- extent of road disruption;
- pavement asset exposure across the network;
- risk maps including annual exceedance probability and potential loss across the network; and
- sensitivity considering shifted range of flood hazard under climate change.

7.2.2 Incorporation of the Fragility Models in the Network Risk Estimation

A majority of the risk mapping methods consider only the flood hazard exposure without including infrastructure susceptibility. The purpose of using fragility curves in network risk assessment is to integrate the physical pavement infrastructure design and condition characteristics in the vulnerability analysis and risk analysis. Figure 7.2 shows the concept of employing fragility models in risk assessment for different road functional classes. Figure 7.2a illustrates the pavement fragility curves for various road functional classes and different damage states. Figure 7.2b shows an example of road functional classes of inundated pavement network. The arrows demonstrate the process of matching fragility functions to the entire inundated road network.

A certain road network normally consists of a variety of functional classes and pavement designs. Fragility functions for each functional class and pavement designs can be generated. By obtaining all the fragility functions for all functional class and types of pavements in the network, the risk of the entire network could be estimated without losing the information of the pavement infrastructure characteristics. The fragility model database could be built, maintained, and periodically updated to keep the pavement physical information the latest.

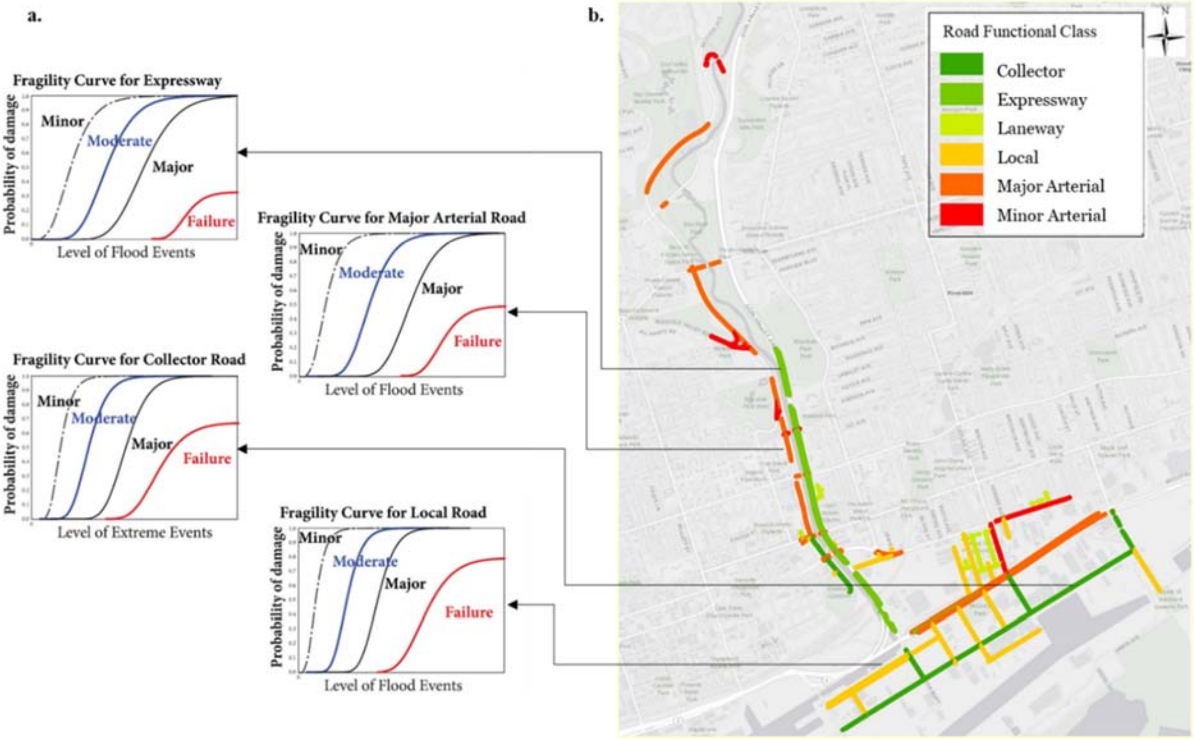


Figure 7.2 Matching Fragility Curves to Functional Classes for Risk Estimation

7.2.3 Categories of Pavement Flooding Risk Maps

By adopting the road network risk assessment approaches, the risk of flooding for the entire network can be quantified. Road network risk maps can be created on GIS platforms to meet the need of easy communication. Table 7.1 shows the types of map that is possible to be created based on the risk assessment process proposed. The output would highly depend on the availability of flood data, pavement network data, pavement fragility models, and cost data.

Table 7.1 Flood Hazard and Risk Maps at a Pavement Network

Type of map	Description
Flood hazard map	Spatial characteristics of flood hazard, i.e. flood depth, flood duration, flood velocity, and so on
Pavement flood hazard exposure map	Spatial distribution of pavement submergence for the road network
Pavement network flooding hazard extent map	Depth/velocity of the pavement flood submergence across the pavement network for various road functional class
Pavement network flooding vulnerability map	Spatial distribution of the pavement vulnerability across the network, i.e. pavement fragility multiply various cost from the aspect of economy, social and environmental consequences such as pavement asset value loss, additional life cycle cost, traffic disruption cost, population affected, and so on
Pavement network flooding risk map (individual scenario)	Spatial distribution of annual exceedance probability for different damage states (e,g, Minor, Moderate and Major Damage) across the pavement network for each road section for a single flood event
Pavement network flooding risk map (sum up)	Spatial distribution of total risk considering a full range of flood scenarios for each road section across the pavement network

Pavement network flooding risk of loss map (individual scenario)	Spatial distribution of the annual loss for different damage states across the pavement network for each road section for a single flood event
Pavement network flooding risk of loss map (sum up)	Spatial distribution of the total risk of annual loss considering a full range of flood scenarios across the pavement network

7.2.4 Pavement Flood Risk Criteria and Evaluation

Risk criteria and evaluation, as the linkage of the risk assessment process and adaptation process, are used to evaluate the level of risk and identify the need to make adaptation plans and take adaptation actions. Figure 7.3 shows the risk criteria for prioritizing the pavement asset adaptation and management concerning both project level and network level management. Five levels of risk for a certain pavement network system are identified. The thresholds value should be based on local policy, available funding, and target level of service.

Figure 7.3 Risk Criteria/Levels for Pavement Asset Adaptation Management

Target risk level describes the lowest risk value indicating the tolerable/acceptable level of risk that adaptation requirement is minimum or no need. The risk criteria for target level could be different for different functional classes, because the requirements of level of service are different for various road classes.

Maximum acceptable level for the network is the level that should be met for the network. It indicates that the average risk for all sections within each functional class should be no more than the risk threshold for the road class. If the risk exceeds the maximum acceptable level for the network, adaptation plans should be made to maintain a satisfactory risk for the entire network.

Maximum acceptable level for individual section is the maximum acceptable risk for a single section. This value can be higher than the maximum acceptable level for the network because the risk for individual section is a single value rather than an average for the network.

Critical/Safety level is the maximum risk level to maintain safe operation. The determination of the threshold value for this risk level could be highly depend on the local regulation requirement for safety considerations. The risk over this level need short term responses.

Emergency level indicates a very high level of risk that the occurrence of this event may cause natural disasters. Local agencies should establish mandatory action requirements for this situation.

7.2.5 Uncertainty and Challenges

There are various sources of uncertainty in the risk estimation. This research introduces climate change sensitivities to demonstrate uncertainty. The climate change sensitivity analysis is a method to determine if there is significant difference between the risk with and without climate-change-induced extreme events. In the following sections, the sensitivity analysis is included in the case study.

There are uncertainties in the flood map generations. Uncertainties exist in data quality, data processing approaches, extrapolation to rare events, assumptions of stationarity and homogeneity on flood frequency analysis, assumptions on the catchments or climate conditions, and so on. Furthermore, uncertainty in the fragility and vulnerability estimation can be high due to limit availability of quality data and historical damage observations for validation.

7.3 Case Study

Urban areas are vulnerable given large population and dense asset distribution. A case study of a local road network located at Lower Don Area in Toronto within the Don River Watershed (Figure 7.4) is performed. The city has experienced many major floods over the past century, especially in recent years, such as August 2005, July 2013, June 2014, July & August 2016, and August 2018, causing significant transportation disruption and economic losses. A detailed risk assessment is performed for the road network of this area to illustrate the proposed methodology.

7.3.1 Case Study Area

The Don River Valley is a major north-south transportation corridor carrying people and traffic into and out of downtown Toronto via the Don Valley Parkway, Bayview Avenue, and the GO transit railway. Adjacent to these transportation corridors, Lower Don River flows through downtown Toronto before discharging into Keating Channel and eventually flowing into Lake Ontario. Due to the urban setting of the catchment areas, the Don River experiences generally low base flows throughout most of the year interspersed with high flows during precipitation events (Stantec and DHI Water, 2017). High intensity storm events have caused flooding of the transportation corridors leading to substantial damage to properties, disruptions to business, and human safety issues in the past decades.

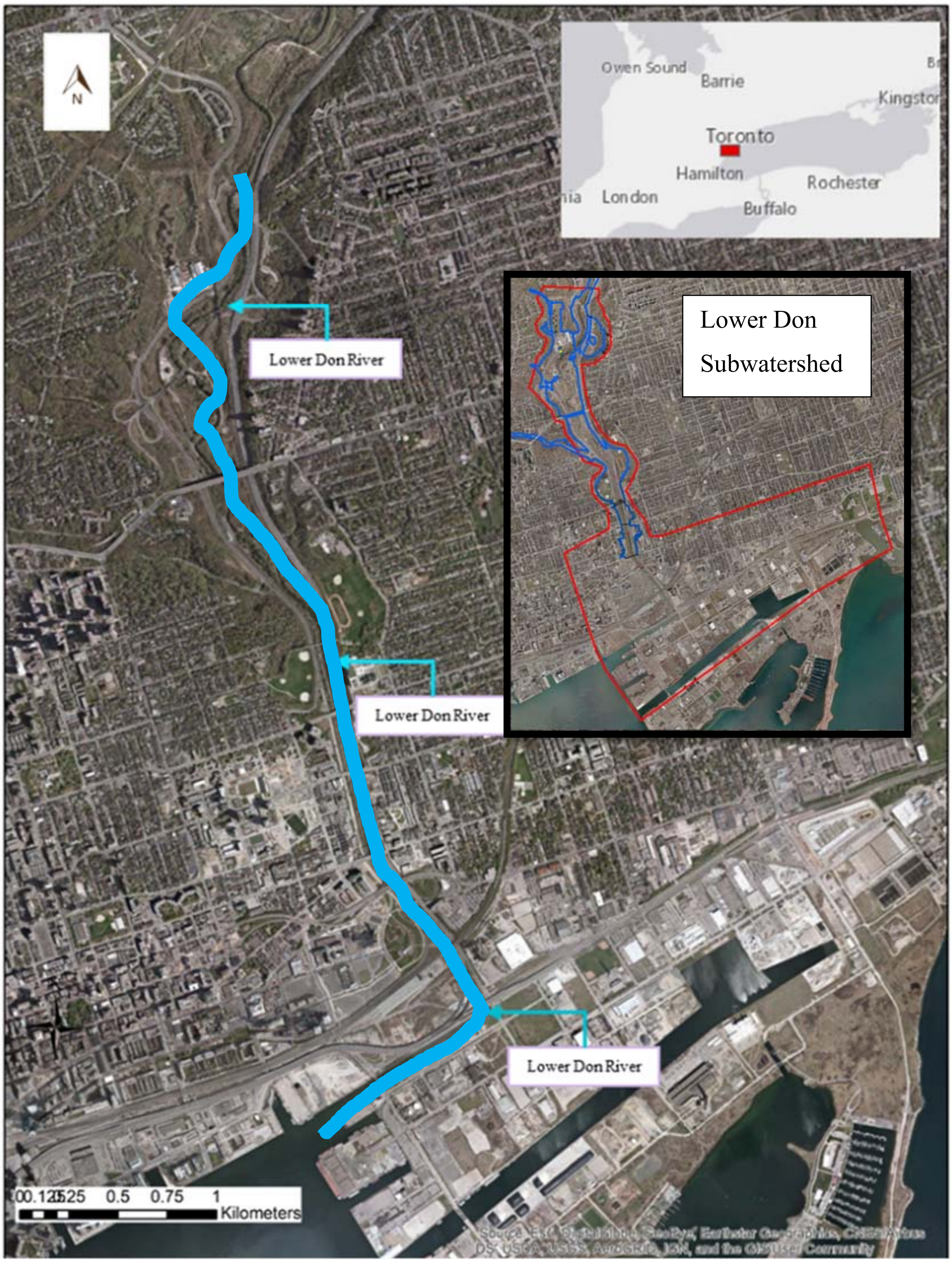


Figure 7.4 Case Study Area: the Lower Don Rive and Lower Don Subwatershed (Esri and TRCA)

7.3.2 Flood Hazard Data

Representative floods in this region normally have return periods of 2-year, 5-year, 10-year, 25-year, 50-year, 100-year. However, the extent of flood could increase under climate change. Thus, in this case study, representative flood events with an additional return period (350-year) are considered for the risk estimation and sensitivity analysis. The 350-year return period flood is included to indicate the climate-change-induced flood hazards in the changing climate. In fact, the selection of flood events is very flexible; a wider range of flood events can be considered as needed.

Toronto and Region Conservation Authority (TRCA) took the effort in generating the regulatory engineered floodline mapping for the Lower Don River providing flood characterization maps and visual tools for communicating the potential flooding issues. Flood hazard data are provided by the TRCA in terms of flood plain maps of return periods of 2, 5, 10, 25, 50, 100, and 350 years for Lower Don Area. The selection of 350-year return period event is based on the prediction from climate scenario RCP 2.6 with using IDF_CC tool Version 3.0. The Global Climate Models (GCMs) selected are an ensemble of bias-corrected BCCAQ (Pacific Climate Impacts Consortium, 2018.), ANUSPLIN300, and CanESM2 models.

The flood map modelling processes involve data review; baseline model comparison; model development; sensitivity analysis; calibration and verification; model results comparison; modelling design storm events; flood modelling and mapping. The flood maps are created by a coupled 1D-2D MIKE FLOOD hydraulic model (DHI, 2011), which is described in detail in the report (Stantec and DHI Water, 2017). A brief overview is presented here to demonstrate the method. The channel survey data, topography data and LiDAR data were collected by the TRCA. Hydrology data were observed by TRCA for defining the inflows in the models for the range of storm events. Hydraulic structure inventory is used to define the locations and geometries of the hydraulic structures for MIKE FLOOD model. 1D river channel model and 2D flexible mesh model are developed and coupled. Sensitivity analysis is performed to determine the impact of changing manning’s Roughness, hydraulic structures, and inflow boundary conditions on simulated flows, and to identify the important parameters for adjusting models during calibration. Measured flow and water level data from historical events (May 29, 2013; July 15, 2012; July 8, 2013 Storm Events) in the case study area are used for model calibration and verification (September 4, 2012 Storm Event). Calibrated model is then used to simulated flood for 2-, 5-, 10-, 25-, 50-, 100-, and 350-year storm events.

7.3.3 Pavement Network data and Other Data

Pavement network information is collected from City of Toronto including pavement network information and map. The information includes pavement functional class across the network, and basic priorities of the pavement assets. Spatial reference used is NAD 1983 UTM Zone 17N. For mapping the pavement network flooding risk, a rectangle boundary is clipped based on the world map in ArcGIS platform to include the pavement network in the case study area, and flooded area for the worst road flooding scenario. All the data used are either already in, or converted to, raster format.

7.3.4 Fragility Model Assumptions

The fragility models created in Chapter 5 are for arterial and collector pavements. In this case study, the road functional class include expressway, major arterial, minor arterial, collector, laneway, and local. It is assumed that expressway, major arterial share the fragility models for the arterial pavement, and the fragility models created by collector pavement is adopted by minor arterial, collector, laneway, and local road. After matching the fragility curves with each of the pavement section, risk estimations are obtained by integrating flood hazard and pavement fragility.

7.3.5 ArcGIS Model Set-up

The flood map data and road network data are analysed in the ArcGIS system. Figure 7.5 shows the processes and calculations involved for estimating the road network risk. The algorithms implemented in ArcGIS is shown in Appendix B ArcGIS Pavement Flooding Analysis Models.

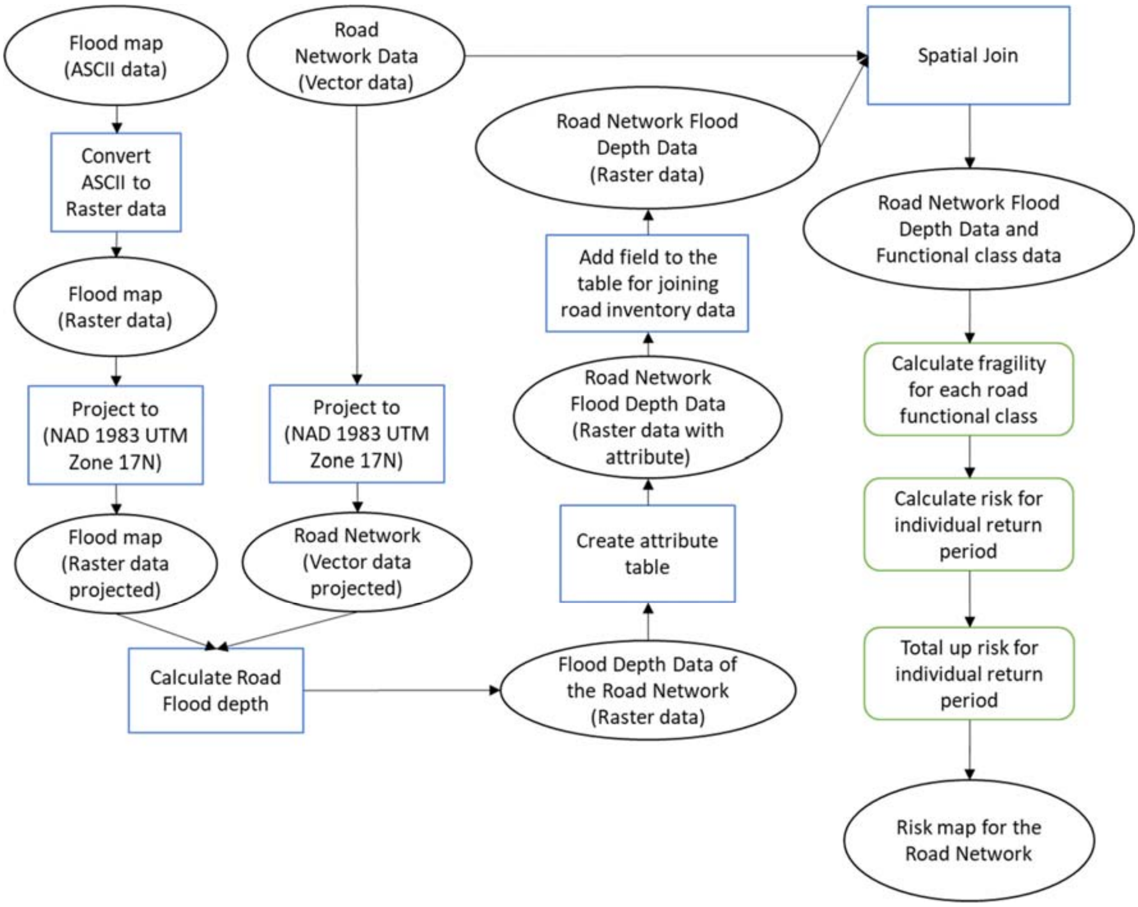


Figure 7.5 ArcGIS Model and Calculations for Road Network Flooding Risk

7.3.6 Results

7.3.6.1 Exposure of the Pavement Network

In this analysis, the extent of the flooded road network varies greatly over the network for different events (Figure 7.6). The spatial distribution of the inundated road network is determined by the flood depth on pavement surface. As flood hazard become more severe (Figure 7.6, i-vii), the spatial extent of the road submergence covers more road sections with the most prevalent one of 350-year return period event (Figure 7.6g).

The number of flooded road sections increases as the return period of the flood event increases (Figure 7.7). The greatest number of inundated road sections for all events in the case study area is major arterial roads type (Figure 7.8). It is noticeable that there is a sharp increase (increased by 42 roads) of the total number of inundated roads when the flood event becomes 100-year return period compared to 50-year return period event. A similar trend is observed for major arterial road, collector roads, and local roads where the number are increased by 9, 8, and 16 roads, respectively. For the laneways, the noticeable jump is from the 25-year to 50-year return period flood event with an increase of 11 roads. Expressway as an important functional class is also inundated, and the number of submerged roads do not show a noticeable increase when flood return period increases from 50-year to 350-year. These results demonstrate that avoiding a noticeable increase in pavement exposure to flood hazards for various road functional classes would lower the traffic disruptions leading to accessibility to various public services and local business.

From the aspect of preserving physical infrastructure asset values of a road network, pavement infrastructure can be designed and maintained to effectively reduce the inundation length of high value assets, because the damage cost is often estimated based on per kilometer value. The total length of inundation increases as the flood events becoming more intensive (Figure 7.9). The length of pavement inundated for each functional class increases as the increase of the return period (Figure 7.10). It can be observed that as the return period increases from 50-year to 100-year and higher, all road functional classes experience a noticeable increase in the inundation length (Figure 7.10). In addition, the inundation length of expressway, generally having the highest asset value assets among all functional classes, increases sharply when the return period increases from 10-year to 25-year. When the return period is increased to 350-year, the inundation length experiences a significant jump for local roads, which have the lowest asset value per kilometer. The proportions of inundation length of each functional class (Figure 7.11) highlight the most affected asset classes across the road network for each of the flood event. It should be emphasized that the value of the road assets does not necessarily reflect social impacts. The optimal adaptation decision can be further informed by investigating a balance between asset value preservation and the reduction of social and business interruption. The flooded road pavement information in the network is shown in Appendix C.

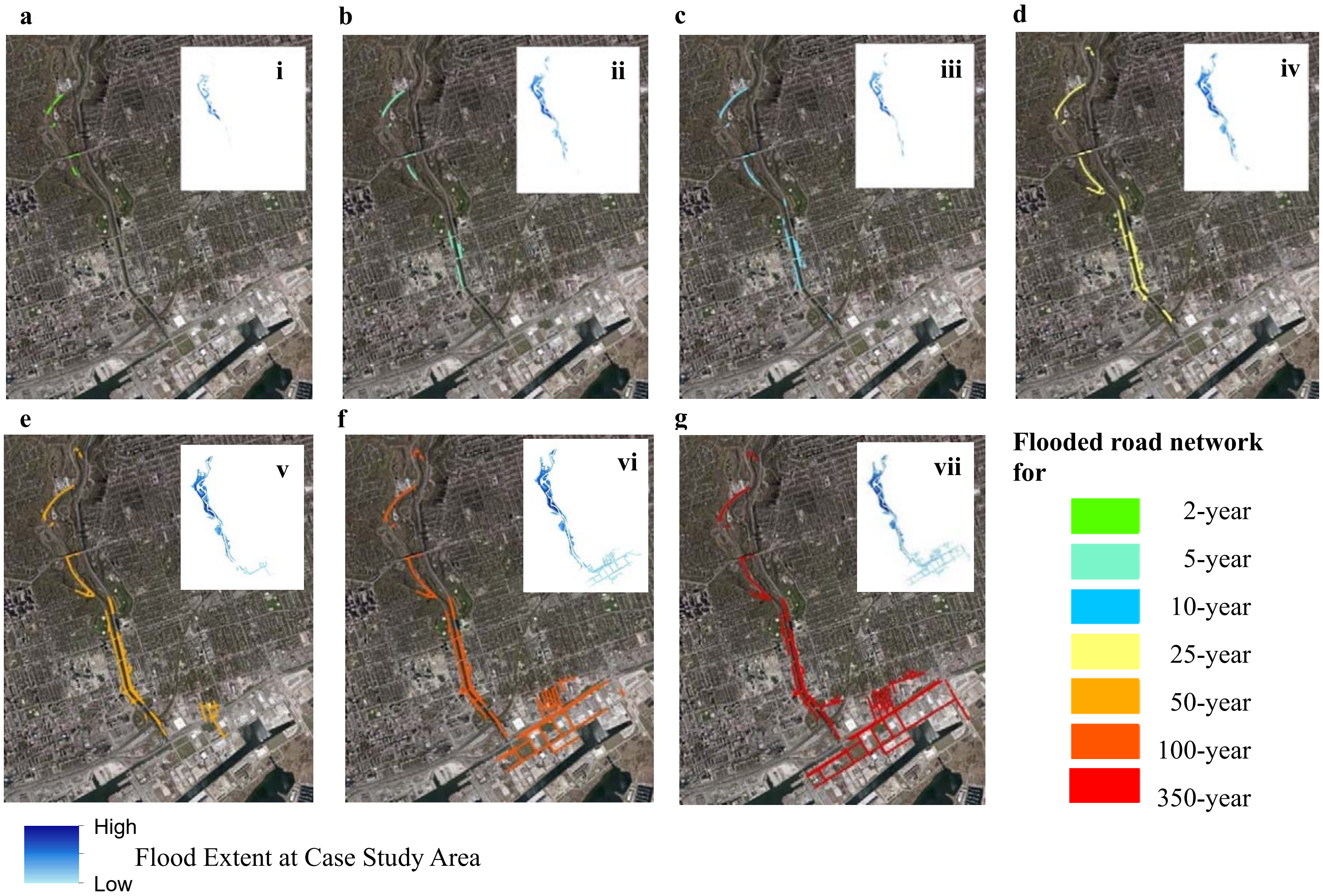


Figure 7.6 Road Network Inundation Maps and Flood Extent for Various Flood Events at the Case Study Area. a-f, Inundated road network for various flood events. i-vii, Flood extent for 2-year, 5-year, 10-year, 25-year, 50-year, 100-year, and 350-year flood events at case study area.

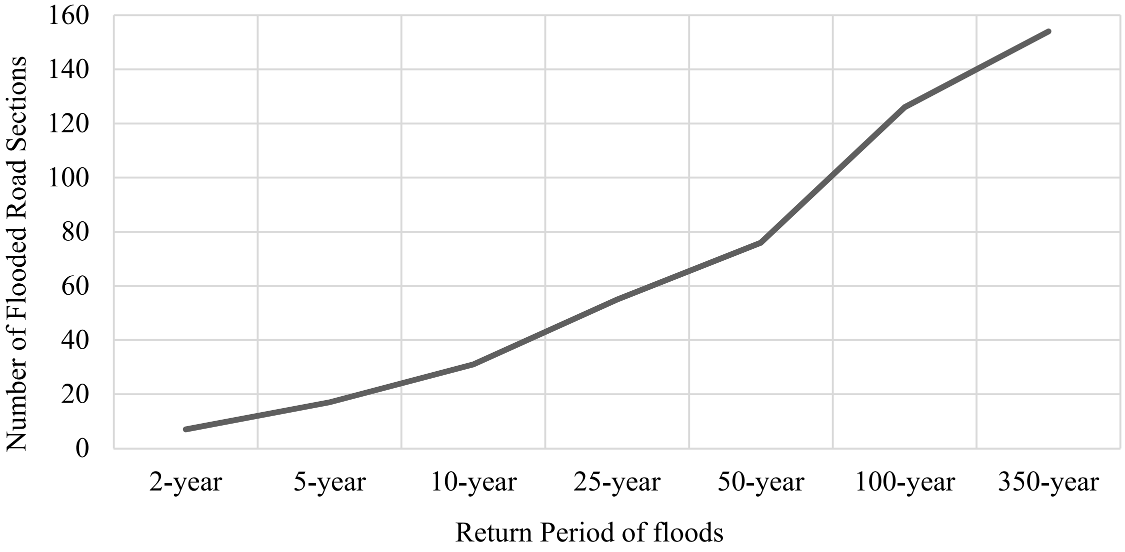


Figure 7.7 Number of Total Flooded Road Pavement Sections

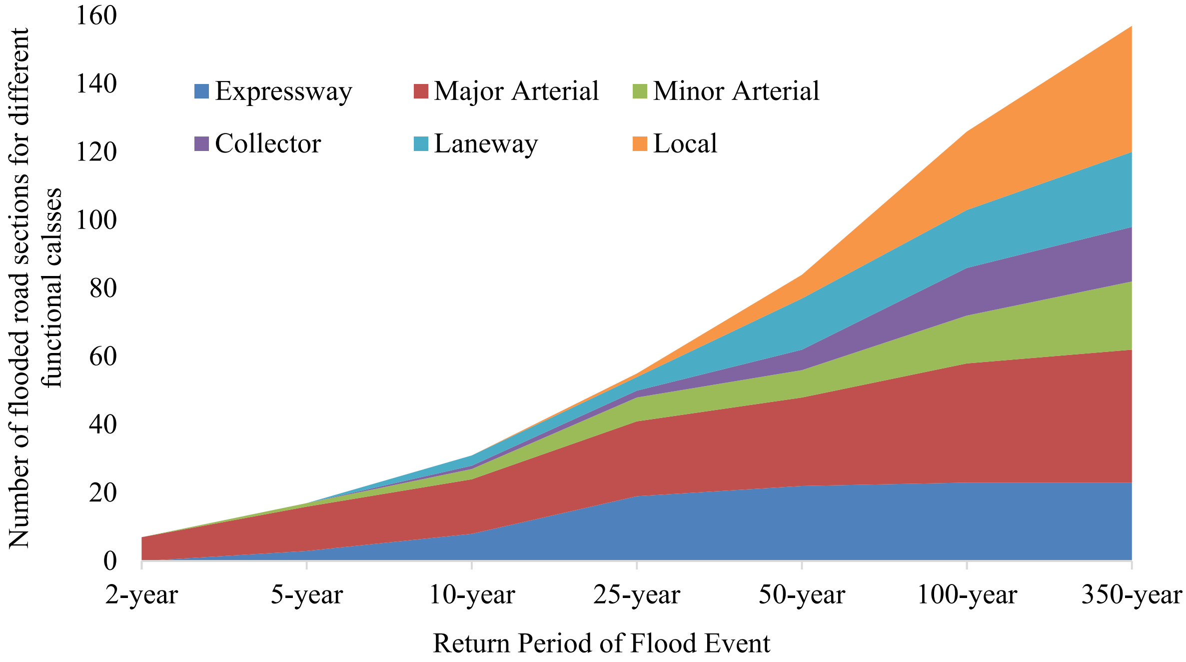


Figure 7.8 Number of Flooded Pavement Sections in Different Road Functional Classes

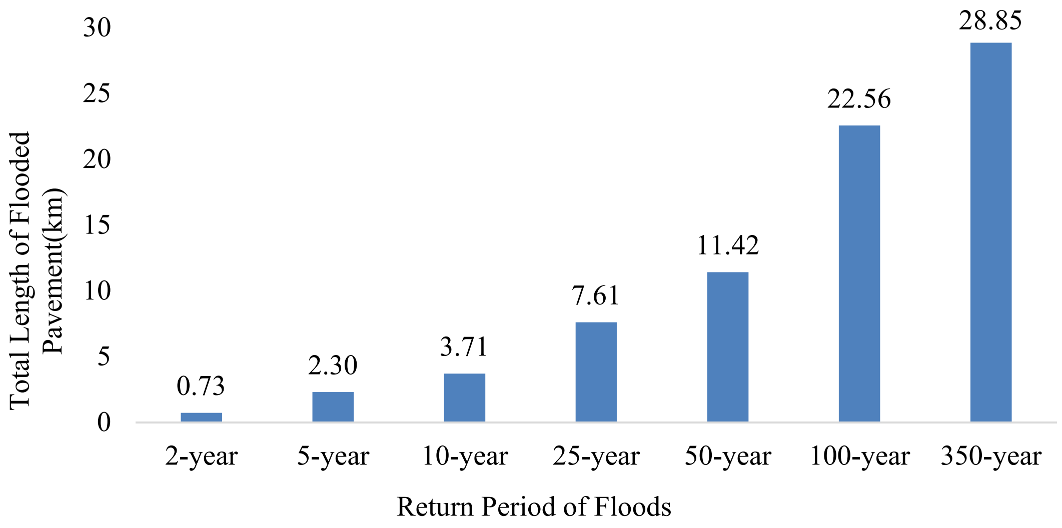


Figure 7.9 Length of Inundated Road Sections

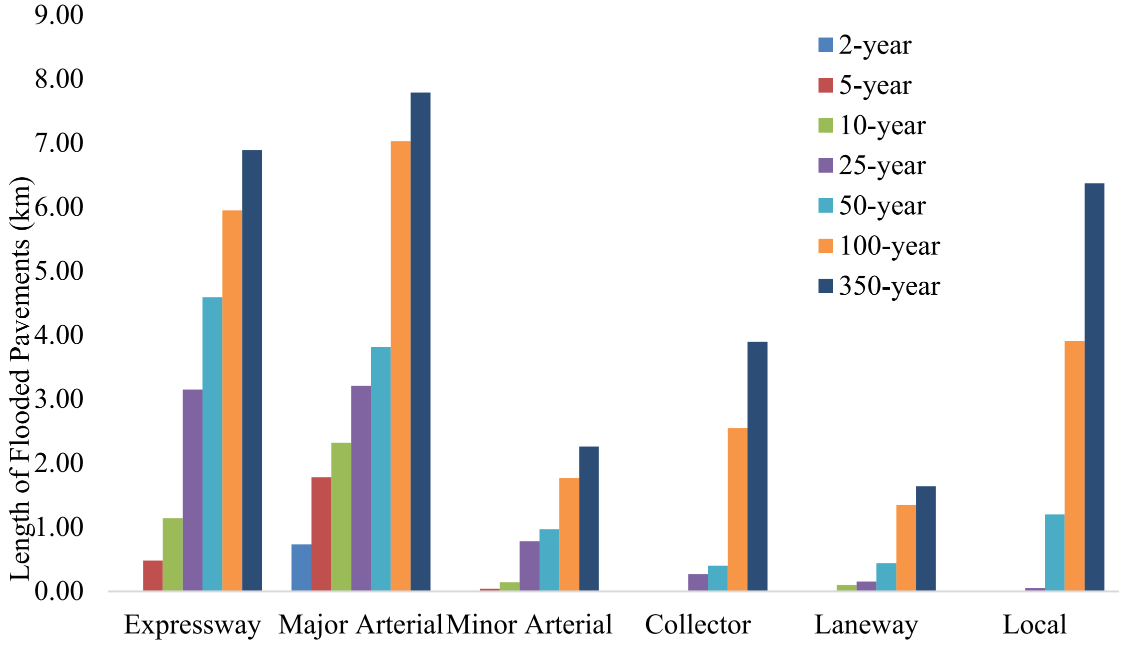


Figure 7.10 Length of Flooded Pavement Categorized by Different Functional Class Across The Road Network

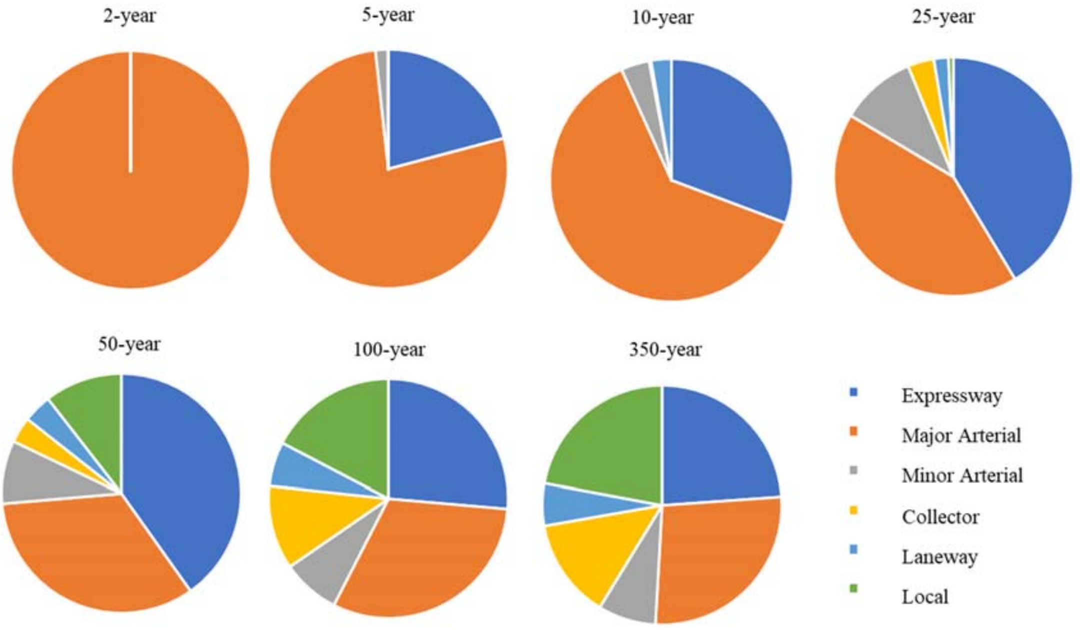


Figure 7.11 Percentage of Road Flooding for Various Functional Class

7.3.6.2 Pavement Network Risk

The total risk for various damage state assumptions of the road network is examined. The total risk maps are generated based on the risks for individual events to illustrate the trend of risk for three pavement damage states (1%, 1.5%, and 2.5% of pavement damage) in the road network as shown in Figure 7.12. Figure 7.12a shows the total risk of occurrence of all flood events for pavement damage more than 1%; Figure 7.12b indicates the total risk of occurrence of all flood events for pavement damage more than 1.5%; and Figure 7.12c illustrates the total risk of occurrence of all flood events for pavement damage more than 2.5%. For pavement damage exceeding 1%, the percentage of road sections with high risk (defined as probability of occurrence greater than 0.95) distributes across most part of the network (Figure 7.12a). As the damage state threshold value increases to 1.5% (Figure 7.12b) and 2.5% (Figure 7.12c), the percentage of road sections with high risk decreases and that with low risk (probability of occurrence less than 0.5) increases. Similar trend is shown in risk maps without considering 350-year return period event (Figure 12d-f). The risk of losses is not calculated because of the lack of cost data.

7.3.6.3 Sensitivity Analysis

In Canada, the current design flood standard is typical the 100-year flood (a flood whose magnitude has a one percent chance of being equaled or exceeded in any year). The sensitivity of the flood risk results to climate-change-induced extreme floods is tested and presented. Figure 7.12 d-f shows the network risk without considering 350-year event, where Figure 7.12d shows the total risk of occurrence of all flood event except 350-year return period event for pavement damage more than 1%; Figure 7.12e demonstrates the total risk of occurrence of all flood event except 350-year return period event for pavement damage more than 1.5%; and Figure 7.12f indicates the total risk of occurrence of all flood event except 350-year return period event for pavement damage more than 2.5%. Total risks cover a range of representative flood event including 2-year, 5-year, 10-year, 25-year, 50-year, 100-year and 350-year return period floods). It is observed that the total risk estimation in road network risk assessment is sensitive to the range of flood hazards chosen; including potential climate-change-induced floods (Figure 7.12 a-c) can significantly increase the risk estimations. Considering the 350-year event (climate change scenario) in the full range of flood hazard, the percentage of road network with low risk is increased from 12.1% to 45.7%, and the percentage of high-risk sections is increase from 46.0% to 79.9% for pavement damage over 2.5%. The methodology can be readily extended to consider more damage states when more observational data of pavement damage are available. These results demonstrate that increasing frequency and intensity of flood events could significantly increase the risk of pavement damage in a road network, and the risk estimation is highly dependent on the flood events considered in the assessment. Future studies can follow the vulnerability estimation method and assess the expected annual losses of pavement assets by investigating the cost for different damage states to provide more risk information in the risk maps.

Some samples of the risk maps created are shown in Appendix D Risk Map Samples.

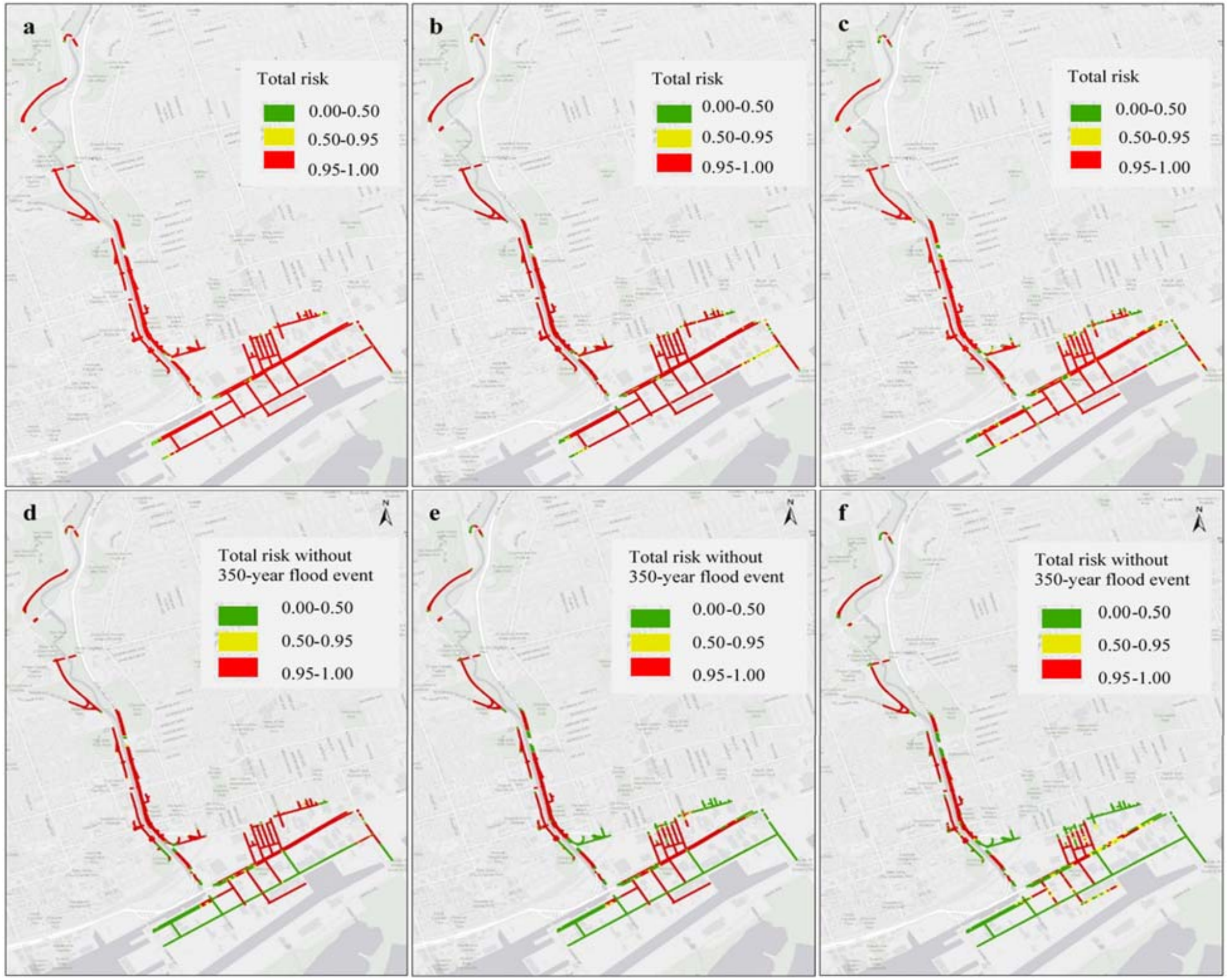


Figure 7.12 Total Risk Maps and Sensitivity Analysis for Different Level of Pavement Damage. **a**, Total risk of occurrence of all flood events for pavement damage more than 1%. **b**, Total risk of occurrence of all flood events for pavement damage more than 1.5%. **c**, Total risk of occurrence of all flood events for pavement damage more than 2.5%. **d.** Total risk of occurrence of all flood event except 350-year return period event for pavement damage more than 1%. **e.** Total risk of occurrence of all flood event except 350-year return period event for pavement damage more than 1.5%. **f.** Total risk of occurrence of all flood event except 350-year return period event for pavement damage more than 2.5%. Flood events include a range of discrete flood event including 2-year, 5-year, 10-year, 25-year, 50-year, 100-year and 350-year return period floods

7.4 Discussions

The main results showing the spatial distribution and characteristics of the affected pavement assets, total risk of occurrence, and sensitivity of the risk estimation are presented in this case study. The risk maps are created, and spatial analysis results are discussed. The results show that the high-risk assets can be identified and analyzed through the risk maps. The increases in frequency and intensity of flood events increase the risk of pavement damage in a road network. The risk is highly dependent on the range of flood events considered in the assessment. The spatial analysis help find the optimum design flood in a network to avoid a noticeable increase in pavement exposure to flood hazards for various road functional classes. From the aspect of preserving physical infrastructure asset values of a road network, pavement infrastructure should be designed and maintained to effectively reduce the inundation length of high value assets.

When applying this flood risk assessment method to specific road network, local observations should be incorporated to calibrate various models to improve accuracy of risk estimation. In future works, more research efforts should aim to generate more accurate fragility curves for local road networks based on available damage data. As more pavement damage data become available, fragility models would achieve a better estimation.

7.5 Summary

An eight-step approach is established to estimate the flood risks across pavement networks. A concept of incorporating fragility models in the pavement network risk analysis is proposed for extending the risk estimation from project level to network level. Various categories of risk maps are identified for different usages in informing adaptation. The network spatial analysis and risk visualization through risk mapping provide a way to quickly identify different level of risk across the networks. Risk evaluation method is also described for identifying the need and prioritization for adaptation planning. The climate change sensitivities, uncertainties, and challenges involved in the network risk assessment are discussed.

To demonstrate the implementation of the approach for pavement network flood risk spatial analysis, a case study is presented at a local road network in an urban setting. The results show that major arterial roads have the greatest number of inundated road sections for all events in the case study area. The length of pavement inundated for each functional class increases as the increase of the return period. For pavement damage exceeding 1%, the percentage of road sections with high risk distributes across most part of the network. As the damage state threshold value increases to 1.5% and 2.5%, the percentage of road sections with high risk decreases and that with low risk increases. The total risk estimation in road network risk assessment is sensitive to the range of flood hazards chosen; including potential climate-change-induced floods can significantly increase the risk estimations. Considering the 350-year event (climate change scenario) in the full range of flood hazard, the percentage of road network with low risk is increased from 12.1% to 45.7%, and the percentage of high-risk sections is increase from 46.0% to 79.9%.

In summary, the methodology for pavement network flood risk assessment provides a practical tool for initiating discussion with stakeholders and identify priority in road networks. The analysis could help raising public awareness, improving pavement infrastructure design code and asset management, assisting adaptation prioritization, determining road infrastructure flood insurance premiums, and adopting preventive actions in the changing climate. Local goals and policies can direct and highlight the assumptions of climate-change-induced extreme events in the estimate of total risk to provide a better picture of future flood risk of road networks and to prepare adaptation in the changing climate.

Chapter 8 Adaptation for Managing Pavement Flooding Risk

This chapter introduces the adaptation strategies, potential options, and implementation guidelines and procedures for mitigating pavement flooding risk in the context of climate change.

8.1 Adaptation, Mitigation and Resilient Infrastructure

Climate adaptation refers to adjustment in natural or human systems to climate change in order to alleviate adverse effects. The Intergovernmental Panel on Climate Change (IPCC) defines adaptation as "*the process of adjustment to actual or expected climate and its effects*". "*In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities*", while mitigation is "*an anthropogenic intervention to reduce the sources or enhance the sinks of greenhouse gases*" (IPCC, 2014).

Adaptation involves processes and actions to reduce the consequences which have already occurred or may be predicted to happen in the future. The goals of adaptation for infrastructure could include the effective management of risks of extreme events on the assets regarding the serviceability, asset preservation, safety, and sustainability. Climate mitigation is to take actions to permanently eliminate or reduce the long-term risk of climate change. For pavement assets, climate change mitigation involves mainly the reduction of emissions in the process of construction, maintenance, and rehabilitation. Hence, tackling the causes of climate change is a proactive strategy, while adaptation is to plan to live with the consequences of climate change. They are complementary strategies for managing the risks of climate change.

It is becoming increasingly clear that actions must be taken not only to reduce generation of the greenhouse gases, but also to address the present and future adverse impacts of climate change through adaptation. As the impact of climate change is already acting on pavement infrastructure and mitigation is not an immediate measure, for the next several decades, the ability of living with the consequences is critical. Although this chapter is focusing on mainly adaptation, it should be noted that the selection of adaptation strategies should not add unnecessary emissions for mitigating purposes. For example, if the adaptation option is to use antistripping materials as asphalt mix to alleviate the moisture stress of the pavement in dealing with excessive rainfall events, materials manufactured with lower life cycle environmental impact should be selected. In other words, the emissions generated from the adaptation alternatives should be a factor in making adaptation decision.

The Intergovernmental Panel on Climate Change (IPCC) defines adaptation as "*The ability of a system and its component parts to anticipate, absorb, accommodate, or recover from the effects of a hazardous event in a timely and efficient manner, including through ensuring the preservation, restoration, or improvement of its essential basic structures and functions*." A resilient system should be able to minimize the negative impacts of adverse events and sustain or even improve its functionality by adapting, reorganizing, and evolving into more desirable configurations to prepare for future climate change. A resilient road infrastructure system could absorb climate-change-induced stresses, maintain its function in the adverse events, and become more sustainable. The properties of resilient pavement networks include:

- Robust infrastructure (maximum flood resistance)
- Functional network (minimum disruption)
- Timely recovery ability (minimum post event recovery, maximum adaptive capacity)

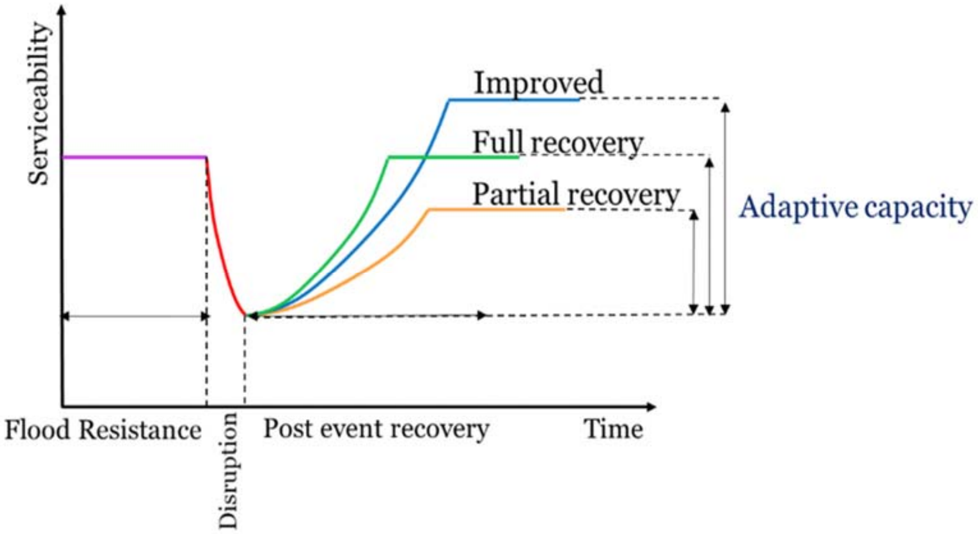


Figure 8.1 Characteristics of Resilient Pavement Infrastructure for Flood Hazards

Figure 8.1 shows the characteristics of resilient pavement infrastructure for flood hazards. It can be used to describe individual pavement sections or pavement networks. When a flood event occurs at a pavement (network), the infrastructure will resist the flood hazard for a certain time. Ideally, a maximum flood resistance is desired. After that, when the cumulative hazard exceeds the resisting capacity of the system, there could be disruption. As a resilience system, minimum disruption is required. During the post event recovery process, less recovery time and maximum adaptative capacity would be ideal. The adaptative capacity describes the ability of the system to recover. The serviceability could bounce back to original (full recovery), partial recovery, or even improved serviceability.

The aim of adaptation can be set to build a resilient system. It should be noted that adaptation not only helps protect infrastructure from climate risk, but also builds resilience to ensure that the society thrives in a changing climate.

8.2 Pavement Flooding Risk Adaptation Strategies

8.2.1 Adaptation Strategies

Climate change adaptation for pavement infrastructure should aim to reduce the risk and increase the resilience of the infrastructure system to an appropriate level. The principles of adaptation will have an impact on how adaptation options are selected. According to the risk assessment framework and methodology proposed in this study, the adaptation options for reducing the risk rely on the three key elements: exposure, fragility, and cost. The general principles for selecting adaptation projects are listed below.

- Reducing hazard exposure. This strategy means decreasing the chance of the intersection of road pavement networks and flood extend. If flooding does not occur on critical infrastructure, there would be no damage. The techniques related to road pavement adaptation activities can be road structure relocation, increasing pavement elevation, and build structural defences.
- Reducing fragility of pavement structures. The fragility of pavements depends on the pavement structural designs and conditions when certain flood hazard happens. The aim can be achieved by applying innovative anti-moisture damage technology, adjusting design standard/code for the changing climate, and ensuring timely maintenance, preservation, and rehabilitation activities to achieve satisfactory pavement conditions. Thus, the pavement structures can be resilient to flood hazards in the changing climate.
- Reducing the cost of pavement damage. The consequences caused by certain damage could be from the economical, social, and environmental aspects. The cost spent for pre-event adaptation activities could potentially save cost post-event. Adaptation methods should target on cost-effective proactive actions to decrease the potential asset value loss and additional pavement life cycle cost for flooding events.

The critical three elements interact with each other. Selection and prioritization of adaptation options is imperative because not all options would be possible due to the constraints such as insufficient resources, capacities, and authority. In order to accommodate the limitations in adjusting one element, one can shift the focus on another element, which can also achieve the goal of reducing risk.

In addition, rarely will adaptation options be designed to address climate risks or opportunities alone (IPCC, 2007). Instead, actions will often be undertaken with other goals (such as profit or poverty reduction) to achieve climate-related co-benefits. Gains in reduced risk and vulnerability, enhanced resilience, or greater welfare will often be co-benefits generated as a result of changes and innovations (Khan et al., 2013).

In the process of implementation, selecting specific adaptation options can be challenging partly due to the uncertainty and cumulative impacts of climate change. Availability of information, access to technology, and funding are the key factors for the best implementation of adaptation actions (Furgal & Prowse, 2008; Yohe & Tol, 2002). Research and development, knowledge, and technology transfer are also important for promoting adaptive capacity.

8.2.2 Categories of Adaptation Options

Adaptation include a wide range of action options that can be summarized in two general categories: structural and non-structural measures for dealing with flooding risk for infrastructure (Ran & Nedovic-Budic, 2016).

8.2.2.1 Structural Measures

Structural measures can be improvement, construction, and maintenance of structures such as pavements, drainage system, levees, dams, and mobile elements (e.g. sandbags) to increase the resilience of road infrastructure and reduce flood exposure. The design codes should be updated to meet the requirement of new structural demand in the changing climate.

Structural measures for reducing flood exposure

Flooding events can result in inundation of pavement infrastructure, leading to reduction of pavement performance. The flooding magnitude can be reduced through different ways (Silva and Costa, 2016).

- Infiltrate: measures to ‘infiltrate’ excessive water include trenches, basins or permeable pavements to reduce the inundation of pavement structure.
- Convey: ‘convey’ is related to the process of transporting rainwater through channels. These channels may vary in size and nature such as side ditches and edge drains. The sizes of these channels can be upgraded according to extent of climate change and risk.
- Store: the storage capacity to collect rainwater before distributing to storm water runoff. This capacity can compensate the capacity of convey system, especially when there is heavy downpour of rain in a short time.
- Avoid: measures to prevent water from contacting pavement structure. Cracking sealing is an effective way to prevent the flood water from getting into pavement structures. Increased elevation of pavements can potentially prevent the ingress of water. Relocation can be an expensive way to avoid flood hazards.

Structural measures for reducing pavement fragility

- Accommodate and maintain. This solution is more flexible allowing the quick adjustment according to the changing climate. It requires more monitoring and pavement maintenance operations. The cost could be relatively low because there is no re-construction project involved.
- Preventative operations. This measurement is a pre-event adaptation. Preventative actions can potentially slow the speed of deterioration and increase the life cycle resilience of the infrastructure to extreme events. The assumption is that future climate projection is reliable. Some adaptation actions can be not cost-effective due to the uncertainty of climate predictions.
- Relocate. This measure can be a very costly adaptation option. The actions should be taken only if the risk is very high and there are no other appropriate solutions. In addition, moving the infrastructure to another location can result in the reduction of

serviceability because the existing one is often considered to provide the optimum service for the public.

- Accept. If the risk is acceptable, no actions are required to take.

8.2.2.2 Non-Structural Measures

Non-structural measures often consider social and institutional aspects to mitigate the risk of flood hazards by applying non-structural techniques, policies and laws, increasing public awareness, warning system, insurance, training and education. Most of the non-structural measures described in this study are contributions of this thesis.

Risk mapping and spatial analysis. A method is developed in this study to achieve one of the important non-structural measures: risk mapping and spatial analysis. Through risk mapping and spatial analysis, the risk information can be estimated and analyzed for determining structural measures and other non-structural measures.

Incorporating the flooding risk assessment and adaptation to pavement asset management system. In this study, there is an extension of the classic pavement asset management system, i.e., climate related pavement flooding risk is considered and quantified in the pavement asset management system. The risk assessment utilizes fragility models for various damage states to estimate the conditional probability of exceeding certain pavement damage for a given flood event under climate change. Based on the outcome of the risk across the network, pavement maintenance options could be selected to optimize the pavement life cycle management. Incorporating this flood hazard management method in pavement asset management system could offer a better pavement asset management. Limitations exist because of the availability and accuracy of the pavement damage information.

Future work could focus on other social and institutional non-structural measures for comprehensively addressing the adaptation of pavement flooding risk in the changing climate.

8.3 Pavement Asset Adaptation Framework

Adapting to climate change is an iterative process, including information collection and analysis, assessment, evaluation, prioritization, planning and design, implementation, and monitoring, which can reduce the risk from climate extremes.

The steps for road pavement climate change adaptation are shown in Figure 8.3. The first step, as a link between risk assessment and adaptation, involves establishing the risk criteria according to goals and policy. The determination of the threshold values at various risk levels are described in detail in Section 7.2.4. Prioritization includes identifying and prioritizing the needs by comparing the target risk and the actual risk estimates resulting in a list of short- and long-term priorities. The optimum combination of project planning should meet the target level of risk or at least mitigate the risk below the critical level and emergency level if there are financial constrains. Budgeting process is to secure funds and control spending for the risk mitigation programs. Alternative options should be evaluated. The technical feasibility, life cycle costs, adaptation action costs, environmental costs, and other social costs should be considered for the selection of the options. Project programming involves making detail plans of treatments to facilitate implementation. At the implementation stage, quality control and quality assurance must be performed to make sure the adaptation actions are effective. This construction process should also be recorded in the pavement asset management system. The last step is monitoring. At the final stage of the process, monitoring can provide feedbacks on the cost efficiency of the adaptation plans and actions. It should be noted that the selection of adaptation strategies should also not add the unnecessary emissions.

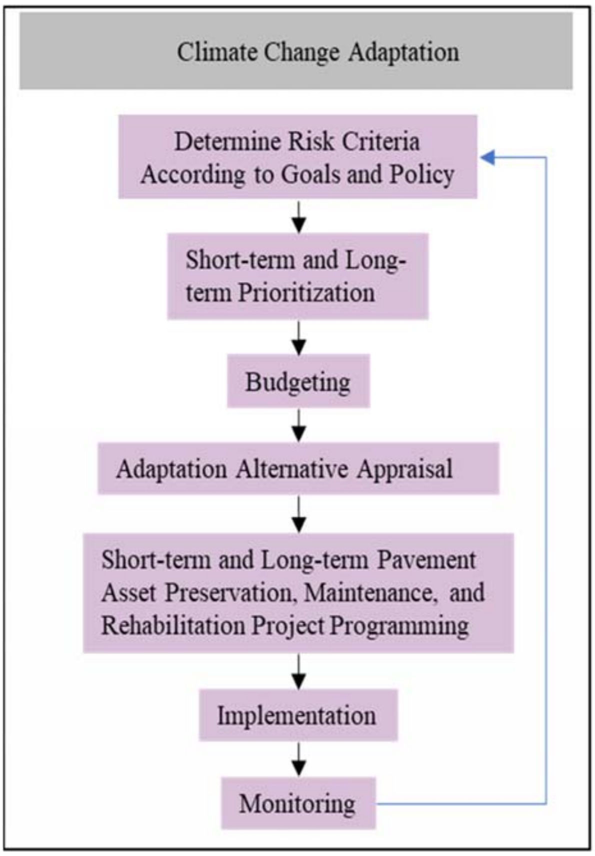


Figure 8.2 Adaptation Procedures

8.4 Pavement Flooding Risk Management and Implementation

8.4.1 Pavement Flooding Risk Management in the Time Horizon

From the aspect of time horizon, pavement flooding risk management can be categorized as pre-flood management, during-event management, and post-flood management.

Pre-flood management includes risk assessment, identification of high-risk pavement flooding areas, and pavement asset adaptation planning and implementation. Pre-flood actions aim to increase the resilience of road pavements and networks for extreme events.

During flood events, risk management and emergency management include road closure alerts and warning, communication, pavement flooding monitoring, and alternative road usage suggestions. During a flood event, real time warning and communication with the public and society are also important to decrease losses.

Post-flood management includes road open time decision making, post-flood cleaning, pavement damage investigation and assessment, identification of damage components, identification of damage patterns, and short-term and long-term pavement maintenance, rehabilitation, and reconstruction planning. The goal of post-event pavement flooding adaptation and management system can be partial recovery, full recovery, and improved system, which indicates the adaptative capacity of the management system. Efficient post-flood management should aim to reduce short-term road disruption and improve long-term pavement performance.

8.4.2 Implementation Guidelines

The implementation guidelines for flooding risk assessment and management are designed according to the time horizon: pre-event, during-event, and post-event of flooding. Users of this guide will be able to proceed systematically through the procedure with necessary decisions. In general, the guideline has been compiled based on the findings of this research however; additional references have been used where applicable. It should be noted that the implementation guide is a recommendation, and the readers are cautioned to use their own engineering judgement when interpreting the procedures and criteria.

The principles and key activities in the guidelines are listed as follows.

General Principles

- Incorporating flooding predictions under climate change in pavement planning, design, construction, and operation process and understanding the uncertainty of the predictions.
- Risk assessment and adaptation should be planned for the service life, and pavement resilience to climate change should be over the life cycle.
- Applying innovative materials and technologies in adaptation plans.

Pre-event Key activities

- Investigating the susceptibility or fragility of pavements to flooding damage. Pre-event investigation can include soil type, water infiltration potential (surface defects, cracking and drainage check), debris deposition potential evaluation (IRI, rutting, potential debris at surrounding environment), pavement material and structural integrity loss potential (raveling, striping and unstable surface and layers), and structural capacity (deflection and thickness).
- Collecting and understanding flood hazard data and flood maps under climate change.
- Assessing the probabilistic pavement risk based on the pre-event pavement fragility and flood potential at the target network. If probabilistic pavement risk is not achievable, applying risk matrix to rate the risk.
- Prioritizing the high-risk sections based on the target serviceability level.
- Planning and programming adaptation activities. Alternatives of maintenance, preservation and rehabilitation activities pre-event for high risk sections should be compared and evaluated to mitigate the risk cost-effectively. The adaptation decisions should be established for improving preparedness and responsiveness for flood hazards, and at the same time achieving benefits for the long-term pavement performance.
- Monitoring the changes of the pavement condition and flood predictions and keeping the risk information and adaptation plans updated periodically.

During-event Key activities

- Establishing road closure/open protocols and warning and alert system.
- Recording the flood characteristics for developing the relationship between pavement damage and flood level.

Post-event Key activities

- Cleaning road and making road closure/opening decisions.
- Evaluating the post-flood pavement performance and identifying damage components.

- Identifying potential damage patterns after flood events to adjust performance prediction models and make reactive decisions. Accurate performance prediction models makes the maintenance program planning more cost-effective during the life cycle.
- Establishing adaptation strategies for different damage patterns and damage components to maintain a satisfactory level of service.
- Monitoring pavement performance post-event in the long term to facilitate data collection and improve the understanding of damage and risk.

8.4.2.1 Pre-Event Implementation Activities and Procedures

Pre-event implementation procedure is illustrated in Figure 8.4. Pre-event, proactive activities including risk assessment should be conducted to inform a cost-effective adaptation decision before the occurrence of flood events.

Probabilistic Risk Assessment Approach

This approach is preferred for the assessment because the probabilistic approach concerns the uncertainty of pavement flooding damage. Chapter 4-7 describe the methodology of probabilistic risk assessment in detail. Flood predictions under climate change should be obtained for generating the flood hazard models. Pavement flooding susceptibility will be represented by the fragility curves. Then, pavement network risk can be estimated and assessed. The risk prioritization can be achieved based on the damage states. An example of risk prioritization criteria is shown in Table 8.1. The descriptions of damage states are presented in Table 5.1. If the number of sections selected is large based on the availability of resource and funding strains, the risk criteria can be adjusted. Sections with high probability of failure and major damage state should be highlighted because the consequences of these damages could be significant.

Table 8.1 Risk Prioritization for Probabilistic Approach

Damage State	Threshold value (Percentage of Pavement Damage)	Risk Criteria
Failure	90%~100%	>30%
Major Damage	60%~90%	>60%
Medium Damage	30%~60%	>70%
Minor Damage	5%~30%	>90%
Insignificant Damage	0~5%	n/a

Data collection. Flood risk maps for representative return periods and extreme events under climate change should be collected. Pavement network maps including pavement type, pavement design, age, functional class and, if possible, pavement condition data should be collected. The fragility curves should be generated based on the existing information for various functional classes in the target road network.

Risk Matrix Approach

This approach includes rating flood level, rating pavement flooding damage susceptibility, and risk estimation using risk matrix.

- *Rating flood level*

If flood data are not accessible, the probability of occurrence of flood hazards is classified into five categories according to the magnitude of the flooding. The rating of flooding probability in the changing climate should be different from the traditional flooding risk rating. An example is shown in Table 8.2. For example, for a pavement section, the depth of flooding ranging from 60~100 cm is rated as occasional under climate change, while this value could be less than 20~60 cm without the impact of climate change.

Table 8.2 Flood level Rating in the Changing Climate

Flooding Depth (cm)	Probability of Occurrence
>300	Unlikely
100~200	Seldom
60~100	Occasional
20~60	Likely
0~20	Very Likely

Rating pavement flooding damage susceptibility

If fragility curves are not available, the pavement flooding damage potential should be investigated and evaluated. The activities include the assessment of soil, pavement type, functional class, water infiltration potential, pavement strength, debris deposition potential, and loss of structural integrity potential across the road network of interest. The score for each aspect includes 5 levels. Based on the scores of each aspect, the overall rating of pavement flooding damage potential can be calculated based on a weighted average, where the weight can be assigned for each parameter according to its importance. An example of the assigned weight for each investigation item is shown in Table 8.3.

Table 8.3 Assigned Weight for Pavement Flooding Damage Potential Evaluation

Investigation Item	Assigned Weight	Total Score
Soil Condition	15%	5
Pavement Type	10%	5
Functional Class	20%	5
Water Infiltration Potential	20%	5
Pavement Strength	15%	5
Debris Deposition Potential	10%	5
Loss of Structural Integrity Potential	10%	5

The equation for weighted average is:

$$\text{Overall score} = \frac{S \times a + P \times b + W \times c + F \ \times d + St \times e + D \times ef + I \times g}{100\%},$$

where

S represents the score for soil evaluation

P represents the score for pavement type

F represents the score for functional class

W represents the score for water infiltration potential

St represents the score for pavement strength

D represents the score for debris deposition potential

I represents the score for loss of structural integrity potential

a, b, c, d, e, f, and *g* are the assigned weights in percentage for each of the item.

The evaluation method for the investigation of soil, pavement type, functional class, water infiltration potential, pavement strength, debris deposition potential, and loss of structural integrity potential is demonstrated in appendix A.

Then, based on the overall score, the overall rating of pavement flooding damage potential can be classified according to the rating criteria. An example of overall rating of pavement flooding damage potential is illustrated in Table 8.4.

Table 8.4 Overall Rating of Pavement Flooding Damage Potential

Overall Score	Damage potential/Consequence
0~1	Very Low
1~2	Low
2~3	Medium
3~4	High
4~5	Very High

Finally, the risk assessment can be done by applying risk matrix approach. Table 8.5 shows the risk matrix and its classification of risk levels. Each of the cells on this 5×5 matrix has been given one of the four colors: red, orange, yellow, and green. The significance of the colors is:

Red (Very High Risk). All pavement flooding risks that fall in the red cells are of great importance. Prevention and mitigation strategies must be planned in advance so as to prevent their occurrence.

Orange (High Risk). These risks are significant that should be addressed. It is advisable to have them included in the risk adaptation strategies.

Yellow (Medium Risk). These are moderate risks which are not considered as high priority. They can be addressed or left for later. However, these risks should not be ignored. The risk assessment should be updated periodically in the changing climate.

Green (Low Risk). These risks are considered low priority or harmless. No adaptation actions are required at the time.

Table 8.5 Pavement Flooding Risk Assessment and Management Matrix

Risk Management Matrix		Damage potential/Consequence				
		Very Low	Low	Medium	High	Very High
Flooding Probability	Unlikely	Medium	High	Very High	Very High	Very High
	Seldom	Medium	High	High	Very High	Very High
	Occasional	Low	Medium	High	High	Very High
	Likely	Low	Low	Medium	Medium	High
	Very Likely	Low	Low	Low	Low	Medium

Either probabilistic approach or risk matrix method can help inform and initiate the adaptation planning and programming at the prioritized sections of the network. The preservation, maintenance, and rehabilitation decisions can be made by reducing the pavement flooding damage susceptibility according to the performance evaluation results. For example, if the water infiltration potential is high, crack sealing or resurfacing actions should be proposed according to the situation. In terms of reducing hazard exposure, if a high flood depth is suspected in a pavement section, flood management options can also help mitigate the risk.

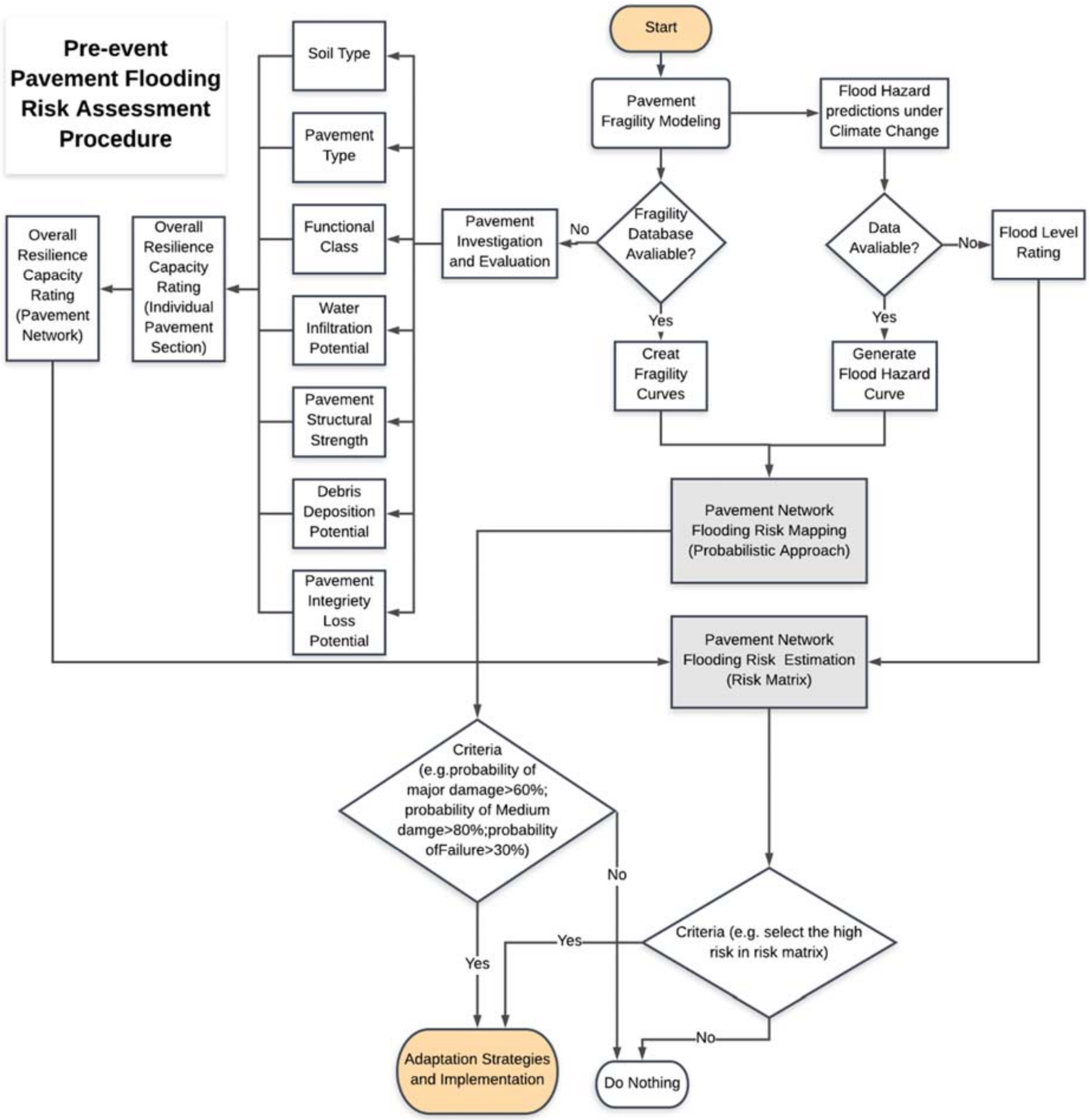


Figure 8.3 Pre-event Implementation Procedures for Pavement Flooding Risk Assessment and Management

8.4.2.2 During-event Implementation

During a flooding event, the spatial characteristics of pavement flood exposure is essential for informing the warning and alerting system, road closure actions, and other emergency activities. The flood characteristics should be recorded for establishing and verifying the correlation to pavement damage.

8.4.2.3 Post-event Implementation Procedures

Post-event procedures are demonstrated in Figure 8.5. Post-event, the road closure/opening decisions is important which affects the damage in the long term. Pavement flooding damage investigation and evaluation across the network should be carried out to identify damage components and damage patterns for performing effective treatment operations. Thus, pavement performance prediction models can be adjusted for effective life cycle pavement management. The pavement performance data before flooding event should also be used for the assessment of damage patterns. Based on the pavement performance data pre-event and post-event, damage patterns can be identified. If performance data pre-event is not available, adaptation treatments can also be planned to mitigate the effect of flooding according to the pavement damage investigation.

The post event response decisions should also consider if the re-evaluation of damage pattern should be of concern based on the long-term pavement damage impact factors, such as road open/closure decisions, climate patterns after the event, and maintenance actions. The considerations of these factors can alter the pavement damage patterns. For example, if the pavement damage is evaluated as a jump effect, the pavement maintenance actions can eliminate the flooding impact soon after the completion of the action. As the decision of road open timing can have a huge impact on how the road deteriorates over time. If the road is open before the flood water has drained out of the pavement structure or if it is still saturated, this will directly impact the post flooding pavement deterioration trend. As a result, damage pattern of jump effect may turn into jump & delayed effect leading to different damage patterns and adaptation actions. Pavement damage data should be recorded for improving the pre-event risk assessment. Monitoring activities post-event can provide feedback to the risk assessment and management system. The recommendations on post-flood pavement testing for pavement damage evaluation are presented in Appendix A.

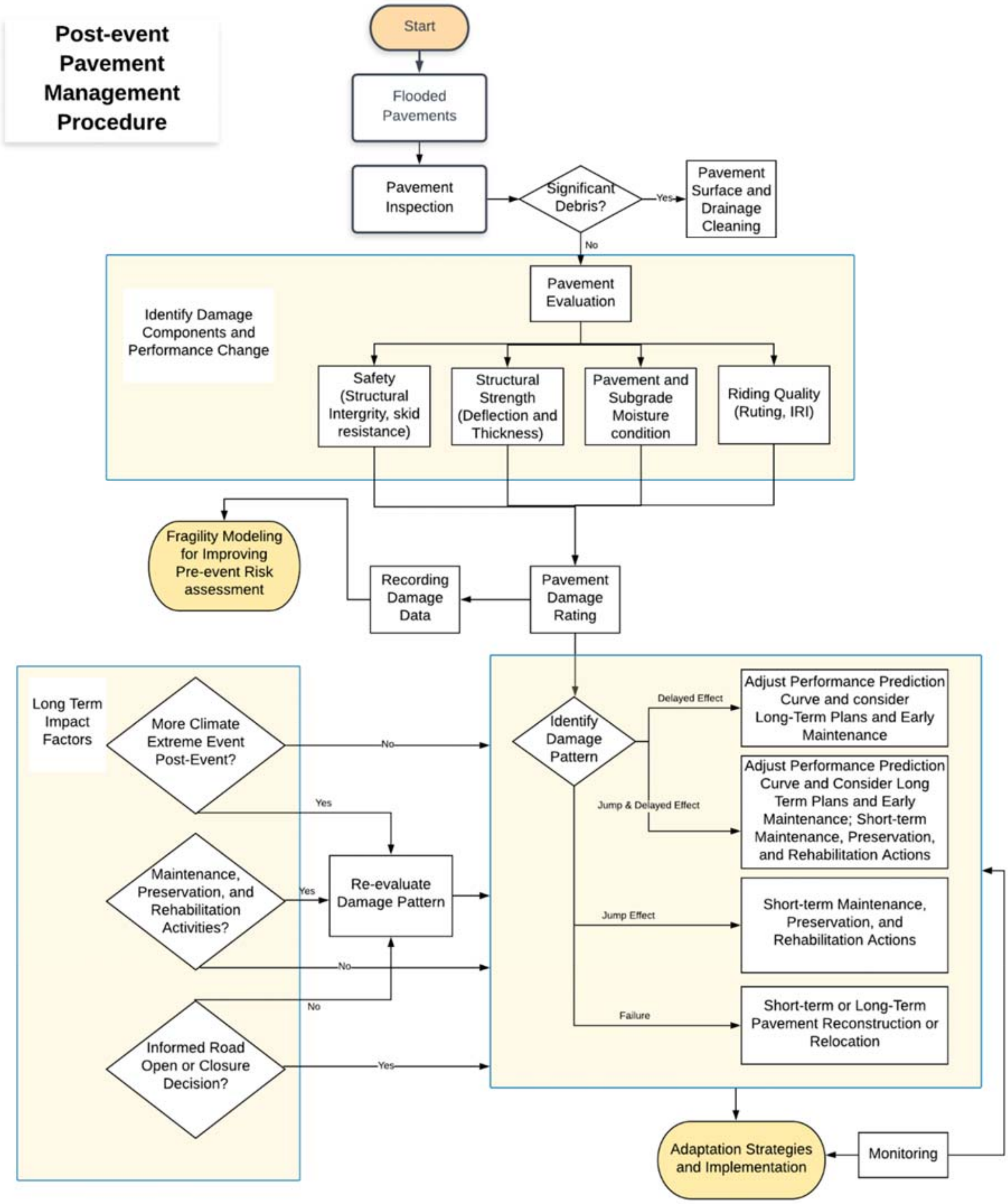


Figure 8.4 Post-event Pavement Flooding Management

8.5 Summary

Adaptation strategies are developed based on the components in the risk assessment, which are: reducing hazard exposure, reducing fragility of pavement structure, and reducing the cost of damage. The adaptation options are categorized by the structural measures and non-structural measures. In terms of the implementation of the research findings of this thesis, this Chapter establishes implementation guidelines and procedures for pavement flooding risk assessment and management for researchers, pavement managers, and stakeholders to manage road pavement flooding risk, increase the resilience of pavements, and adapt to the changing climate. The key activities include pre-event risk assessment (probabilistic approach and risk matrix approach), during-event activities, and post-event evaluation for long-term risk management.

Further studies are needed for developing detailed adaptation alternatives and solutions and calculating the cost-effectiveness for specific cases.

Chapter 9 Conclusions, Recommendations and Future Research

9.1 Conclusion

In pavement design and management, historical climate design data are becoming less representative of the future climate in the changing climate. For mitigating the risk from flooding in the changing climate, a pavement flooding risk assessment framework and methodology, adaptation strategies, and implementation guides are developed. The risk quantification methodology enables the informed management and adaptation decisions for increasing the resilience of pavement assets networks under climate change. The outcomes of the research help to advance pavement design and management practices for dealing with flood hazards in the changing climate.

The following conclusions are drawn based on the research presented in this thesis.

Flood hazard assessment in the changing climate

- Pavement flooding damage can occur due to pluvial flooding, fluvial flooding, coastal flooding, reservoir flooding, ground water flooding, and ice jam flooding with different causes and features.
- The flood hazard curves generated by the proposed probabilistic flood hazard analysis method achieved a quantitative estimation of flood hazard for various climate change scenarios. Flood hazard curves demonstrate the relationship between level of flood and annual exceedance probability.
- Road pavement infrastructure may be subjected to more frequent and intense extreme precipitation events in the case study area causing more pavement flooding. The new extreme events should be incorporated in pavement design and management practices.

Pavement flooding damage analysis

- Factors impacting flooded pavement damage include flood depth, flood duration, flood velocity, flood debris, flood contaminants, and their interactions.

- Flooded pavement damage components can include layer material degradation, surface texture loss, interlayer bonding loss, and layer movement resulting in increased cracking/surface defects, structural deformation, reduced safety, decreased riding quality, and loss of service life.
- Pavement flooding damage can follow four patterns: delayed effect, jump effect, jump & delayed effect, and direct failure.
- Impact factors of the flooded pavement damage include flood load, pavement design and conditions, human interferences after flooding, and climate patterns after the flooding event.
- The temporal characteristics of pavement flooding damages consist of pre-event, during-event, and post-event. The spatial characteristics include soil type, pavement type, pavement conditions, and road functional class. These characteristics are the key elements included in the adaptation implementation procedures.

Pavement flooding fragility analysis

- Fragility analysis provides a practical tool for evaluating the uncertainty of pavement flooding damage. Fragility modelling method can quantify the conditional probability of exceeding certain damage state given a level of flood hazard. It represents the susceptibility of pavement structure to flood hazards.
- The process of fragility analysis helps to understand the relationships among exceedance probability of pavement damage, flood hazards, pavement structural designs, pavement conditions, and damage states, which allows making the adaption decisions to reduce fragility of pavement infrastructure.
- IRI trends that are accelerated after flooding events are introduced during the life cycle leading to the separation of terminal IRI values, which is assessed as the jump & delayed effect from case study 1.
- The extreme events can lead to a significant loss of pavement life, in case study 1 this loss of life was up to 303 days. Considering the analysis period is 20 years, the loss is

more than 4% of a pavement's life. More flood cycles lead to shorter pavement life, which is caused by the accelerated deterioration after the flood cycles.

- Increasing precipitation levels under climate change increases the probability of pavement damage in each damage state for different designs from the fragility models in case study 2.
- By incorporating performance simulation and experimental testing, fragility modelling method three (section 5.2.4) can address the water penetration effects and the influence of flood hazard on aged pavement in the context of limited availability of damage data.

Pavement flooding risk assessment

- The quantitative pavement flooding risk assessment methodology at the project level integrates the findings of (i) the flood hazard analysis- annual exceedance probability of certain flood level under climate change; (ii) the fragility characteristics – probability of exceeding certain damage given an event; and (iii) vulnerability – the consequences of certain pavement damage.
- Risk assessment framework provides a tool to analyze the interactions among flood levels, pavement structural designs, damage states, risk of occurrence, and risk of asset value losses. Pre-event, risk can be assessed by the proposed method by incorporating potential future hazard and pavement fragility to come up with preventive actions decisions.
- Considering the climate from 2017 to 2100, the extreme precipitations from representative concentration pathway (RCP) 8.5 climate scenario results in asset value losses as high as CAD$112,471 and CAD$46,487 per kilometer for arterial and collector pavements, respectively. The risk of asset value losses is approximately 10% of the initial construction cost for both arterial and collector pavements in the case study.

- The risk of major damage is not the highest when compared to the risks of minor and moderate damage, because the major damage has a lower occurrence resulting in lower asset value losses.
- Better results can be obtained with more information and better models for each component including climate, flood, pavement, and road network.

Pavement network flooding risk assessment and spatial analysis

- The risk mapping and spatial analysis achieved by the eight-step approach can estimate and analyze the flood risks across the pavement networks. The methodology provides a practical tool for risk prioritization and initiating discussion with stakeholders and identify priority in road networks.
- Incorporating fragility models in the pavement network risk analysis extents of risk estimation from project level to network level possible.
- Network spatial analysis and risk visualization through risk mapping provide a use-friendly tool for identifying different levels of risk across the networks.
- The case study demonstrates that the length of pavement inundated for each functional class increases as the return period increases.
- For pavement damage exceeding 1%, the percentage of road sections with high risk is distributed across most parts of the network. As the damage state threshold value increases to 1.5% and 2.5%, the percentage of road sections with high risk decreases and that with low risk increases.
- Total risk estimation in road network risk assessment is sensitive to the range of flood hazards chosen; including climate-change-induced floods can significantly increase the risk estimations. Considering the 350-year event (climate change scenario) in the full range of flood hazard, the percentage of road network with low risk is increased from 12.1% to 45.7%, and the percentage of high-risk sections is increased from 46.0% to 79.9%.

Climate change adaptation

- Adaptation strategies established from this research are reducing hazard exposure, reducing fragility of pavement structure, and reducing the cost of pavement damage.
- Adaptation implementation guidelines and procedures are established for pavement flooding risk assessment. The key activities include pre-event risk assessment, during-event activities, and post-event evaluation.

9.2 Contributions

The following list presents the contributions to the current state-of-the-art on pavement flooding risk assessment and management research. They are the results of the findings and conclusions presented in the thesis.

1. For mitigating the risk from flooding in the changing climate, this research incorporates risk assessment to pavement asset management system. The risk quantification framework and methodology enable informed management and adaptation decisions for increasing the resilience of pavement networks. The framework is systematic, comprehensive, and universal and capable of providing a complete picture of risk of road.
2. This thesis provides a methodology for incorporating climate change implications into pavement design and asset management.
3. The research provides a systematic framework and comprehensive analysis of pavement flooding damage, including damage processes, causes, components, damage patterns, impact factors, and temporal and spatial characteristics. A holistic view is created for researcher, practitioners, and stakeholder to get a deeper understanding of the essential elements in the problem.
4. Probabilistic pavement flooding damage analysis is achieved by introducing the theory of fragility analysis. Fragility models, an important component in the risk quantification, provide estimations of conditional probability of exceeding certain pavement damage

given a flood event. The models can describe the susceptibility of pavement structure to flooding damage.

5. Pavement flood risk mapping and spatial analysis methodology are developed in this thesis. The spatial analysis empowers the assessment of pavement network risk and its prioritization. The pavement risk maps enable the visualization of the risk for easy communication.
6. A set of implementation guidelines and procedures is developed for pavement flooding risk assessment and management in the changing climate. The procedures facilitate the implementation of the risk assessment using probabilistic approach or risk matrix approach. The guidelines set out the principles and key activities and help assist engineers answering the questions on how to address climate change in pavement asset design management and what to do to adapt pavement system to climate change.

9.3 Recommendations for Future Work

Based on the findings from this research and the current state-of-the-art of pavement flooding risk assessment and management research, the following is a list of recommendations for future works:

1. Collect more data on pavement damage from real event observations to improve fragility models. There are limitations of the pavement damage data, because the MEPDG performance simulations does not simulate the flood water damage of aged asphalt mix. More accurate water damage prediction methods should be developed. In addition, lab and field investigations can be carried out to obtain data on pavement flooding damage. The impact of other flood characteristics such as flood water velocity and the combination of the characteristics should be investigated to improve the accuracy of the prediction.
2. Develop a method to update the fragility models of a pavement during its life cycle. This work would improve the risk assessment throughout the life cycle. Accumulation

of the models for typical pavement designs enable the establishment of a pavement fragility curves database.

3. Develop an interactive tool or software for quickly scanning for flooding risk in a pavement network. It would be helpful for a city to adopt such a tool to get a quick and general understanding of the flooding risk of their pavement networks in the changing climate.
4. Evaluate the cost of adaptation for pre-event and post-event activities for a range of cases considering the avoided economical, social and environmental consequences, and the gained benefits to achieve the recommendations of best adaptation practices. This work could include the appraisal of adaptation alternatives for various case studies and climate scenarios.
5. Consider the occurrence of multi-hazards during the life cycle. For example, in the context of climate change, the rising temperature and increased freeze-thaw cycles are other hazards for pavements.

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Appendix A Recommendations on Pavement Evaluation for Pavement Flooding Risk Assessment and Management in the Changing Climate Implementation Guideline

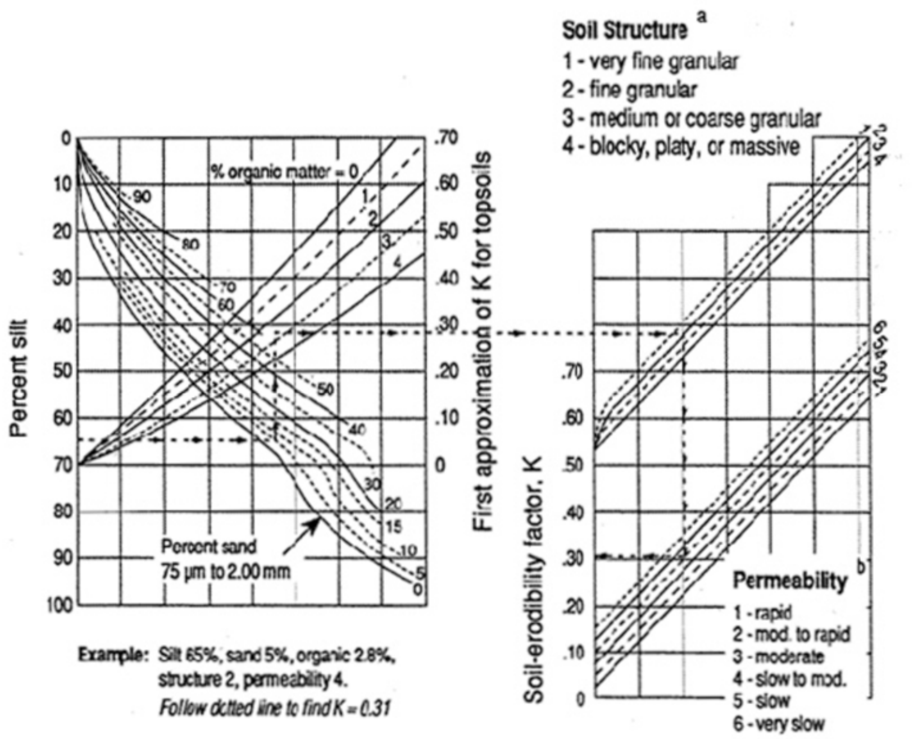
Table A.1 Recommended Pre-event Pavement Investigation and Evaluation

Factors	Indicators	Category	Rating
Pavement type		Impermeable	The investigations can be done for different types of pavement.
		Flexible pavement	
		Asphalt on concrete	
		Concrete on asphalt	
		Rigid pavement	
Soil Type	Soil erodibility Estimate the K factor using the Wischmeier Nomograph (Figure A.1)	Very weak k>=0.8	1
		Weak 0.6<k<0.8	2
		Moderate 0.2<=k<=0.6	3
		Strong 0.1<k<0.2	4
		Very Strong k<=1.0	5
Road functional class		Local	1
		Collector	2
		Minor Arterial	3
		Major Arterial	4
		Expressway	5
Water Infiltration Potential	Cracking inspection, surface defects, drainage check	Very High	1
		High	2
		Moderate	3
		Low	4
		Very Low	5
Pavement Strength	Deflection, Structural Number, Elastic Modulus of Layers	Very Weak	1
		Weak	2
		Moderate	3
		Strong	4
		Very Strong	5
Debris Deposition Potential	Surrounding environment inspection (mud, silt, tree branch, and other potential unstable elements)	Very Likely	1
		Likely	2
		Moderate	3
		Unlikely	4
		Very Unlikely	5
Loss of Structural Integrity Potential	Raveling, stripping, loosen materials on the surface, etc.	Very Likely	1
		Likely	2
		Moderate	3
		Unlikely	4

		Very Unlikely	5

Evaluation of Soil erodibility

Soil erodibility is recommended by Ministry of Transportation of Ontario Drainage Management. The Wischmeier Nomograph generates a Factor, K, with a value between 0 and 1.0, which categorizes the erodibility of the soil. The higher the value of K, the greater the erodibility of the soil (Ministry of Transportation of Ontario, 2013).



Example: Silt 65%, sand 5%, organic 2.8%, structure 2, permeability 4.
Follow dotted line to find K = 0.31

a. **Soil Structure Equivalents**

1 - Very fine granular	Very fine sand
2 - Fine granular	Fine or medium sand
3 - Medium or coarse granular	Coarse sand or gravel
4 - Blocky, platy, or massive	Clay

b. **Permeability Equivalents**

1 - Rapid	Gravel
2 - Rapid to moderate	Sand
3 - Moderate	Silty sand to sandy silt
4 - Moderate to slow	Clayey silt
5 - Slow	Silty clay
6 - Very slow	Light to heavy clay

Figure A.1 Wischmeier Nomograph (1971) for Soil Erodibility Evaluation

Table A.2 Recommended Post-Event Pavement Investigation and Evaluation

Investigation Item	Indicators	Testing recommendation and standards
Safety	Skid resistant or friction factor	The locked wheel tester • AASHTO T 242: Frictional Properties of Paved Surfaces Using a Full-Scale Tire

		• ASTM E 274: Skid Resistance of Paved Surfaces Using a Full-Scale Tire
	Structural integrity	Visual inspection (potholes, loss of layer materials)
	Rut depth	• ASTM E1703/E1703M: Standard Test Method for Measuring Rut-Depth of Pavement Surfaces Using a Straightedge
Structural Strength	Deflection	Falling Weight Deflectometer; Dynaflect; Benkelman beam • ASTM D4694, Standard Test Method for Deflections with a Falling-Weight-Type • Impulse Load Device • AASHTO T 256: Standard Method of Test for Pavement Deflection Measurements • ASTM D4695: Standard Guide for General Pavement Deflection Measurements
Pavement and subgrade moisture condition	Subsurface moisture condition	Ground Penetrating Radar • ASTM D6432: Standard Guide for Using the Surface Ground Penetrating Radar Method for Subsurface Investigation
Riding quality	Roughness	Inertial profiler • ASTM E1926: Standard Practice for Computing International Roughness Index of Roads from Longitudinal Profile Measurements

Appendix B ArcGIS Pavement Flooding Analysis Modelling Code

```
# python model.py
# Created on: 2019-10-21 10:06:32.00000
#   (generated by ArcGIS/ModelBuilder)
# Description:
# ---------------------------------------------------------------------------

# Import arcpy module
import arcpy


# Local variables:
Jan_12_Functional_Class_Street_Name_shp = "\\\\fileu\\users$\\libggis3\\Desktop\\SecID_Func_Class Jan 16 download\\Jan_12_Functional_Class_Street_Name.shp"
v2Year_Depth_asc = "\\\\fileu\\users$\\libggis3\\Desktop\\Jul12\\2Year-Depth.asc"
ASCIITo_2yr = "F:\\Temp\\ASCIITo_2yr"
ASCIITo_2yr_ProjectRaster_tif = "F:\\Temp\\ASCIITo_2yr_ProjectRaster.tif"
Jan_12_Functional_Class_Street_Name_shp__2_ = "\\\\fileu\\users$\\libggis3\\Desktop\\SecID_Func_Class Jan 16 download\\Jan_12_Functional_Class_Street_Name.shp"
Jan_12_Functional_Class_Stre1_shp = "F:\\Temp\\Jan_12_Functional_Class_Stre1.shp"
Extract_ASCIITo1_tif = "F:\\Temp\\Extract_ASCIITo1.tif"
rastercal = "F:\\Temp\\rastercal"
Int_rastercal2_tif = "F:\\Temp\\Int_rastercal2.tif"
Int_rastercal2_tif__2_ = Int_rastercal2_tif
Int_rastercal2_tif__3_ = Int_rastercal2_tif__2_
Int_rastercal2_tif__4_ = Int_rastercal2_tif__3_
RasterT_Int_ras1_shp = "F:\\Temp\\RasterT_Int_ras1.shp"
RasterT_Int_ras1_SpatialJoin_shp = "F:\\Temp\\RasterT_Int_ras1_SpatialJoin.shp"

# Process: ASCII to Raster
```

```
arcpy.ASCIIToRaster_conversion(v2Year_Depth_asc, ASCIITo_2yr, "FLOAT")

# Process: Project Raster
arcpy.ProjectRaster_management(ASCIITo_2yr, ASCIITo_2yr_ProjectRaster_tif,
"PROJCS['NAD_1983_UTM_Zone_17N',GEOGCS['GCS_North_American_1983',DATUM['D_Nor
th_American_1983',SPHEROID['GRS_1980',6378137.0,298.257222101]],PRIMEM['Greenwich',0.0
],UNIT['Degree',0.0174532925199433]],PROJECTION['Transverse_Mercator'],PARAMETER['Fals
e_Easting',500000.0],PARAMETER['False_Northing',0.0],PARAMETER['Central_Meridian',-
81.0],PARAMETER['Scale_Factor',0.9996],PARAMETER['Latitude_Of_Origin',0.0],UNIT['Meter',
1.0]]", "NEAREST", "", "", "", "", "NO_VERTICAL")

# Process: Project
arcpy.Project_management(Jan_12_Functional_Class_Street_Name_shp__2_,
Jan_12_Functional_Class_Stre1_shp,
"PROJCS['NAD_1983_UTM_Zone_17N',GEOGCS['GCS_North_American_1983',DATUM['D_Nor
th_American_1983',SPHEROID['GRS_1980',6378137.0,298.257222101]],PRIMEM['Greenwich',0.0
],UNIT['Degree',0.0174532925199433]],PROJECTION['Transverse_Mercator'],PARAMETER['Fals
e_Easting',500000.0],PARAMETER['False_Northing',0.0],PARAMETER['Central_Meridian',-
81.0],PARAMETER['Scale_Factor',0.9996],PARAMETER['Latitude_Of_Origin',0.0],UNIT['Meter',
1.0]]", "NAD_1927_To_NAD_1983_NADCON",
"PROJCS['MTM_3Degree',GEOGCS['GCS_North_American_1927',DATUM['D_North_American_
1927',SPHEROID['Clarke_1866',6378206.4,294.9786982]],PRIMEM['Greenwich',0.0],UNIT['Degre
e',0.0174532925199433]],PROJECTION['Transverse_Mercator'],PARAMETER['False_Easting',304
800.0],PARAMETER['False_Northing',0.0],PARAMETER['Central_Meridian',-
79.5],PARAMETER['Scale_Factor',0.9999],PARAMETER['Latitude_Of_Origin',0.0],UNIT['Meter',
1.0]]", "NO_PRESERVE_SHAPE", "", "NO_VERTICAL")

# Process: Extract by Mask
arcpy.gp.ExtractByMask_sa(ASCIITo_2yr_ProjectRaster_tif, Jan_12_Functional_Class_Stre1_shp,
Extract_ASCIITo1_tif)

# Process: Raster Calculator
```

```
arcpy.gp.RasterCalculator_sa("\"%Extract_ASCIITo1.tif%\"* 10000", rastercal)

# Process: Int
arcpy.gp.Int_sa(rastercal, Int_rastercal2_tif)

# Process: Build Raster Attribute Table
arcpy.BuildRasterAttributeTable_management(Int_rastercal2_tif, "NONE")

# Process: Add Field
arcpy.AddField_management(Int_rastercal2_tif__2_, "Flood_Depth", "FLOAT", "", "", "", "",
"NON_NULLABLE", "NON_REQUIRED", "")

# Process: Calculate Field
arcpy.CalculateField_management(Int_rastercal2_tif__3_, "Flood_Dept", "[Value] / 10000", "VB",
"")

# Process: Raster to Polygon
arcpy.RasterToPolygon_conversion(Int_rastercal2_tif__4_, RasterT_Int_ras1_shp,
"NO_SIMPLIFY", "Value", "SINGLE_OUTER_PART", "")

# Process: Spatial Join
arcpy.SpatialJoin_analysis(RasterT_Int_ras1_shp, Jan_12_Functional_Class_Stre1_shp,
RasterT_Int_ras1_SpatialJoin_shp, "JOIN_ONE_TO_ONE", "KEEP_ALL", "ID \"ID\" true true false
0 Long 0 0
```

Appendix C Road Pavement Information in the Network Risk Assessment

Table C.1 The Street Name of Road Pavement Assets in the Network Flooding Risk Analysis

No.	ASSET_ID	STREET	FROM_STREE	TO_STREET
1	06949.000	SAULTER ST S	COMMISSIONERS ST	VILLIERS ST
2	06950.000	SAULTER ST S	VILLIERS ST	[S] LAKE SHORE BLVD E [BRANCH]
3	01238.000	CARLAW AVE	COMMISSIONERS ST	[S] LAKE SHORE BLVD E [BRANCH]
4	02162.090	[NB] DON VALLEY PKWY [BRANCH]	QUEEN ST E	[N/E] QUEEN ST E [RAMP]
5	03090.801	[EB] FREDERICK G GARDINER [BRANCH]	DON RDWY	BOOTH AVE
6	04876.000	LOGAN AVE	COMMISSIONERS ST	[S] LAKE SHORE BLVD E [BRANCH]
7	02162.100	[NB] DON VALLEY PKWY [BRANCH]	[N/E] QUEEN ST E [RAMP]	DUNDAS ST E
8	02162.110	[SB] DON VALLEY PKWY [BRANCH]	QUEEN ST E	DUNDAS ST E
9	02162.120	[NB] DON VALLEY PKWY [BRANCH]	DUNDAS ST E	[E] DUNDAS ST E [RAMP]
10	02162.130	[NB] DON VALLEY PKWY [BRANCH]	DUNDAS ST E [RAMP]	GERRARD ST E
11	035-01	POTTERY RD	BROADVIEW AVE	BAYVIEW AVE
12	02162.150	[NB] DON VALLEY PKWY [BRANCH]	GERRARD ST E	[S/E] DANFORTH AVE [RAMP]
13	02162.006	[NB] DON VALLEY PKWY [BRANCH]	GARDINER EXPY WB EXPRESS	DON VALLEY PKWY N
14	02162.010	[NB] DON VALLEY PKWY [RAMP]	FREDERICK G GARDINER	[E] DON VALLEY PKWY [BRANCH]
15	02162.030	[NB] DON VALLEY PKWY [BRANCH]	[E] DON VALLEY PKWY [RAMP]	EASTERN AVE DIVERSION [RAMP]
16	02162.040	[NB] DON VALLEY PKWY [BRANCH]	[E] EASTERN AVE DIVERSION [RAMP]	[154 m S] EASTERN AVE DIVERSION
17	02162.060	[NB] DON VALLEY PKWY [BRANCH]	EASTERN AVE DIVERSION	QUEEN ST E
18	02162.070	[SB] DON VALLEY PKWY [BRANCH]	EASTERN AVE DIVERSION	QUEEN ST E
19	08005.000	VILLIERS ST	DON RDWY	SAULTER ST S
20	21195.300	OLD BREWERY LANE	QUEEN ST E	[46 m N] QUEEN ST E
21	04809.100	LESLIE ST (TO)	COMMISSIONERS ST	[S] LESLIE ST (TO) [RAMP]
22	04809.200	LESLIE ST (TO)	[S] LESLIE ST (TO) [RAMP]	[137 m S] LAKE SHORE BLVD E

No.	ASSET_ID	STREET	FROM_STREE	TO_STREET
23	03090.751	[WB] FREDERICK G GARDINER [BRANCH]	DON RDWY	BOOTH AVE
24	04809.300	[E] LESLIE ST (TO) [BRANCH]	[137 m S] LAKE SHORE BLVD E	[S] LAKE SHORE BLVD E [BRANCH]
25	00944.000	BOUCHETTE ST	BASIN ST	COMMISSIONERS ST
26	00945.000	BOUCHETTE ST	COMMISSIONERS ST	[S] LAKE SHORE BLVD E [BRANCH]
27	02660.120	[S] EASTERN AVE DIVERSION [BRANCH]	ADELAIDE ST E	[E] DON VALLEY PKWY [BRIDGE]
28	02625.000	EASTERN AVE	CYPRESS ST (TO)	BAYVIEW AVE
29	01714.000	COMMISSIONERS ST	DON RDWY	SAULTER ST S
30	01716.000	COMMISSIONERS ST	BOUCHETTE ST	LOGAN AVE
31	01718.000	COMMISSIONERS ST	LOGAN AVE	CARLAW AVE
32	02337.000	DUNDAS ST E	RIVER ST	[W] DON RIVER [BRIDGE]
33	02338.000	DUNDAS ST E	[E] DON RIVER [BRIDGE]	CARROLL ST
34	02033.000	DAVIES AVE	QUEEN ST E	THOMPSON ST
35	00452.000	BASIN ST	BOUCHETTE ST	[410.10 m E] BOUCHETTE ST [END]
36	02605.000	EAST DON RDWY	[S] EAST DON RDWY [END]	QUEEN ST E
37	03901.000	HEWARD AVE	EASTERN AVE	QUEEN ST E
38	10299.000	[30.50 m N] EASTERN AVE	WINNIFRED AVE	CAROLINE AVE
39	10302.000	[30.50 m E] LARCHMOUNT AVE	EASTERN AVE	[74.50 m N] EASTERN AVE
40	10306.000	[27.60 m E] CAROLINE AVE	EASTERN AVE	[35.10 m S] QUEEN ST E
41	10310.000	[40 m W] PAPE AVE	EASTERN AVE	[30.50 m N] EASTERN AVE
42	10467.000	[36.60 m S] EASTERN AVE	CARLAW AVE	MORSE ST
43	10461.000	[85.30 m N] LAKE SHORE BLVD E	MORSE ST	CARLAW AVE
44	10462.000	[39 m E] LOGAN AVE	[36.60 m S] EASTERN AVE	[110.10 m N] LAKE SHORE BLVD E
45	10463.000	[110.10 m N] LAKE SHORE BLVD E	LOGAN AVE	MORSE ST
46	10464.000	[34.70 m E] BOOTH AVE	[236.80 m S] EASTERN AVE	[36.60 m S] EASTERN AVE

No.	ASSET_ID	STREET	FROM_STREE	TO_STREET
47	10465.000	[236.80 m S] EASTERN AVE	BOOTH AVE	LOGAN AVE
48	10460.000	[39.60 m E] MORSE ST	[193.50 m S] EASTERN AVE	[36.60 m S] EASTERN AVE
49	10469.000	[36.60 m S] EASTERN AVE	LOGAN AVE	MORSE ST
50	301-01	DON VALLEY PKWY [RAMP A]	[EB] EASTERN AVE DIVERSION	[NB] DON VALLEY PKWY
51	301-02	DON VALLEY PKWY [RAMP B]	QUEEN ST	[NB] DON VALLEY PKWY
52	301-03	DON VALLEY PKWY [RAMP C]	DUNDAS ST	[NB] DON VALLEY PKWY
53	301-47	DON VALLEY PKWY [RAMP WW]	[SB] DON VALLEY PKWY	[WB] RICHMOND ST W
54	301-11	DON VALLEY PKWY [RAMP K]	BAYVIEW BLOOR RAMP	[NB] BAYVIEW AVE
55	301-15	DON VALLEY PKWY [RAMP P]	[NB] BAYVIEW AVE	BAYVIEW BLOOR RAMP
56	10602.010	[73.20 m N] MATILDA ST	[30.50 m W] CARROLL ST	CARROLL ST
57	10599.010	[27.40 m W] CARROLL ST	[30.50 m N] MATILDA ST	[73.20 m N] MATILDA ST
58	04621.000	[N] LAKE SHORE BLVD E [BRANCH]	CARLAW AVE	LESLIE ST (TO)
59	04620.000	[S] LAKE SHORE BLVD E [BRANCH]	LOGAN AVE	CARLAW AVE
60	10601.000	[30.50 m N] MATILDA ST	[76.20 m W] CARROLL ST	[27.40 m W] CARROLL ST
61	02338.500	[N/E] DUNDAS ST E [RAMP]	DUNDAS ST E	[E] DON VALLEY PKWY [BRANCH]
62	10460.100	[39.60 m E] MORSE ST	[193.50 m S] EASTERN AVE	[85.30 m N] LAKE SHORE BLVD E
63	02660.170	[S] EASTERN AVE DIVERSION [BRANCH]	BROADVIEW AVE	LEWIS ST
64	02660.150	[S] EASTERN AVE DIVERSION [BRANCH]	[E] DON VALLEY PKWY [BRIDGE]	[S/E] EASTERN AVE DIVERSION [RAMP]
65	05527.100	MUNITION ST	[S] VILLIERS ST [BRANCH]	[N] VILLIERS ST [BRANCH]
66	301-10	DON VALLEY PKWY [RAMP J]	[S] BAYVIEW BLOOR RAMP [SIDE]	UPPER HUMBER DR
67	00574.800	BAYVIEW AVE	FRONT ST E	EASTERN AVE
68	00574.810	BAYVIEW AVE	EASTERN AVE	[181 m N] EASTERN AVE

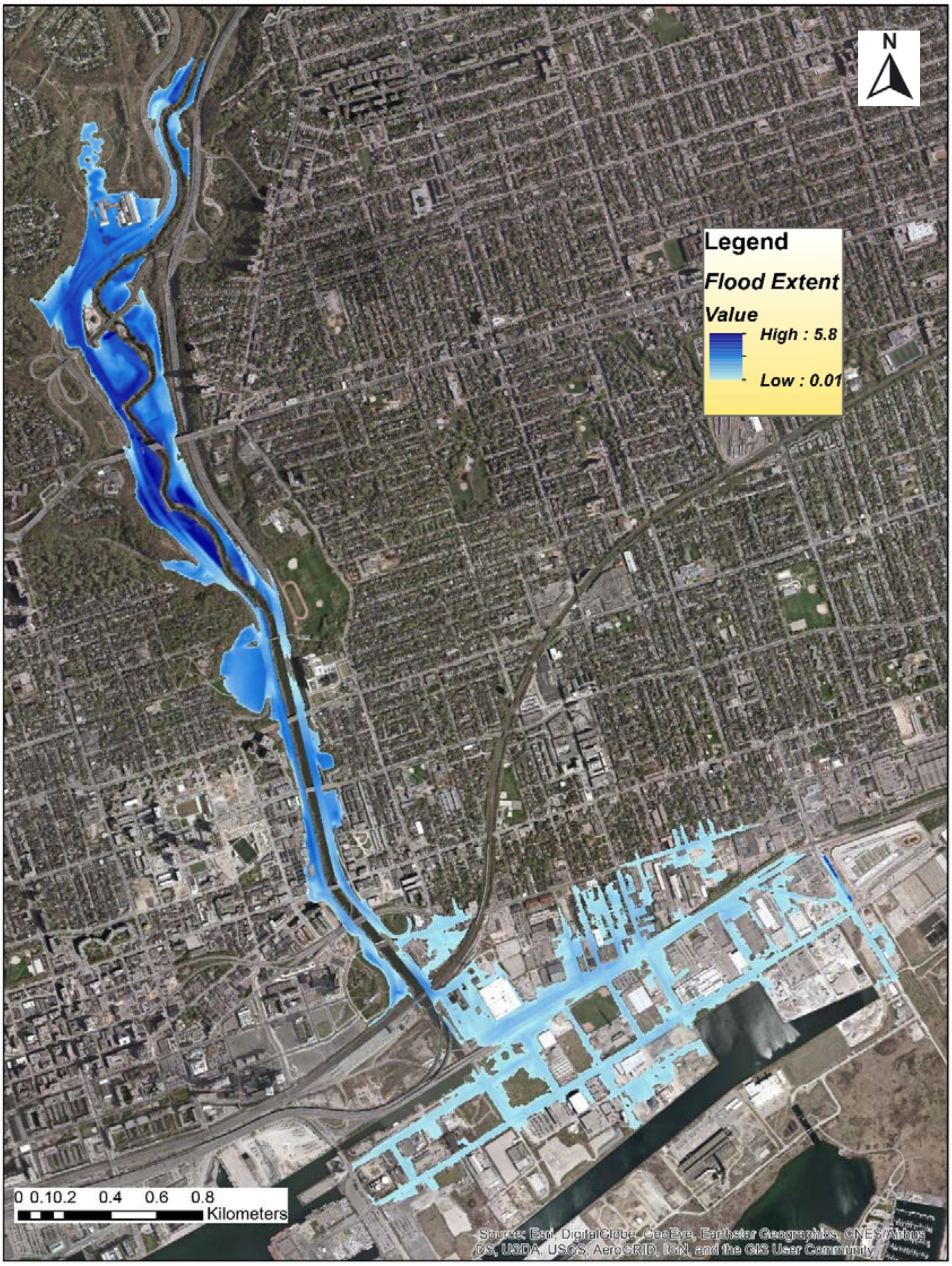
No.	ASSET_ID	STREET	FROM_STREE	TO_STREET
69	00574.820	BAYVIEW AVE	[181 m N] EASTERN AVE	[N] KING ST E [BRANCH]
70	01715.000	COMMISSIONERS ST	SAULTER ST S	BOUCHETTE ST
71	01719.000	COMMISSIONERS ST	CARLAW AVE	LESLIE ST (TO)
72	01289.000	CAROLINE AVE	EASTERN AVE	QUEEN ST E
73	00722.000	BERKSHIRE AVE	EASTERN AVE	QUEEN ST E
74	02643.000	EASTERN AVE	BERKSHIRE AVE	RUSHBROOKE AVE
75	02643.500	EASTERN AVE	RUSHBROOKE AVE	MOSLEY ST
76	01044.000	BROADVIEW AVE	SUNLIGHT PARK RD	[S] EASTERN AVE DIVERSION [BRANCH]
77	02034.000	DAVIES AVE	THOMPSON ST	MATILDA ST
78	01295.300	CARROLL ST	MATILDA ST	[73.20 m N] MATILDA ST
79	02641.000	EASTERN AVE	CAROLINE AVE	LARCHMOUNT AVE
80	02642.000	EASTERN AVE	LARCHMOUNT AVE	BERKSHIRE AVE
81	02635.000	EASTERN AVE	LOGAN AVE	MORSE ST
82	02637.000	EASTERN AVE	CARLAW AVE	HEWARD AVE
83	02640.000	EASTERN AVE	WINNIFRED AVE	CAROLINE AVE
84	02160.000	[W] DON RDWY [BRANCH]	COMMISSIONERS ST	VILLIERS ST
85	03900.000	HEWARD AVE	[132.50 m S] EASTERN AVE [END]	EASTERN AVE
86	035-01.2	POTTERY RD [RAMP]	BAYVIEW AVE	POTTERY RD
87	03243.000	GERRARD ST E	[E] DON RIVER [BRIDGE]	BLACKBURN ST
88	02628.000	EASTERN AVE	LEWIS ST	[W] RAILWAY LANDS - CNR [BRIDGE]
89	04481.000	KING ST E	RIVER ST	[W] QUEEN ST E [BRIDGE]
90	05909.000	PAPE AVE	EASTERN AVE	QUEEN ST E
91	04614.000	[S] LAKE SHORE BLVD E [BRANCH]	DON RDWY	SAULTER ST S
92	04616.000	[S] LAKE SHORE BLVD E [BRANCH]	BOUCHETTE ST	LOGAN AVE
93	04618.000	[N] LAKE SHORE BLVD E [BRANCH]	LOGAN AVE	MORSE ST
94	04619.000	[N] LAKE SHORE BLVD E [BRANCH]	MORSE ST	CARLAW AVE
95	04622.000	[S] LAKE SHORE BLVD E [BRANCH]	CARLAW AVE	LESLIE ST (TO)
96	04623.000	[S] LAKE SHORE BLVD E [BRANCH]	LESLIE ST (TO)	[547 m] LESLIE ST (TO)

No.	ASSET_ID	STREET	FROM_STREE	TO_STREET
97	04826.000	LEWIS ST	EASTERN AVE	[30.50 m N] EASTERN AVE
98	04826.100	LEWIS ST	[30.50 m N] EASTERN AVE	QUEEN ST E
99	04713.000	LARCHMOUNT AVE	EASTERN AVE	QUEEN ST E
100	05195.000	MATILDA ST	DAVIES AVE	CARROLL ST
101	06181.200	PRINCE EDWARD VIADUC	[W] BLOOR ST E [BRIDGE]	[E] BLOOR ST E [BRIDGE]
102	05430.000	MORSE ST	[N] LAKE SHORE BLVD E [BRANCH]	[156 m N] LAKE SHORE BLVD E
103	05432.000	MORSE ST	[156 m N] LAKE SHORE BLVD E	EASTERN AVE
104	04877.000	LOGAN AVE	[N] LAKE SHORE BLVD E [BRANCH]	EASTERN AVE
105	05527.000	MUNITION ST	COMMISSIONERS ST	[S] VILLIERS ST [BRANCH]
106	06242.000	QUEEN ST E	DAVIES AVE	CARROLL ST
107	06730.020	ROSEDALE VALLEY RD	[N] ROSEDALE VALLEY RD [BRANCH]	BAYVIEW AVE
108	06730.030	[S] ROSEDALE VALLEY RD [BRANCH]	ROSEDALE VALLEY RD	BAYVIEW AVE
109	06730.000	ROSEDALE VALLEY RD	[94 m S] BLOOR ST E	[N] ROSEDALE VALLEY RD [BRANCH]
110	06730.010	[N] ROSEDALE VALLEY RD [BRANCH]	ROSEDALE VALLEY RD	BAYVIEW AVE
111	08002.000	[N] VILLIERS ST [BRANCH]	CHERRY ST	MUNITION ST
112	08004.000	[N] VILLIERS ST [BRANCH]	MUNITION ST	DON RDWY
113	08376.000	WINNIFRED AVE	EASTERN AVE	QUEEN ST E
114	02660.060	[N] EASTERN AVE DIVERSION [BRANCH]	[W] DON VALLEY PKWY [RAMP]	DON VALLEY PKWY
115	01295.400	CARROLL ST	[73.20 m N] MATILDA ST	[134.10 m N] MATILDA ST
116	04808.000	LESLIE ST (TO)	[72 m N] UNWIN AVE	RAILWAY LANDS - CNR
117	04481.100	[N] KING ST E [BRANCH]	RIVER ST	BAYVIEW AVE
118	04481.200	KING ST E	[W] QUEEN ST E [BRIDGE]	QUEEN ST E

No.	ASSET_ID	STREET	FROM_STREE	TO_STREET
119	01238.500	CARLAW AVE	[S] LAKE SHORE BLVD E [BRANCH]	[N] LAKE SHORE BLVD E [BRANCH]
120	03242.000	GERRARD ST E	[W] DON RIVER [BRIDGE]	[E] DON RIVER [BRIDGE]
121	04615.000	[S] LAKE SHORE BLVD E [BRANCH]	SAULTER ST	BOUCHETTE ST
122	02337.010	DUNDAS ST E	[W] DON RIVER [BRIDGE]	[E] DON RIVER [BRIDGE]
123	08001.000	[S] VILLIERS ST [BRANCH]	CHERRY ST	MUNITION ST
124	08003.000	[S] VILLIERS ST [BRANCH]	MUNITION ST	DON RDWY
125	04809.000	LESLIE ST (TO)	RAILWAY LANDS - CNR	COMMISSIONERS ST
126	04617.000	[N] LAKE SHORE BLVD E [BRANCH]	BOOTH AVE	LOGAN AVE
127	10599.020	[27.40 m W] CARROLL ST	[88.40 m N] MATILDA ST	[118.90 m N] MATILDA ST
128	06600.400	RIVER ST [RAMP]	KING ST E [OVERPASS]	BAYVIEW AVE
129	02660.130	[N] EASTERN AVE DIVERSION [BRANCH]	[E] DON VALLEY PKWY [BRIDGE]	BROADVIEW AVE
130	04613.000	[N] LAKE SHORE BLVD E [BRANCH]	DON RDWY	BOOTH AVE
131	06600.300	[E] RIVER ST [LEG]	[E] RIVER ST [RAMP]	BAYVIEW AVE
132	00576.020	BAYVIEW AVE	RIVER ST	ROSEDALE VALLEY RD
133	00576.040	BAYVIEW AVE	ROSEDALE VALLEY RD	PRINCE EDWARD VIADUC
134	02660.180	[N] EASTERN AVE DIVERSION [BRANCH]	BROADVIEW AVE	LEWIS ST
135	00576.080.09	BAYVIEW AVE	BAYVIEW BLOOR RAMP	POTTERY RD
136	00576.060	BAYVIEW AVE	PRINCE EDWARD VIADUC	[S] BAYVIEW-BLOOR RAMP [RAMP]
137	01711.000	COMMISSIONERS ST	CHERRY ST	MUNITION ST
138	01712.000	COMMISSIONERS ST	MUNITION ST	DON RDWY
139	02639.000	EASTERN AVE	PAPE AVE	WINNIFRED AVE
140	02638.000	EASTERN AVE	HEWARD AVE	PAPE AVE
141	00576.010	BAYVIEW AVE	GERRARD ST E	RIVER ST [RAMP]
142	0576.010	BAYVIEW AVE	RIVER ST [RAMP]	RIVER ST
143	06600.200	[E] RIVER ST [RAMP]	RIVER ST	BAYVIEW AVE

No.	ASSET_ID	STREET	FROM_STREE	TO_STREET
144	01239.000	CARLAW AVE	[N] LAKE SHORE BLVD E [BRANCH]	EASTERN AVE
145	06241.000	QUEEN ST E	KING ST E	DAVIES AVE
146	06240.100	QUEEN ST E	[W] DON RIVER [BRIDGE]	KING ST E
147	07717.000	SUNLIGHT PARK RD	BROADVIEW AVE	EASTERN AVE
148	07716.100	SUNLIGHT PARK RD	[137.50 m W] BROADVIEW AVE	BROADVIEW AVE
149	07716.000	SUNLIGHT PARK RD	[W] SUNLIGHT PARK RD [END]	[137.50 m W] BROADVIEW AVE
150	00927.000	BOOTH AVE	LAKE SHORE BLVD E	EASTERN AVE
151	00576.000	BAYVIEW AVE	DUNDAS ST E	GERRARD ST E
152	00575.000	BAYVIEW AVE	[N] KING ST E [BRANCH]	DUNDAS ST E
153	02162.000	DON RDWY	VILLIERS ST	[S] LAKE SHORE BLVD E [BRANCH]

Appendix D Risk Map Samples



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure D.1 Flood Maps for 350-year Return Period Events at Lower Don Area

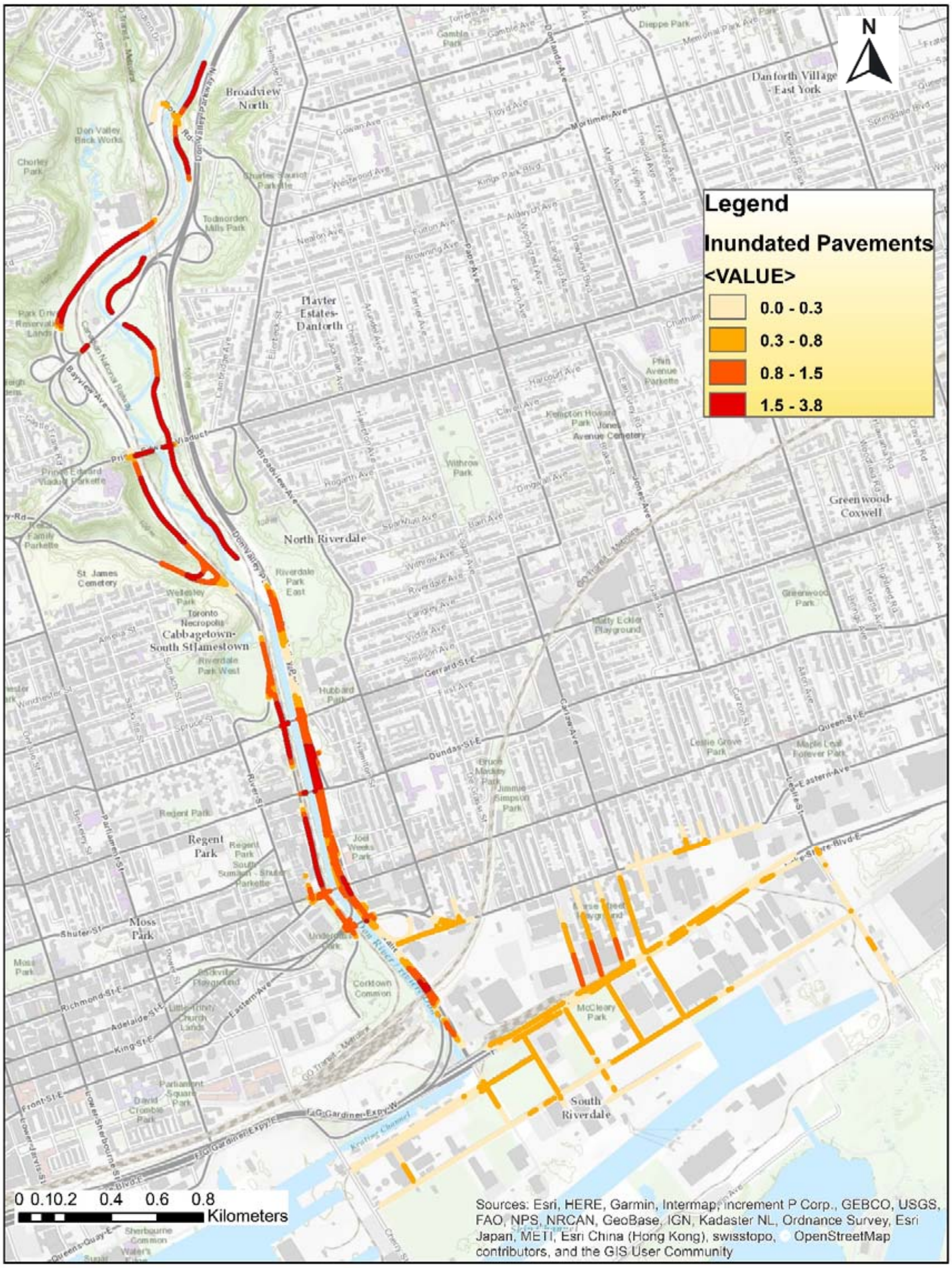


Figure D.2 Pavement Flooding Depth (meter) for 350-year Events at Lower Don Area

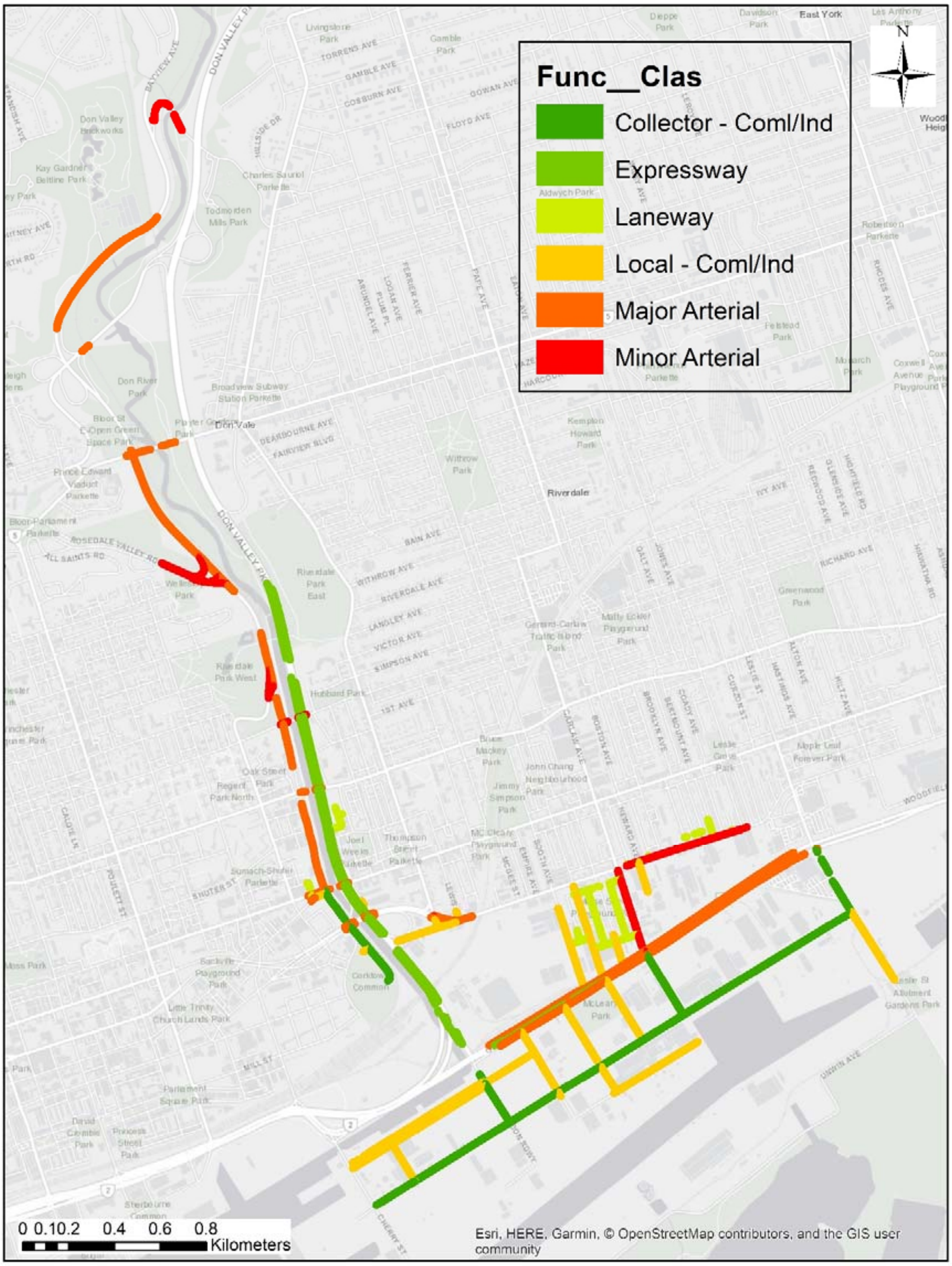
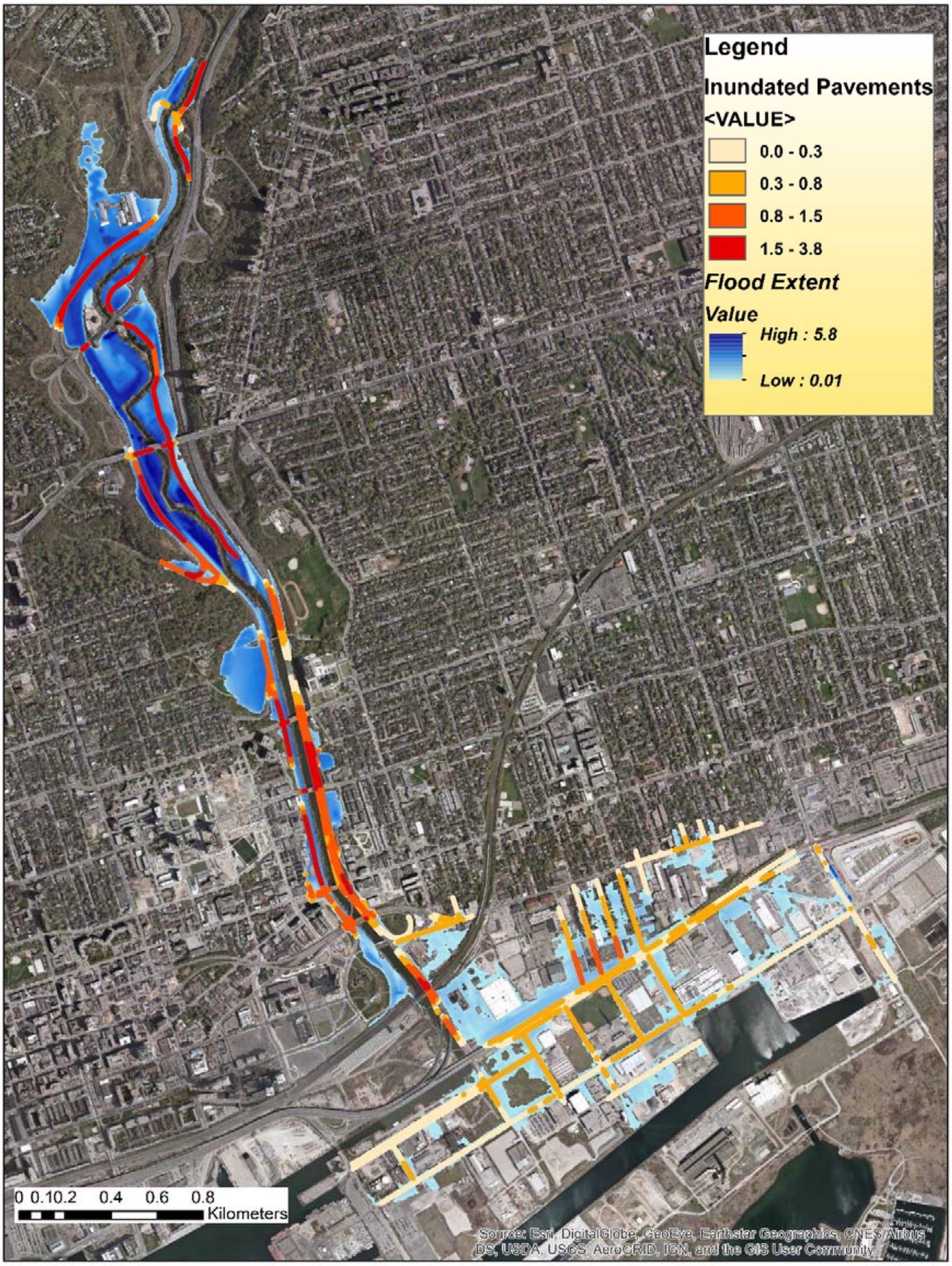


Figure D.3 Pavement Functional Class Distribution across the Network for 350-year Events



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure D.4 Pavement Flooding Exposure for 350-year Events

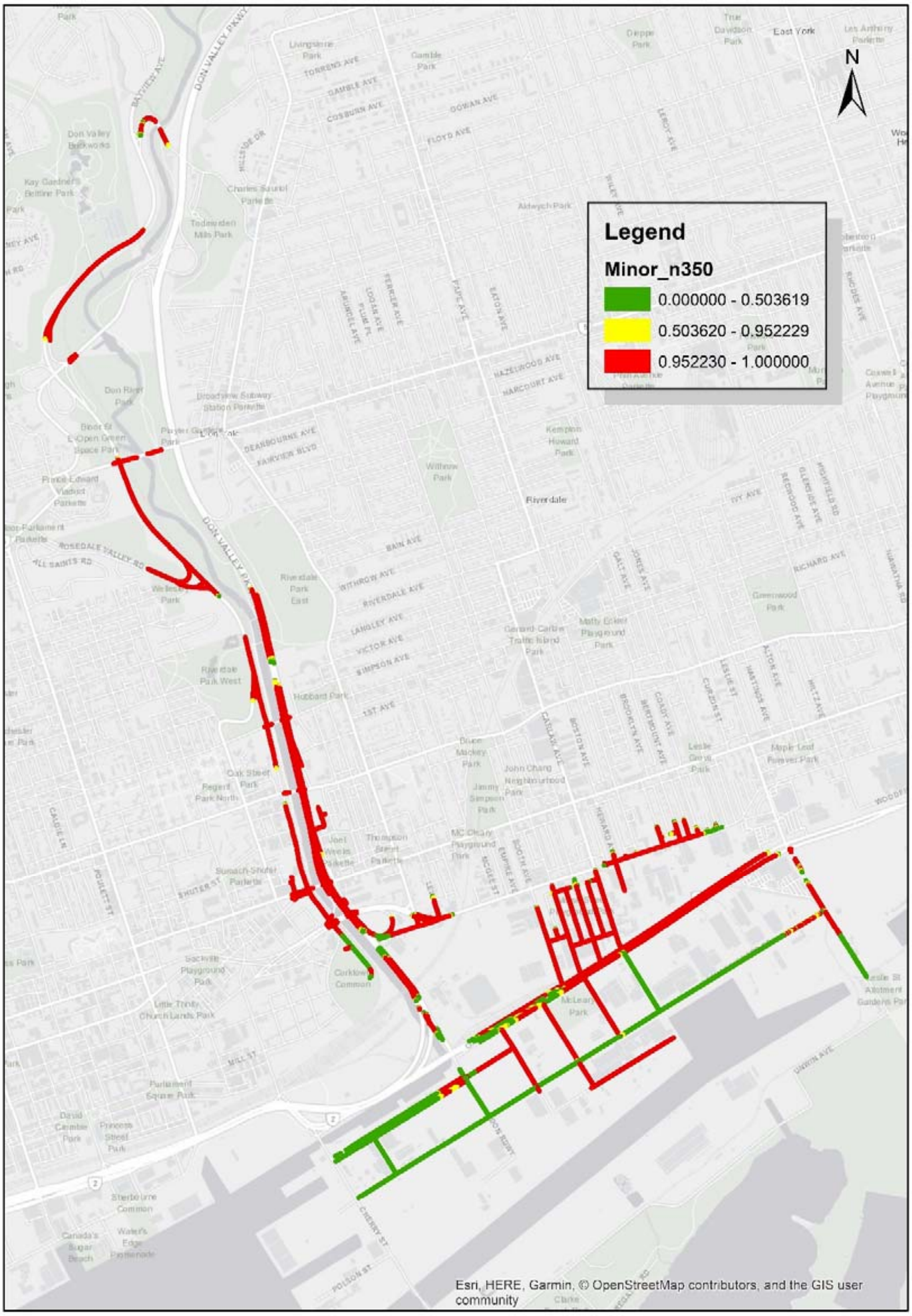


Figure D.5 Pavement Flooding Risk Map (Minor Risk) without 350-year Return Period Flooding