Navigating Tracks of Resilience: Integrating Climate Change Flood Risks into Rail Transit Infrastructure Design, Asset Management, and Operations & Maintenance

Quentin Chiotti
Department of Environmental Science, University of Toronto Scarborough, Toronto, ON, Canada
E-mail: drq.chiotti@utoronto.ca

ABSTRACT

This paper describes how to navigate through the application of a climate risk assessment throughout the lifecycle of rail and transit infrastructure, addressing design standards, asset management, and operations and maintenance practices. With increasing climate change, a proactive, inclusive, transparent, and evidence-based approach towards managing flood-related risks can help safeguard infrastructure assets, ensure reliability, and meet expectations for performance, revenue, and service delivery. The approach addresses vulnerabilities, takes into account current and planned measures that shape adaptive capacity, and considers various resilience options and strategies that are aimed to reduce risk to projected changes in acute and chronic climate conditions. By embedding climate risk considerations in procurement and throughout asset lifecycle, this approach supports sustainable transit development and enhances the sector's ability to withstand future physical climate hazards.

Drawing from select examples in Canada and Australia, this paper illustrates how to navigate through an assessment using the PIEVC Protocol, in relation to managing flood risk for legacy assets and new infrastructure projects for rail and transit. The discussion further outlines four key challenges for effective flood risk management that are often encountered in the climate risk assessment process: (i) using the right climate data, that is informed by historical experience and accepts the wide range of uncertainty in climate change projections; (ii) understanding the complexities of impacts, including interactions between natural and built systems; (iii) consideration of costs and benefits associated with adaptation options; and (iv) the adoption of adaptation expenditure pathways that cut across design, asset management, and operations and maintenance activities. The discussion highlights that managing future fluvial/riverine and pluvial/overland flood risks with climate change is a complex process, potentially involving cumulative, compounding, and cascading impacts; that it requires consideration of interdependencies with ancillary systems; and requires the engagement of internal and external multistakeholders from across disciplines.

KEYWORDS: climate change, flood risk management, adaptation pathways

1 INTRODUCTION

Extreme weather and the direct impacts of climate change continue to be cited among the top global risks (Elsner et al., 2025). Flooding is widely considered to be the most damaging of climate hazards to the condition of public infrastructure assets, and the services dependent upon them. This also applies to rail and transit infrastructure across Canada, and by extension will become an even bigger and more costly concern as the climate changes and heavy rainfall, sea level rise, and flood risk increases (Ness et al., 2021). Builders, owners and operators of rail and transit systems and the infrastructure that supports the delivery of freight and passenger services face a daunting challenge of designing and constructing new infrastructure and/or managing legacy assets to be climate resilient to flood risk due to acute and chronic changes in climate, such as heavy rainfall events and slow changes in watersheds and sea level, respectively.

Operations and maintenance functions must also be enhanced in response to increasing flood risks, as well as emergency management and business continuity planning.

Managing future flood risks can be supported by the application of climate change risk assessment tools, in order to identify medium and high risks to climate hazards, followed by the identification and implementation of measures that reduce vulnerability and enhance resilience and adaptive capacity. While various frameworks exist to undertake such an analysis (e.g., ISO 31000 and the suite of ISO 1409X standards), the Public Infrastructure Engineering Vulnerability Committee (PIEVC) Protocol (ICLR, 2016a and 2016b) is the tool that is widely used in Canada and has been required through Climate Lens in order to receive Federal funding for new public infrastructure projects since 2018 (Infrastructure Canada, 2023). The PIEVC Protocol provides a useful framework for assessing climate-related risks, and it may be helpful to users and practitioners to understand the process based on real world examples, appreciate some of the potential challenges that they may encounter, and consider important lessons learned that will help maximize the outcomes of their efforts. At minimum, a climate risk assessment is a "check the box" exercise that identifies medium and high risks in order to meet regulatory requirements, but at maximum it presents an opportunity and a mechanism to educate, inform, and push decision makers to consider how climate risk and adaptation cuts across the entire procurement process, and implement a pathway to enhance adaptive capacity and resilience in infrastructure assets and the services that they provide.

A climate risk assessment approach has the potential to provide useful insights into flood risks for the design, management and operations of rail and transit infrastructure, and as such needs to be viewed as just one step along the long journey ahead to take actions that reduce the vulnerability of assets, enhance adaptive capacity, and ensures more reliable service delivery in face of climate change. Given the extent of legacy assets, the challenges for the design of new infrastructure projects, and the uncertainty and complexities of climate change, risk management must be seen as a process that faces an uphill battle managing assets and delivering safe and reliable service as the climate changes and more frequent and intense rainfall and flood events occur. This paper emphasizes the urgency to take action on adaptation – the process of adjustment to actual or expected climate and its effects, in order to moderate or avoid harm or exploit beneficial opportunities, and resilience – the capacity of interconnected social, economic and ecological systems to cope with a hazardous event, trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity and structure (IPCC, 2014).

The discussion begins by providing a brief background and science-based context regarding the urgency and necessity of adaptation. This is followed by an outline of the six steps that are typically taken during a climate risk assessment process using the PIEVC Protocol that includes adaptation measures, through the lens of transit and rail infrastructure. The discussion then highlights four challenges that are typically encountered during the climate risk process that warrants close attention pertaining to managing flood risk: (i) the importance of using the right climate data; (ii) understanding the complexities of impacts; (iii) the emergence of cost and benefit considerations associated with the selection and implementation of adaptation options; and (iv) the adoption of adaptation expenditure pathways that cut across design, asset management, and operations and maintenance functions.

2 BACKGROUND AND CONTEXT

In 2024 the annual global surface mean temperature momentarily exceeded 1.5°C above the pre-industrial baseline period (1850-1900), driven by a continuing increase in CO_2 concentration levels in the atmosphere. Recent measurements indicate that levels at the Mauna Loa Observatory in Hawaii have reached 427.49 ppm (as of December, 2025), up from 315.71 ppm when records began in March 1958 (Web-1). Global emissions of greenhouse gases due to fossil fuel combustion and land use changes have increased steadily since the 1950s, and while they reached a new high in 2024, in recent years the rate of growth has been slowing, thanks in part to commitments and actions made by signatories to the Paris Climate Agreement in 2015. These emission reduction commitments, however, will not be sufficient to prevent global mean temperatures from reaching a level that is 2°C above pre-industrial levels by 2050, let alone by the end of this century. Emerging from the recent Conference of the Parties (COP) 30 meetings held in Belém, Brazil, was the harsh reality that global average temperatures could rise anywhere from an extremely optimistic scenario of +1.5°C to a more likely scenario based on existing policies and actions of +3.3°C by 2100. It has been argued that global efforts to meet Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC) should be given a failing grade, and as a result an urgent call for action on adaptation is needed for public infrastructure assets (Chiotti and Van Vliet, 2024).

In Canada annual mean temperatures have been increasing at twice the global average and are projected to continue to rise faster under future high emissions scenarios. While there are reports that Canada's public infrastructure, transportation included, is at risk to extreme weather and climate change (Ness et al., 2021), insured Catastrophic Losses over the past 40 year have increased substantially, exceeding $9 Billion in 2024 (Web-2). Uninsured losses have been even greater, and this does not take into account the costs associated with service disruptions and reputation incurred by rail and transit providers. Many of the extreme weather events affecting transportation infrastructure have involved heavy rainfall and flooding. However, the actual impacts and associated costs for rail and transit across Canada is not well documented, perhaps reflecting a low level of awareness of climate-related risks, but also due to the scarcity of published studies that assessed these hazards (e.g., see Haghighi et al., 2025). A review of published PIEVC reports indicates an absence of transit related assessments (Web-3), perhaps reflecting issues around confidentiality, liability, political bias, and other factors.

Nonetheless, in recent years there has been a rapid emergence of activities across rail and transit systems and projects towards managing climate change risks, including Metrolinx, Canada's largest regional transit provider (e.g., Metrolinx, 2018). A record heavy rainfall and flood event on July 8th, 2013, followed by a freezing rain/ice storm event in December of that year, prompted senior management at Metrolinx to create a senior advisor position in climate risk and resilience, and publicly commit to develop a corporate climate change adaptation strategy by 2018 (Metrolinx, 2015). This resulted in a climate change risk assessment using the PIEVC Protocol that was applied to a selection of legacy infrastructure assets (AECOM et.al., 2016), of which heavy rainfall and flooding was a prominent hazard of concern. In addition, climate risks via the application of the PIEVC Protocol was included as a requirement outlined in the Project Agreements for multiple new transit projects and was incorporated into both the Metrolinx Sustainability Design Standard DS-05 (Metrolinx, 2021a) and the Climate Change Informed Data Standard (Metrolinx, 2021b). Many of their new Light Rail Transit Lines, Subways, and Rail Expansion Projects are subject to these standards. Similarly, recent record flooding in Australia, especially in New South Wales in 2021 and 2022, elevated concerns over flood risk and damages to freight and passenger rail infrastructure assets and service delivery, resulting in the procurement of a high-level flood risk assessment based on historical conditions and future climate change projections. Drawing selectively from these examples provides important lessons learned when managing flood risks under climate change.

3 CLIMATE CHANGE RISK ASSESSMENT

In 2005 the Public Infrastructure Engineering Vulnerability Committee was created by Engineers Canada to develop the PIEVC Protocol to provide a framework/process to conduct a vulnerability assessment of climate change impacts on Canada's public infrastructure. Since its release in 2011, the assessment tool has been applied to over 100 different infrastructure assets, initially to legacy assets, and more recently to new infrastructure projects (MacMillan et al., 2024). For this paper it is important to note that to date, no studies on transit and rail have been publicly released, even through PIEVC-based assessments have been conducted in this sector and in some cases are being used to inform the design, construction, and operations and maintenance of new infrastructure projects (e.g., AECOM et al., 2016).

In 2020 the PIEVC Protocol and Program were assumed by the PIEVC Program Alliance, consisting of the Institute for Catastrophic Loss Reduction ("ICLR"), the Climate Risk Institute ("CRI") and Deutsche Gesellschaft für Internationale Zusammenarbeit ("GIZ") GmbH. Since then a number of new complementary protocols have been developed, referred to as the PIEVC family of protocols, and these are compliant with ISO 31000 Risk Management - Guidelines, ISO 31010 Risk Management – Risk Assessment Techniques, and ISO 14090/14091/14092 Adaptation to Climate Change Standards (Nodelman et.al, 2022). The PIEVC Protocol provides a qualitative step-by-step framework/process for assessing the risk, vulnerability, and adaptive capacity of the interactions between infrastructure assets and climate parameters, with both current conditions and future projections as illustrated in ISO 31000:2018 (Figure 1).

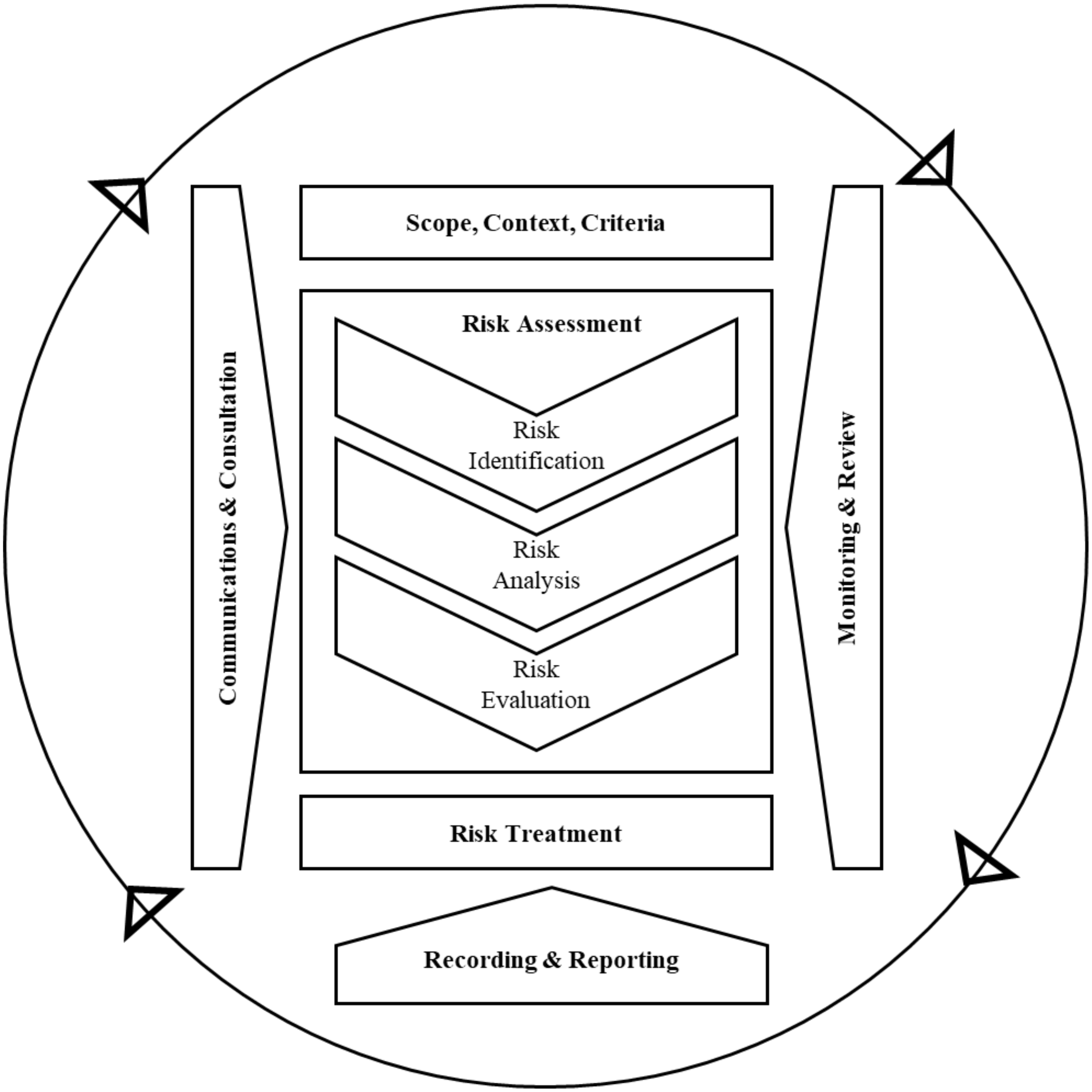

Figure 1: Risk Assessment Process (from ISO 31000:2018)

Detailed explanations of the steps involved and the potential output from each is outlined elsewhere (e.g., Web-4), but for the purposes of this paper they are worth reviewing through a flood mitigation lens that illustrates the importance of applying the PIEVC Protocol to legacy assets and new infrastructure projects. From a scoping and engagement perspective, the PIEVC process represents an opportunity to bring together internal and external subject matter experts and other stakeholders in a structured and focused manner to evaluate climate risk to legacy assets and/or new infrastructure projects. Managing flood risk effectively is rarely the responsibility of a single agency, and more often than not requires a coordinated, multistakeholder solution. Responsibility for climate risk and adaptation cuts across business units and stakeholders, and the PIEVC process can help break through silos that tend to exist in agencies, companies and government.

The PIEVC process provides a structured and transparent framework to assess flood risk that can be applied to legacy assets and/or new infrastructure projects and can consider risks from both pluvial and fluvial flooding at various spatial and temporal scales, including cascading, compounding, and cumulative effects. In terms of rail and transit infrastructure, whether it is assets covered in the asset management plan for legacy infrastructure, or the infrastructure outlined in the Project Agreement for new projects, the number of assets captured in a climate risk assessment can be substantial. It is important to have widespread consensus on the assets to be included in the assessment, and consistency across projects where multiple consortia may be responsible for discrete segments of a subway or corridor. In either case the selection of assets should be guided by ASTM classification standards for buildings and railroads (e.g., Charette et.al., 1999). In the case of transit and rail, this could include subway/LRT lines, tunnels and corridors, stations and facilities, and fleet vehicles, categorized by asset class, asset groups, and asset elements. For example, a Rail Corridor may include track, bridges, abutments and piers, retaining walls and embankments, signal bridges, etc. that may be exposed to flooding.

The PIEVC process can push stakeholders to confront what they know and what they don't know about flood risk, especially from a historical perspective in face of a changing climate. This involves addressing what Donald Rumsfeld would describe as Known Knowns, Known Unknowns, Unknown Unknowns, and the less recognized Unknown Knowns. Uneven documentation of washouts, differential flood exposure across watercourses, and the variable conditions of legacy assets (especially bridges, crossings and culverts) are just some of the data and knowledge gaps that can apply to individual assets as well as linear systems or networks. Not all flood risks are alike or equal, and one can expect that there will be different levels of consequences that could occur, depending upon the degree of flooding and the impacts on assets and service delivery. Consequences can be evaluated based on an agency's enterprise risk matrix and their level of risk tolerance, and in its place the PIEVC process provides multiple infrastructure response considerations such as functionality, environmental effects, and even watershed and surface water conditions. In practice, consequences have been assessed for transit and rail infrastructure in terms of asset performance, level of service delivery, and safety for employees, contractors, and customers.

The calculation of risk is a function of frequency of a critical threshold for a specific climate parameter being met or exceeded multiplied by the likelihood of its occurrence during a future time period (e.g. typically 2050s and 2080s) relative to the historical baseline (e.g. 1981-2010) (Figure 2). A high emissions scenario is also typically used, such as the SSP5-8.5 scenario, which assumes fossil-fuelled development, high consumption, and high economic growth, that generates the greatest changes in climate that are consistent with a "worst case" risk approach. There is the opportunity here to consider vulnerability and adaptive capacity specifically, as existing or planned actions may affect the likelihood of a flood event damaging infrastructure assets and disrupting service. Along a rail corridor well known for its risk of flooding (located adjacent to a watercourse below the 2-year flood level), for example, a severe storm event on July 8, 2013, led to a combination of record overland and riverine flows, causing water levels to overtop tracks and submerge a commuter train, stranding 1,400 customers (Chiotti et al., 2017). Improvements in operational protocols, weather forecasting, direct stream level monitoring, track level monitoring, and rail corridor monitoring by close circuit camera, have reduced the risk of another flooded train to virtually zero. Tracks would continue to be at risk to overtopping and flooding, but the likelihood of a train being exposed and trapped in a flood was reduced considerably. Nonetheless, plans to electrify this rail corridor and/or increase rail service (two-way, all-day service) would increase flood risk exposure considerably by increasing the frequency of trips, perhaps requiring a transformative design and construction of an adaptation response in the form of an elevated corridor, costing billions of dollars in order to reduce risk to a more tolerant level.

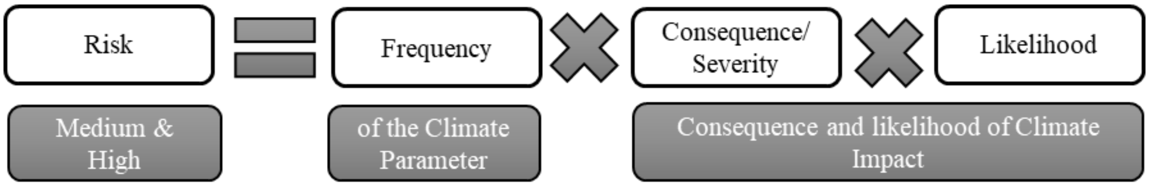

Figure 2: Risk Equation

For special cases where an initial assessment is inconclusive, an engineering analysis may be required, especially for key infrastructure assets. If a deeper dive engineering analysis is not possible, it is not surprising to discover during the PIEVC process that equivalent studies have already been undertaken. For example, in the case of managing potential flood risk to an operations, maintenance and storage facility that was to be located within a regional storm floodplain, the proposed site was subject to a stormwater management report where the application of a sustainable/climate design standard of increased precipitation and/or peak flows were to be applied, that are consistent with climate change projections of Intensity-Duration-Frequency (IDF) statistics (Metrolinx, 2021a). Adaptation measures being considered include improvements in culvert size, the addition of a green roof, and the strategic implementation of low impact development measures on site such as permeable paving and bioswales, among others.

Risk treatment involves the identification, selection and implementation of adaption measures to reduce vulnerability and risk, and it is important to recognize that there is likely to be some degree of residual risk that will occur, despite whatever actions are taken. In the case of new infrastructure projects, for example, one can anticipate that when designing track, stations, or maintenance facilities, and their respective asset components, some transfer of residual risks across procurement to other business functions will be inevitable (Figure 3). These residual risks, from limitations in design standards, will then need to be managed through asset management plans and capital planning over the service life of the assets, while maintenance and operations departments will be responsible for the remaining residual risks through their annual, seasonal and daily activities. Operation activities will be enhanced and supported through (i) water level monitoring of watercourses vis-à-vis track, crossings and bridges; (ii) the installation of ballast sensors; (iii) monitoring of key infrastructure assets through the use of closed circuit camera; and (iv) the installation of weather station instruments along bridges or other key infrastructure assets that provide real time data for precipitation, temperature, high wind gusts, and other climate hazards. When in rare cases infrastructure assets fail and disasters happen, those responsible for emergency management and business continuity planning will need to be engaged.

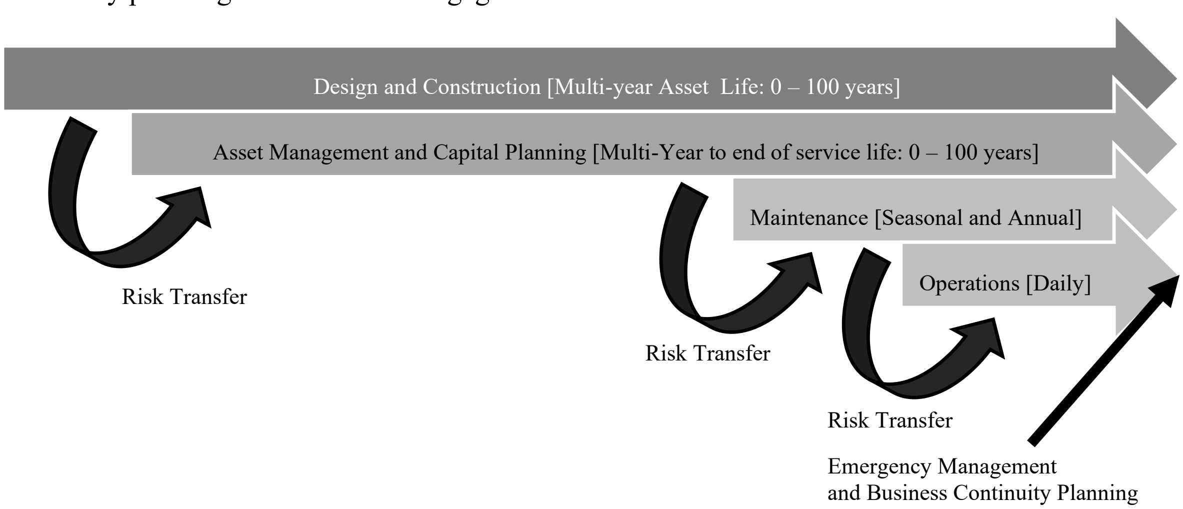

Figure 3: Risk Transfer Across Procurement and Business Functions (from Metrolinx, 2021b)

4 KEY CHALLENGES

Whether it is applying the PIEVC process to legacy assets or new infrastructure projects, a number of challenges are likely to be encountered. Based on experience with assessing flood risk for legacy assets and new infrastructure projects for transit and rail systems in Canada and Australia, the following four challenges are worth noting, in particular how asset owners and designers can pursue four different adaptation expenditure pathways, or a combination of them, to ameliorate flood risk over the lifecycle of infrastructure.

4.1 Using the Right Climate Data

Using the right climate data for climate risk assessment is fundamentally important, noting that it should be informed by historical experience and accepts the wide range of uncertainty in climate change projections. While it is widely accepted that climate is no longer stationary and that historical trends are no longer a good indicator of future climate conditions, in recent years many locales have been experiencing record heavy rainfall and flood events, which shape perceptions of current and future flood risk. It is important then to situate assets that are being assessed within the recent historical context (e.g., past 30 years), especially recent extreme events that are more reflective of the changing climate and then consider how the rainfall contributing to these flood events are projected to change even moreso in the future. The City of Toronto, for example, has experienced record rainfall and flood events in 2005, 2013 and 2024, with each exceeding the historical 1-100 year storm amounts, and are comparable to future projections under high emission scenarios for median values, if not also upper percentiles.

Since there is more confidence in climate change projections of temperature than precipitation, it has been recommended that precipitation projections should be used for the purposes of risk assessment rather than to inform design standards (Cannon et al., 2020). IDF projections are based on existing weather stations and are somewhat dependent upon the length and accuracy of the historical record. In Canada, there has been a long and slow deterioration of the weather station network across the country and many large gaps exist which then requires extrapolation to determine IDF statistics for many locations. Fortunately, in Canada we have data portals that provide credible and defensible projections of IDF statistics, notably the Western IDF CC Tool portal (Web-5) and the Federally supported climatedata.ca portal (Web-6). Future projections of IDF statistics are calculated using different methods, such as the Equidistant Quantile Matching Algorithm, which is precipitation based, and the Clausius-Clapeyron relationship, which is based on temperature scaling, and are spatially extrapolated to areas where there is limited historical data.

Regardless of the data source and method selected, it is important to recognize how this data can support a climate risk assessment. Total precipitation amounts for multiple types of storms for convection events can be helpful (e.g., short term events such as 15-minute, 1-in-10-year storms; slightly longer term events such as a 2-hour, 1-in-100-year storm), but some decision-makers and practitioners may find it more important to have changes in IDF Statistics translated into changes in return periods, typically examining how historical storms will become more frequent in the future. In conjunction with the IDF data portals noted above, this information can be coupled with NOAA's National Weather Service flood return period calculator to illustrate how specific storms will become more frequent in the future (Web-7). For example, different decision-makers for design, asset management, or operations and maintenance may find that knowing that a 2-hour, 100-year storm could become a 1-20 year storm by the 2050s is more important than knowing that the total precipitation for such an event could be 20 mm above the historical baseline.

In the case of Australia, a climate risk assessment focusing on flooding was applied to a large, state-wide rail network, where the scope was greatly influenced by the availability of data for asset condition, landscape elevations, and climate. A large geographical area known for multiple floods over this past century (including 10 since 2012), recent back-to-back mega-floods during 2021 and 2022 had elevated the need for a climate risk assessment that was a desk top exercise, which was followed by an unofficial site visit in 2024. Noting that the rail network traversed highly differentiated landscapes, ranging from corridors crossing multiple rivers in a regulated watershed dominated by dams and reservoirs, suburban/commuter communities with concrete stormwater channels constructed in the 1970s, and predominantly agricultural tablelands surrounded by mountains, the assessment required making major assumptions regarding geography and topography. While the weather station network and historical climate dataset were many times greater than what exists in Canada (e.g., over 17,000 weather stations were in the Australian Government Bureau of Meteorology database, from which about 400 were selected for the historical weather assessment), future climate projections were limited to daily precipitation amounts, requiring creativity in the translation of heavy rainfall events into flooding. Based on expert judgement, rainfall and flood conditions were differentiated between site specific flooding (24-hour rainfall event for flash flooding), flooding within a catchment area (72-hour rainfall event for slow flooding), and watershed-wide flooding (168-hour rainfall event for prolonged riverine flooding) (Chiotti et al., 2022).

4.2 Complexity of Impacts

The pathway from heavy rainfall to flooding, resulting in damage to infrastructure assets, disruptions in service delivery, and potential injuries and death is not always linear or simple, and can be quite complicated if not complex. Understanding the complexities of impacts, especially in terms of ecosystem conditions and hydrology that can shape flooding is critically important, noting that compounding, cascading and cumulative effects can greatly influence the degree of flooding and other disasters (UNDRR, 2022). Broader watershed issues where a combination of soil saturation levels, drought, wildfires, and removal of vegetative cover has the potential to exacerbate water flows after periods of heavy rainfall that can unfold over weeks, if not months, and in some cases even longer. Similarly, snowpack, glacial melt, spring rainfall and freshet, and even ice jams can be compounding factors not easily projected by climate models or through the application of a climate risk assessment, thereby likely requiring expert judgement and acceptance of more uncertainty when determining potential impacts and the level of risk. On an urban basis the interplay between fluvial and pluvial flooding, and where the age and capacity of adjoining stormwater management systems can limit the conveyance of water flows is another example of complexity that challenges our ability to estimate risk.

From an adaptation perspective complex outcomes also highlight the importance of nature-based solutions, especially at the watershed level, not just when applied in situ at specific asset locations. While this generally applies to issues around water quality (e.g., when preserving upper watershed ecosystems and forests reduces the need for downstream end of pipe water treatment solutions), the same may also apply to water quantity and flood risk. Hardened and impervious surfaces will exacerbate runoff during heavy rainfall events, potentially maxing out stormwater management system capacity, causing backflows, or preventing outflows from occurring. In contrast, the enhancement of natural infrastructure will help reduce and slow the total amount and rate of runoff, in addition to generating multiple co-benefits such as carbon sequestration, biodiversity, and recreation, among others.

4.3 Costs and Benefits of Adaptation Measures

Risk treatment and the consideration of adaptation measures inevitably involve consideration of costs and benefits, both in terms of embedding resiliency into the design standards of new infrastructure, and in the repair, refurbishment and rebuilding of legacy infrastructure assets. The financial benefits of implementing adaptation measures in face of climate change and increased flood risks are compelling, as is the business case for adaptation. Generally, for every dollar invested in adaptation and resilient infrastructure, the return on investment is between \$13-\$15 from a combination of direct and indirect savings (Sawyer et al., 2022). A report from the Financial Accountability Office of Ontario (FAO) that examined changes in extreme rainfall, extreme heat, and freeze-thaw cycles on transportation infrastructure under a high emissions scenario, builds the business case even further (Afroz et al., 2022). The FAO compared cumulative climate-related infrastructure spending through asset management and capital improvements until the end of this century, comparing no adaptation with reactive and proactive adaptation responses. The report found that proactive adaptation will cost about 33% less than a no adaptation response, and slightly less than reactive adaptation, and that the residual risk will be highest with no adaptation, and progressively lower with reactive and proactive adaptation. A recent national assessment report builds upon these findings and makes the case to apply proactive adaptation to public infrastructure across the country (Ness et al., 2026).

Through the PIEVC process the costs and benefits for adaptation options can be evaluated qualitatively (e.g., Low, Medium and High), and applied to multiple criteria, including costs, effectiveness of adaptation, barriers to action, and difficulty of implementation, in addition to designating responsibility to design or operations and maintenance, and identifying whether the measure involves monitoring and evaluation (Tonto et al, 2024). For legacy rail infrastructure assets in Australia, a number of financial metrics were considered, and the results overwhelmingly supported the view that by implementing a strategic approach to climate change resilience, the future likely costs of flooding can be reduced substantially (Partners in Performance et al., 2022). The assessment found that the value of risk (e.g., magnitude of repair costs, immediate revenue losses, emergency response costs, and long-term reputational costs) from flooding could increase significantly by mid-century, the annual risk value (e.g., expected annual damages or losses) could be reduced substantially, and that capital investments in infrastructure resilience could yield a much larger net present value whereby the avoided losses over decades would far exceed upfront capital costs of adaptation and resilience measures.

4.4 Adaptation Expenditure Pathways

In terms of developing and implementing an adaptation strategy to reduce flood risks for legacy and new infrastructure assets under a changing climate, it is important to recognize that responsibility will fall upon multiple business units, each with their own business cycle, and each with their own time horizons and planning schedules (e.g., see Viner et al., 2015). It is possible to imagine multiple approaches to design, manage, maintain and operate rail and transit infrastructure assets and service delivery into the future, but four are presented here (Figure 4) as representative examples, with each pathway considering cumulative expenditures and residual risk by the end of this century (Maclellan and Chiotti, 2016). Companies or agencies may follow one or a combination of adaptation expenditure pathways for their legacy and new infrastructure assets, depending upon their risk tolerance and other considerations.

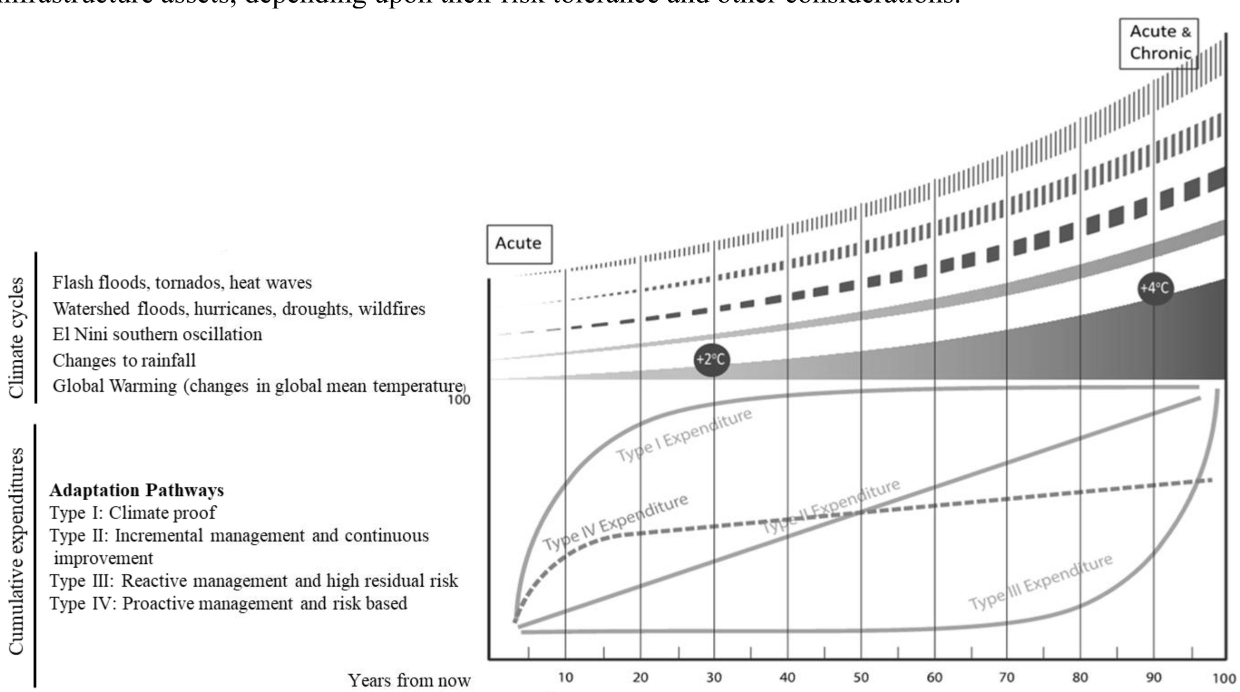

Figure 4: Managing Climate Change Risks Through Adaptation Pathways (adapted from Viner et al., 2015)

The Type I adaptation expenditure pathway aims to be climate proof, that typically involves designing new infrastructure to the highest possible climate standard, with the expectation that asset management and operations and maintenance functions will be minimized throughout the lifetime of the asset. In this case residual risks will also be minimized upon commission, but at the cost of substantial upfront expenditures. The Type II adaptation expenditure pathway tends to apply to the management of legacy assets and is most effective when the improvement is incremental and there is a corporate commitment to continuous improvement. Residual risks tend to be manageable during normal or slightly abnormal conditions, but this approach remains vulnerable to extreme weather conditions. The degree of improvement must be agile and able to respond quickly to any unexpected changes in climate, otherwise risk losing ground and incurring an increasing adaptation deficit.

The Type III adaptation expenditure pathway applies to managing an expansive array of legacy assets, especially for systems and networks that are old, designed to outdated standards, where the state of good repair is poor, and where finances are limited. Capital expenditures, asset management, and operations and maintenance functions are kept to a minimum, and following a “hope for the best” approach tends to leave the owners and operators of these assets continuously exposed to maximum risk, and where a reactive and costly response is the likely, if not inevitable, outcome. The most prudent and cost-effective approach that seeks an illusive “sweet spot” for balancing expenditures with risk is the Type IV adaptation expenditure pathway that is characterized by a proactive management approach which is risk based. This pathway lends itself to the application of a climate risk assessment using the PIEVC process. Design standards of new infrastructure assets and capital improvements for deteriorating legacy assets are given priority but expenditures are less than what is needed to achieve a climate proof standard. The level of standard achieved is very much related to the level of risk tolerance in face of potential future floods. This results in initial expenditures relative to the other pathways being medium to high, followed by minimal, and more manageable expenditures applied for asset management and ongoing operations and maintenance functions.

5 CONCLUSIONS

There is growing acceptance that adaptation to climate change is no longer a “nice to have” option but is necessary to reduce vulnerability and enhance adaptive capacity for legacy assets and new public infrastructure projects. This applies to transit and rail, and particularly in response to future changes in heavy rainfall and increased flood risk. Many agencies and companies are already taking steps to address climate change and flood risks, but overall they need to do more in face of a rapidly changing climate. Managing future risks will benefit from being informed by science and should be evidence-based, and a good starting point is to apply a climate risk assessment to legacy and new infrastructure assets. In this regard the PIEVC Protocol is a useful tool, and the process is a constructive multi-step approach to assess climate change flood-related risks and develop/implement appropriate design and management practices that reduces vulnerability and leads to more adaptive and resilient infrastructure. Using the right climate data, including projections of future IDF statistics, consideration of cumulative impacts, and demonstrating the financial costs and benefits of implementing adaptation measures, are just some of the key elements of the climate risk assessment process.

Managing climate-related risks is complex and challenging, but there is a strong business case to support adaptation and flood mitigation for transit and rail infrastructure. Whether it is the design of new infrastructure or the management of legacy assets, improvements can be made that are cost effective, will prolong the lifecycle of infrastructure assets, and deliver safety benefits. It is important to recognize that some risk transfer can be expected, which will ultimately be left in the hands of those responsible for operations and maintenance activities. Multiple adaptation expenditure pathways are possible, but applying a risk approach will help decision makers make more informed choices in face of climate change.

REFERENCES

AECOM, RSI and TRCA (2016) Metrolinx PIEVC Climate Change Vulnerability Assessment – Final Report , Metrolinx RQQ-2015-IN-021, AECOM, Markham, ON, Canada, 196 p.

Afroz, S., Rhodes, N. and Park, J. (2022) Costing Climate Change Impacts to Public Infrastructure: Transportation – Assessing the financial impacts of extreme rainfall, extreme heat and freeze-thaw cycles on public transportation infrastructure in Ontario, Financial Accountability Office of Ontario, Toronto, ON, Canada, 52 p.

Cannon, A., Jeong, D., Zhang, X. and Zwiers, F. (2020) 2020 Climate-Resilient Buildings and Core Public Infrastructure: An Assessment of the Impact of Climate Change on Climatic Design Data in Canada . Environment and Climate Change Canada, Gatineau, QC, Canada, 106 p.

Charette, R. and Marshall, H. (1999) UNIFORMAT II Elemental Classification for Building Specifications, Cost Estimating, and Cost Analysis, U.S. Department of Commerce, Technology Administration, National Institute of Standards and Technology NISTIR 6389, 93 p.

Chiotti, Q. and Van Vliet, D. (2024) "A call to action: the emergence of climate change adaptation in infrastructure planning", ReNew Magazine, April/May, pp. 10-12.

Chiotti, Q., Chan, K., Gulecoglu, E., Belaieff, A. and Noxon, G. (2017) Planning for Resiliency: Toward a Corporate Climate Adaptation Plan, Metrolinx, Toronto, ON, Canada, 86 p.

Chiotti, Q., Moreno, N. and Manas, M. (2022) Climate Hazards Report, Matrix-Solutions, Calgary, AB, Canada, for the Australian Rail Track Corporation, 73 p.

Elsner, M., Atkinson, G. and Sahidi, S. (2025) The Global Risks Report 2025, 20th Edition Insight Report, World Economic Forum, Geneva, Switzerland, 104 p.

Haghighi, E., Kasreai, A., Famurewa, S., Strandberg, G., Sas, G. and Garmabaki, A.H.S. (2025) "Climate change risks on railway infrastructure: A systematic review and analysis", Sustainable Cities and Society, 129, pp. 1-20.

Infrastructure Canada (2023) The Climate Lens – Investing in Canada Infrastructure Program, General Guidance v 2.1, Infrastructure Canada, Ottawa, ON, Canada, 25 p.

Institute for Catastrophic Loss Reduction (2016a) PIEVC Engineering Protocol for Infrastructure Vulnerability Assessment and Adaptation to a Changing Climate: Principles and Guidelines. Version PG-10.11 (June), Institute for Catastrophic Loss Reduction, Toronto, ON, Canada, 184 p.

Institute for Catastrophic Loss Reduction (2016b) PIEVC Engineering Protocol for Infrastructure Vulnerability Assessment and Adaptation to a Changing Climate: Vulnerability Assessment Module, Version VA-10.11 (June), Institute for Catastrophic Loss Reduction, Toronto, ON, Canada, 79 p.

International Organization for Standardization (2018) ISO 31000:2018 Risk Management – Guidelines, Second edition. 22 p.

IPCC, 2014: Summary for policymakers. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., and White, L.L. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1-32.

MacLellan, J. and Chiotti, Q. (2016) 'Climate Decision Timelines' *Presented at:* The Forest Climate Workshop, Association of Registered Professional Foresters of New Brunswick, New Brunswick Climate Change Research Collaborative, March 7th to 9th Fredericton, NB, Canada.

MacMillan, K., Symonds, M, and Sparling, E. (2024) PIEVC Meta-Analysis Summary Report. A publication of the PIEVC Program. Institute for Catastrophic Loss Reduction and Climate Risk Institute, Toronto and Sudbury, ON, Canada, 56 p.

Metrolinx (2014) Metrolinx Five Year Strategy, 2015-2020, Metrolinx, Toronto, ON, Canada, 30 p.

Metrolinx (2018) Metrolinx Climate Adaptation Strategy, Metrolinx, Toronto, ON, Canada, 36 p.

Metrolinx (2021a) DS-05 Sustainable Design Standard, Version 1.0, Metrolinx, Toronto, ON, Canada, 108 p.

Metrolinx (2021b) DS-25 Climate Change Informed Data Standard, Version 1.0, Metrolinx, Toronto, ON, Canada, 17 p.

Ness, R., Clark, D.G., Bourque, J., Coffman, D., and Beugin, D. (2022) Under Water: The Costs of Climate Change for Canada's Infrastructure. Canadian Institute for Climate Choices, Ottawa, ON, Canada, 81 p.

Ness, R., Carriere, A. and Gauer, V. (2026) Prepare or Repair: How climate-proofing public infrastructure pays off. Canadian Climate Institute, Ottawa, ON, Canada, 46 p.

Nodelman, J., Nodelman, J., Shippee, N., O'Driscoll, J., and Sparling, E. (2022) PIEVC© Family of Resources Catalogue: A Guide for Selecting Climate Risk Assessment Methods, Data, and Supporting Materials, published by the PIEVC Global Partnership, 56 p.

Partners in Performance, VIRIDI Global and Matrix-Solutions (2022) Australian Rail Track Corporation Climate Resilience Final Report, VIRIDI Global, Ottawa, ON, Canada, 62 p.

Sawyer, D., Ness, R., Lee, C. and Miller, S. (2022) Damage Control: Reducing the costs of climate impacts in Canada. Canadian Climate Institute, Ottawa, ON, Canada, 86 p.

Tonto, F., Iwanicki, A., Chiotti, Q. and Felio, G. (2024) Ontario Line – Southern Civil, Stations and Tunnel Project: Vulnerability Assessment Report, prepared by Matrix-Solutions, Guelph, ON, Canada, for the Ontario Transit Group, 115 p.

UNDRR (2022), Scoping Study On Compound, Cascading And Systemic Risks In The Asia Pacific 2021, United Nations Office for Disaster Risk Reduction (UNDRR), Geneva, Switzerland, 60 p.

Viner, D., Rawlins, M., Allison, I., Howarth, C. and Jones, A. (2015) Climate change and business survival: The need for innovation in delivering climate resilience. Mott MacDonald, p. 10-11.

Websites:

Web 1: https://gml.noaa.gov/ccgg/trends/ consulted December 31st, 2025.

Web 2: https://bac-quebec.qc.ca/en/insurance-issues/disaster/ consulted December 20th, 2025.

Web 3: https://www.pievcanalysis.ca/ consulted December 21st, 2025

Web 4: https://pievc.ca/ consulted December 21st, 2025

Web 5: https://www.idf-cc-uwo.ca/ consulted December 28th, 2025

Web 6: https://climatedata.ca/ consulted December 28th, 2025

Web 7: https://www.weather.gov/epz/wxcalc_floodperiod consulted December 29th, 2025