



Review and Analysis of Climate Change Vulnerability Assessments of Canadian Water Management and Drainage Infrastructure

B.C. Ministry of Transportation and Infrastructure

Nodelcorp Consulting Inc.

Pacific Climate Impacts Consortium

Revision 2

Mar 14, 2014

With support from Natural Resources Canada through the Adaptation Platform



Natural Resources
Canada

Ressources naturelles
Canada

Canada

Table of Contents

1	Introduction	3
2	Methodology.....	4
2.1	Coverage	4
2.2	BCMoTI Vulnerability Assessment Results	7
2.3	Focus.....	9
2.4	Limitations	10
2.5	Evaluation Criteria.....	11
3	Observations	12
3.1	High-Level Summary.....	12
3.2	Synthesis	17
3.2.1	Vulnerability to HISD Events was Identified in Every Assessment Reviewed	17
3.2.2	The Need for Relevant Climate Information	17
3.2.3	Assessment Methodologies can Affect Reported Risk Profiles	19
3.2.4	Sequences and Combinations of Weather, Terrain and Topography are Important	20
4	Conclusions	22
5	Summary of Recommendations Identified in the Analysis.....	23

1 Introduction

The BC Ministry of Transportation and Infrastructure (BCMoTI) has engaged in a number of projects to determine risk and vulnerability to transportation infrastructure in BC from future changes in climate. The intent is to understand potential risks to the transportation system and develop adaptation measures to address potential issues.

This report details the findings from a review of 25 vulnerability assessment reports from across Canada. The intent of this review and analysis is to identify risks to Canadian water management and drainage infrastructure from changing climate, as identified through engineering vulnerability assessments completed across Canada. Based on risk commonalities from these assessments, we will identify scenarios that could lead to potential failure of water management and drainage infrastructure components.

In this assessment we identified developing risk patterns by reviewing and synthesising results from previous Vulnerability Assessment Reports that were completed using the Public Infrastructure Engineering Vulnerability Committee (PIEVC) Protocol. The focus is identifying similarities in risk among assessments completed on water related infrastructure in general, and risk from vulnerability assessments of transportation infrastructure, which is our particular interest. Therefore, specific interest includes reviewing transportation infrastructure risk studies completed by the BC Ministry of Transportation and Infrastructure (BCMoTI) on five highway segments in the province of British Columbia between June 2010 and September 2013.

This analysis contains information that can be used by infrastructure owners and engineering professionals to incorporate considerations of changing climate conditions into the design, construction, operation, maintenance, and management of elements of water handling infrastructure systems including drainage, and specifically road infrastructure systems.

This background will provide a firm basis for the development of tools such as a best practices guidance document for general application across Canada and a Technical Bulletin developed by BCMoTI for application regarding the development and operation of the BC highway system.

This project benefited from partnering with Natural Resources Canada under their Adaptation Platform intended to advance adaptation to climate change in Canada. BC MoTI has contributed to the Coastal Management theme through the initiative of ***Development of Best Management Practices to Address Extreme Precipitation Events that Affect Coastal Regions of Canada.***

2 Methodology

2.1 Coverage

In the initial stage of the project we anticipated reviewing six vulnerability assessment reports that may share commonalities with BCMoTI work, and the first two BCMoTI vulnerability assessment reports, as outlined in **Table 2.1**.

Table 2.1 – Synthesis Reports Suggested in Original Work Plan

Assessment	Owner	Issues Relevant to Current Project
Roads Infrastructure		
Coquihalla Highway – Hope to Merritt Section	BCMoTI	Highway Water Management and Drainage
Yellowhead Hwy 16	BCMoTI	Highway Water Management and Drainage
Quesnell Bridge	City of Edmonton	Highway Water Management and Drainage
Coastal Infrastructure		
Castlegar Stormwater Treatment System	Castlegar B.C.	BC Water Management and Drainage
Metro Vancouver Sewerage System	Metro Vancouver	Coastal Water Management and Drainage
Placentia Water Resources Infrastructure	Government of Newfoundland and Labrador	Coastal Water Management and Drainage
Fraser Sewerage System	Metro Vancouver	Coastal Water Management and Drainage
Shelburne Sewage Treatment Plant	District of Shelburne – Nova Scotia	Coastal Water Management and Drainage

As we progressed with this work we noted a pattern of similar vulnerabilities arising in almost every PIEVC vulnerability assessment. As a consequence, we expanded the scope of our review to cover every currently published PIEVC vulnerability assessment report. This resulted in a total of 25 assessments including the five assessments conducted directly by BCMoTI. This allowed us to conduct a reasonably comprehensive review of common infrastructure risk elements across a wide range of infrastructure types. As well, the expansion in scope allowed us to consider the implications of these issues across a wider range of Canadian jurisdictions and regions.

While 25 assessments may be a small sample to be statistically robust, the analysis nonetheless started to uncover a pattern of risks across a range of infrastructure types and regions in Canada.

The five BCMoTI vulnerability assessments included in this analysis are outlined in **Table 2.2**. The 20 non-BCMoTI assessments considered are outlined in **Table 2.3**.

Table 2.2 - BCMoTI Highway Infrastructure Vulnerability Assessments

#	Date	Infrastructure	Protocol Version
1	Jun 2010	Coquihalla Highway (B.C. Highway 5) between Nicolum River and Dry Gulch	Ver 9
2	Apr 2011	Yellowhead Highway 16 between Vanderhoof and Priestly Hill	Ver 9
3	Sep 2013	Highway 20 in the Bella Coola Region	Ver 10
4	Sep 2013	Highway 37A in the Stewart Region	Ver 10
5	Sep 2013	Highway 97 in the Pine Pass Region	Ver 10

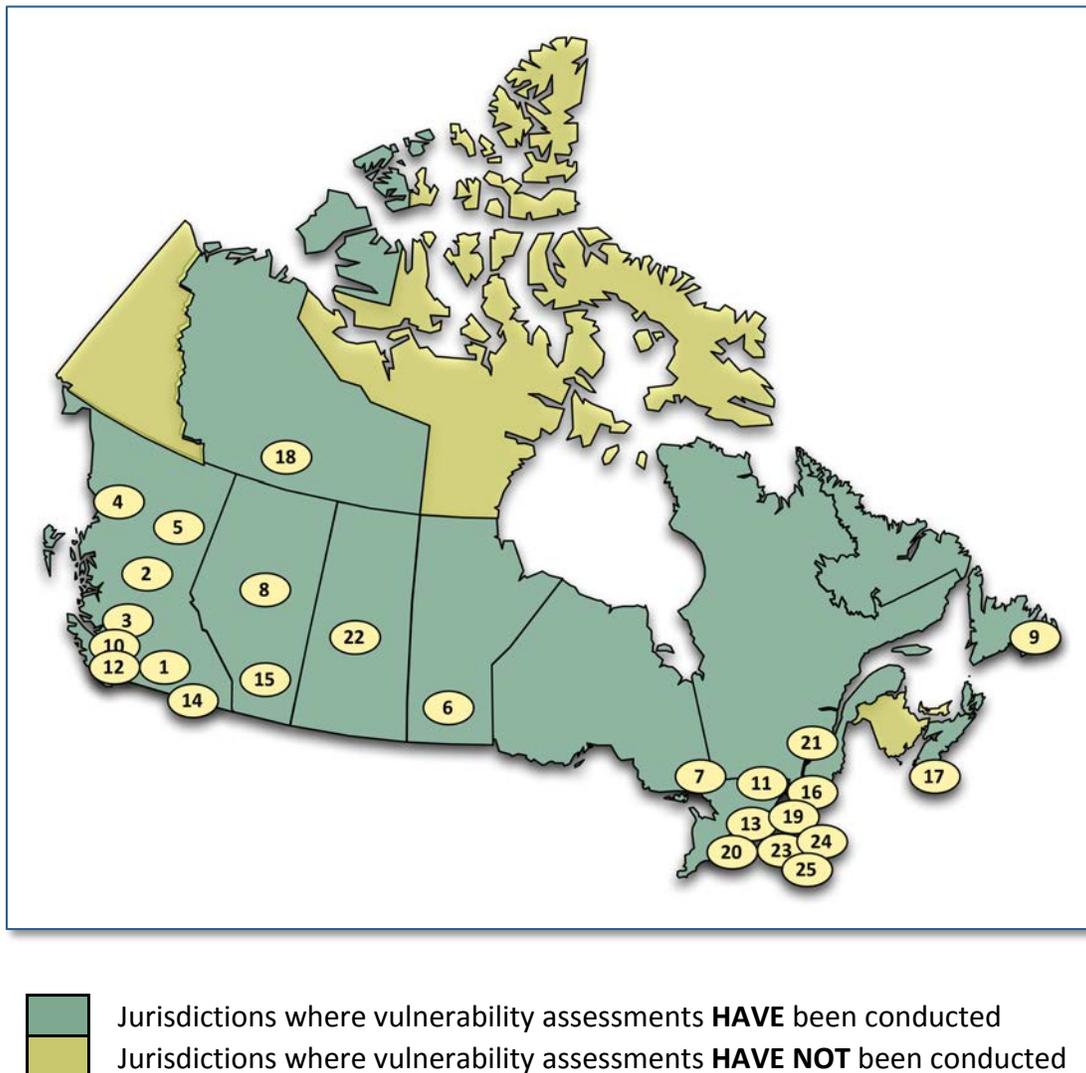
Table 2.3 - PIEVC Infrastructure Vulnerability Assessments Considered in the Synthesis Review

#	Date	Owner	Region	Infrastructure	Protocol Version
6	Nov 2007	Portage la Prairie	MB	Water Resources Infrastructure	Ver 3
7	Mar 2008	City of Greater Sudbury	ON	Roads	Ver 7.1
8	Mar 2008	City of Edmonton	AB	Quesnell Bridge	Ver 7.1
9	Mar 2008	Town of Placentia	NL	Water Resources Infrastructure	Ver 7.1
10	Apr 2008	Metro Vancouver	BC	Metro Vancouver Sewerage Area	Ver 7.1
11	Apr 2008	Government of Canada	ON	Buildings	Ver 7.1
12	Dec 2009	Metro Vancouver	BC	Fraser Sewerage Area	Ver 9
13	Jun 2010	Toronto Regional Conservation Authority	ON	Flood Control Dams	Ver 9
14	Oct 2010	City of Castlegar	BC	Stormwater Systems	Ver 9
15	May 2011	City of Calgary	AB	Water Supply and Treatment	Ver 9
16	Jun 2011	Town of Prescott	ON	Sanitary Sewage	Ver 9
17	Aug 2011	City of Shelburne	NS	Sewage Treatment	Ver 9
18	Oct 2011	Government of the Northwest Territories	NT	Highway 3	Ver 9
19	Dec 2011	City of Toronto	ON	Culverts	Ver 9
20	Feb 2012	City of Welland	ON	Stormwater - Wastewater	Ver 10
21	Mar 2012	Trois Rivieres	QC	Drainage	Ver 10
22	Mar 2012	University of Saskatchewan	SK	Buildings	Ver 10

#	Date	Owner	Region	Infrastructure	Protocol Version
23	Jun 2012	Infrastructure Ontario	ON	Buildings	Ver 10
24	Sep 2012	Toronto Community Housing Authority	ON	Buildings	Ver 10
25	Sep 2012	Toronto Hydro	ON	Electricity Distribution	Ver 10

The geographic coverage of this review is outlined in **Figure 2.1**. The review considered most of the provinces and territories of Canada. Only Prince Edward Island, New Brunswick, the Yukon and Nunavut are not represented in this review. We understand that several of these jurisdictions will be hosting PIEVC vulnerability assessment work under the 2013-2014 Natural Resources Canada funding initiative.

Figure 2.1 – Map of Vulnerability Assessment Locations



2.2 BCMoTI Vulnerability Assessment Results

To date, BCMoTI has conducted five climate change vulnerability assessments. The first two assessments, the Coquihalla and Yellowhead Highway work, considered a very broad range of infrastructure components and climate parameters. These assessments identified common risk drivers; the impact of high-intensity, short-duration (HISD) rainfall events on highway drainage infrastructure. The risk was more pronounced on the Coquihalla Highway, where the increasing future intensity and frequency of Pineapple Express atmospheric river events was identified as a very significant driver. However, a similar pattern of risk was identified for the Yellowhead Highway.

HISD events can vary in size depending upon the region and the infrastructure involved. For example, in the Coquihalla Highway assessment identified an extreme rainfall intensity event as > 76 mm of rain over a period of 24 hours. Conversely, the Yellowhead Highway assessment considered an extreme rainfall event to be > 35 mm of rain over a similar period, while the most recent assessment of Highways 20, 37A and 97 used a value of > 98 mm. Similarly, the other 20 vulnerability assessments considered in this review each defined extreme rainfall events on a site and infrastructure specific basis.

While HISD events were common risk drivers on all five of the BCMoTI vulnerability assessments, they were not the only risk drivers identified. In **Table 2.4** we provide a high level summary of the overall risk profiles identified by the five BCMoTI vulnerability assessments.

Table 2.4 – High Level Summary of Risk Profiles Identified by BCMoTI Vulnerability Assessments

Vulnerability Assessment	Summary of Findings
Coquihalla	<p>The team originally conducted the risk assessment on 560 potential climate-infrastructure interactions. Based on the analysis the team identified:</p> <ul style="list-style-type: none"> ▪ 435 interactions with low or no material risk; ▪ 111 interactions with medium risk; and ▪ 14 interactions with high risk. <p>Of the 111 medium level risks, the majority were relatively minor with risk scores in the range 12 to 18.</p> <p>All 14 high level risks were associated with HISD events. In fact, in these categories even the medium risk items scored quite high - generally greater than 18 and often higher than 30. Thus, these climatic events yielded all the high risk and high-medium risk climate-infrastructure interactions.</p>

Vulnerability Assessment	Summary of Findings
Yellowhead	<p>The team originally conducted the risk assessment on 178 potential climate-infrastructure interactions. Based on the analysis the team identified:</p> <ul style="list-style-type: none"> ▪ 137 interactions with low or no material risk; ▪ 41 interactions with medium risk; and ▪ No interactions with high risk. <p>Within the medium risk category, 11 interactions scored in the range 25 to 36: high-medium risk. Of these 25 high-medium risks, 20 (80%) were related to HISD events. The high medium risks included:</p> <ul style="list-style-type: none"> ▪ Bridge structure sensitivities to high temperature (two interactions); ▪ Sensitivity to freeze/thaw impacts on winter maintenance (one interaction); and Sensitivities to sprig freshet impacts on culvert systems (two interactions).
Bella Coola	<p>The team originally conducted the risk assessment on 90 potential climate-infrastructure interactions. Based on the analysis the team identified:</p> <ul style="list-style-type: none"> ▪ 35 interactions with low or no material risk; ▪ 53 interactions with medium risk; and ▪ 2 interactions with high risk <p>Higher risks were associated with the impact of freshet conations on protection works and bridge end fill.</p> <p>Within the medium risk category, 26 interactions scored in the range 25 to 36: high-medium risk. Of these 26 high-medium risks, 7 (27%) were related to HISD events. The other 19 were associated with freshet events. These events are seen to challenge protection works, stabilization works and drainage elements in a very similar fashion to HISD events.</p>
Stewart	<p>The team originally conducted the risk assessment on 106 potential climate-infrastructure interactions. Based on the analysis the team identified:</p> <ul style="list-style-type: none"> ▪ 54 interactions with low or no material risk; ▪ 50 interactions with medium risk; and ▪ 2 interactions with high risk <p>Higher risks were associated with the impact of freshet conations on protection works and bridge end fill.</p> <p>Within the medium risk category, 23 interactions scored in the range 25 to 36: high-medium risk. Of these 23 high-medium risks, 6 (26%) were related to HISD</p>

Vulnerability Assessment	Summary of Findings
	<p>events. The other 20 were associated with freshet events. These events are seen to challenge protection works, stabilization works and drainage elements in a very similar fashion to HISD events.</p>
Pine Pass	<p>The team originally conducted the risk assessment on 110 potential climate-infrastructure interactions. Based on the analysis the team identified:</p> <ul style="list-style-type: none"> ▪ 38 interactions with low or no material risk; ▪ 52 interactions with medium risk; and ▪ 20 interactions with high risk <p>High risks were associated with the impact of freshet conations and HISD events on protection works and bridge end fill and third party utilities. Of the high risks, five were directly related to HISD events while the others were associated with freshet conditions.</p> <p>Within the medium risk category, 15 interactions scored in the range 25 to 36: high-medium risk. Of these 15 high-medium risks, 8 (53%) were related to HISD events. The other 20 were associated with freshet events. These events are seen to challenge protection works, stabilization works and drainage elements in a very similar fashion to HISD events.</p>

The reader should exercise caution in reviewing the results from the Bella Coola, Stewart and Pine Pass vulnerability assessments. These three assessments were focused primarily on drainage and water management impacts on the highways. They did not cover the broad range of potential climate factors that were considered in the Coquihalla and Yellowhead Highway assessments. However, the summary presented in **Table 2.4** clearly indicates the sensitivity of all five highways to HISD events and other events that are very similar in character to HISD events. Even where freshet conditions drove the overall risk profile, HISD events were nonetheless significant risk factors in all five assessments.

2.3 Focus

Despite regional and infrastructural differences, the assessments all contemplated how specific infrastructure designs responded to HISD events. Depending on the infrastructure design, threshold values used to define HISD events may have varied, but the infrastructures have all been designed to respond to the regional climate defined from the historic weather record. The focus of this current review was to assess how these unique infrastructure designs responded to these conditions as a means of establishing the overall veracity of standard engineering practices that were used to design and build these systems.

The BCMoTI vulnerability assessments all identified that particular combinations of weather and local conditions could exacerbate the impact of HISD events. Some of these combination events could not be modeled using standard climate projection processes. However, through application of the professional judgment of the assessment teams, these combinations were determined to present significant levels of risk. Based on this experience, one focus of our review was to assess the potential for similar combination risk drivers in the other 20 assessments.

Based on these observations, and the fact that extreme storm events have occurred recently in specific locations affecting BC highways, BCMoTI focused the recent work on identifying the impact of HISD events on three highway infrastructure systems covering a range of geographical regions in BC. The same pattern of risk emerged from these assessments; all three highway segments were found to have elevated risk profiles arising from HISD events' impact on highway drainage infrastructure components. Similar sensitivities were identified for events arising from spring freshet conditions that resulted in very similar challenges to the highway infrastructure systems as HISD event.

Based on the BCMoTI findings, we focused this present analysis on the incidence of HISD events. In our review, we did not directly contemplate other risk drivers for the infrastructure systems. In addition, we considered implications of differing risk assessment approaches outlined in the PIEVC Protocol on risk profiles identified in risk assessments covered by the 20 non-BCMoTI assessment reports. We included the review of different risk assessment methodologies in the present work because different risk assessment methodologies may yield slightly different risk profiles that could potentially have a bearing on subsequent work such as a best practice guidance document that we will develop based on this analysis.

2.4 Limitations

While we are confident that the present analysis can provide a reasonable high-level assessment of common risk drivers, we have noted the following limitations with this analysis.

1. Twenty-five assessment reports, covering a range of infrastructure types, do not represent a robust sample that would allow statistically significant analysis.

Recommendation:

- a. BCMoTI should continue to evaluate the impact of HISD events on BC's highway infrastructure and update Ministry Technical Bulletins accordingly.**
2. This review did not contemplate potential emerging risk patterns associated with other infrastructure systems or climate drivers. Based on this present analysis, the reader should not conclude that drainage issues are the only common risk drivers across Canada's infrastructure systems. Other common risk drivers may exist but were not within the scope of the current work.

Recommendation:

- a. As the PIEVC database of case studies grows, Engineers Canada should implement a broader synthesis review assessment covering all infrastructure types and the entire range of climate change risk drivers across Canada**
3. This review was based on PIEVC vulnerability assessments conducted over the five-year period 2007 through 2012. The work does not contemplate the updated AR5 climate change projections identified in the most recent IPCC report.

Recommendation:

- a. As climate projections evolve PIEVC vulnerability assessments should be reviewed and updated to capture any evolving risk drivers.**

2.5 Evaluation Criteria

We used several criteria to establish where vulnerability assessments identified HISD events as drivers of infrastructure vulnerability. These included assessments that:

- Identified HISD events with **high** risk scores (normally a PIEVC Protocol risk score ≥ 36);
- Identified HISD events with **high-medium** risk scores (PIEVC Protocol risk scores in the range 25 to 35);
- Made specific reference to HISD events contributing to the risk profile;
- Commented that HISD events may be an issue that was outside of the scope of that particular assessment;
- Made recommendations to enhance the capacity of drainage appliances; or
- Made recommendations regarding the operation and maintenance of drainage system components.

3 Observations

3.1 High-Level Summary

We present our high-level summary of our review in **Table 3.1**.

Table 3.1 – High Level Summary of Findings

#	Owner	Infrastructure	HISD Risks Identified	Primary Risk	Secondary Risk	Comments
1	BCMoTI	Coquihalla Highway Nicolum River to Dry Gulch	✓	✓		<ul style="list-style-type: none"> Very high risk to highway drainage systems due to Pineapple Express events
2	BCMoTI	Yellowhead Highway 16 Vanderhoof to Priestly Hill	✓	✓		<ul style="list-style-type: none"> No high risks identified High-Medium risk to highway drainage systems due to Pineapple Express Events
3	BCMoTI	Highway 20 Bella Coola Region	✓	✓		<ul style="list-style-type: none"> HISD and sustained rainfall events increase vulnerability of culverts, slope stability and protection works Pineapple Express events present a significant risk to the infrastructure in terms of drainage management issues
4	BCMoTI	Highway 37A Stewart Region	✓	✓		<ul style="list-style-type: none"> HISD and sustained rainfall events increase vulnerability of culverts, slope stability and protection works Pineapple Express events present a significant risk to the infrastructure in terms of drainage management issues
5	BCMoTI	Highway 97 Pine Pass Region	✓	✓		<ul style="list-style-type: none"> Pine Pass, although exhibiting the same general pattern of risk, tended to demonstrate the most intense risk responses Pineapple express not primary driver of higher risk profile but convective storms identified as a concern Increased risk profile arose from a combination of the geomorphology of the Pine Pass region and also the

#	Owner	Infrastructure	HISD Risks Identified	Primary Risk	Secondary Risk	Comments
						specific design features of this particular highway segment
6	Portage la Prairie	Water Resources Infrastructure	✓		✓	<ul style="list-style-type: none"> Intense rain and water intake infrastructure one of the highest risk scores Primary focus on extreme events (tornado) and long duration events (drought)
7	City of Greater Sudbury	Roads	✓	✓		<ul style="list-style-type: none"> A number of recommendations made to address the risk of rainfall on drainage infrastructure components Debris flow raised as an issue Study focus on detailed numerical analysis Did not have sufficient data to reach conclusions regarding future capacity deficits
8	City of Edmonton	Quesnell Bridge	✓	✓		<ul style="list-style-type: none"> Bridge drainage systems were deemed to be vulnerable to intense rainfall and to combined events leading to flooding The study was conducted during the design phase of a major bridge rehab project and resulted in increasing the drainage capacity of the bridge over the levels outlined in the original specification
9	Town of Placentia	Water Resources	✓	✓		<ul style="list-style-type: none"> Risk to culvert systems from predicted increase in high intensity rainfall events Recommended greater scrutiny of changes in local permeability conditions and debris flow
10	Metro Vancouver	Metro Vancouver Sewerage	✓		✓	<ul style="list-style-type: none"> High intensity - short duration precipitation events increases risk of failure of combined sewer collection mains Assessment only had precipitation projections to the 24-hour event level. Limited the ability to provide robust

#	Owner	Infrastructure	HISD Risks Identified	Primary Risk	Secondary Risk	Comments
						input on the impact of HISD events. However, they observed that there would be a higher risk of such events under projected climate change conditions.
11	Government of Canada	Buildings	✓		✓	<ul style="list-style-type: none"> • Building envelopes vulnerable due to increased precipitation in fall, winter and spring • Storm drains identified as components vulnerable to changing climate conditions
12	Metro Vancouver	Fraser Sewerage	✓		✓	<ul style="list-style-type: none"> • Increased rainfall impact on collection systems increasing risk of combined sewer overflow events • No mention of atmospheric river events (Pineapple Express)
13	Toronto Regional Conservation Authority	Flood Control Dams	✓		✓	<ul style="list-style-type: none"> • Largest potential impact on dam structures could be changes to inflow regimes due to change in HISD precipitation events • Identified by team but deemed to be outside of the scope of the study
14	City of Castlegar	Stormwater Systems	✓	✓		<ul style="list-style-type: none"> • Wildfire contributing to debris flow increases pressure on drainage systems
15	City of Calgary	Water Supply and Treatment	✓		✓	<ul style="list-style-type: none"> • Drought and flood identified as highest risk drivers • Issues compounded by forest fire leading to water quality issues and debris flows
16	Town of Prescott	Sanitary Sewage	✓	✓		<ul style="list-style-type: none"> • Precipitation events have the most significant impact on the sanitary sewage system • Inflow from precipitation events overwhelms the system
17	City of Shelburne	Sewage Treatment	✓	✓		<ul style="list-style-type: none"> • Intense rain found to create high risks for sanitary manholes, sanitary gravity mains and pipe connections and fittings • Hurricane events noted as drivers of high risk

#	Owner	Infrastructure	HISD Risks Identified	Primary Risk	Secondary Risk	Comments
18	Government of the Northwest Territories	Highway 3	✓	✓		<ul style="list-style-type: none"> • HISD events Identified as high risk to ditches and flow Channels • Flooding identified as high risk to ditches and flow Channels • High Medium risks associated with rainfall intensity and drainage appliances • Field inspections identified subsidence and other structural concerns at culvert sites • Primary focus of assessment was permafrost thaw but still identified HDIS issues
19	City of Toronto	Culverts	✓	✓		<ul style="list-style-type: none"> • HISD, hurricane and 5-day rainfall events increase vulnerability of culvert structures, roadways and watercourse features • Highly analytical process applied that did not focus on impacts to other utilities sharing the corridors nor combination events • While every culvert assessed was given an overall medium risk score, the study nonetheless identified that under the conditions outlined above the culverts did not have sufficient capacity to carry the flow. This would result in overland flow disrupting and potentially damaging third party properties and business operations.
20	City of Welland	Stormwater - Wastewater	✓	✓		<ul style="list-style-type: none"> • Stormwater collection systems found vulnerable to heavy rain, 5-day total rainfall and winter rain • Intense rainfall and 5-day rainfall events projected to increase in frequency • Current systems designed using 1963 vintage IDF curves
21	Trois Rivieres	Drainage	✓	✓		<ul style="list-style-type: none"> • Extreme, HISD events create

#	Owner	Infrastructure	HISD Risks Identified	Primary Risk	Secondary Risk	Comments
						<p>vulnerabilities to pumping stations, drainage at individual lots, catch basins, natural streams, sewers, etc.</p> <ul style="list-style-type: none"> • Recommendations for catch basin maintenance programs • Recommended development of technical understanding of infrastructure component hydraulic conditions to facilitate engineering analysis
22	University of Saskatchewan	Buildings	✓		✓	<ul style="list-style-type: none"> • Longer drier periods but increased frequency of HISD events • Drainage systems and roofing systems vulnerable to increase HISD events
23	Infrastructure Ontario	Buildings	✓		✓	<ul style="list-style-type: none"> • Vulnerability to water penetration due to higher incidents of HISD events • Drainage systems and roofing systems may be compromised due to similar events • HISD events identified as lower tier of risks but were nonetheless present
24	Toronto Community Housing Authority	Buildings	✓		✓	<ul style="list-style-type: none"> • Rainfall/drainage events scored as high-medium risks wrt to parking services, sidewalks and drainage • Not highest risk item in assessment, but there as a second tier risk
25	Toronto Hydro	Electricity Distribution	✓		✓	<ul style="list-style-type: none"> • Drains and vaults may flood if rainfall cannot be drained fast enough • Debris contributes to risk. Minimal damage to vault but may limit access • Heavy rain may be a risk to below-grade switches that are not submersible. May not be able to drain water from underground vaults fast enough. • Risk of electricity system components being damaged by culvert washouts, as utility corridors tend to parallel culverts.

3.2 Synthesis

In this section we integrate the findings outlined in **Table 3.1** to extract commonalities and patterns that emerge from our analysis of the 25 infrastructure assessments included in this review.

3.2.1 Vulnerability to HISD Events was Identified in Every Assessment Reviewed

Without exception, every vulnerability assessment report that we reviewed identified HISD events as risk factors affecting infrastructure system designed to manage water flow. Where the studies directly looked at drainage systems, these factors were generally deemed to **be high-medium** or **high** risk drivers. Even where assessments did not identify HISD events as high risk, they were often identified as coincident or related risks associated with other factors that were deemed to drive the infrastructure's risk profile. For example, in the Portage La Prairie study the primary concern identified was drought but HISD events following long dry periods were identified as nonetheless significant concerns.

This review considered 8 of 11 provincial and territorial jurisdictions in Canada. These impacts were observed in every region we considered. The weather drivers for the HISD events may vary, but the vulnerabilities are consistently observed. For coastal BC the primary driver of HISD events was typically identified as Pineapple Express atmospheric river type events. Inland, the driver may be attributed to convection storms, while the Atlantic region would typically attribute them to tropical storm or hurricane events.

Without exception, the climate projections prepared for the vulnerability assessments projected increases in HISD events.

Recommendation:

- **Given the high incidence of infrastructure vulnerability to HISD events, these events should be included in every PIEVC vulnerability assessment or, when excluded, the practitioner should provide written rational for this decision**

3.2.2 The Need for Relevant Climate Information

This review clearly exposed the need for high-quality, locally relevant climate information. Earlier PIEVC case studies relied on smaller numbers of climate model runs based on a limited number of greenhouse gas emission scenarios. This increased the level of uncertainty associated with the vulnerability assessment outcomes.

Climate projections are much more robust when based on larger numbers of ensembles producing more climate model runs or by picking specific ensembles of models. This suggests that obtaining robust climate projection information for any one particular project could be

expensive. This may present a significant barrier to smaller organizations contemplating vulnerability assessment work. However, climate organizations are aware of this and are beginning to make climate data available for specific uses; and tailor their output for differing uses. Increasingly, it will be necessary to provide central repositories for robust, locally relevant climate information. The Pacific Climate Impacts Consortium (PCIC) is doing this now for BC climate information

Recommendation:

- **It is important to establish repositories of regionally relevant, robust, climate and weather information and make that information generally available to practitioners. It is not sufficient that agencies generate and compile the information; it must also be user accessible and understandable to others besides climate specialists**

We also observed that climate experts from outside of a study region might overlook or underestimate the impact of unique local weather phenomena. Instead, they may rely solely on weather data and climate forecast information, underestimating synoptic analysis that is informed through local knowledge. For example, in two BC based studies; the Metro Vancouver Sewerage and Fraser Sewage vulnerability assessments identified HISD events as risk drivers there was no mention whatsoever of Pineapple Express or atmospheric rivers. These studies were completed in the same timeframe and in generally the same region of Canada as the Coquihalla Highway assessment that placed a significant emphasis on such events. We noted that in all three case studies the climate projections were rigorously and professionally executed. However, for the Coquihalla Assessment the team had access to a local expert who was able to provide a regionally relevant synoptic analysis. As a consequence, the Coquihalla assessment identified Pineapple Express as significant risk driver while in the other two studies HISD events did not emerge with similarly significant risk profiles.

Recommendation:

- **It is important to filter climate information through locally relevant climate and weather expertise. A local expert may apply their knowledge, or climate information may be ground truthed through local residents that have a physical, holistic, understanding of local weather conditions**

Finally, we observed that some jurisdictions were using very dated climate information in their day-to-day engineering, operation and maintenance activities. For example, the City of Welland assessment noted that 1963 vintage IDF curves were still being used for designing drainage systems as recently as 2012.

Recommendation:

- **Engineering, operations and maintenance practices must be based on the most up-to-date climate information including relevant climate projections. Reliance on old information will increase the risk of water management and drainage system failure**

3.2.3 Assessment Methodologies can Affect Reported Risk Profiles

We noted that there might be a misconception that risk assessment processes based on computational approaches are more robust and reliable than other, more judgment-based, methodologies.

Teams that used quantitative approaches nonetheless frequently make professional judgment decisions regarding numerical factors/parameters to include in their calculations. Thus, the professional judgment is buried deep in the numerical analysis. While the process has the appearance of being more precise, it is primarily founded on the professional judgment of numerical information. The process generally requires analysis based on technical training and skills and non-engineers on the team may find it difficult to follow and fully understand.

The added value is that the engineers on the team may be more comfortable with this way of applying professional judgment. The downside is that it is often presented as a more rigorous methodology than the other approaches outlined in the PIEVC Protocol. This is not true. There are very few situations where the assessment team will have sufficient data to avoid professional judgment, and it is highly unlikely that the team will have sufficient data for future conditions to draw sound calculation-based conclusions.

We also noted that studies relying strictly on analytical methods for assessing probability and severity scores might be underestimating overall risk scores. These studies might miss potential circumstances that have not been observed historically and therefore do not have a strong numerical basis for their estimation. That is, what has not been historically observed is not considered as a potential risk.

The essence of risk management is the identification of hazardous conditions *before* they actually occur in order to mitigate the impacts of those hazards. This causes a dilemma. The events that are most likely to cause previously unidentified failures are the very same events for which teams will have no numerical data to use computational methodologies.

The flip side of this issue is that teams that rely solely on professional judgment might overlook robust data based on historical events. In such cases it is possible that the assessment may overestimate risk profiles.

Recommendation:

- **It is important that vulnerability assessments strive for a balance between strictly analytical or strictly judgment based processes. Professional judgment can provide greater insight into the implications of quantified risks and numerical analysis can provide assurance that professional judgment is based on real, quantifiable, hazards.**

3.2.4 Sequences and Combinations of Weather, Terrain and Topography are Important

Our review highlighted that the risks associated with HISD events could be significantly exacerbated by sequences of events or events occurring in combination.

There are many different sequences and combinations of events that can aggravate the impact of HISD events. However, these sequences and combinations can be generalized into two overarching categories:

1. Combinations of Weather Events and Physical Conditions

In our review of case studies we noted that debris flow could significantly increase the impact of an HISD event. Assessment teams would often contemplate the sequences of events that could lead to these high debris flow situations. Contributors included:

- High wind events that contribute both natural and man-made detritus to streams and rivers;
- Forest fire kill increasing char, ash and tree branches in streams and rivers; and
- Mountain Pine Beetle kill contributing dead trees and debris.

When materials from these and other sources wash into ditches, streams and rivers during HISD events, the combination of very high water flows and debris can block culverts, drainage appliances and bridge abutments, which may have otherwise managed the water volumes arising from the event.

Such situations are an amalgamation of weather and non-weather factors that combine to create high-risk conditions for drainage infrastructure systems.

2. Sequences and Combinations of Weather Events

Assessment teams studies found that HISD event could be exacerbated by sequences and timing of weather events.

For example, HISD events accompanied by high wind and hail could combine debris, hail and large volume of water, resulting in drainage clogging and reduced overall capacity. This is especially the case when the mechanism driving the event is convection. The combination of high intensity rainfall, wind and hail can complicate drainage issues. Wind creates more debris. Hail clogs drainage appliances.

The assessments also considered the sequencing of precipitation events. For example, while a drainage system could accommodate long periods of low to medium intensity rain, the teams concluded that when an HISD event follows such periods, drainage systems could be overwhelmed. The prolonged period of low to medium intensity rainfall saturates the ground, resulting in very low permeability. When the HISD event occurs, the ground cannot

absorb any more water, resulting in much larger overland water flows than may have been considered in the drainage system design.

Sometimes, the studies evaluated these matters in detail while in other cases they were raised as a subjective qualifier of risk exposure estimates. In any case, there is an emerging theme of sequence and combination events compromising drainage infrastructure capacity leading to increased vulnerability to HISD events.

Finally, we noted that there are occasions where combinations or sequences could potentially provide opportunities to reduce risks. For example, in some studies drought was identified as a high-risk issue and HISD events were also identified. In these situations, infrastructure owners have opportunities to inspect, maintain, repair or upgrade drainage appliances during dry periods so that the infrastructure would be better equipped to deal with the HISD event when it ultimately occurred.

Recommendations:

- **Simply relying on IDF curves may not be sufficient. It is also important to take weather factors such as wind, hail, and rain on snow into account. These are contributing factors can overwhelm water management and drainage appliances that have been designed using only IDF curve information. Design should also consider:**
 - **The physical nature of the watershed including terrain and topography (or changes in this),**
 - **External factors such as Mountain Pine Beetle and forest fire can contribute to debris flows or clogs that can seriously compromise infrastructure.**

4 Conclusions

1. Every vulnerability assessment report that we reviewed identified HISD events as risk factors affecting infrastructure systems designed to manage water flow. These impacts were observed in every region we considered. Without exception, the climate projections prepared for the vulnerability assessments projected increases in HISD events
2. This review very clearly exposed the need for high-quality, locally relevant climate information
3. Climate projections are much more robust when based on larger ensembles of climate model runs or on specifically chosen ensembles. Obtaining robust climate projection information for any one particular project could be expensive presenting a significant barrier to smaller organizations contemplating vulnerability assessment work. Climate information providers are working on providing users with relevant data for decision making
4. Climate experts from outside of a study region might overlook or underestimate the impact of unique local weather phenomena
5. Some jurisdictions may still be using very dated climate information in their day-to-day engineering, operation and maintenance activities
6. There is a common misconception that risk review processes based on computational approaches are more robust and reliable than other, more judgment-based, methodologies
7. The risks associated with HISD events could be significantly exacerbated by sequences of events or events occurring in combination

5 Summary of Recommendations Identified in the Analysis

The nine recommendations identified by our analysis outlined above are reiterated below. These recommendations are identical to those identified within each section of the report, but we have gathered them to facilitate a holistic understanding of the possible interrelationships between the various recommendations.

1. BCMoTI should continue to evaluate the impact of HISD events on BC's highway infrastructure and update Ministry Technical Bulletins accordingly
2. As the PIEVC database of case studies grows, Engineers Canada should implement a broader synthesis review assessment covering all infrastructure types and the entire range of climate change risk drivers across Canada
3. As climate projections evolve PIEVC vulnerability assessments should be reviewed and updated to capture any evolving risk drivers.
4. Given the high incidence of infrastructure vulnerability to HISD events, these events should be included in every PIEVC vulnerability assessment or, when excluded, the practitioner should provide written rationale for this decision
5. It is important to establish repositories of regionally relevant, robust, climate and weather information and make that information generally available to practitioners. It is not sufficient that agencies generate and compile the information; it must also be user accessible and understandable to others besides climate specialists
6. It is important to filter climate information through locally relevant climate and weather expertise. A local expert may apply their knowledge, or climate information may be ground truthed through local residents that have a physical, holistic, understanding of local weather conditions
7. Engineering, operations and maintenance practices must be based on the most up-to-date climate information including relevant climate projections. Reliance on old information will increase the risk of water management and drainage system failure
8. It is important that vulnerability assessments strive for a balance between strictly analytical or strictly judgment based processes. Professional judgment can provide greater insight into the implications of quantified risks and numerical analysis can provide assurance that professional judgment is based on real, quantifiable, hazards.
9. Simply relying on IDF curves may not be sufficient. It is also important to take weather factors such as wind, hail, and rain on snow into account. These are contributing factors can overwhelm water management and drainage appliances that have been designed using only IDF curve information. Design should also consider:

- The physical nature of the watershed including terrain and topography (or changes in this),
- External factors such as Mountain Pine Beetle and forest fire can contribute to debris flows or clogs that can seriously compromise infrastructure.