Climate Change Implications on Pervious Concrete Pavement Design in Canada

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Abstract

Future changes in precipitation and extreme flood events represent risks for urban infrastructures in Canada. Pervious concrete pavements (PCP) are normally designed to reduce the runoff water and avoid urban flooding as a stormwater management solution. As a result, it is important to adapt PCP design to changing climate by considering site-specific projected storm intensities and durations. In this study, first, a series of sensitivity analysis were performed using PerviousPave software to test the robustness of its structural and hydrological models. Secondly, projected data from simulated Intensity Duration Frequency (IDF) curves were incorporated in PerviousPave software to investigate the relative impact of climate change on the PCP's hydrological design. Integrating future trends in storm intensity with hydrological design offered a more efficient use of PCP for stormwater management in urban developments.

Introduction

Extreme precipitation events are expected to increase in Canada due to climate change. In general, it is anticipated that an extreme event which currently occurs once in 20 years may happen about once in 5 years by late century under a 'business-as-usual' GHG emission scenario. That is to say, an extreme precipitation of a certain magnitude is expected to become more frequent. Also, the precipitation magnitude with a certain recurrence interval is expected to increase. In other words, the amount of 24-hour extreme precipitation which occurs once in 20 years on average is projected to increase as much as 25% by late century under a 'business-as-usual' GHG emission scenario [1]. Occurrence of these extreme events in view of climate change will have a bearing on transportation infrastructure in form of more frequent and intense rainfalls or downpours from thunderstorms.

In light of future changes in precipitation and higher risk of flooding, it is necessary to adapt urban infrastructure design, accordingly. To date, many locations around the world have used Pervious Concrete Pavements (PCP) in parking lots, walkways and city streets with low truck traffic to reduce rainwater runoff and to maximize groundwater recharge while maintaining a highly unsaturated surface. Although PCP is deemed to not be as strong as conventional rigid pavement from the mechanical properties point of view, its benefits in terms of stormwater management and low-impact on environment are undoubtedly most obvious. PCP has shown high promise in physical, chemical and biological storm water purification, as well. In physical purification mechanism, most of the solid suspended particles are removed from the stormwater owing to the sinuous/curvaceous paths in the internal structure of PCP. Through chemical purification, pollutants are precipitated due to their reaction with hydroxide ions and carbonate ions which were released during concrete contact with polluted water. Finally, microbial activities which occur in PCP voids can consume and dissolve the suspended materials [2]. Previous studies in Canada [3, 4] have also indicated promising results with both laboratory and field performance of PCP.

Currently, unlike for traditional rigid pavement systems, there exist only very limited standard design procedures and response analysis methods for PCP systems. Among very few available ones, PerviousPave software [5], developed by American Concrete Pavement Association (ACPA), provides structural and hydrological design solutions for several applications including parking lots. In PerviousPave, concrete surface thickness is calculated based on the anticipated traffic loads, service life and site factors. On the other hand, PerviousPave determines the minimum subbase/reservoir thickness required to meet stormwater management goals, considering the volume of stormwater to be processed by PCP within the allowable detention time. In a study conducted by Rodden et al., thickness designs recommended by PerviousPave were successfully validated against those of other existing means [6].

While historical rainfall intensity-duration-frequency (IDF) curves are considered as the most important inputs for hydrological design of the PCP systems, under changing climate conditions and future emission scenarios also known as Representative Concentration Pathways (RCP), historical/observed IDF curves may not be valid to guarantee optimum hydrological performance of PCP. Consequently, it is crucial to understand how deviation from observed precipitations may relatively influence the PCP hydrological design.

Methodology

All analysis in this study was carried out using ACPA's PerviousPave software. First, to capture the impact of different structural and hydrological variable on a typical PCP design (Figure 1), a sensitivity analysis was initially conducted, according to the range of parameters outlined in Table 1. Next, to understand the implications of climate change on PCP hydrological design, a series of analyses using the obtained data from web based IDF_CC tool [7] were undertaken to optimize the reservoir layer thickness. To account for the possible impact of climate change on planning, designing and construction of PCP, projected IDF curve information from IDF_CC tool were used for multiple Canadian cities. IDF_CC tool predicts the IDF curves based on provided historical observed data combined with data from Global Circulation Models (GCMs) for future scenarios. Table 2 shows the locations within specific regions which were selected in this study. It is worth noting that all selected stations were defined under gauged locations module with different recorded data availability situations.

Sensitivity Analysis

Figure 2 shows the sensitivity of predicted Fatigue Damage (*FD*) to *ADTT* at different growth rates based on PerviousPave's default axle types and load groups for parking lot applications. It should be stressed that a design reliability factor of 80 percent and a design life of 20 years were assumed in all case. As illustrated in Figure 2, higher number of load applications can significantly affect the fatigue performance of the PCP due to relatively low flexural strength of the pervious concrete. Within examined range of *ADTT* when growth rate is the highest, *FD* may vary as high as 65 percent. Therefore, truck loading in excess of the design traffic has the potential to remarkably reduce the structural integrity of the PCP. It must be further realized that the anticipated growth rate and future development in the vicinity are particularly substantial in structural design of the PCP.

In addition, flexural strength of pervious concrete, stated in terms of 28-day modulus of rupture (*MR*), is a key factor in fatigue life prediction. In fact, allowable number of traffic repetitions to failure (N_f) is associated with the Stress Ratio (*SR*) parameter which is defined as equivalent stress divided by modulus of rupture. Thus, *FD* will be greatly affected depending on the *MR* value, as shown in Figure 3. It was found during the course of sensitivity analysis that increasing *MR* value within specified range can reduce the fatigue damage near 60 percent. Another key design parameter is the composite static modulus of support (k-value) for a system of subbase/subgrade. Mainly, it is important to initially estimate the composite k-value based on anticipated reservoir/subbase layer properties and then adjust the k-value for the selected reservoir/subbase thickness as determined via hydrological analysis. Table 3 shows examples of k-value outputs internally calculated by the software while considering one layer of granular subbase layer having a typical resilient modulus of 150 MPa on top of three subgrade types. These k-values correspond to combinations of subbase layer thicknesses and subgrade resilient moduli as independent values. It is should be emphasized that the built-in composite k-value calculator in PerviousPave functions very differently than the commonly-used AASHTO 1993 procedure (i.e. constant conversion factor of 19.4). Figures 4 and 5 show the predicted *FD* at different subgrade resilient modulus levels and different subbase resilient modulus levels, respectively. As can be seen, increasing the subgrade resilient modulus from 20 to 35 MPa led to reduction in *FD* by almost 45 percent. Although higher compaction may improve the resilient modulus of the subgrade soil, it can adversely affect the hydrological performance of PCP by reducing soil infiltration rate. On the other hand, the sensitivity of *FD* to subbase resilient modulus was not found to be as high as that of the subgrade resilient modulus. Thus, in case of lower strength subgrade soils, thicker or stabilized subbase may be required to fortify the support condition.

Hydrological Analysis

In PerviousPave, the required subbase thickness to meet stormwater needs is determined based on the Los Angeles County Method [5]. Depending on site factors, design storm type expressed in terms of return period and duration will dictate the required subbase thickness, while maintaining water detention time within acceptable range. Equations (1) to (4) indicate the embedded formula in the software to calculate the subbase thickness and water detention time.

$$h_s = \frac{1}{r_s}\left(\frac{12\,V}{A_p} - h_{curb} - r_c h_c\right) \qquad \text{Equation (1)}$$

$$V = (A_p + A_b)\frac{I}{12} \qquad \text{Equation (2)}$$

$$h_s = \frac{1}{r_s}\left(\left(1 + \frac{A_b}{A_p}\right) I - h_{curb} - r_c h_c\right) \qquad \text{Equation (3)}$$

$$E \times t_d = h_{curb} + r_c h_c + r_s h_s \qquad \text{Equation (4)}$$

In which, h_s is the thickness of subbase layer (in.), r_s is the void ratio of subbase layer (%), V is the volume of water (ft^3), A_p is the pervious concrete area (ft^2), A_b is the impervious area (ft^2), r_c is the void ratio of pervious concrete (%), h_c is the thickness of pervious concrete (in.), h_{curb} is the curb height (in.), t_d is the detention time of water (hr), E is the permeability rate of soil (in./hr) and I is the storm intensity (in.).

Commonly, the storage capacity contributions from concrete layer and curb height are not taken in to account in wet-freeze climates. Assuming that the pervious subbase with a typical void ratio of 40% will fully provide the required water storage, Equations (3) and (4) can be simplified to Equations (5) and (6), respectively.

$$h_s = 2.5\,(1+R)I \qquad \text{Equation (5)}$$

$$t_d = \frac{(1+R)I}{E} \qquad \text{Equation (6)}$$

In which *R* is the ratio of impervious area to pervious area in the facility. With this assumption, the sensitivity of required subbase thickness to storm intensity at different *R* values was analyzed as shown in Figure 6. It is evident from Figure 6 that the volume of water to be processed will particularly increase at higher storm intensities and higher R-values. Also, Figure 7 shows the sensitivity of water detention time to different soil permeability rates at the reference storm intensity of 70 mm. As can be seen in Figure 7, the water detention time in PCP before complete drawdown of the entire captured water volume can be significantly higher in the areas of low permeability soils. Normally, it is desirable to discharge the stored water within 24 hours after runoff cessation [3].

Climate Change Implications

To evaluate the impact of climate change on hydrological design of PCP, 24-hr precipitation data for 2-year and 10-year storm events were extracted from IDF_CC tool as shown in Figure 8 (a) and (b). Besides the baseline case, the projected precipitation data were derived from RCP 8.5 under two 30-year analysis cycles in future reflecting short-term (2020-2049) and long-term (2050-2079) impacts for RCP 8.5 or 'business-as-usual' scenario. As seen in Figure 8(a) and (b), the amounts of 24-hr precipitation presented in mm are generally expected to rise in future, which indicates the probability for increased storm water volume and surface runoff. Among seven selected locations, maximum amounts of 24-hr precipitations under the baseline and future scenarios were noted at City of St. John's for both 2-year and 10-year storm events.

To meet the hydrological aims of the PCP with respect to runoff reduction and water quality improvement, the pervious subbase needs to adequately store the heavier flow in view of climate change. Assuming that the minimum required concrete thickness to service the traffic loads is determined by structural design algorithm, optimized subbase thicknesses combined with other necessary mitigation techniques can provide more storage volume below concrete in order to ensure that projected stormwater needs are met. Also, it is important to satisfy the water detention time requirements given the subgrade soil permeability rate. By assuming subgrade permeability of at least 10 mm/hr, the minimum required subbase thicknesses for different *R* values and climate scenarios were determined using the software, as summarized in Tables 4 and 5. In all calculations, the subbase void ratio was considered as 40 percent (default value) and no storage capacity was included for concrete surface and curb height (zero ponding). It is clear that replacing impervious areas with pervious areas is an alternative to reduce the required subbase thicknesses.

In summary, there are major benefits associated with capturing more urban runoff based on local design goals in view of climate change in Canada. Larger volumes of PCP-processed water may contribute to enhanced groundwater supply and quality. Therefore, adapting PCP hydrologic design methods to climate change conditions by employing updated IDF curves at the local level can improve water conservation practices. Besides, preventing future floods by means of climate-adapted PCP design can help reduce safety risks, infrastructure damage and facility access disruption.

Conclusions

In the study presented herein, a series of sensitivity analysis were carried out to evaluate the structural and hydrological models in ACPA's PerviousPave software against a range of key design parameters. Examining sensitivity of the models to change in mechanical, climatic and site-related properties provided insight into the importance of each tested variable. More so, a series of scenario analysis were conducted to investigate the implications of heavier and more frequent precipitation events on hydrological design of PCP in view of climate change for seven cities in Canada. Using projected IDF curves generated from IDF_CC tool, relative increase in required subbase thickness was calculated to accommodate for future extreme events. Results of this study suggest a heavier emphasis on environmental aspects of PCP in terms of urban stormwater management. Future work could develop more robust infiltration and drainage models in order to enhance hydrological simulation of PCP.

Acknowledgments

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TABLES

Table 1: *Input parameters used in sensitivity analysis*

Analysis	Parameter	Range	Reference Value
Structural	ADTT	2 -7	2
	Growth Rate (%)	1,2 and 3	2
	Modulus of Rupture (MPa)	3.6, 3.8, 4.0 and 4.2	4.0
	Subbase Resilient Modulus (MPa)	100, 150, 200 and 250	150
	Subgrade Resilient Modulus (MPa)	20, 25, 30 and 35	30
Hydrological	Storm Intensity (mm)	40, 50, 60, 70, 80, 90 and 100	70
	Ratio of Impervious to Pervious Area (*R*)	0.50, 0.75, 1.0, 1.25 and 1.50	1.0
	Soil Permeability (mm/hr)	10, 20, 30, 40 and 50	30

Table 2: *Selected stations for climate change analysis*

Region	City	Station ID	Lat.	Long.	Number of Years with Recorded Data
Atlantic	St. John's, NL	8403506	47.62	-52.74	35
Central	Montréal, QC	702S006	45.47	-73.74	61
	Toronto, ON	6158731	43.68	-79.63	64
Prairies	Calgary, AB	3031094	51.11	-114.00	61
	Regina, SK	4016560	50.43	-104.67	52
	Winnipeg, MB	502S001	49.92	-97.25	57
West Coast	Vancouver, BC	1108395	49.19	-123.18	63

Table 3*: Calculated composite static k-value from PerviousPave*

Resilient Modulus of Subgrade (MPa)	Granular Subbase Layer Thickness (mm)			
	100	**150**	**200**	**250**
10	23	26	30	33
30	61	66	70	75
50	96	100	105	111

***Table 4:** Subbase/Reservoir Layer Thickness* (mm) for 2-Year Strom Event*

City	**Analysis Cycles**								
	Baseline			**2020-2049**			**2050-2079**		
	R=0.5	**R=1.0**	**R=1.5**	**R=0.5**	**R=1.0**	**R=1.5**	**R=0.5**	**R=1.0**	**R=1.5**
Calgary	140	190	240	150	200	250	160	210	270
Montreal	180	240	300	190	260	320	200	280	350
Regina	150	200	250	160	220	270	160	220	270
St. John’s	240	320	400	270	360	450	290	390	480
Toronto	170	230	280	190	250	310	200	260	330
Vancouver	190	260	320	200	270	330	220	290	360
Winnipeg	190	250	310	200	270	330	200	270	340

* Assuming subgrade soils with permeability of at least 10mm/hr for 24-hr maximum detention time

Table 5: Subbase/Reservoir Layer Thickness* (mm) for 10-Year Strom Event

City	**Analysis Cycles**								
	Baseline			**2020-2049**			**2050-2079**		
	R=0.5	**R=1.0**	**R=1.5**	**R=0.5**	**R=1.0**	**R=1.5**	**R=0.5**	**R=1.0**	**R=1.5**
Calgary	240	310	390	250	340	420	270	360	450
Montreal	260	340	430	280	370	460	320	420	520
Regina	280	370	460	290	390	490	310	410	510
St. John’s	320	430	530	350	470	590	370	500	620
Toronto	270	360	450	300	390	490	310	420	520
Vancouver	270	360	450	290	380	480	310	410	510
Winnipeg	280	370	470	300	400	500	320	420	530

* Assuming subgrade soils with permeability of at least 10mm/hr for 24-hr maximum detention time

FIGURES

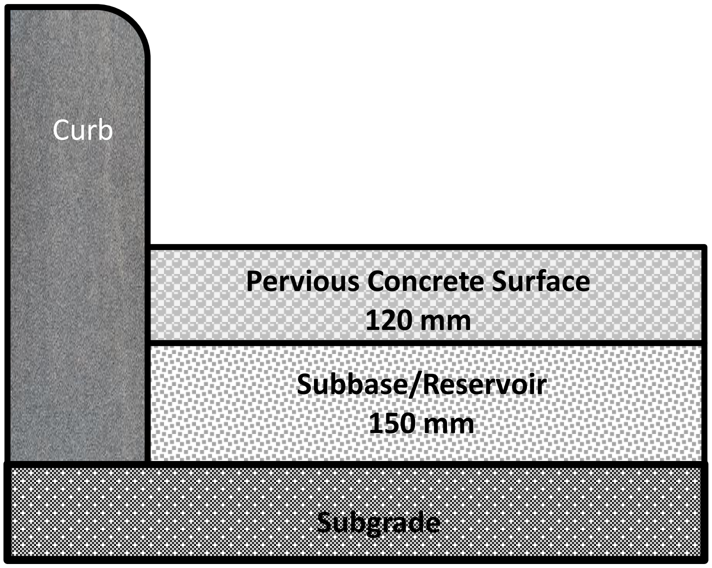


Figure 1: *PCP structure used for sensitivity analysis*

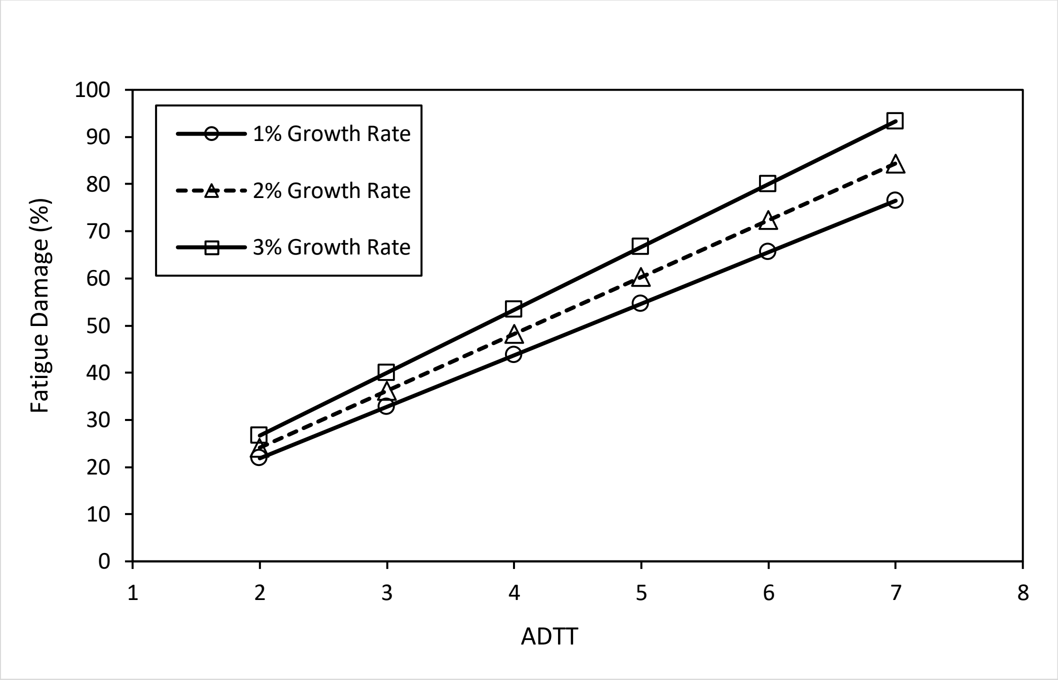


Figure 2: *Sensitivity of fatigue damage to traffic loading*

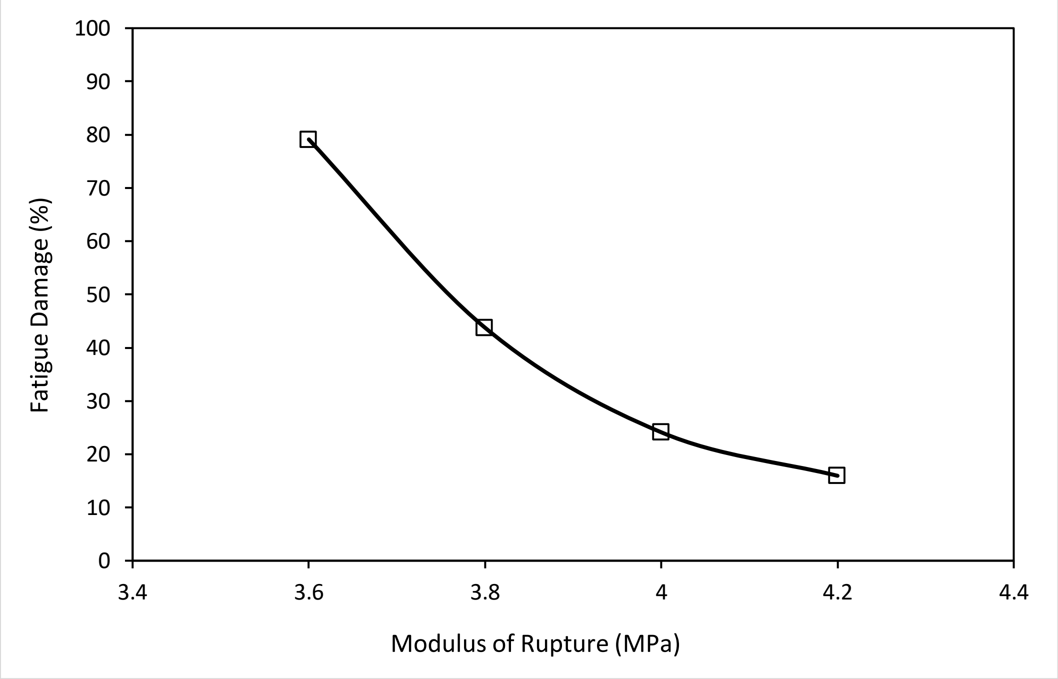


Figure 3: *Sensitivity of fatigue damage to flexural strength*

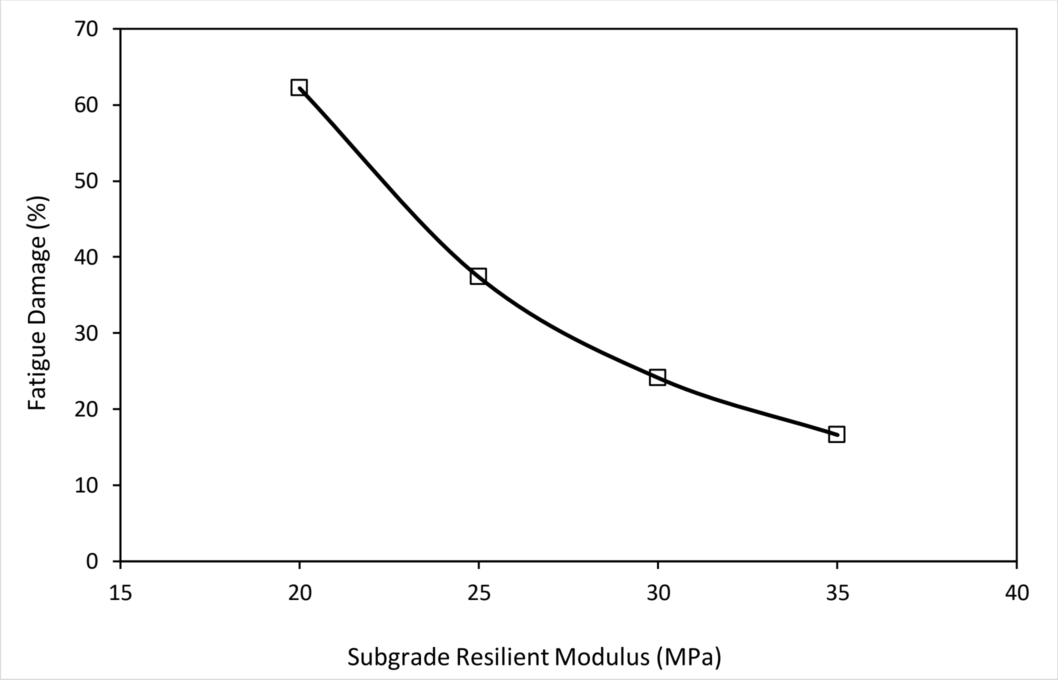


Figure 4: *Sensitivity of fatigue damage to subgrade resilient modulus*

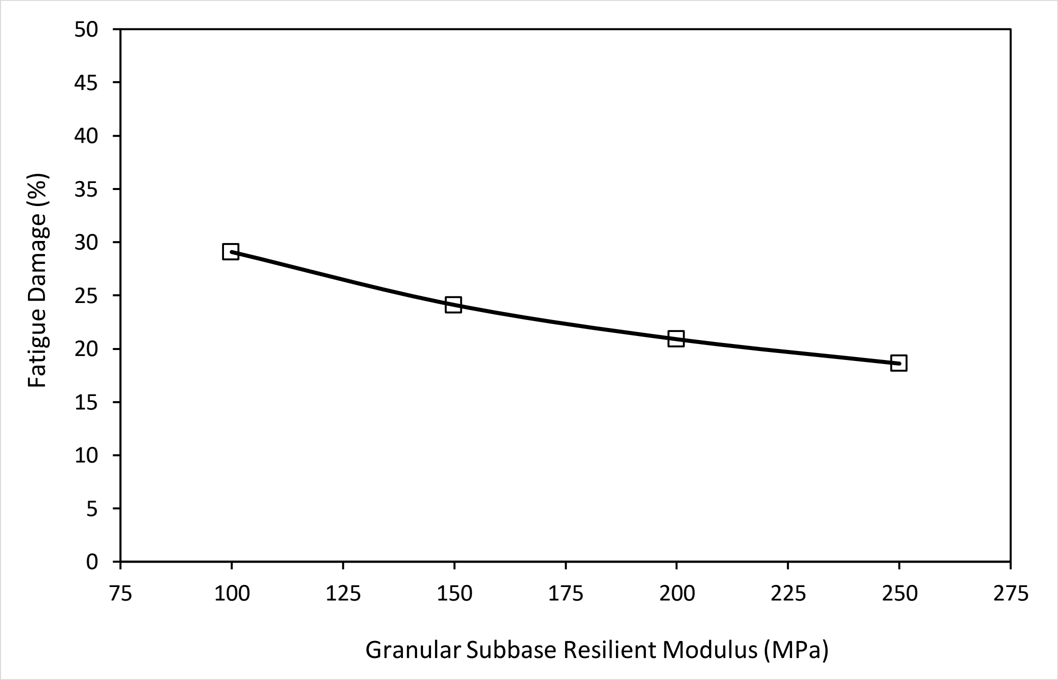


Figure 5: *Sensitivity of fatigue damage to subbase resilient modulus*

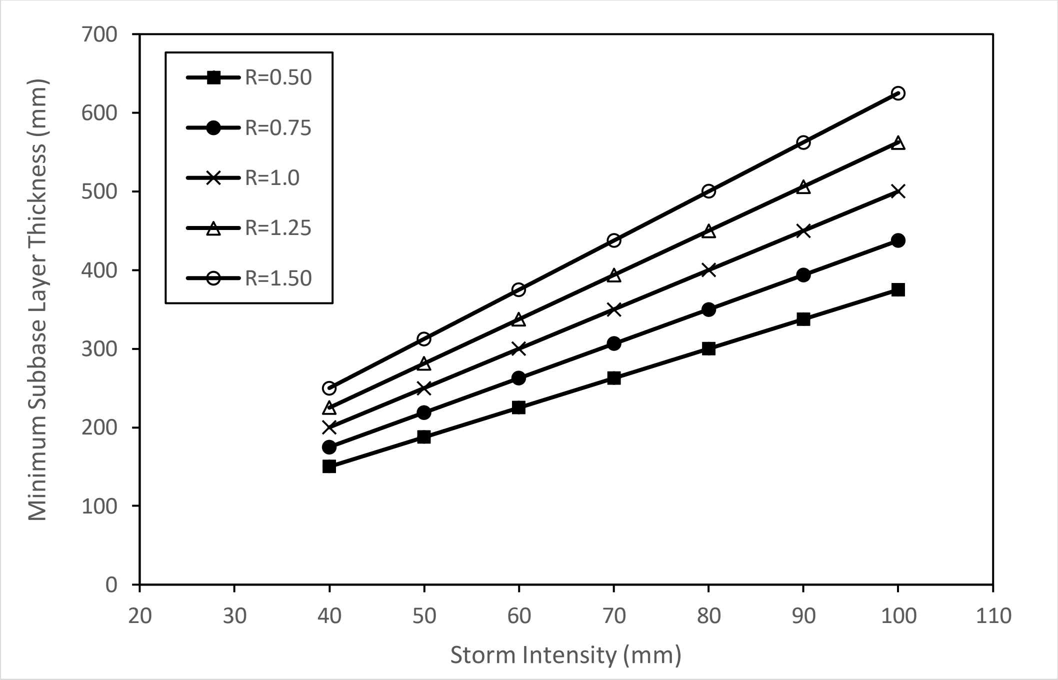


Figure 6: *Effect of site factors on minimum subbase thickness*

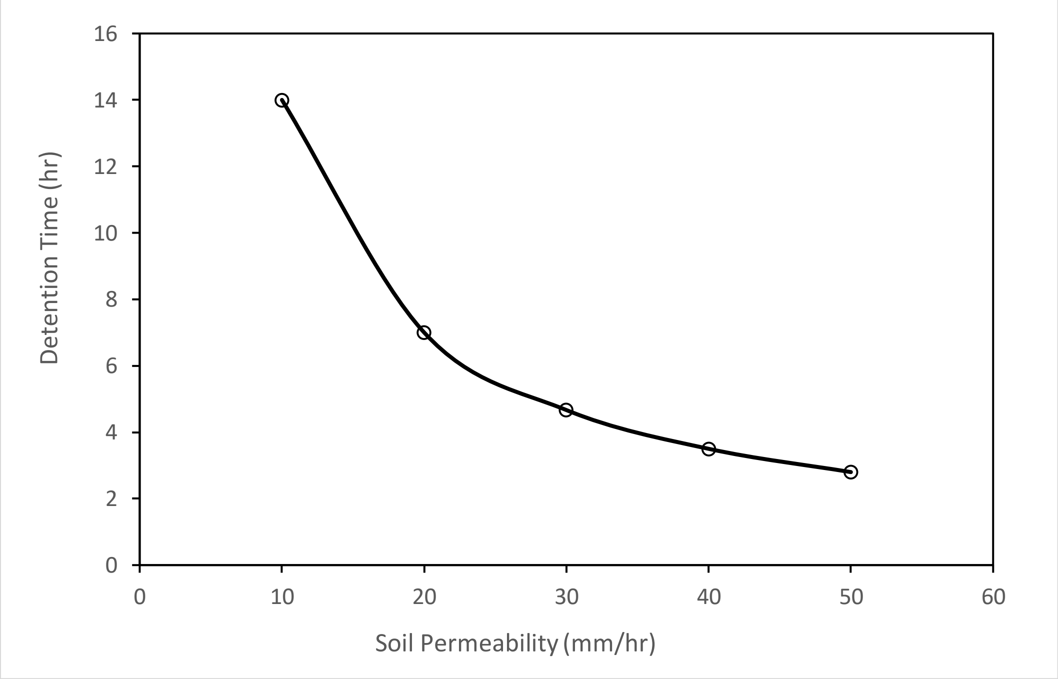
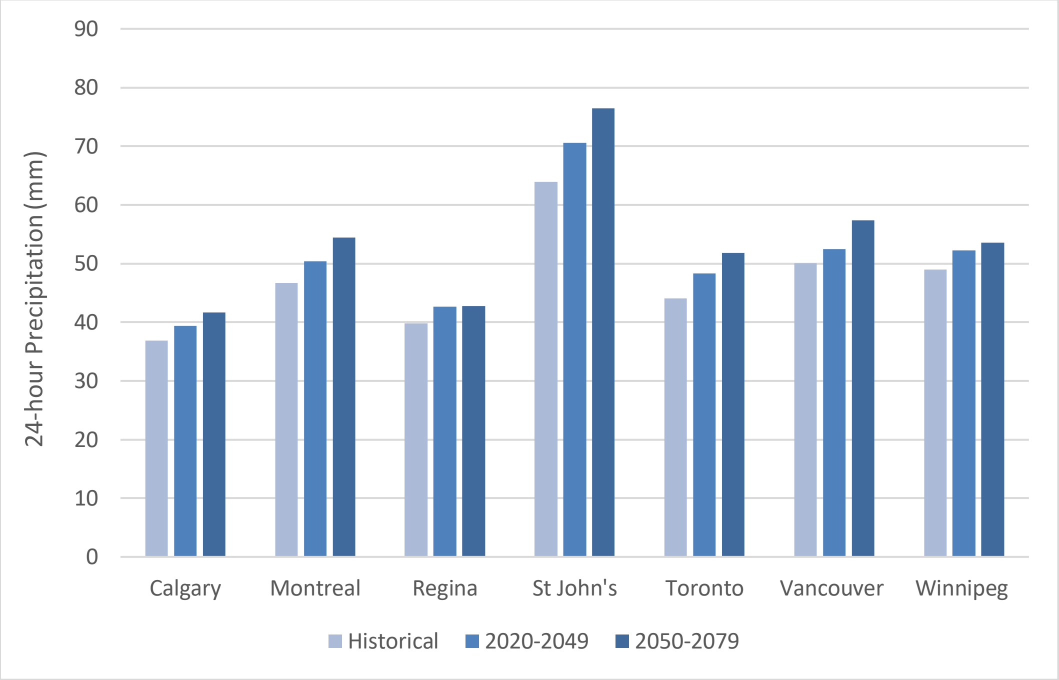
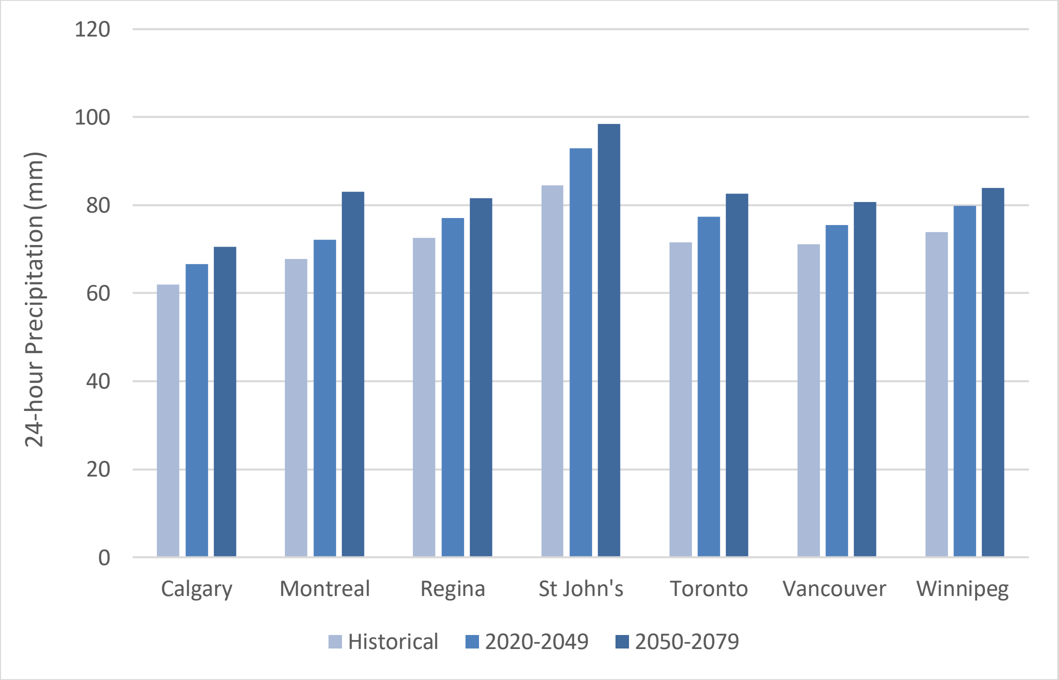


Figure 7: *Effect of soil permeability on water detention time*



(a)



(b)

Figure 8*: 24-hour Precipitation for* ***(a)*** *2-year storm and* ***(b)*** *10-year storm under RCP 8.5 scenario*