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Recent comprehensive risk assessment projects conducted by the Canadian Conservation Institute have shown that, under certain conditions, risks associated with hazards such as fire, earthquake and tornado rank as priority risks relative to all other risks facing heritage collections. Risk analysis using the ABC Method based on incidence and severity data, or on an expert model that relates specific features and behaviours (control levels) with the degree of damage to the collections, can help identify factors that generate Magnitude of Risk scores categorized as High to Extreme for such events. Flood risk scores at least in the High category if collections are stored below or on grade in locations at risk of overland flooding, storm surge or tsunami. Fire risk falls in the Extreme category for collections in combustible or fire-resistive buildings that lack automatic fire detection or suppression and exhibit poor compartmentation, and in many buildings at the wildland-urban interface. Earthquake is categorized as an Extreme risk in non-seismically stable buildings in regions prone to violent or extreme shaking, or as a High risk when the building is stable but storage and display fittings lack seismic protection in regions at risk of at least very strong shaking. Physical damage due to severe winds would score as a High risk in many building types in regions at risk of Category 3–5 hurricanes or EF3–5 tornadoes even when the chance of a direct hit is small. When such disaster risks are categorized as High to Extreme, mitigation is highly recommended and may be cost-effective. Reducing the likelihood of the hazard may be difficult or impossible; therefore, facility improvements that reduce negative consequences on collections during an event are recommended, in addition to preparations for effective response and recovery.

De récents projets d'appréciation exhaustive des risques menés par l'Institut canadien de conservation ont montré que, dans certaines conditions, les risques associés à des dangers comme les incendies, les séismes et les tornades sont prioritaires comparativement aux autres risques auxquels sont exposées les collections patrimoniales. L'analyse des risques à l'aide de la méthode ABC, basée sur des données liées à la fréquence et à la gravité des risques ou sur un modèle spécialisé qui met en rapport des caractéristiques et comportements précis (niveaux de contrôle) avec l'ampleur des dommages subis par les collections, peut aider à déterminer les facteurs qui entraînent des scores de magnitude du risque de catégorie « Élevé » à « Extrême » pour les dangers susmentionnés. Le score de risque pour une inondation est considéré au minimum comme « Élevé » si les collections sont entreposées au niveau du sol ou en dessous dans des endroits où il y a un risque d'inondations terrestres, d'ondes de tempête ou de tsunami. Quant au risque d'incendie, il est classé comme « Extrême » pour les collections dans des bâtiments de construction combustible ou incombustible qui sont sans dispositif de détection automatique d'incendie ou système d'extinction d'incendie automatique et qui ont un mauvais compartimentage, ainsi que dans de nombreux bâtiments en milieu périurbain. Le risque associé aux séismes est considéré comme « Extrême » lorsque les collections sont dans des bâtiments non parasismiques dans des régions faisant l'objet de secousses violentes ou extrêmes. Il est jugé « Élevé » lorsque le bâtiment est parasismique, mais que ses installations d'entreposage ou d'exposition n'offrent aucune protection contre les tremblements de terre dans une région où il pourrait y avoir au moins de très fortes secousses. Le risque de dommages matériels causés par des vents violents est « Élevé » pour de nombreux types de bâtiments situés dans des régions où pourraient se produire des ouragans de catégorie 3 à 5 ou des tornades de catégorie 3 à 5 (échelle de Fujita amélioré), même si la probabilité de dommages directs est faible. Lorsque le risque de catastrophe est classé d'« Élevé » à « Extrême », la prise de mesure d'atténuation est fortement recommandée et peut être rentable. Il pourrait toutefois être difficile, voire impossible, de réduire la probabilité de danger. On recommande donc d'améliorer les installations de façon à réduire les conséquences négatives qu'un phénomène pourrait avoir sur les collections et de planifier des mesures d'intervention et de rétablissement en cas d'incident.

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INTRODUCTION

Resources to maintain and care for cultural heritage are always limited. Disasters, which are by nature rare events, are not likely to affect an individual institution during the career of many heritage professionals. As a result, the risk of such events may not get sufficient attention until the disaster occurs.

In 2013, southern Alberta experienced widespread flooding. The Town of High River, located 70 kilometres south of Calgary, was flooded severely and fully evacuated. The Museum of the Highwood and its off-site collection storage were both flooded. Because re-entry to the town was controlled by emergency management officials, access to the museum facilities for the purpose of collection salvage did not occur until two weeks after basement storage spaces were filled with water. The loss to the collection due to this flood was staggering. Only about 30% of the collection artifacts were salvaged.[1] To make the loss even more emotionally devastating, the collection had just recently been moved into off-site storage space in the Highwood Memorial Centre, a community centre owned by the Town of High River, after a fire three years earlier made storage in the attic of the museum's main building – the town's former railway station – no longer advisable. That fire resulted in the total loss of only a few artifacts, although many more were damaged by smoke and soot.

The risk of flooding of below grade spaces at the location chosen for this new off-site storage had been documented, although it was not widely understood. The provincial flood risk map of downtown High River at the time located the Highwood Memorial Centre within the 100-year flood fringe of the Highwood River.[2] How was it that museum staff did not have strong enough arguments to prevent a move into this location, which was not their preferred storage solution?

In this case, an institution with a collection in danger of damage from overland flooding did not fully understand the risk of an event expected "once in 100 years," or, stated more accurately, an event having a 1% chance of occurring each year, which means it could occur again in any year. How can those of us responsible for heritage preservation identify when institutions are at greater risk of such potentially disastrous loss? Perhaps more importantly, how can we provide such institutions with effective arguments to support sometimes costly mitigation measures?

This paper applies what has been learned through risk assessment to build an approach to screening for "disaster risks" as a first step towards understanding and effective mitigation. A number of risks to heritage collections are experienced as emergencies: sudden events with the potential to cause damage that require immediate action.[3] Heritage institutions often address such risks in an emergency response plan. Implementing the procedures described in such plans may lessen the consequences of an emergency incident through quick, appropriate response and collections salvage, and in certain contexts, evacuation of collection items in advance to a safer location. When the consequences of a hazard are localized or a building is designed to lessen its impact, reliance on an emergency plan for further risk reduction may provide a reasonable level of care. In certain contexts, however, emergency risks are likely to result in "disaster," or "a great or sudden misfortune," as the word is commonly defined.[3] In the context of risks to heritage collections, the potential for loss of heritage value is significant: considerable loss of or damage to the physical materials that embody the aesthetic, historic, evidential and communal significance[4] of collection objects is expected. Even if a heritage institution has an up-to-date emergency plan in place (and many do not[5]), the procedures may not adequately address response needs for major incidents, many of which affect the wider community, not just the institution. The discussion below presents an approach to identifying the circumstances in which certain hazards – fire, floods, earthquake and extreme winds – ought to be classified as disaster risks for heritage institutions, risks that demand more than just a good emergency response plan.

Analyzing Risks Using the ABC Method

Between 2010 and 2017, the Canadian Conservation Institute (CCI) conducted risk assessment projects for five heritage institutions: two historic house museums, an art gallery, an archive and a science and technology museum. CCI uses the ABC Method[6] to analyze risks to collections, in which three components of risk are quantified for each identified specific risk, one for likelihood and two for the associated consequences:

A. How often will the event occur?

B. How much value will be lost in each affected item? and

C. How much of the heritage asset is affected?

Responses to each question are converted into a 5-step logarithmic scale where a maximum score of 5 out of 5 represents 1 year between events (question A), 100% loss of value per item (question B) or 100% of the current heritage asset value affected (question C). These scores are added together to give a Magnitude of Risk (MR) score on a 15-point logarithmic scale where the maximum score of 15 represents the risk of 100% asset loss in 1 year.[7]

The risk analysis process is based on evidence combined with experience-based judgement, using quantitative data, such as information from hazard maps and collection databases, whenever possible. Each risk analysis is supported by careful, detailed argument. Because the answers to questions A, B and C are uncertain, a low estimate and a high estimate are provided in each case, in addition to the most probable value suggested by the available evidence.[8] The probable, high and low scores for each question are averaged and then added to generate the expected Magnitude of Risk (MR expected) score[9] which better characterizes risks where uncertainty is not symmetrically distributed around the probable estimate.

The implications of the Magnitude of Risk scores are indicated by a colour-coded scale[10] from 5 (a Negligible risk) to 15 (a Catastrophic risk) (**Table I**). Like the Richter scale for earthquakes, this logarithmic scale permits easy comparison of risks of very different magnitude on a single graph, but may make differences between risks appear small (**Figure 1 left**). The difference in magnitude is better conveyed using a linear scale (**Figure 1 right**), which shows the Risk, or fraction of asset loss per year,[11] and indicates more forcefully how much more significant the higher risks are than those that score less.

ABC Scores of Emergency and Disaster Risks

Emergency risks can score across the ABC Method scale depending on the nature of the hazard and the effectiveness of mitigation measures in place. When the Magnitude of Risk scores and their associated priority categories are expressed in terms of equivalent percent loss of collection value per number of years (**Table I**), heritage professionals can begin to decide at what level emergencies should be considered disaster risks (**Figure 2**).

Emergencies that are assessed as Negligible or Medium priority risks (blue and green, $MR < 9.5$) would not be considered disasters. Such events result in trace to tiny overall loss to collections if they occur frequently: many objects may be very slightly damaged or a small fraction of those of average value completely destroyed. Significant loss across much or all of a collection, although this would be a disaster, is so rare as to be improbable. When defined in this way, one might agree that the level of care provided might be adequate. Improvements to reduce risks categorized as Medium or Negligible could be possible but could wait until higher risks are reduced. Meanwhile, accepting these risks, while maintaining any measures that control their magnitude, including well-developed emergency response procedures, might be considered sufficient.

Table I. ABC Method Magnitude of Risk scale with implications.[10]

Magnitude of Risk	Examples of Predicted Loss	Priority Category	Colour
15	100% loss every 1 year	Catastrophic	red
14	10% loss every 1 year 100% loss every 10 years		
13	1% loss every 1 year 10% loss every 10 years 100% loss every 100 years	Extreme	orange
12	1% loss every 10 years 10% loss every 100 years 100% loss every 1,000 years		
11	1% loss every 100 years 10% loss every 1,000 years 100% loss every 10,000 years	High	yellow
10	0.1% loss every 100 years 1% loss every 1,000 years 10% loss every 10,000 years		
9	0.1% loss every 1,000 years 1% loss every 10,000 years	Medium	green
8	0.01% loss every 1,000 years 0.1% loss every 10,000 years		
7	0.001% loss every 1,000 years	Negligible	blue
6	0.0001% loss every 1,000 years		
5	0.00001% loss every 1,000 years		

Emergencies that fall in the High risk category (yellow, $9.5 \leq MR < 11.5$) are characterized by predicted loss of greater concern. These Magnitude of Risk scores represent, for example, the total loss of 10 to 100 objects in a collection of 10,000 artifacts from an event likely to occur once every 100 years, or the loss of 100 to 1,000 objects from the same collection in an event that is expected once every 1,000 years. Events in this category that result in less than total loss would affect a larger fraction of the heritage asset. The level of collection care may seem reasonable, but improvements to reduce the risk are recommended. High risk emergency events could cause serious disruption. When the expected overall loss to the heritage asset for each event is significant, such emergencies would be considered disasters.

Most would agree that emergency risks at the Extreme priority level (orange, $11.5 \leq MR < 13.5$) can be considered disaster risks, since a significant fraction of heritage value is expected to be lost for events of any frequency. Included are risks that occur every 100–1,000 years that are expected to result in a 10–100% loss of heritage value. Risk reduction measures that reduce vulnerability to future events are highly recommended. Certainly Catastrophic risks (red, $MR > 13.5$) are not acceptable if heritage preservation is the goal and should be avoided. All value would be lost every few years to a few decades. Fortunately, such risks to heritage institutions have not yet been identified in Canada.

When emergency events are likely to occur relatively frequently – at least once every 30 years on average or a 3% chance each year (to the right of the dashed vertical line in **Figure 2**) – they may be captured within institutional records and/or memory. Staff may have experienced an emergency incident or at least heard of one from colleagues. Aware of the danger to collections, they have probably advocated for improved care, if they have

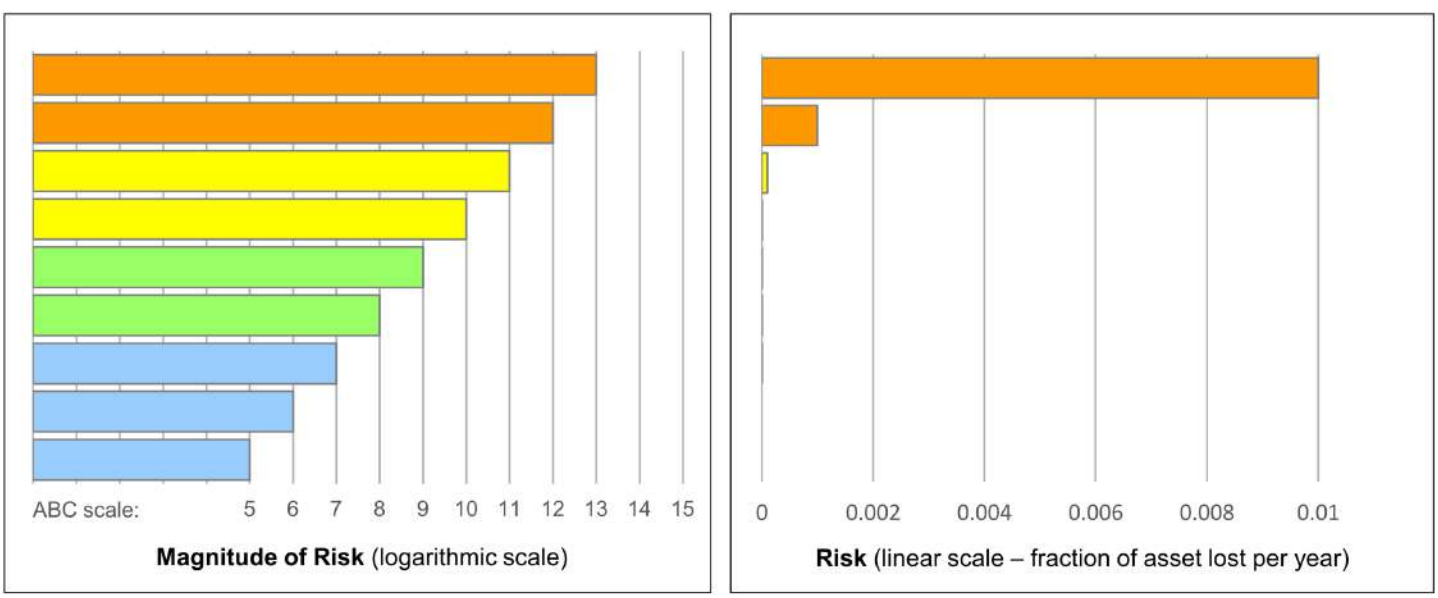

Figure 1. Relative size of risks generated by the ABC Method compared on logarithmic (left) and linear (right) scales.

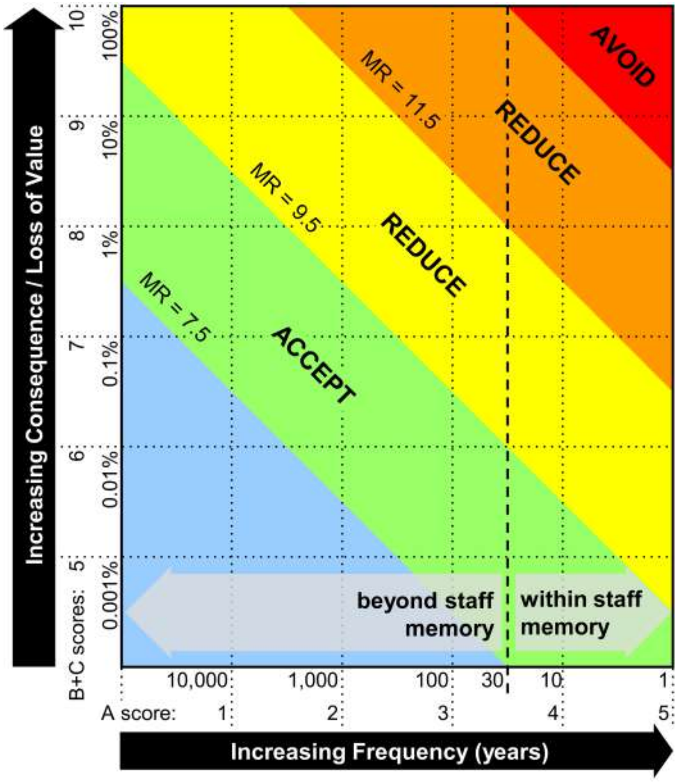

Figure 2. ABC risk categories shown as a function of event frequency (A score) and consequences (combined B and C scores) with recommendations for action in response to emergency risks. The dashed vertical line separates more frequent emergency events that staff are probably aware of and plan for from rare events which may be less well understood.

not yet implemented changes, perhaps due to lack of resources. Reasonable plans for emergency response may also be in place. Even if the frequency of the event remains unchanged, stop-gap mitigation measures would likely reduce the loss of heritage value, making it less probable that these are High to Extreme risks.

When such events occur less frequently (to the left of the dashed vertical line in **Figure 2**), staff may have a poor understanding of the risk and may be less well prepared. Of particular interest, therefore, are the contexts in which less frequent events have significant consequences, namely, High to Extreme disaster risks.

DISASTER RISKS IN CANADIAN HERITAGE INSTITUTIONS

The results of five CCI comprehensive risk assessments – projects that identified and analyzed all forms of loss to heritage collections – demonstrate that disaster risks due to fire, water, earthquake and severe weather are priorities for individual Canadian institutions (**Figure 3**). High to Extreme disaster risks are prominent in summary graphs for all five institutions.[12] The Magnitude of Risk scores for key hazards (e.g., earthquake) were calculated by adding the linear Risk scores from associated specific risks (e.g., damage to ceramics, damage to ceilings) (**Table II**).[13] The Magnitude of Risk scores were computed from the sum as follows:

$$\text{MR} = 15 + \log(\text{sum of the fractions of asset loss per year})$$
$$= 15 + \log(\text{sum of the individual Risks})^{11}$$

Disaster and emergency risks are coloured in **Figure 3** and **Table II** according to the priority level assigned to the Magnitude of Risk score by the categories of **Table I**. Non-emergency risks are indicated in grey in **Figure 3**, not because these are unimportant but in order to highlight the relative position of the disaster risks.[14] Overlaying the scores for all specific emergency risks from these comprehensive risk assessments onto **Figure 3** shows that most emergency risks occur less frequently than every 30 years (**Figure 4**). Those that occur more frequently are likely to be Negligible or Medium risks; none are Extreme. The ABC scores of emergency risks for at least these Canadian institutions are consistent with the assumption that frequent emergencies are generally not associated with severe damage.

Fire Risks

Fire is the greatest risk for both historic house museums (**Figure 3 top left** and **right**). Fire is an Extreme risk (expected MR of 12.2) for these institutions due to the presence of only basic fire protection systems, with gaps in compartmentation that might otherwise control fire spread and, in one case, a combustible wood frame structure. Fire protection is good enough for life safety since egress can be rapid, but it is not good enough for property protection, especially when much of the heritage value lies in the buildings themselves.

We analyze fire risks using the control level model developed by Tétreault from Canadian fire statistics and expert judgement.[15] Fire frequency is associated with control levels that represent typical levels of fire prevention and protection in museums in Canada. Measures include building construction and fire protection systems, as well as site location and fire prevention training and inspections. In this method, predicted loss of value associated with each control level averages over fires of all sizes, as well as taking into account the number of floors and rooms in a building. The loss of value is computed across the entire collection and is captured in the B score; therefore, the C score equals 5 if all or most of the collection is in one building.

Both historic house museums were determined to be at Control Level 1, which provides the least efficient protection against fire and is associated with a mean time between fire events of 140 years (expected A score of 2.9). Loss of value to artifacts or building components affected by fire is expected to be large (expected B score of 4.3) and is concentrated in one building (C score of 5).[16]

Fire was also an Extreme risk (expected MR of 12.1) for the archives due to gaps in fire protection measures in its three facilities. Collections stored in shared, off-site commercial warehouses that lacked fire-rated walls and, in one case, fire suppression were at risk of high levels of damage due to fire spread. On-site vaults were in themselves well protected by

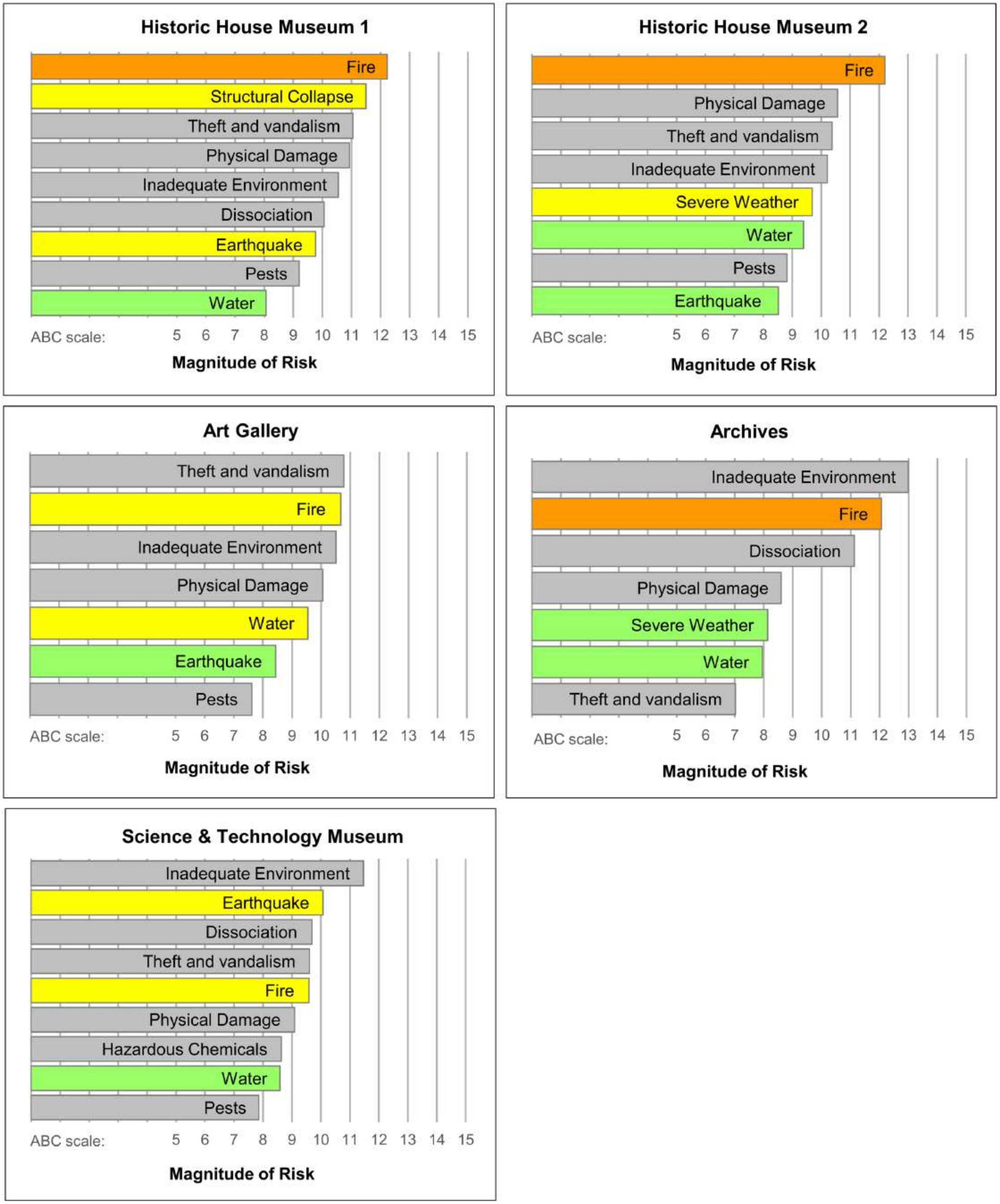

Figure 3. Risk rankings for five institutions. Specific risks have been grouped by key hazards. Emergency risks are coloured according to the convention of Table I for the ABC Magnitude of Risk scale.

Table II. ABC and Magnitude of Risk (MR) scores and linear Risk values for specific emergency and disaster risks in five Canadian heritage institutions. MR scores are coloured according to the convention of Table I for the ABC Magnitude of Risk scale.

Institution	Expected Scores				
Hazard and Specific Risks	A score	B score	C score	MR score	Risk*
Historic House Museum 1					
Fire					
Fire in house with no suppression	2.9	4.3	5.0	12.2	1.68×10^{-3}
			Total fire risk:	***12.2***	***1.68×10^{-3}***
Structural Collapse					
Damage from snow to lower roof	3.2	3.2	0.3	6.7	4.55×10^{-9}
Roof collapse due to improper roof repair	3.5	5.0	2.9	**11.5	3.13×10^{-4}
			Total structural collapse risk:	***11.5***	***3.13×10^{-4}***
Earthquake					
Damage from earthquake to ceramics	2.3	4.3	2.2	8.8	6.97×10^{-7}
Damage from earthquake to ceilings	2.3	3.8	3.6	9.7	5.07×10^{-6}
			Total earthquake risk:	***9.8***	***5.76×10^{-6}***
Water					
Flood due to water main break	3.5	2.0	1.0	6.5	3.19×10^{-9}
Plumbing leaks	3.9	3.0	1.1	**8.1	1.12×10^{-7}
			Total water risk:	***8.1***	***1.16×10^{-7}***
Historic House Museum 2					
Fire					
Fire in house with no suppression	2.9	4.3	5.0	12.2	1.54×10^{-3}
Fire in outbuilding with modern addition	2.5	4.7	3.6	10.8	6.58×10^{-5}
			Total fire risk:	***12.2***	***1.61×10^{-3}***
Severe Weather					
Damage from severe weather	3.2	3.7	1.4	8.3	1.89×10^{-7}
Damage from tornado (EF2–EF4)	0.3	4.5	4.8	**9.7	4.68×10^{-6}
			Total severe weather risk:	***9.7***	***4.87×10^{-6}***
Water					
Plumbing leaks	3.7	3.0	1.1	7.8	6.04×10^{-8}
Basement flooding due to extreme rainfall	3.3	3.0	2.1	8.4	2.77×10^{-7}
Building leaks	4.2	3.3	1.8	9.3	2.08×10^{-6}
			Total water risk:	9.4	2.41×10^{-6}
Earthquake					
Damage by earthquake to ceramics	2.3	4.3	1.9	8.5	3.35×10^{-7}
			Total earthquake risk:	***8.5***	***3.35×10^{-7}***
Art Gallery					
Fire					
Fire in building with partial suppression	2.8	2.8	5.0	**10.7	4.67×10^{-5}
			Total fire risk:	***10.7***	***4.67×10^{-5}***
Water					
Plumbing leaks	2.1	3.0	2.2	**7.4	2.40×10^{-8}
Flooding due to extreme rainfall or water main break	1.3	3.8	3.1	8.2	1.65×10^{-7}
Building leaks	3.8	3.8	1.9	9.5	3.32×10^{-6}
			Total water risk:	***9.5***	***3.51×10^{-6}***
Earthquake					
Damage from earthquake to art that swings	2.3	1.8	3.2	7.3	2.18×10^{-8}
Damage from earthquake to sculpture	2.3	3.0	2.4	7.7	5.39×10^{-8}
Damage from earthquake to framed art that falls	2.3	3.5	2.5	8.3	2.00×10^{-7}
			Total earthquake risk:	***8.4***	***2.76×10^{-7}***

*Risk = fraction of asset lost per year = 10^{MR-15}. The total Magnitude of Risk for each group = 15 + log(sum of the individual Risks).
**Occasionally, the MR score may not equal the sum of the ABC scores due to rounding.

Table II. ABC and Magnitude of Risk (MR) scores and linear Risk values for specific emergency and disaster risks (cont'd).

Institution / Hazard and Specific Risks	Expected Scores: A score	B score	C score	MR score	Risk*
***Archives*‡**					
Fire					
Fire in off-site storage with partial suppression	2.9	4.2	4.0	11.1	1.26×10^{-4}
Fire in off-site storage with no suppression	2.9	4.5	4.2	11.6	4.21×10^{-4}
Fire in main building with partial suppression	2.9	4.0	4.9	11.8	6.04×10^{-4}
			Total fire risk:	***12.1***	***1.15×10^{-3}***
Severe Weather					
Damage from tornado (EF2–EF4)	0.3	4.0	3.8	8.1	1.36×10^{-7}
			Total severe weather risk:	***8.1***	***1.36×10^{-7}***
Water					
Mould following water leaks	1.8	3.0	2.0	6.8	6.25×10^{-9}
Minor leak	4.1	2.3	0.7	7.1	1.34×10^{-8}
Major leak	2.8	3.0	2.0	7.8	6.87×10^{-8}
			Total water risk:	***7.9***	***8.84×10^{-8}***
Science & Technology Museum					
Earthquake					
Earthquake damages artifacts‡	2.3	3.5	4.3	10.1	1.18×10^{-5}
			Total earthquake risk:	***10.1***	***1.18×10^{-5}***
Fire					
Fire in storage buildings, campus 1	1.9	2.4	4.0	8.3	2.12×10^{-7}
Fire in storage buildings, campus 2‡	2.2	2.4	4.9	**9.6	3.65×10^{-6}
			Total fire risk:	***9.6***	***3.86×10^{-6}***
Water					
Building leaks in archives	4.6	2.2	-0.9	5.9	8.29×10^{-10}
Building leaks in hangar, campus 1	4.0	1.5	1.0	6.5	3.12×10^{-9}
Building leaks in storage, campus 1	4.6	2.2	1.0	**7.7	5.45×10^{-8}
Building leaks in storage, campus 2‡	5.0	2.2	1.3	8.5	3.27×10^{-7}
			Total water risk:	***8.6***	***3.85×10^{-7}***

‡Collections in these buildings have been moved into newly constructed or renovated facilities since the risk assessment was completed.
*Risk = fraction of asset lost per year = 10^{MR-15}. The total Magnitude of Risk for each group = 15 + log(sum of the individual Risks).
**Occasionally, the MR score may not equal the sum of the ABC scores due to rounding.

both compartmentation and fire suppression, but were located in a shared office building with only basic fire protection, lacking sprinklers in spaces where fire was more likely to start.[17] Although the Magnitude of Risk scores were lower for individual facilities, which each housed only a fraction of the collection (**Table II**), the risk to the institution – the sum of these risks – differed only slightly from that of the historic house museums.

Even when fire risks are apparently well managed, the Magnitude of Risk score may remain High, indicating the need for ongoing vigilance. Fire remained one of the higher risks at the art gallery (MR of 10.7), although not an Extreme risk. Here fire was still a concern because older parts of the building surrounding collection storage, including art education studios and a reference library, had no fire suppression, although the vaults themselves did. Fires – smoke especially – may also be poorly contained due to an open floor plan and lack of fire-rated separations between galleries. Facilities at the science and technology museum were well equipped with fire protection systems and procedures throughout, but lack of a dedicated telephone line for the fire alarm lowered the control level achieved in some parts. The overall fire risk scored at the low end of the High category (MR of 9.6), about ten times lower than the fire risk at the art gallery. Most of this fire risk was associated with buildings on one campus of the science and technology museum, buildings that have since been replaced by a new, purpose-built collections storage facility. On a second campus where fire protection was comprehensive, the risk scored in the Medium category (MR of 8.3), demonstrating that fire risks need not be high risks.

Weather-related Risks

The second highest disaster risk for both historic house museums concerned weather-related issues, although each case was different. Historic house museum 2 is located in an area at risk of severe weather, a concern since the house itself holds as much value as the collections within. High winds are

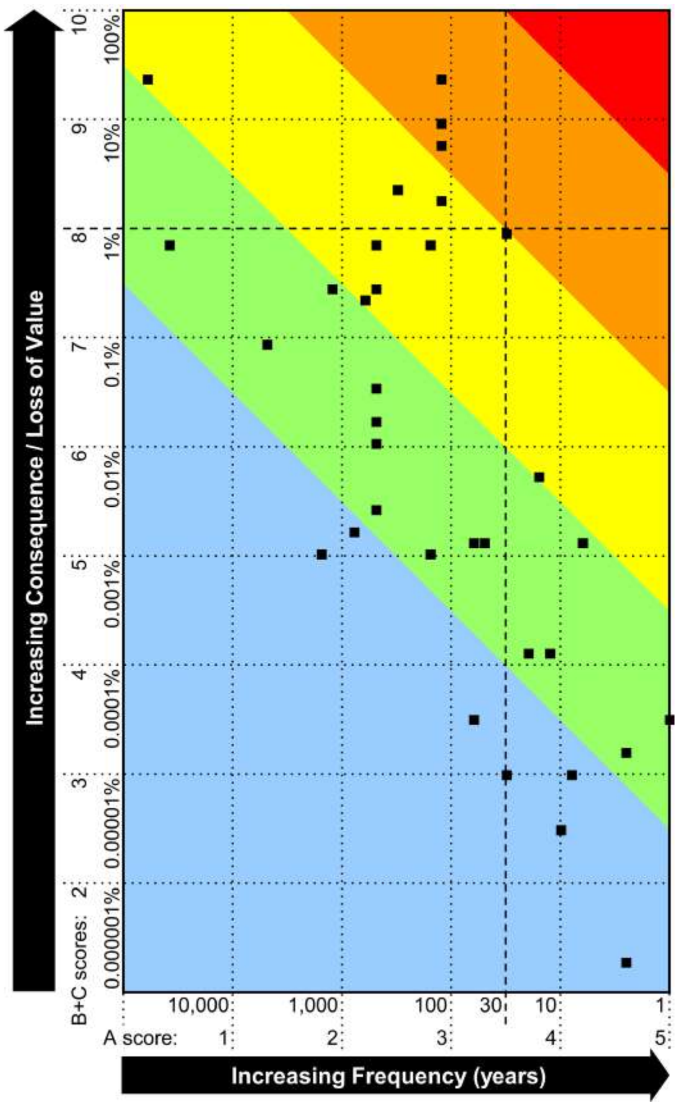

Figure 4. Specific emergency risks from five Canadian heritage institutions plotted against event frequency (A score) and consequences (combined B and C scores). The dashed vertical line (A score of 3.5) separates risks that are relatively frequent from those that are less frequent. The dashed horizontal line (B+C scores of 8) separates risks that cause significant damage from those that cause less damage.

likely to damage only the house exterior, particularly the roof, which is not original. Greater damage to both building and collections is expected in a direct hit by an EF2–EF4 tornado. The building is likely to be destroyed and most of the contents damaged by winds of this magnitude (180–410 km/hr), resulting in a substantial loss of value to the entire asset, which makes this a High risk (MR of 9.7[18]) despite a low estimated frequency of EF2–EF4 tornadoes in the region (0.07% chance in 30 years, A score of 0.3).

The archives is located in an area with similar tornado frequency. The Magnitude of Risk score for that institution was only Medium (MR of 8.1[18]), more than ten times lower than the magnitude of the risk for the historic house museum, because collections were housed in three different buildings that are not likely to be hit in one incident. Moreover, the buildings themselves were not part of the heritage asset: damage to them would be considered sacrificial and would not contribute to loss of heritage value. In less severe incidents, damaged buildings could still provide partial protection to the collections within. For similar reasons, risk due to hailstorms, which are common in the region, was not assessed: collections are unlikely to be significantly affected.

Structural collapse was identified as a High risk for historic house museum 1. This risk would present itself as a weather-related emergency – failure of the roof under snow load, for example – but is, in fact, a cumulative water risk due to the poor quality of the back roof of the building, which was expected to cause water infiltration and subsequent rot of the wooden joists.

Earthquake Risk

Earthquake was identified as a High risk (MR of 10.1) for the science and technology museum, an institution located in a region of moderate seismic hazard.[19] The earthquake event analyzed is the "10% chance in 50 years" or the "1 in 476 year event" (A score of 2.3), which is expected to cause damage equivalent to level VIII on the Modified Mercalli (MM) Intensity Scale.[20,21] Building collapse was unlikely for this institution, but the crowded condition of storage along with the lack of seismic restraint at the time of the risk assessment put many artifacts at risk of toppling and/or falling off shelves. Large artifacts stored on the top shelves of racking not designed for seismic stability were at particular risk. Even if the loss of value to the average, often robust artifact was expected to be small (3%, expected B score of 3.5), 10% to 30% of the collection was expected to be damaged to some degree (expected C score of 4.3).

Earthquake was a surprising disaster risk for one of the historic house museums, since the building is not located in a high risk seismic zone. In this case, the poor condition of painted ceilings of high value – ceilings at risk even from visitor traffic in rooms above – indicated a potential for significant loss in a relatively mild earthquake if left untreated. By comparison, the earthquake risks analyzed for the other historic house museum and the art gallery in the same seismic risk zone were Medium risks, as expected for relatively robust buildings and well supported collections. Earthquake risk was not analyzed for the archives located in a low risk seismic zone.

Water Risks (Floods, Leaks)

Although water leaks, whether through a building envelope needing maintenance or from plumbing issues, have affected each of the institutions assessed, not one was located on a flood plain and few had collections stored or exhibited below grade. Catastrophic overland flooding of the type that affected the Museum of the Highwood in 2013 was not at all likely. Water leaks were expected to be relatively frequent, but with damage isolated to a few artifacts or building components. When leaks were frequent and the cause not immediately addressed, institutions usually took measures to protect collections, thus reducing the frequency of events that caused damage to collection objects. Circumstances that could result in sudden release of massive amounts of water into collection spaces were not identified. Thus with one exception, water leaks scored as Medium risks (MR expected between 7.9 and 9.4), risks that can be well managed with appropriate emergency response procedures, assuming reasonable building maintenance.

The one exception was the art gallery, where the water risk was assessed as a High risk with an expected Magnitude of Risk score of 9.5, just above the upper boundary of Medium risks. The difference lies primarily in a greater loss of value to individual artworks (expected B scores of 3.0–3.8) as compared to artifacts or records (expected B scores of 1.5–3.3) in the other collections: even minor damage could be considered a large loss to the integrity of an artwork and its appraisal value. Water leaks that affected the heritage asset were actually judged to be more frequent in most of the other institutions.

RECOGNIZING DISASTER RISKS

If we had done a risk assessment for the Museum of the Highwood, we would have analyzed the overland flood risk for the collection stored below grade within the 100-year flood fringe and categorized it as Extreme. An estimate for frequency of 100 years, based on the typical return period for overland flood within a flood plain, gives an A score of 3 to the question "How often will the event occur?" Since most objects in the collection are made of materials that are sensitive to water – certainly to the silty river water expected in overland flooding – the answer to the second question, "How much value will be lost in each item?" would be 10–100%, a large to total loss, generating a B score of 4.5. Since the bulk of the collection was stored below grade and heavy flooding would result in considerable water accumulation (~30 cm or more), an incident would affect at least all artifacts on the floor and on the lowest shelves, if not those stored higher. Flooding could thus be expected to result in loss to 30–80% of the collection value, for a C score of 4.5. Together these scores give a Magnitude of Risk score of 12 – well within the Extreme category – a good rationale for finding another storage solution that could easily have been shown to be cost-effective.

Completing risk assessments are an excellent way of alerting heritage institutions to their disaster risks. Risks are analyzed within the specific context of an institution and account for all factors that influence frequency of events and the expected level of damage. Given the effort required, however, this may not be feasible for many. Instead, the ABC scores can be examined in order to characterize the types of emergency incidents that would generate High to Extreme Magnitude of Risk scores, providing criteria that can be used to screen institutions for their vulnerability to disaster risks.

Defining Disaster Risks to Collections in Terms of Frequency and Loss

Only under certain circumstances are heritage institutions exposed to disaster risks, which, by definition, involve significant loss. When described according to the ABC Method parameters, disaster risks result in:

- considerable damage to each affected item (B score)
- across a significant fraction of the heritage asset (C score)
- in an event that may not occur frequently (A score)
- that would be categorized as at least a High risk (MR score).

For the consequences of a collections emergency (B+C scores) to be significant, the institution has to be exposed to hazards capable of causing great damage. Fires, floods, earthquakes and storms are all capable of causing considerable damage to individual collection items (high B scores). Most buildings provide reasonable protection to heritage collections from milder forms of these hazards. Damage is often localized; when it touches collections, few artifacts are affected. Damage to the building itself could often be considered sacrificial from the perspective of collections preservation, although it may be costly to repair and thus a serious issue for the institution.

When the typical museum building offers inadequate protection from the hazard, much of the heritage asset is vulnerable to damage (high C scores). To illustrate the extent of loss caused by disaster risks, consider a collection of 10,000 items, an average size in Canada.[22] If a large fraction (10%) of such collections is affected in a single incident, 1,000 items are damaged, assuming the simplest case that all items have equal value. In many institutions, this is most likely when collection objects in storage are affected by the emergency incident, since most of the heritage asset – 80% of the collection on average[23] – is often found there. Higher object density in storage also makes damage to a large fraction more likely. To generate an equivalent loss, half of the 20% of the collection on display (on average), which usually occupies more space than the same number of objects in storage, would need to be affected. Where almost all of the collection is on display, as is found in some historic house museums, the hazard would similarly need to affect a significant fraction of the display area.

Exceptional cases may be particularly vulnerable to disaster risks. A large fraction (10%) of a small collection, for example, may comprise a few objects. A tenth of the heritage value of some collections may be held in a small number of "treasures" that are often on display. Heritage buildings, archaeological sites or collections displayed outdoors are directly exposed to many hazards without the benefit of a protective shelter.

If they occurred frequently, highly damaging events would always be categorized as Extreme (or Catastrophic) risks. As already discussed, shorter mean times between such events, however, are less likely in heritage institutions: the risks would be mitigated to meet preservation objectives. For events that tend to fall outside of recent memory, the need for risk mitigation may be less evident.

Events with significant consequences tend to occur less frequently and are primarily associated with High and Extreme risks (**Figure 4**). Emergency hazards that occur once in 100 to 1000 years (A score of 2–3) always rank as High to Extreme risks when the consequences are severe. But even when the likelihood is lower, disaster risks may still rank High. A frequency of once every 3000 years (A score of 1.5) marks the boundary between High and Extreme risks when loss is total. The same frequency combined with an overall loss of value of 1% (combined B+C score of 8), would generate a score of 9.5, the lower boundary of the High category on the ABC Magnitude of Risk scale. When hazards are likely to cause an intermediate 10% overall loss (combined B+C score of 9), an expected frequency of once in 30,000 years (A score of 0.5) will categorize a risk as High.

The following sections describe factors that combine with key hazards – flood, fire, earthquake and severe wind events (hurricane and tornado) – to create High or Extreme disaster risks to heritage collections. Generic risks were modelled using the ABC Method based on information about such hazards, the degree of damage they commonly cause, and their frequency. Forms of each hazard associated with significant damage were identified. The level of damage to each item was assessed for a mixed collection at the point of salvage, prior to cleaning or conservation treatment. Frequency was estimated where possible using hazard maps. For most of these hazards, how often events occur in a particular location is usually expressed as the return period, return interval or recurrence interval. For risk analysis, the return period value was used to estimate the frequency used to compute the A score, although the two are not identical.[24] The modelled risks pertain to collections housed in a single building typical of heritage institutions in Canada. Only potential loss to heritage collection objects is considered in modelling these risks, not loss to heritage buildings, although the latter would certainly contribute to risk magnitude, particularly in historic house museums. Estimates of the expected A, B, C and Magnitude of Risk scores, and the assumptions that inform these scores are presented in **Table III.** The risk factors associated with disaster risks for each hazard are summarized in a chart (**Table IV**) to facilitate screening for disaster risks. While smaller losses due to emergency events are also of concern and would benefit from emergency preparedness, exposure to these higher risks demands mitigation. Recognizing risks of this magnitude is a necessary first step towards planning appropriate investment in risk reduction.

Flood, Storm Surge, Tsunami

Floods involve the accumulation of water in normally dry places. Collections submerged in silty, contaminated water and/or tossed around by the combined effects of buoyancy and water movement will experience considerable soiling and damage. When most collection objects are submerged as a result of flooding, the loss of value is expected to range from large to total (10–100%, B score of 4 or higher). Objects less vulnerable to the effects of water may only be soiled. Objects sitting at the water line may be only partly damaged. Items made from sensitive organic materials such as paper, photographic materials or wood, may be lost, especially if immersed for many days or if delay in salvage results in mould. Strong currents or wave action can sweep collections out of buildings or destroy buildings in extreme cases of overland flooding, storm surge or tsunami. When lower water levels are more likely, as is the case for most floods associated with inadequate municipal water infrastructure, a wider range of loss per item, from 1% to 100% (B score of 3 or higher), would be expected due to partial damage of more artifacts.

For a significant fraction of the collection to be affected, water needs to accumulate in spaces where much of the collection is housed. When collection storage is all below grade, 80% of the collection, on average,[23] is vulnerable to loss if flood waters can rise to the ceiling (high C score of 4.9). Since collections are displayed in rooms and galleries on or above grade in most heritage institutions, total loss (100%) is not expected. The fraction affected will vary with the height of the flood waters, but accumulation of even 30 cm of water is likely to affect at least 10% of such a collection, generating a low C score of 4. When similar accumulation can occur on grade, as in a flood plain,[25] collections stored and displayed there are exposed to a High risk. Sufficient water relative to the volume of the collection rooms is required for this level of risk, such that 5–10% of the collection is affected, usually items on or near the floor or on lower shelves in storage.

Such water accumulation is usually associated with overland flooding caused by bodies of water overflowing their banks or by unusually heavy rainstorms that overwhelm municipal storm drains. In coastal regions, tsunami or storm surges can deliver similar large quantities of water. Water released from the failure of large water mains can also produce this kind of flooding in adjacent collection spaces. Such failure is more likely as water systems age and thus in older neighborhoods where pipes are nearing the average expected service life of 80–85 years[26] and have not yet been upgraded. The amount of water released by poorly maintained roofs or by plumbing leaks is unlikely to accumulate to this level within most buildings. When collections are reliably stored off the floor – a basic preventive conservation recommendation[27] – direct damage to a high number of items is far less likely from water leaks alone, even in rooms below grade where water from any source will eventually accumulate.

The frequency of flood events depends on the nature of the hazard and geographic location. Exposure to overland flooding is commonly identified by using flood hazard maps[28] often based for regulatory purposes on a design flood with an annual probability of exceedance of 0.01, the "100-year" return period flood.[29] This typical flood return period is used to estimate frequency of floods affecting buildings situated within a documented flood plain, giving an A score of 3. The warming of the atmosphere that characterizes climate change alters many processes related to flood generation and thus is expected to increase the likelihood of such incidents[30] and would particularly affect relatively low-lying areas. Even a 500-year event generates an A score of 2.3 and would be associated with a High risk when collections are stored below grade.

Flooding in coastal regions is related to the frequency of extreme sea level events such as tsunami and storm surge. Recent estimates indicate that tsunami run-up of up to 1.5 metres along the outer Pacific coast of British Columbia has an expected return period of less than 100 years, while higher

Table III. Low (L), most probable (P) and high (H) ABC estimates and expected Magnitude of Risk scores for selected disaster risks in Canada.

Hazard	Frequency mean time between events (years)	A score How often will the event occur?			Consequences	B score How much value will be lost in each affected item?			C score How much of the heritage asset is affected?			Expected Scores*			
		L	P	H		L	P	H	L	P	H	A	B	C	MR*
Flood, overland	100	3.0	3.0	3.0	Collection storage below grade flooded	4.0	4.5	5.0	4.0	4.5	4.9	3.0	4.5	4.5	12.0
Flood, overland	100	3.0	3.0	3.0	Collection storage on grade flooded	4.0	4.5	5.0	3.7	4.0	4.0	3.0	4.5	3.9	11.4
Flood, inadequate municipal water systems	50-100	3.0	3.1	3.3	Collections storage below grade flooded	3.0	4.0	5.0	2.0	3.0	4.7	3.1	4.0	3.2	10.4
Storm surge	40-100	3.0	3.2	3.4	Building is destroyed	4.5	5.0	5.0	4.5	5.0	5.0	3.2	4.8	4.8	12.9
Storm surge	40-100	3.0	3.2	3.4	Collection storage on or below grade flooded	4.0	4.5	5.0	4.0	4.5	4.9	3.2	4.5	4.5	12.1
Tsunami, outer Pacific coast, 1.5 m run-up	42-98	3.0	3.2	3.4	Collection storage on and below grade flooded	4.5	5.0	5.0	4.5	4.8	5.0	3.2	4.8	4.8	12.8
Tsunami, Pacific coast, 1.5-3 m run-up	98-475	2.3	2.5	3.0	Building and collections destroyed	4.5	5.0	5.0	4.5	5.0	5.0	2.6	4.8	4.8	12.3
Tsunami, Atlantic coast, 1.5-3 m run-up	475-2,475	1.6	1.8	2.3		4.5	5.0	5.0	4.5	5.0	5.0	1.9	4.8	4.8	11.6
Fire – Control Level 1	80-200	2.7	2.9	3.1	Building fire of any size damages collections	4.4	4.5	4.6	5.0	5.0	5.0	2.9	4.5	5.0	12.4
Fire – Control Level 2	80-200	2.7	2.9	3.1		4.3	4.4	4.6	5.0	5.0	5.0	2.9	4.4	5.0	12.3
Fire – Control Level 3	90-230	2.6	2.8	3.0		2.4	2.9	3.4	5.0	5.0	5.0	2.8	2.9	5.0	10.7
Fire – Control Level 4	410-1,000	2.0	2.1	2.4		2.0	2.6	3.1	5.0	5.0	5.0	2.2	2.6	5.0	9.8
Wildland Fire – highest risk WUI zone	50-100	3.0	3.1	3.3	Building ignites and burns	4.5	5.0	5.0	4.5	5.0	5.0	3.1	4.8	4.8	12.8
Wildland Fire – higher risk WUI zone	101-150	2.8	2.9	3.0		4.5	5.0	5.0	4.5	5.0	5.0	2.9	4.8	4.8	12.6
Wildland Fire – high risk WUI zone	151-500	2.3	2.5	2.8		4.5	5.0	5.0	4.5	5.0	5.0	2.5	4.8	4.8	12.2
Wildland Fire – medium high risk WUI zone	501-1500	1.8	2.0	2.3		4.5	5.0	5.0	4.5	5.0	5.0	2.0	4.8	4.8	11.7
Wildland Fire – medium risk WUI zone	1501-5,000	1.3	1.5	1.8		4.5	5.0	5.0	4.5	5.0	5.0	1.5	4.8	4.8	11.2
Wildland Fire – medium low risk WUI zone	>5,000	1.3	1.3	1.3		4.5	5.0	5.0	4.5	5.0	5.0	1.3	4.8	4.8	11.0
Earthquake – high hazard zone	476	2.3	2.3	2.3	Building collapses	4.0	4.5	5.0	4.5	5.0	5.0	2.3	4.5	4.8	11.7
Earthquake – high hazard zone	145	2.8	2.8	2.8	Many collection objects topple,crash or are crushed	2.0	3.5	5.0	3.0	4.0	4.5	2.8	3.5	3.8	10.2
Earthquake – moderate hazard zone	310-976	2.0	2.3	2.5		2.0	3.5	5.0	3.0	4.0	4.5	2.3	3.5	3.8	9.6
EF3–5 Tornado – highest risk zone	36,000-44,000	0.4	0.4	0.4	Building is destroyed	4.0	4.5	5.0	4.5	5.0	5.0	0.4	4.5	4.8	9.7
EF3–5 Tornado – higher risk zone	44,000-54,000	0.3	0.3	0.4		4.0	4.5	5.0	4.5	5.0	5.0	0.3	4.5	4.8	9.6
EF3–5 Tornado – high risk zone	54,000-73,000	0.1	0.2	0.3		4.0	4.5	5.0	4.5	5.0	5.0	0.2	4.5	4.8	9.5

*averages of the A, B and C scores and their sum (MR); occasionally, the MR score may not equal the sum of the ABC scores due to rounding.

Table IV. Screening chart listing factors associated with High (yellow) to Extreme (orange) risks due to emergency hazards.

To use the table to screen for disaster risks:

1. Check off the factors in the left column that apply to the building of interest in which heritage collections are housed. It may be necessary to consult hazard maps, if exposure to the hazard is uncertain.
2. For each hazard that has a factor checked in the left column, determine the degree to which the building protects against the hazard. Check off any factors in the right column that apply. It may be necessary to consult with experts, such as fire safety or structural engineers, if the degree of protection is uncertain.

When both columns are checked, the collection in the building is exposed to a disaster risk for that hazard. The colour of the checked box in the right column indicates whether the risk is High (yellow) or Extreme (orange).

Hazard	Risk Factors		
Flood	□ building located within a 100-year flood plain / flood fringe	✚	□ collection stored below grade on site (orange)
		✚	□ collection stored on grade on site (yellow)
	□ building near old water main or faulty storm sewers	✚	□ collection stored below grade on site (yellow)
Storm surge	□ building located within a storm surge hazard zone	✚	□ building not designed to withstand storm surge or collections stored on or below grade (orange)
Tsunami	□ building located within a tsunami inundation zone	✚	□ building not designed to resist tsunami or collections stored on or below grade (orange)
Building fire	□ combustible structure □ fire resistive structure with poor compartmentation	✚	□ no automatic fire detection and/or no fire suppression (orange)
	□ fire resistive structure with automatic fire detection	✚	□ no automatic fire suppression (yellow)
Wildland fire	□ building located in the wildland-urban interface in high hazard regions	✚	□ high to extreme structure and site fire hazard (orange)
	□ building located in the wildland-urban interface in medium hazard regions	✚	□ high to extreme structure and site fire hazard (yellow)
Earthquake	□ building in region exposed to at least violent earthquake shaking (MM IX+)	✚	□ building lacks seismic protection (orange)
	□ building in region exposed to at least very strong earthquake shaking (MM VII+)	✚	□ collection storage and display methods are not seismically stable (yellow)
Hurricane	□ building in region exposed to major hurricane (Category 3-5)	✚	□ building not designed to resist hurricane force winds (orange)
Tornado	□ building in region exposed to EF3-EF5 tornadoes	✚	□ building not designed to resist extreme winds (yellow)

run-up (3 metres) or tsunami in lower risk regions in Canada occur roughly as frequently as the earthquakes with which they are usually associated.[31] The frequency of storm surge caused by the high winds and low pressures of tropical or extra-tropical cyclones[32] is assessed through documentation of annual sea level maxima. Collection damage in buildings located in at risk zones is most likely to result from extremely high levels that occur every 40–100 years.[33] Climate change is expected to have an impact on this frequency as a result of sea level rise, coastal erosion and increased storminess.[33,34]

Based on this understanding of how floods impact collections, flood risks are likely to be High or Extreme (by the categories of **Table I**) if collection storage is (**Table IV**):

- on or below grade within a flood plain,
- below grade and adjacent to old water mains or faulty storm sewers, or
- on or below grade in a zone at risk of storm surges or tsunami.

The first factor, collection storage below grade, applied to the flooding of the Museum of the Highwood in 2013. Flooding of photographic collections belonging to the Peterborough Museum and Archives in 2004 was associated with the second factor, below grade storage in a municipality with inadequate storm sewers.[35,36] Given the recent frequency of severe flood events in Canada, insurance companies may be reluctant to insure collections stored below grade in flood plains, a reasonable decision in light of such risk. Heritage institutions that have difficulty obtaining collections insurance may have added incentive to move collections out of such high risk storage.

Fire

Fire has the potential to completely destroy many heritage materials through combustion. Even those that resist burning, such as stone, can be damaged through cracking and spalling.[37] Partial damage of objects, charring and soiling by soot to varying degrees, combined with water damage due to fire suppression, are commonly observed following fire incidents. If fire impacts a collection space, therefore, significant damage of affected items is expected.

All heritage collections are at risk of fire. To be a disaster risk, however, it must be probable that fire will spread to areas where collection value is concentrated. Fires that reach collections storage will certainly affect a large number of objects, especially where entire collections are stored in a single compartment. If fire is able to spread through interconnected exhibition spaces, a significant fraction of the heritage asset could also be affected. According to data on fires in Canadian museums, most fires start in non-collection spaces;[17] therefore, building features that promote fire spread characterize institutions at greatest risk. Such characteristics include:

- combustible building structure (e.g., wood frame construction),
- lack of compartmentation (e.g., walls, doors and ceilings not fire-rated; open floor plan or stairwells, doors left open),
- lack of automatic fire detection, which delays response especially outside of business hours, and
- lack of automatic fire suppression.

Museum buildings with all or most of these characteristics fall into Control Levels 1–2 as defined by Tétreault,[38] where the mean time between fires of any size is estimated to be 140 years[39] (expected A score of 2.9). The chance of spread to an entire floor or the whole building is more likely when fire protection measures are most basic (Control Level 1). In such buildings, 1 in 4 fires is expected to spread to the entire structure. If the building provides protection equivalent to Control Level 2 – constructed using fire-resistive finishes like brick, stone, stucco, drywall or plaster, with walls fire-rated for 1 to 2 hours around collection storage, and a fire alarm system with fire detectors – 1 in 5 fires is expected to spread to the entire structure.[40] As such, the predicted loss of heritage value is very high (expected B+C scores of 9.4–9.5). The fire risk in such buildings is categorized as Extreme.

Better compartmentation and detection are required to further reduce the chance of fire spread. Museum buildings in which exhibition galleries are closed off from adjoining spaces with 1-hour fire-rated walls and doors, and that have automatic smoke detection in collection spaces and a fire alarm system that is continuously monitored, among other measures,[38] provide protection equivalent to Control Level 3. Fire frequency is still high (estimated mean time between fires of 160 years,[39] expected A score of 2.8) but the chance of a whole building fire is much reduced (less than 1 in 100[40]). The expected overall loss of heritage value is considerably lower (expected B+C score of 7.9). The fire risk in such buildings is categorized as High. Predicted fire frequency drops significantly – estimated mean time between fires of 720 years[39] (expected A score of 2.2) – for institutions classified as Control Level 4, namely, non-combustible buildings with fire suppression in collection storage rooms.[38] The lower frequency combined with a further reduction in consequences (expected B+C score of 7.6) generates an expected Magnitude of Risk score (9.8) that remains within the High category, highlighting the need for vigilance with respect to structure fires in such heritage institutions.

Wildland Fire

Collections may be particularly vulnerable to fire in heritage institutions located near forest or grasslands where wildland fires occur, the wildland/urban interface (WUI). Such locations are at risk of extreme fires characterized by high intensity and rapid growth that can overwhelm firefighting capacity. Given sustained ignition, caused directly by flame or radiant heat or, more likely, indirectly by embers falling on the building or combustible materials near the building, complete destruction of the entire structure and contents is likely.[41-44] The risk is thus modelled assuming near total loss of value to each item (expected B score of 4.8) across most of the collection (expected C score of 4.8).

Exposure to wildland fires does not automatically result in damage. Formal evaluation of building and site characteristics, as well as area hazards, permits assessment of the hazard level.[45,46] Buildings destroyed by wildfire are likely to have high to extreme fire hazard ratings.[47] Building ignition is likely when:

- management of fuels on the site is poor, *and*
- the building is not designed to resist burning.

The mean time between wildland fires, or return interval, is less well documented than that of other natural hazards, although recent fires damaging urban areas, such as those in West Kelowna, British Columbia in 2009, in Slave Lake, Alberta in 2011 and in Fort McMurray, Alberta in 2016, have raised awareness of this risk. Climate change may also be impacting the frequency and size of wildland fires in Canada.[48,49] Recent research has estimated fire return intervals by forest ecoregion in Canada,[50] which may be as short as once every 50 years (expected A score of 3.1) in the highest risk regions (**Figure 5**).[51] Canadian heritage institutions in the wildland-urban interface are more likely to be located in southern and coastal regions where return intervals are longer, on the order of 1500–5000 years (expected A score of 1.3–1.5). The Magnitude of Risk score for a collection in a poorly protected facility at the wildland/urban interface ranges from High to Extreme (by the categories of **Table I**), depending on the return interval associated with the region (**Tables III** and **IV**).

Earthquake

Earthquakes of great intensity, as described by the Modified Mercalli Intensity Scale (MM VII and higher),[20,52,53] have the potential to cause the significant damage that characterizes disaster risks, either through collapse of the building or severe shaking of contents. Only collections in higher risk seismic hazard zones in Canada (**Figure 6**,[19] Zones 2–4 on NATHAN World Map of Hazards[54]) are exposed to such earthquakes.

The worst damage would result from building collapse, which would severely damage all or most of a collection within (expected B and C scores of 4.5 and 4.8 respectively). The earthquake that has a 10% chance of occurring in 50 years – the 476-year event (A score of 2.3) – can damage structures to this degree in high seismic hazard zones. Although poorly built structures could suffer partial collapse in very strong to severe shaking (probable maximum intensity of MM VII–VIII), such damage is more likely where violent shaking (MM IX or higher) would be sufficient to damage even substantial structures. Buildings exposed to violent shaking are located in the highest seismic hazard zones in Canada, as shown in red on the seismic hazard map presented in **Figure 6**: the west coast including all of Vancouver Island and the British Columbia Lower Mainland, parts of the Yukon, the Charlevoix-Kamouraska region in Quebec, and parts of the far north. Older buildings of masonry construction that have no seismic retrofitting are most likely to collapse. The type of soil under the building also contributes to the risk, as some dampen and others amplify shaking intensity. Collections in such buildings are exposed to an Extreme risk by the categories of **Table I** (**Table III**).

Shaking associated with earthquake intensity of MM VII or higher is sufficient to topple and crush contents even if the

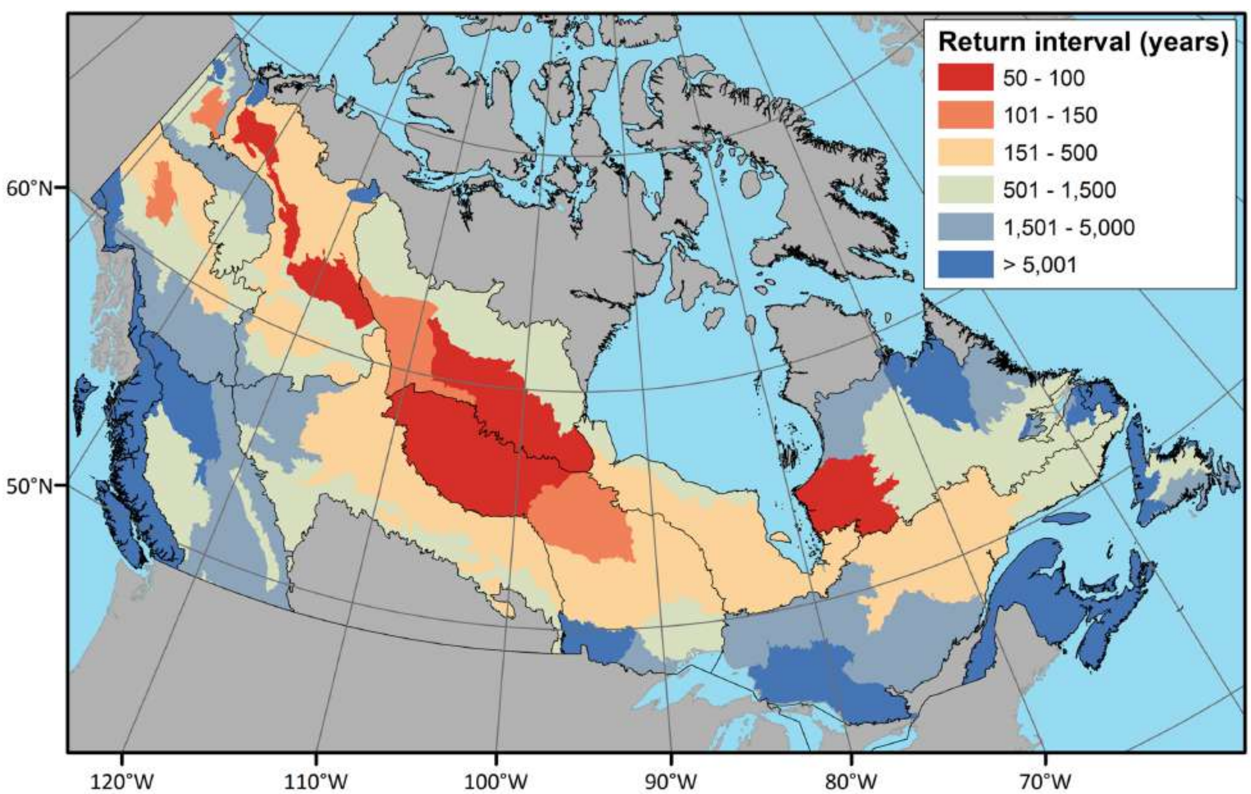

Figure 5. Estimated fire return interval within Canada's forested ecosystems.[51] ©Coops *et al.*, 2018, licensed under CC BY 4.0.

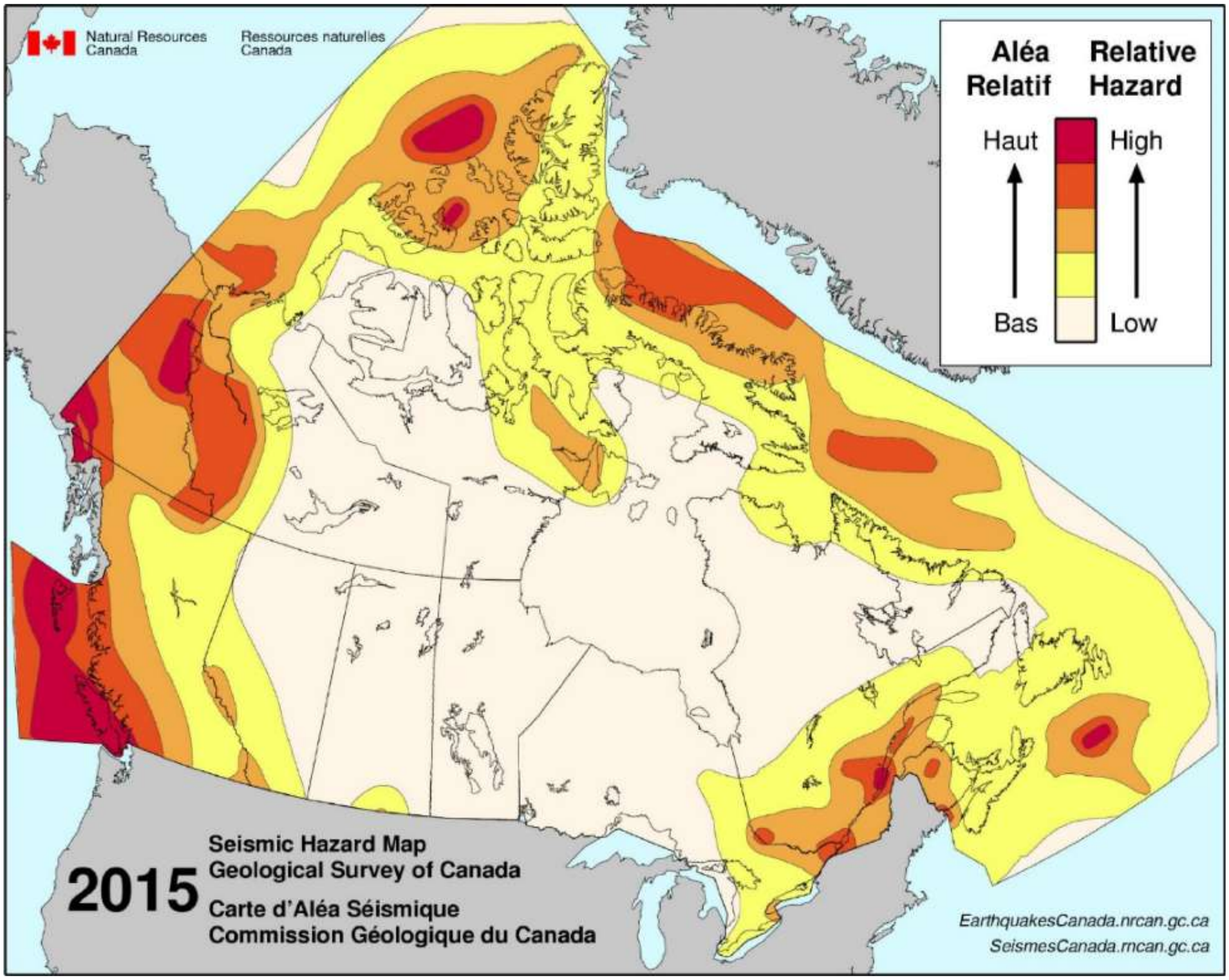

Figure 6. Simplified Canadian seismic hazard map.[19] Source: Natural Resources Canada, 2015. Reproduced with the permission of the Department of Natural Resources, Government of Canada, 2020

building does not collapse. The effects of shaking would be apparent across all collection spaces, both storage and display. The level of damage, assuming "normal" storage and display methods, would be somewhat lower than that associated with building collapse (expected B and C scores of 3.5 and 3.8 respectively). In zones of highest seismic hazard in Canada, such damaging shaking has a 30% chance of occurring in 50 years[19] (a one in 145 year event, A score of 2.8). In zones of moderate seismic hazard – the orange and dark orange hazard zones in **Figure 6**, regions that include cities like Ottawa, Montreal and Quebec City – such shaking has a 5–15% chance of occurring in 50 years[19] (expected A score of 2.3). In both seismic hazard zones, the Magnitude of Risk scores are categorized as High (**Table III**).

Location in a high seismic hazard zone does not automatically represent an earthquake disaster risk. Canadian building code has accounted for regional seismic hazard to some degree since 1953.[55] Buildings that house heritage collections will have appropriate seismic protection that prevents collapse if built to recent code. Because of the life safety risk, older buildings may have been assessed and retrofitted to prevent collapse. Modifications to display and storage methods to protect vulnerable collections from shaking damage may have been implemented at least to some extent in vulnerable institutions, which would reduce the extent of likely damage.

A heritage institution is exposed to an Extreme disaster risk when its building (**Table IV**):

- is located in an earthquake zone at risk of "violent" shaking, *and*
- lacks appropriate seismic protection to prevent collapse.

Seismic evaluation of older buildings by engineers would determine whether collapse is likely. A High disaster risk is present when the building is not likely to collapse but (**Table IV**):

- is located in an earthquake zone at risk of at least "very strong" shaking, *and*
- lacks appropriate seismic protection for collections in storage and on display.

Normal storage and display techniques, such as unbraced shelving and unrestrained objects and/or display or storage mounts would not protect all collection objects in the event of such an earthquake.

This analysis focuses on the impact of the physical forces of earthquake events. Destructive earthquakes may also result in secondary damage due to fires, floods and theft. The main damage may be due to coastal flooding by tsunami that results from an offshore earthquake. This latter case is considered a type of overland flooding and is addressed under flood risks.

Extreme Wind Events

Like those of earthquakes, the physical forces of certain wind storms have the capacity to destroy a building and its collections and thus constitute a disaster risk. Since buildings are designed to account for expected regional wind loads, loss to collections associated with severe weather is usually not extensive, often related to rain infiltration through localized damage to roofs or the building envelope. Some types of extreme weather, however, can destroy the building envelope, in part if not in full, removing the protection it provides to a collection and thus causing considerable damage to much of a collection on display and in storage (expected B and C scores of 4.5 and 4.8 respectively). Such extreme winds are associated with cyclonic storms or hurricanes, and tornadoes.

Hurricane

Devastating to catastrophic building damage is associated with sustained wind speeds greater than 178 km/hour, wind speeds that characterize major hurricanes (Categories 3–5), as described by the Saffir-Simpson Hurricane Wind Scale.[56,57] In North America, hurricanes of this magnitude are limited to the eastern U.S. coastal areas. Return periods for major hurricanes – from 14–22 years along the coastal regions in the Carolinas, Florida and Louisiana to 120–290 years along the Maine coast[58] – generate Magnitude of Risk scores that would be classified as Extreme in buildings not designed or retrofitted to resist major hurricane force winds (**Table IV**). Given the relative frequency of tropical storms and hurricanes in these coastal regions, the need for mitigation may be recognized by many heritage institutions. Preparedness measures for each event are also possible due to the advanced notice given for most storms.

To date, hurricanes that have made landfall in Canada have been classified as Category 2 or lower since offshore water temperatures are too cold for stronger cyclones.[59] Although such hurricanes can damage buildings and collections (and result in loss of life), the damage is rarely extensive enough to rank as a High or Extreme risk to heritage assets. The historic record for such a rare event is relatively "short," however. Given the right conditions – a major hurricane that moves in rapidly, with coastal waters that are warmer than usual and atmospheric conditions that maintain the storm's strength – a Category 3 hurricane in Atlantic Canada is "remotely possible."[59] Estimating the risk to collections from such rare storms remains speculative without informed estimates of their frequency. Since building codes are less likely to account for the strongest winds in regions where the risk is lower, heritage or museum buildings in Atlantic Canada may be more susceptible to catastrophic damage than their better warned and prepared counterparts in the southern United States, should such a rare event occur.

Heritage buildings and collections may be at High to Extreme risk of water damage from storms even in regions that have no history of major hurricanes. Post-tropical cyclones that have affected Canada have been associated with intense rainfall or storm surges along the coast[32] that can cause damage like that associated with overland flooding, as previously discussed.

Tornado

A direct tornado hit can destroy a building and crush or disperse its contents. Severe or total destruction is usually associated with EF4–EF5 tornadoes, which have wind speeds of 270 km/hr and higher, as described by the Enhanced Fujita Scale.[60,61] Even EF3 tornadoes, with wind speeds estimated in the range of 225–265 km/hr, can lift the metal deck or concrete roof slab off a typical institutional building[62] and can significantly damage solid masonry houses (many heritage buildings)[63] or totally destroy buildings of lighter weight construction, such as warehouses[64] that are sometimes used for off-site collection storage. It is reasonable to assume almost total overall loss of heritage value in collections housed in buildings that sustain a direct hit (expected B and C scores of 4.5 and 4.8 respectively).

Estimating the probability of a direct hit by an EF3–EF5 tornado is complicated by the paucity of data available for such rare events. Modelling by scientists associated with the University of Toronto and Environment Canada provides the most recent mapping of tornado hazard zones in Canada.[65,66] The three highest hazard regions, which correspond to the areas with the most confirmed and probable tornadoes in **Figure 7**, have an estimated annual frequency of 1.5–3 tornadoes of any size (EF0–EF5) per year per 10,000 square kilometres, which corresponds to return periods of 33,000 to 67,000 years, as estimated by Cheng et al.[67] Of these, roughly 3% are likely to be severe to violent (EF3 or higher).[68] The return period of an EF3–EF5 tornado can be estimated using such frequency data for tornadoes of each size in conjunction with estimates of their corresponding median path area (2–25 km^2)[69] in the manner used by Cheng et al.[70] In the three highest hazard regions in Canada, an EF3–EF5 tornado is expected to hit a particular location once in 36,000–54,000 years (a 0.2–0.3% chance in 100 years), generating an A score of 0.3–0.4. Thus, at present, the risk to heritage collections in buildings located in a zone at risk of EF3–EF5 tornadoes in Canada will be categorized at most as a High risk (**Table IV**) with an expected MR of 9.5–9.7 (**Table III**).

REDUCING DISASTER RISKS

When the magnitude of a disaster risk ranks High to Extreme (by the categories of **Table I**), risk reduction is strongly recommended, not just the development of emergency response procedures or promoting better "resilience." Risk reduction can be achieved by lowering the frequency and/or the immediate consequences of an event (**Figure 8**). For fire, reducing both the probability of ignition *and* the consequences of an event is fundamental to reduction of the risk. For natural

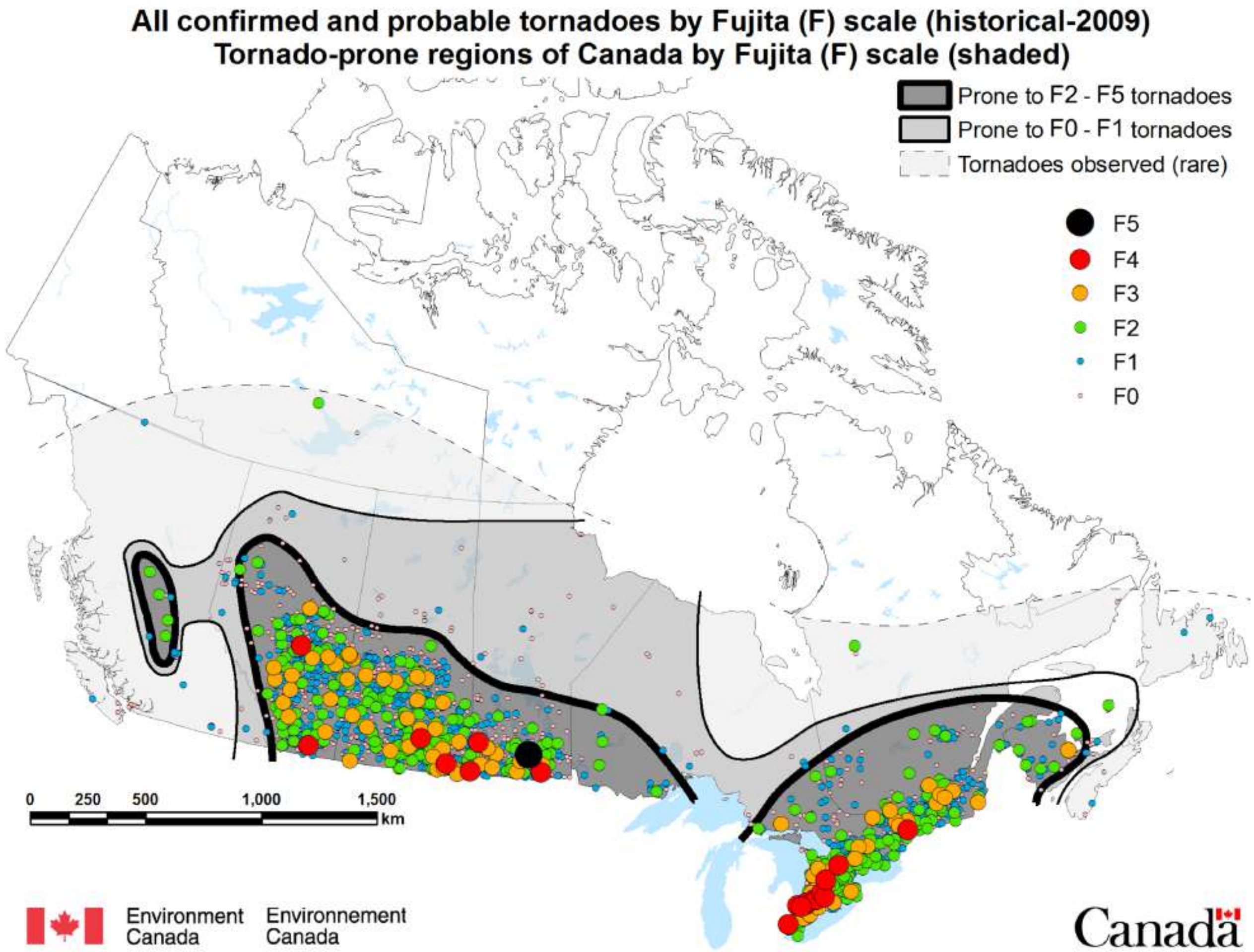

Figure 7. Tornado prone regions in Canada.[65] Source: Environment Canada, 2011. Reproduced with the permission of the Department of Environment and Climate Change Canada, 2020.

hazards, however, reducing the frequency of exposure is not possible except by changing location. As the example of the High River flood illustrates, avoidance of dangerous locations can and should be part of a planning decision. Safer places are not necessarily far away in the case of floods or wildfires. But changing location may not be a desirable option, particularly for heritage buildings on their original site. Mitigation measures thus often focus on reducing the impact on buildings and collections.

Although the goal may be to reduce all disaster risks down to the Medium category, reduction of Extreme risks down to the High category is already a significant improvement and may be all that is feasible. A drop in the Magnitude of Risk score by 1 log unit represents a 90% reduction of the risk.

Since risk analysis identified fire as a High or Extreme emergency risk in every institution studied to date, we have analyzed the effect of the installation of automatic fire suppression on the magnitude of fire risks. Automatic fire suppression is a fire protection measure that CCI has long recommended.[71,72] Although it does not eliminate fire risk, it can substantially reduce the spread of fire and therefore the risk of disastrous building fires that result in loss of much of the heritage asset. **Figure 9** compares the fire risk for the historic house museums and the archives with the reduction in risk achieved if *the only thing* that is done is the installation of automatic fire suppression. The fire risk reduction illustrated for the archives is for the specific fire risk at the storage facility that lacked any fire suppression system. The reduction of the risk was modelled using data collected by the U.S. National Fire Protection Association. While installing a fire suppression system on its own may not change the control level of the building and thus the likely frequency of fires, the NFPA data suggest that the number of fires that spread beyond the room of origin in sprinklered buildings as compared to their non-sprinklered counterparts decreases by 44% in one and two-family dwellings similar to historic house museums[73] and by 47% in storage facilities.[74] The change in Magnitude of Risk scores appears small when compared on the logarithmic scale (**Figure 9 left**). When compared on a linear scale, however, the size of the reduction, which is close to 50%, is evident (**Figure 9 right**). Analysis of the cost-effectiveness of all risk mitigation options for one of the historic house museums using optimization software has shown that installation of sprinklers is the one option recommended if funds are available.[75] Securing such funding remains a

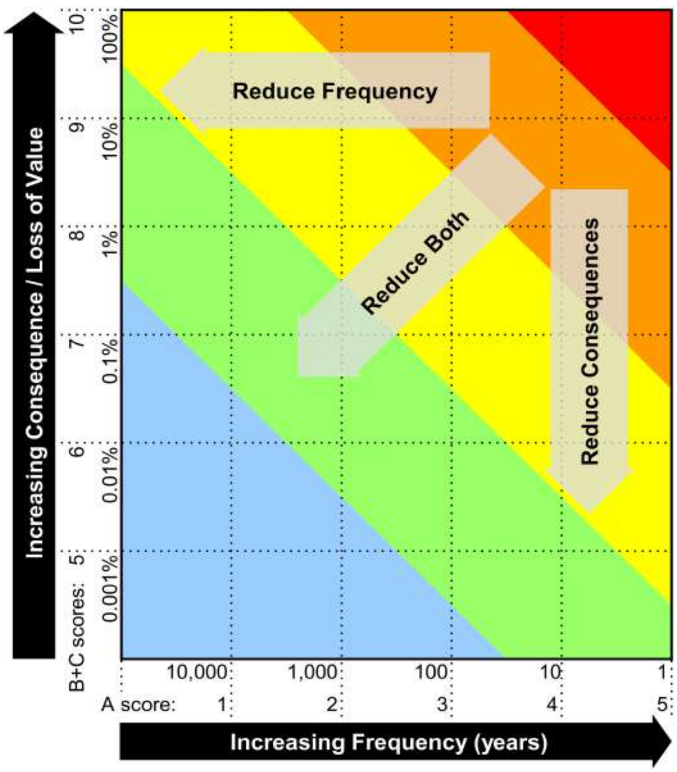

Figure 8. Effect of reduction options that target frequency versus consequences on the Magnitude of Risk category.

challenge in many contexts. Designing fire suppression systems that respect the integrity of historic buildings may also be a challenge but has been accomplished.[76]

Fire risk is expected to approach the Medium risk category only when non-combustible building methods are used (e.g., concrete construction), when fire suppression is provided in storage, and when high fire risk locations are avoided. Current fire code may provide such protection for newly built or renovated heritage institutions. We find, however, that fire risk from a heritage perspective is often underestimated because fire officials understandably focus on life safety rather than property protection, particularly in older structures where code may not necessarily be applied retroactively. It should be noted that building characteristics that offer fire protection must be complemented by appropriate inspections and maintenance of fire protection systems and by staff training to meet the requirements of fire risk control levels.

Many disaster risks can be reduced through modifications to building or storage design. Just as storing collections at least 10–15 cm off the floor significantly lowers the risk of water leak damage, storing collections above grade in flood risk zones or, ideally, avoiding below grade storage entirely would eliminate most High to Extreme overland flood risks. Storage and display fittings can also be designed to withstand earthquakes.[77] Buildings themselves can be modified or constructed to lower flood risks,[78] to withstand tsunami,[79] or to resist seismic forces,[80-83] the severe winds of hurricanes and tornadoes,[84-87] and the effects of wildland fires.[88,89] Management of site vegetation around structures located in the wildland-urban interface can also reduce wildland fire risks.[41] Retrofitting or constructing a building to reduce disaster risks is not inexpensive. Estimates of cost-effectiveness have, nevertheless, provided compelling evidence in support of reduction of High to Extreme risks even when the cost of the option is high.[75]

CONCLUSION

Examination of comprehensive risk assessments carried out by CCI for Canadian heritage collections over the last decade has uncovered frequent occurrence of emergency risks in the High to Extreme priority categories. Modelling the risks associated

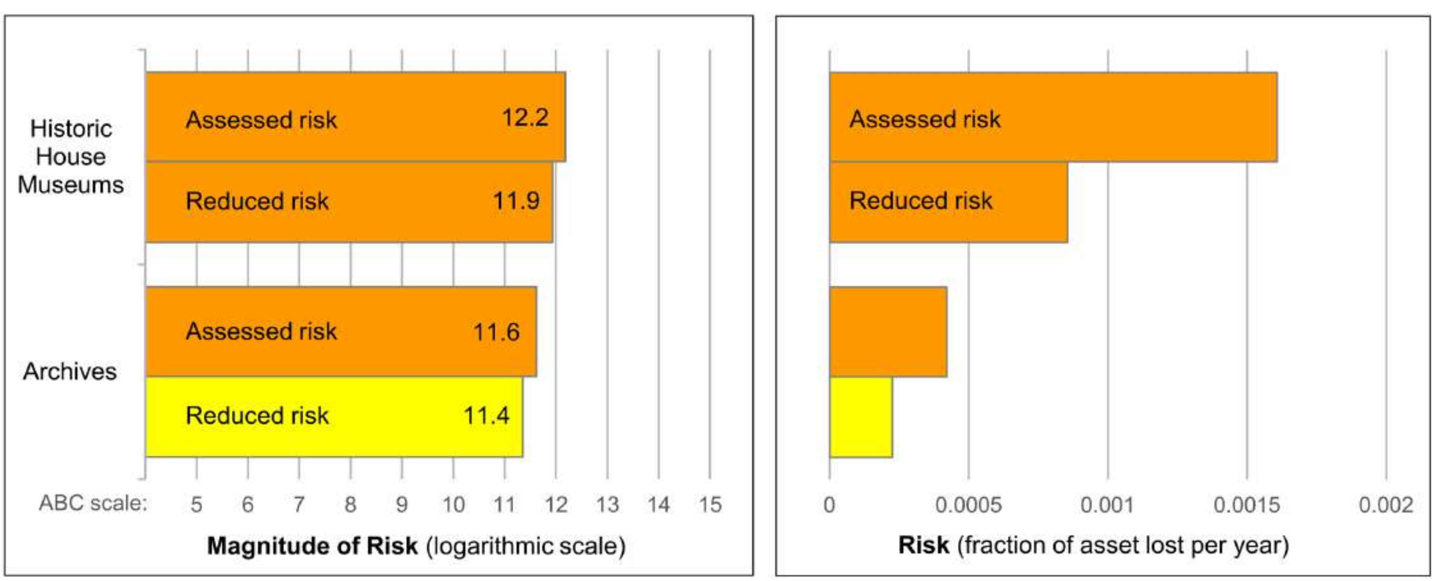

Figure 9. Predicted fire risk reduction as a result of the installation of sprinklers in two historic house museums and one archive building housing collections shown on logarithmic (left) and linear (right) scales.

with hazards such as flood, fire, earthquake and extreme winds using the ABC Method has permitted the generation of short lists of interacting factors that offer a simple approach to screening for many of the biggest risks that can occur. Unlike previous preventive conservation checklists that were long lists of recommendations with no priority order, this evidence-based, semi-quantitative screening points to disaster risks that demand attention: first for more systematic risk assessment to confirm the level of risk for a specific institution, followed by risk reduction methods when necessary.

Since the first of CCI's risk projects, it has been clear that delivering comprehensive risk assessments as a routine service was not feasible. Our goal became one of finding risk patterns that could support straightforward assessments by individual institutions themselves. The screening method described above does not identify or quantify all risks – not even all those that cause great loss, which can also result, for example, from poor storage conditions, theft and vandalism, or handling and wear over time. However, the method can help heritage professionals assess whether the collection of a particular Canadian heritage institution is threatened by any of a known group of disaster risks.

Most risks to heritage collections cannot be eliminated entirely. Even with effective and expensive risk reduction, the remaining risk may still be relatively large and require ongoing vigilance and preparation for effective emergency response and recovery. This is normal. Reducing a High or Extreme disaster risk as much as is feasible, whether by 90% or even 50%, is one of the most important parts of a preventive conservation plan. Evidence-based screening provides a simple first step to identifying and managing such disaster risks.

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This paper is dedicated to the Museum of the Highwood staff in recognition of their fortitude in the face of disasters they need not have faced.

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7 Michalski and Pedersoli, *The ABC Method*, 2016, pp. 130, 161–162.

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9 The calculation of the expected Magnitude of Risk (MR expected) score is not described in the ABC Method manual but is provided in the CCI Risk Management Database developed for use in CCI comprehensive risk assessments and used in CCI-ICCROM-RCE risk management training courses. The calculation used in this paper assumes that the probable, high and low scores for questions A, B and C follow a triangular distribution, a common continuous probability distribution. The mean of the three scores for each question is used instead of its probable value in the calculation of the Magnitude of Risk score as follows: $MR\ (expected) = 1/3(A_{low} + A_{probable} + A_{high}) + 1/3(B_{low} + B_{probable} + B_{high}) + 1/3(C_{low} + C_{probable} + C_{high})$.

10 Michalski and Pedersoli, *The ABC Method*, 2016, Table 23, p. 137.

11 The linear quantity, Risk, is related to the logarithmic value Magnitude of Risk as follows: $MR = 15 + \log\ (Risk)$. Michalski and Pedersoli, *The ABC Method*, 2016, p. 130.

12 The inadequate environment risks at the top of the risk rankings for the archives and the science and technology museum reflect the presence of many less stable materials that need cool storage to avoid significant loss within a century, such as magnetic media, acetate film, colour photographs, certain plastics and acidic paper.

13 The phrase “specific risk” is used in this paper as it is defined for the ABC Method: “a unit or package that can be usefully analyzed and quantified.” See Michalski and Pedersoli, *The ABC Method*, 2016, p. 65.

14 Similarly high ranking disaster risks can be observed in reports of risk assessment projects at museums that employ the Cultural Property Risk Analysis Model (CPRAM). At the Royal British Columbia Museum, the generic risk, Physical Forces Type 1, heavily influenced by earthquake risk, affected the greatest number of collections. See Lee, Kasey and Delphine Castles, “Collections Risk Assessment at the Royal BC Museum and Archives,” *Collections*, vol. 9, no. 1, 2013, pp. 9–27. Similarly, the fire risk ranked highest for the Denver Museum of Nature and Science. See Southward, Jude, Heather Thorwald, Garnet Muething and Rob Waller, “Collections Risk Assessment at the Denver Museum of Nature & Science,” *Collections*, vol. 9, no. 1, 2013, pp. 71–92. For the CPRAM method see: Waller, Robert, *Cultural Property Risk Analysis Model: Development and Application to Preventive Conservation at the Canadian Museum of Nature*, Göteborg Studies in Conservation 13 (Göteborg: Göteborg Acta Universitatis Gothoburgensis, 2003); Waller, Robert, “Comprehensive risk assessment: Applying the cultural property risk analysis model to the Canadian Museum of Nature,” in: *NATO Science for Peace and Security Series-C: Environmental Security: Real Time and Deliberative Decision Making*, edited by I. Linkov, E. Ferguson, and V.S. Magar (Dordrecht, The Netherlands: Springer, 2008), pp. 179–190.

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