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FRAMEWORK FOR DESIGN OF FLOOD-RESILIENT BUILDINGS IN A CHANGING CLIMATE

Attar, Ahmed[1,2], Khaliq, M. Naveed[1], Lounis, Zoubir[1] and Armstrong, Marianne[1]
[1] National Research Council of Canada, Ottawa, Ontario, Canada
[2] Ahmed.Attar@nrc-cnrc.gc.ca

Abstract: Increased frequency and costs of floods in Canada and changing climate conditions present many technical and economic challenges to the building and infrastructure design community. Lack of national standards for flood risk assessment and flood-resistant design of buildings are the major challenges identified by many Canadian stakeholders at a recent Workshop on Floods and Climate Change. To address these challenges, inputs from various levels of federal, provincial, territorial and municipal governments, national and international experts from engineering and climate science, insurance industry, agencies involved in flood mitigation, and the public sector are required to identify the knowledge gaps and the best possible path towards a harmonized framework for enhancing flood- and climate-resilience of buildings and infrastructure, based on a broad consensus and recommendations of all experts and stakeholders. This paper presents a harmonized framework for flood-resilient design of buildings in a changing climate. The framework considers: strategic engagement of federal, provincial, territorial and municipal stakeholders; improved interaction between code developers, structural engineers, and climate scientists; expertise of flood modellers and hydraulic engineers; and feedback from codes regulators, experts involved in codes implementation and code users. These engagements, interactions and feedbacks can be made possible through targeted national workshops.

1 Introduction

The National Research Council of Canada (NRC) is leading the Climate-Resilient Buildings and Core Public Infrastructure (CRB-CPI) project, with funding from the Federal Government of Canada, through Infrastructure Canada, to develop new and revised codes, standards, guidelines and decision-support tools in order to enhance the resilience of new and existing buildings and CPI (including roads, bridges, water and wastewater systems, and rail transit gateways) against climate change and extreme weather events (Infrastructure Canada 2016; Global News 2017). Within this multi-year project, improving resilience of buildings and CPI against floods has been identified as an important research need for two reasons, namely: (i) the costly flood disasters of the last two decades in Canada; and (ii) the documented scientific evidence that the frequency and intensity of future floods will increase due to anticipated climate change (IPCC 2014). Currently, in the National Building Code (NBC), there are no provisions for structural design of buildings to address flood-related loads as opposed to wind and snow loads (NBC 2015).

Across Canada, different flood mitigation criteria and design recommendations have been developed by provincial and municipal governments. These measures lack consistency and uniformity at the national scale, since a unified framework for identifying flood hazards and risks is not available, specifically for buildings and infrastructure design (Attar et al. 2017). Therefore, it is important to evaluate the state of practice in the design of flood-resilient buildings and infrastructure in order to develop a harmonized framework for future development of the NBC. It is also important to evaluate options for flood mitigation and retrofitting of existing buildings and CPI.

In Canada, provincial and municipal governments use flood maps to inform zoning and bylaws for land use planning purposes. Most of these maps are now more than 25 years old and were developed using one-dimensional hydraulic models and a two-zone concept that separates the floodplain into two components, namely: (i) floodway; and (ii) flood fringe. The available flood maps have several limitations, which include: (i) lack of consistency in terms of mapped flood standards at the national level; (ii) coarse resolution topographic data; (iii) outdated information on hydraulic structures and land use; and (iv) insufficient spatial information on flood depths and velocities–these are important parameters for evaluating flood-related loads on buildings and CPI (Khaliq and Attar 2017). In addition, most of the existing maps correspond to open-water situations and do not reflect the impact of ice-jam related flooding despite the relevance of freshwater ice in Canadian rivers and lakes (IWD 1976). Since flood loads can also vary with time, time-dependent information on flood depth and velocity parameters is also required to assess vulnerability of buildings and CPI. The uncertain impact of climate change on the frequency and intensity of future floods adds another layer of uncertainty that makes the application of existing flood maps challenging not only for the development of zoning and regulations but also for deriving information for the development of building codes (Khaliq and Attar 2017). Additionally, on-going land use change can significantly alter the flooding characteristics of a region. In some riverine areas, flow regulation and upstream flood mitigation can have unintended consequences on downstream infrastructure (Zwiers and Zhang 2017). Since flood maps were developed for land use planning purposes and not for the design of buildings and CPI, the utility of existing flood maps remain largely an open question in the context of codes and standards.

Though variations do exist, floods are typically divided into the following three groups: (i) riverine floods; (ii) flash floods (caused by high intensity rainfall in urban and fast responding areas); and (iii) coastal floods due to various combinations of, among other factors, tides, storm surge, wave effects, and in some cases, coincident high discharge from rivers and creeks into the coastal zone. Flood loads arising from these different types of floods, which are observed across different regions of Canada, need to be addressed appropriately for developing new model codes and design guides.

This paper focuses on buildings part of the CRB-CPI project and presents a framework for flood-resilient design of buildings in a changing climate and discusses various components of the framework and related research needs. The key components of the framework rely on: strategic engagement of federal, provincial, territorial and municipal stakeholders; improved interaction between code developers, structural engineers, and climate scientists; working directly with flood modellers and hydraulic engineers; and exploiting feedback from codes regulators, experts involved in codes implementation and code users (see Figure 1). Targeted national workshops are expected to promote communication and interactions between various stakeholders and experts.

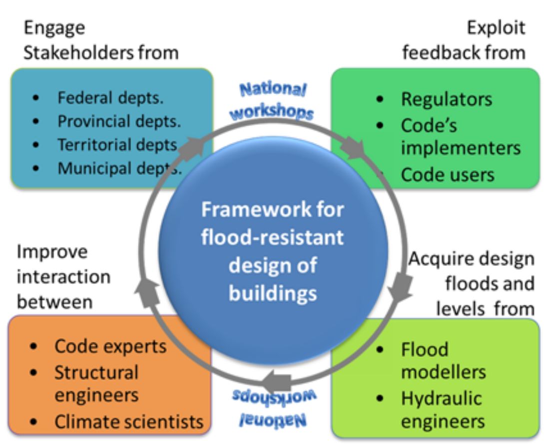

Figure 1: Involvement of various stakeholders and experts in the development of the framework for flood-resistant design of buildings.

The paper is organized as follows: Section 2 presents an overview of the status of floodplain maps in Canada and discusses gaps in data, standards and tools in the context of flood risk assessment to support development of new codes and standards. Section 3 pertains to the framework for the design of flood- and climate-resilient buildings and offers an enlightening discussion on various components of the framework. Such a framework is central to the development of new codes, standards, guides and decision-support tools for improved climate and flood resilience. A targeted discussion on climate change aspects is provided in Section 4. Finally, concluding remarks, including a set of action items, are presented in Section 5. It is important to note that most of the contents of the paper rely and build on the broad consensus and recommendations of experts who participated in the International Workshop on Floods and Climate Change: Codes and Standards Perspective, held in Ottawa on 13–14 July 2017 (Attar et al. 2017). Information related to various provincial/territorial initiatives and viewpoints of select large municipalities on flood mapping and mitigation efforts can be found in the Workshop Proceedings (Attar et al. 2017).

2 Status of Riverine and Coastal Flood Mapping in Canada

The majority of flood mapping work in Canada was carried out through a federally administered program, the Flood Damage Reduction Program (FDRP), on a cost sharing basis between the provinces/territories and the Federal Government (IWD 1976; Environment and Climate Change Canada 2016). When the FDRP concluded in 1995/96, the responsibility for updating and maintaining flood mapping was delegated to provinces and territories. Most of the flood maps, produced within the FDRP, were targeted to show flood extents following the two-zone concept, i.e. the floodway and the flood fringe (IWD 1976; Environment and Climate Change Canada 2016):

- The floodway is the portion of the floodplain where flood velocities are expected to equal or exceed 1 m/s and/or water depths equal or exceed 1 m corresponding to the designated/regulatory/design flood, which varies across the country. In this zone, development and site alteration would cause a danger to public health and safety (or property damage). Therefore, developments in this zone are generally prohibited.
- The flood fringe is the remainder portion of the floodplain where the flood velocities are under 1 m/s and the water depth is below 1 m. In this zone, developments are generally regulated following an approval process and necessary flood proofing.

In some parts of Canada, floodway is defined as the area that is within the reach of a 20-year return period flood level and flood fringe is defined as the area that is between the 20- and 100-year return period flood levels (Khaliq and Attar 2017). In some jurisdictions, additional freeboard above the flood design level is also specified (Khaliq and Attar 2017). It is important to note that the design flood levels, plus freeboard considerations, were adopted for flood mitigation and land use planning purposes and not specifically for structural design of buildings. In the case of developments in flood fringe areas, structural stability was implicitly attempted through mandatory flood proofing requirements, suggesting an indirect connection with the objectives of building codes.

The floodway and flood fringe concepts discussed above are specific to riverine floods. Hazard zone definitions in coastal areas are typically categorized according to heights above a designated high water level allowing for tides, storm surge, waves and other effects, and/or minimum setback distances from a specified high water level. Recently, Murphy (2017) performed an initial evaluation of approaches to coastal flood risk assessment and management in Canada and internationally. This evaluation found that current frameworks for coastal flood risk assessment in Canada are intended primarily for land use planning applications, and reflect a fixed standard-based approach, which does not explicitly take into account the consequences resulting from flood events with lower or higher probabilities than the designated standard.

3 A Framework for Implementation of Flood-Resistant Design in Building Codes/Guides

The focus of this Framework is on buildings for which currently there are no provisions in the NBC for flood-resistant design. The NBC's objectives are to have buildings that provide "safety, health, accessibility and protection against fire" (NBC 2015; Irwin 2017). Although design or construction to resist flooding is currently not addressed explicitly in the NBC, some negative effects from extreme weather events (e.g. compromised structural safety, structural damage and deterioration of the building) are indirectly addressed as "other loads" (NBC 2015). Current code objectives do not however include performance criteria related to protection of property or minimization of damage to property. As mentioned before, flood hazard mapping methods currently in use in different regions of Canada generally do not take building performance or design criteria into account.

Consistent to the suggestions made by Irwin (2017), issues related to flood loads in the NBC may be grouped into the following broad categories:

- Mapping flood hazards and risks in a consistent manner for codes and standards in order to designate areas where flood loads would be expected;
- Development of provisions for structural design of buildings against flood loads;
- Development of provisions for design of building envelope and choice of materials (including flood-resistant measures for existing buildings) to prevent flood damage and reduce cost of remediation and health consequences; and
- Designation of places of refuge/shelters in the event of a flood.

The above points are discussed further in the following four sections, which form the basis of the framework for flood-resistant design of buildings (see Figure 2).

3.1 Development of Uniform Methods for Consistent Mapping of Flood Risks for Building Design

Natural Resources Canada (NRCan) under the National Disaster Mitigation Program of Public Safety Canada is currently developing best practice Canadian flood mapping guidelines to inform land use planning and development bylaws (https://www.publicsafety.gc.ca/cnt/mrgnc-mngmnt/dsstr-prvntn-mtgtn/ndmp/index-en.aspx). For building design purposes, flood maps produced following these guidelines may lead to different interpretations among jurisdictions due to the varying impacts on existing buildings in different regions. Such flood maps will not necessarily be tailored to the objectives of the NBC. Therefore, there is a need to develop consistent standards to assess and designate flood hazards and risks in a quantitative manner in order to achieve objectives of the NBC. Design flood hazard levels could be standardized in the NBC to meet the code objectives, in a similar manner to what is currently done for other hazards such as earthquake, wind, and snow. This could be achieved by developing minimum requirements for flood resilience of buildings (ASCE/SEI 7-16 2017).

3.2 Development of Code Provisions for Flood-Resistant Buildings

According to Jones (2017), there are several issues that need to be addressed for the development of flood code provisions in the NBC as discussed below:

- Mapping flood hazards – What flood levels should be mapped, and which ones should be used to support the NBC objectives? What methods of analysis and modelling and associated data are appropriate for determining and mapping flood hazards for building design in different parts of Canada? What flood hazard or risk zones are appropriate for the NBC?
- Non-stationarity of flood hazard – In the context of a changing climate, there is a need to examine the concept of flood return period and associated return level, which is generally derived on the assumption of a stationary climate.
- What types of construction should be allowed/prohibited in different flood hazard zones? Should floodway be treated differently than flood fringe? Should all flood fringe areas be treated the same? Should flood proofing in flood fringe be associated with structural performance of buildings? These

points are based on the assumption that the two-zone mapping concept, practiced largely in Canada, will continue to be practiced in riverine areas in the future. Similarly, for areas prone to other types of flooding (e.g. pluvial, coastal, etc.), what hazard zone definitions are appropriate?

- Failure of buildings – There is a difference between structural failure, and damage or loss of use when a building gets flooded. Code provisions should address both issues in the case of floods.
- Building importance – Code provisions should treat certain buildings/structures differently based on the consequences of their failure, including how critical they are for the community or operations (e.g. post-disaster buildings, such as hospitals).
- Building performance objectives – What is the expected performance level for buildings against floods? Should performance expectations vary with building type?

All of these issues should be considered in the context of exiting flood hazards and within the context of potential future flood hazards (e.g. when considering the impact of climate change on floods).

Similarly to what is currently provided in the ASCE/SEI 7-16 Standard "Minimum Design Loads for Buildings and Other Structures" (ASCE/SEI 7-16 2017), a new section could be added in Part 4 of the NBC (NBC 2015) on Structural Design for Floods and in Part 5 on Design of Building Envelope for Floods. However, in the absence of a national consensus of acceptable flood hazards and risks, the definition of floodway zones and fringe zones could still be left to local jurisdictions. The NBC could provide a method on how to account for flood loads, given that the building is in a defined flood zone. The provisions could be graded for different levels of importance of the building so that post disaster buildings (e.g. hospitals and shelters) are designed for more extreme flood events and/or higher levels of reliability in a similar manner as recommended in the USA (FEMA-543 2007).

The NBC requirements for large buildings are different from those for housing (and other small buildings). Small buildings may not be engineered, which creates a preference for prescriptive requirements vs. performance-based requirements. Appropriate prescriptive approaches for protecting small buildings and houses from flooding should be developed. Consensus on methods of identifying and mapping flood hazards will be necessary to develop effective code provisions.

The types of requirements that could be used as the basis for code provisions would need to be defined, including simple requirements, such as minimum elevation for habitable and other space and utility equipment, basement construction and use, etc.

Prior to the development and implementation of requirements for flood-resistant design of buildings in the NBC, there is a need to assess whether provisions to address other loads in the current NBC are adequate for flood risks and whether the scope of the code can be expanded to address this issue during design and construction of buildings. Otherwise, adding "Flood Resistance" or "Mitigation against Floods" as an additional objective of the NBC could be discussed between the CCBFC (Canadian Commission on Building and Fire Codes), and federal, provincial/territorial and municipal authorities.

3.3 Development of Standards/Guidelines for Flood Protection Measures

The CSA (Canadian Standard Association) is working on standards related to protection of basements, i.e. provision of pumping systems, backflow valves and back-up power, use of flood resistant materials, etc. This work is focused mainly on protection against high-intensity rainfall related local flooding and does not encompass riverine or coastal flooding.

The long-standing experience of flooding in the Province of Manitoba had already led to the development of various performance-based design options. These guidelines could be used as seed documents for a national set of performance options in the short term, while longer-term development and discussion of code provisions become available.

Guidance is also needed on flood-resistant measures for existing buildings. This should be incorporated in the CCBFC and PTPACC (Provincial/Territorial Policy Advisory Committee on Codes) scoping work.

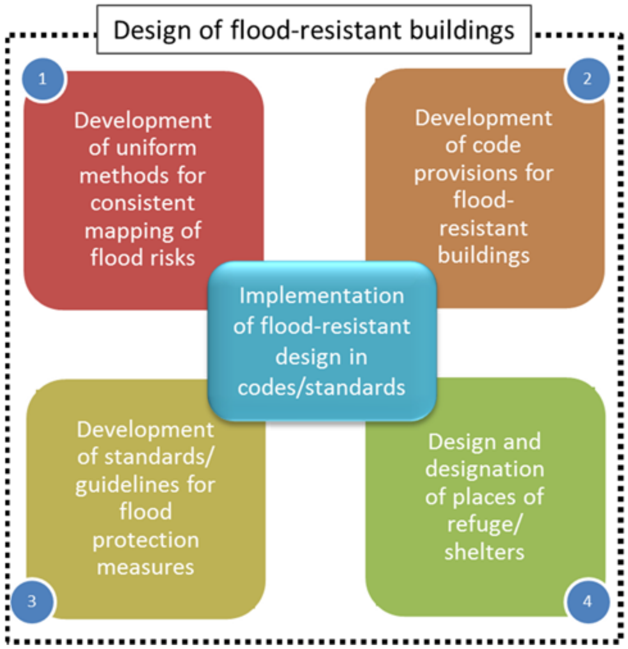

Figure 2: A schematic of the framework for implementation of flood-resistant design in building codes, standards and guides.

3.4 Design and Designation of Places of Refuge/Shelters

Some tall buildings in urban areas could be designated as places of refuge/shelters in the event of a flood (Irwin 2017). The idea has begun to be considered for cities impacted by hurricanes and storm surge, for example, where evacuation of a large number of people immediately before (and after) a storm has practical limitations. Such buildings would need to have special features (structural resilience, backup power, water storage tanks, on-site waste disposal capacity, food supply and communications). The services expected would not be very different from systems used on ocean liners so that they could be relatively self-sufficient for a period of a few days after an extreme event (FEMA-543 2007).

The feasibility of this approach could be challenged since emergency services are not used to distinguish individual buildings within flood zones. However, the idea deserves further consideration and it could enhance the ability of a community to recover after a major event. The City of San Francisco is looking at this concept with respect to earthquakes. In the USA, refuge buildings/shelters are now considered in the context of tsunamis (ASCE/SEI 7-16 2017).

4 Consideration of Impacts of Climate Change on Floods

Climate change is expected to impact intensity and frequency of floods which will further complicate the process of code provisions development and future revisions. There is a need to investigate the impact of climate change on design flood levels and how these will be incorporated in codes and standards, considering the non-stationary conditions due to climate change and uncertainties associated with the estimation of flood magnitudes in a changing climate.

Some changes seem more logical than others: e.g. global sea-level-rise (although the exact magnitude in the future is uncertain) and increased precipitation resulting from a future warmer atmosphere that can hold more moisture (IPCC 2014). These changes will also affect flood hazards and risks. However, suitable guidance on how to predict future flood hazards and risks is lacking. While there are significant uncertainties in climate change projections, uncertainty is not a new concept in engineering design. Climate uncertainty can be treated like other forms of uncertainty that engineers and building designers routinely deal with. In general, uncertainty in engineering practice is dealt with by applying load factors or by adjusting the probability level at which design loads are set to achieve a given level of reliability (Irwin 2017). For example, design wind loads in Canada are currently specified as those having 0.02 annual probability of exceedance with a load factor of 1.4 applied as an allowance for uncertainties (NBC 2015). In the USA, rather than applying a load factor, the annual probability for wind is set at an appropriately lower value of 0.0014 (equivalent to designing a building to withstand a 700-year return period wind event) for Occupancy Risk Category II structures (ASCE/SEI 7-16 2017).

Most climatic data in design codes are based on historical records assuming the climate is stationary. Such an assumption is in question as the statistics that define different climatic loads could be time-dependent in a changing climate. Hence, the non-stationary nature of precipitation extremes, sea levels and other climate-related factors contributing to floods will need to be evaluated and considered in the development of code provisions for flood-resistant design of buildings.

Since the traditional concept of return period partially loses its utility in a changing climate, the language used to describe hazard and risk levels based on this traditional concept may need to be revised. Probability of exceedance during selected time periods of relevance such as the building's design life, life cycle, planning horizon or a typical amortization period, could be a better alternative. However, there is currently no universally accepted and agreed upon approach for calculating the probability of exceedance of a given flood hazard level during selected periods of relevance in a changing climate. Therefore, additional work is warranted to develop related guidelines and recommendations.

For building design requirements or adaptation measures to resist floods, the state of future projections of climate change is also important as the projections diverge considerably into the distant future (IPCC 2014). Therefore, some consideration should also be given to possible timelines or trigger points for adaptation, considering the design life of buildings and the increasing uncertainty/spread in projections into the distant future. For example, it might be possible to use a mid-range or high-range climate change scenario for buildings with short life spans. However, longer design life buildings might be designed for low- or mid-range scenarios, with the expectation that adaptation measures could be implemented in the future to accommodate climate change impacts when the impacts are known with more certainty based on additional data that will become available. This approach is consistent to that taken by the BC Ministry of Environment with sea-level-rise projections.

Another strategy that could be used to address flood loads in the face of scientific uncertainties is to make decisions using a "low regrets" approach, i.e. adding robustness to designs in a cost-effective manner as a general policy (Irwin 2017). For example, providing extra room in new developments to accommodate additional measures, consistent to projected changes in temperature, precipitation and flood severity. Another strategy that could be used for flood-resilient design of buildings in the face of significant climate change uncertainty is to incorporate adaptation principles and strategies in the design philosophy. This approach is well established internationally and along similar lines, Engineers Canada (https://pievc.ca/protocol) provides a high-level structured, formalized process for engineers to assess climate risks and vulnerabilities and to establish the adaptive capacity of various structures (e.g. buildings).

5 Concluding Remarks

To enhance the resistance of existing buildings to flood loads and to develop requirements for designing flood-resistant buildings for future implementation in the NBC, a number of focused tasks and supporting analyses need to be carried out in a systematic manner as described below:

- Development of requirements for the design of buildings to resist or adapt to flood-related loads in defined flood zones using a set of well-defined performance objectives for buildings of varying importance, including residential, industrial, and post-disaster buildings.
- Development of flood resistance requirements for retrofitting of existing buildings of varying importance.

- Development of requirements for the design of building materials and systems (including building envelope) to resist damage from flooding.
- Development of standard approaches for evaluating flood hazards and risks to buildings across Canada, considering associated uncertainties and effects of climate change.
- Development of datasets needed to assess flood risks in urban and fast responding areas, such as precipitation intensity duration frequency (IDF) curves based on both historical data and climate change projections. Future IDF curves and other information need to be easily interpreted by the user community, including engineering consultants and codes developers and regulators. Also, historical IDF curves should be assessed from a non-stationary perspective for identifying regions or areas where changes in observed records have occurred over time.
- Development of a Section for potential inclusion in the NBC for implementing requirements for the design of buildings to resist flood loads.

In spite of a long history of research, the science behind future projections of climatic loads including floods is still evolving and probably will continue to evolve in the near future. Therefore, guidelines on future revisions of the NBC based on improved projections need to be developed and incorporated in the NBC as a living Section of the code.

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