6TH INTERNATIONAL CONFERENCE
ON FLOOD MANAGEMENT
September 2014 - São Paulo - Brazil

THE VALUE OF A COASTAL FLOOD RISK ASSESSMENT FOR THE CITY OF VANCOUVER IN A CHANGING CLIMATE

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ABSTRACT: The City of Vancouver, Canada, has recognised that despite global mitigation efforts, climate change will impact the City's future. Anticipated impacts include more intense and frequent wind and rain storms and sea level rise. Adaptation to these climate changes will require a mix of policy, planning and engineering responses. Prior to identifying preferred mitigation strategies, a comprehensive understanding of the consequences of sea level rise and ocean flooding is required. The City of Vancouver is undertaking a coastal flood risk assessment (CFRA) to acquire a broad base of technical, policy and planning knowledge that will be used to develop a robust and defensible approach to flood risk.

A multi-disciplinary consultant team is working together with the City to develop the inputs for a risk assessment, including inundation mapping, vulnerability assessments and an asset inventory. These data sets together with flood damage information from HAZUS, a flood consequence tool developed by US FEMA and supported by Natural Resources Canada, was be used to look at consequences to coastal flooding.

Over the course of the project, the team has recognized the many uncertainties and gaps in the process of developing a CFRA for a modern, dense, urban city such as Vancouver. Especially when considering the long planning horizons required to prepare for and adapt to sea level rise. This paper highlights the many obstacles and gaps in the assessment, but also describes the inherent value of the process and results. These include increased understanding of hazards and vulnerabilities, and the development of useful visual tools for engagement, planning and education.

Key Words: Flood Risk, Sea Level Rise, Climate Change, Urban Flooding, Gap Analysis

1. INTRODUCTION

In the summer of 2013, the World Bank and OECD released a report listing the world's most at risk cities to coastal flooding, placing Vancouver at number 11 (Hallegatte et al. 2013). This was on the heels of several large flood events in neighbouring jurisdictions: New York's superstorm Sandy in October 2012, the June 2013 flooding of southern Alberta that covered large swathes of Calgary, and the July 2013 rainstorm that inundated Toronto. All this reinforced the need to study and ultimately adapt to changing coastal flood risk in Vancouver. Prior to these events, the City had already recognised this need. In its 2012 Climate Change Adaptation Strategy (City of Vancouver 2012), the City recognized that despite global mitigation efforts, climate change will impact the City's future. Anticipated impacts include more intense and frequent wind and rain storms and sea level rise. One key action in the Strategy was the development of a Coastal Flood Risk Assessment (CFRA) for the City. The first phase of the CFRA project was initiated in July 2013 with the goal of establishing coastal flood hazard, highlighting community vulnerabilities, and establishing consequences to coastal flooding in the present and future climate. A summary of this work, with a focus on the identified obstacles and gaps, is presented in this paper. The second phase of work to be completed by the spring of 2015 will look at mitigation and adaption options for the City using a structured-decision-making approach. This paper aims to show that there is significant value in the process of developing a flood risk assessment despite the many gaps and uncertainties associated with this type of research. This is especially relevant given that many adaptation and mitigation options will need to be planned, if not implemented, in the near future without a robust understanding of what coastal flooding may look like 100 years from now.

The City of Vancouver lies on the western edge of Canada (Figure 1). It and the neighbouring electoral district of UBC have 83 km of shoreline. Most of the shoreline abuts the Georgia Strait, the body of water that separates the mainland from Vancouver Island. Vancouver Island acts as a barrier between the City and the Pacific Ocean, it cannot however reduce the impacts of future sea level rise. To the south of the City lies the mouth of Fraser River, a large river with a mean annual discharge of approximately 3,500 m^3/s, much of which comes down during the annual spring freshet. However, in reach that borders the City, river elevations are dominated year-round by the backwatering effects of the ocean. And therefore, all 83 km of City shoreline will be impacted by increasing sea levels in future.

Figure 1: Location and detail of Vancouver, Canada (Wikimedia commons image)

2. FLOOD RISK IN VANCOUVER – WHY AND WHAT DO WE NEED TO KNOW?

The identity of Vancouver is intertwined with its position on the coast; iconic images of the City nearly always include shoreline. The coastal and riverine floodplains are centres of commercial, social, economic and ecologic activity, and as such they are home to City, regional, provincial and national assets. These assets are subject to damage when floods occur.

Given that we use our floodplains for a range of commercial, social, economic and environmental purposes, we need to acknowledge and plan for flooding in a way that improves the resilience of our built form and encourages safety and well-being for our communities. As the City looks to the future and a changing climate, sea level rise in particular, the need to understand the potential impacts of coastal flooding is crucial for decision-making (Figure 2). We can't manage and reduce our risk until we know what it is.

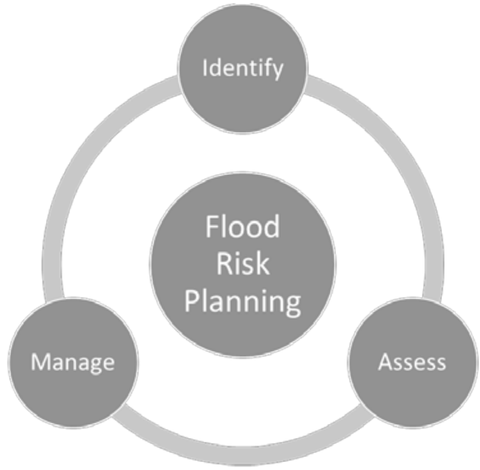

Figure 2: Flood risk planning process

Flood risk assessment is widely considered to be the best tool to make decisions that will mitigate flood impacts over time (European Comission 2003; Jha, Bloch, and Lamond 2012), and is being used around the world (Australia (Queensland Reconstruction Authority 2013); New Zealand (Rouse 2012), Japan, Netherlands and the United States(US Army Corps of Engineers et al. 2011); and the UK (Environment Agency 2009)) as countries and cities grapple with increasing flood risk in a changing climate. Risk assessment for flood management is only in its infancy in Canada, where regulatory standards-based management is the norm.

Flood risk is a function of both the likelihood of an event occurring and the consequences of that event occurring (Figure 3). Flood consequence is defined as a function of flood hazard - where water will go - and vulnerability - what's in the way.

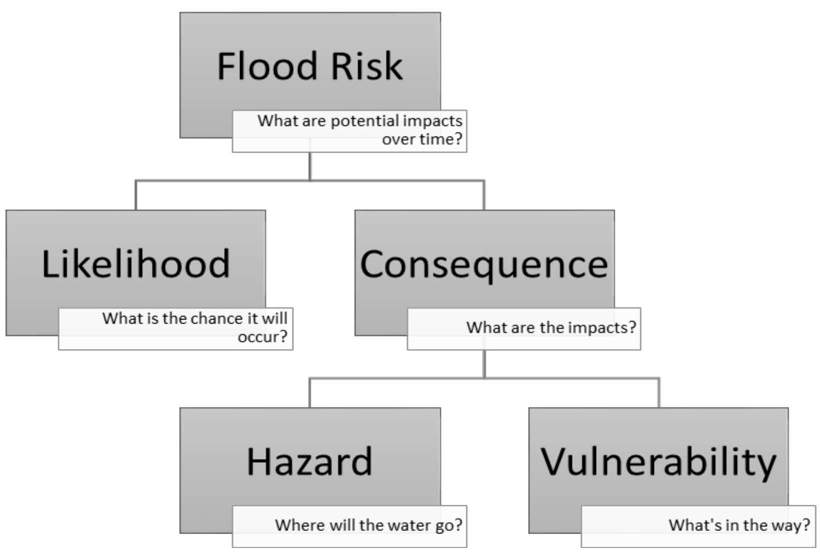

Figure 3: Flood risk as a function of hazard, likelihood and vulnerability (after (Queensland Reconstruction Authority 2013))

As just discussed, risk is a function of both likelihood and consequence (Figure 4), which helps decision-makers consider and compare both a high likelihood, low consequence event and a low likelihood, high consequence event on an equal footing (Figure 5). This becomes particularly important as we look across long time-horizons. A nuisance flood that occurs annually over several decades may in fact be more impactful than a catastrophic flood that occurs just once. A risk assessment can be used to compare both the impacts and the potential benefits of mitigation options for the whole spectrum of nuisance to catastrophic events.

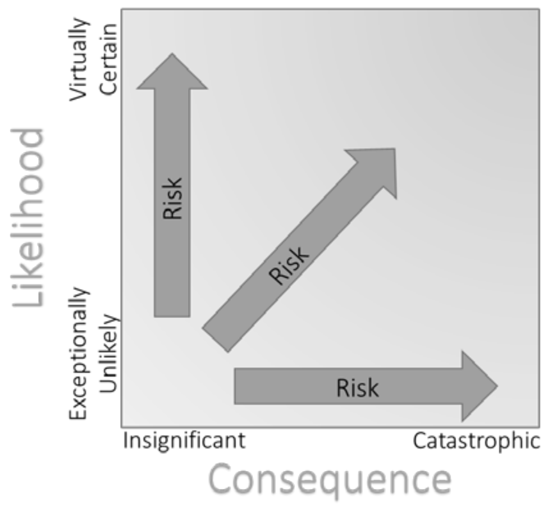

Figure 4: Risk as a function of likelihood and consequence; Figure 5: Nuisance and catastrophic flooding

3. FLOOD CONSEQUENCES OR IMPACTS

Water on a floodplain itself is not a problem. The impacts of flooding occur when water interacts with natural and human environments in a negative sense, causing damage, disruption and occasionally death. Flood impacts are varied, and can be described in many ways.

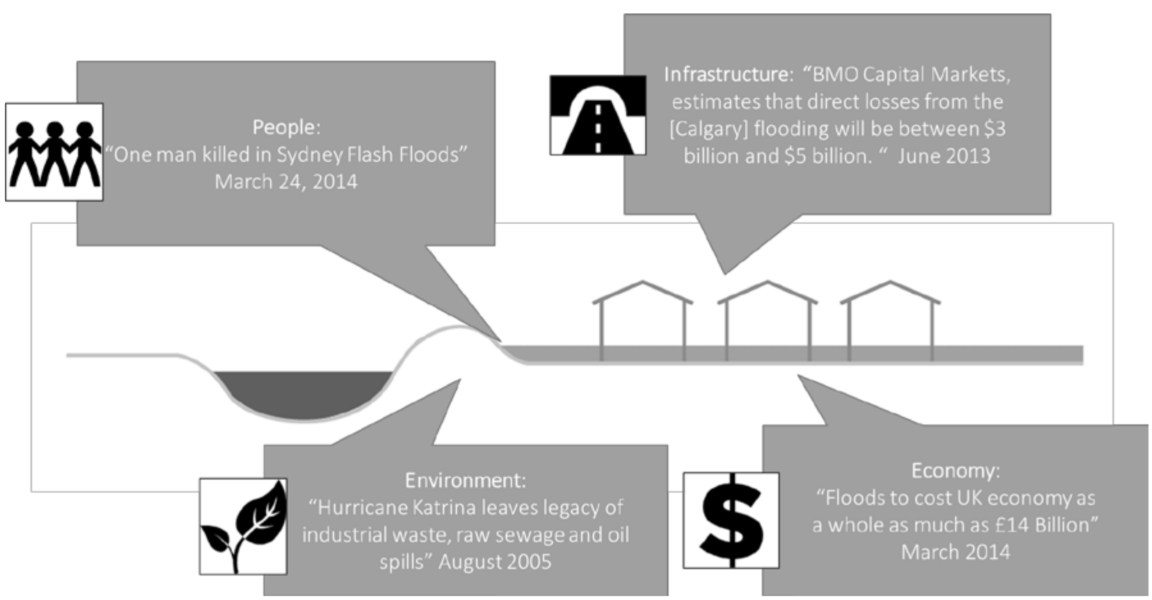

Figure 6: Flood impacts by receptor

3.1 Flood Impact Typologies

The source-pathway-receptor model is a common method of looking a flood risk, where the impacts are defined by the ‘receptors’ or elements at risk on a floodplain (Frank Messner et al. 2006; RIBA). These include people, buildings/infrastructure, natural environments and the economies that link them (Figure 6). These groupings are one means of considering and organising flood impacts for practical reporting, however it must be noted that there are many linkages and common elements between these groups.

3.1.1 Direct and Indirect Flood Impacts

Flood impacts can be further divided into direct and indirect impacts. **Direct** impacts describe all harm that relates to the immediate physical contact of water to people, infrastructure and the environment. Examples include damages to buildings, impacts to building contents and other assets, damage to the environment and loss of human life. Whereas, **indirect** impacts are those caused by the disruption of the physical and economic links in the region as well as the costs associated with the emergency response to a flood. For example, businesses losses because of interruption of normal activities, or costs associated with traffic disruption when roads are impassable.

3.1.2 Flood Impacts by Tangibility

The effect of a flood on the environment, human or community health, or the loss of life are difficult to quantify, and are therefore considered to be **intangible** impacts. Whereas, the **tangible** dollar losses from a damaged building or ruined inventory in a warehouse are more easily calculated. This does not mean that tangible losses are more important than the intangibles, just that they are easier to quantify and assess. The inclusion of intangible impacts is desirable for the development of a robust flood risk assessment (Frank Messner et al. 2006).

3.2 **Calculating Flood Impacts**

Estimates of potential flood impacts are an essential piece of a flood risk assessment (see Figure 3). A general approach to estimating flood impacts is to first assess potential flood damages to the various elements at risk: people, infrastructure, environment and the economy. Infrastructure damage is by far the easiest to quantify (it is a direct tangible impact), and is commonly calculated as a percent of damage to a structure. This in turn is translated into a cost or loss by considering the amount of money or other resources required to repair, rebuild, replace or move the damaged structure (Figure 7). Similar, although more subtle, calculations can be made to look at damages and losses to people, the environment and the economy; these calculations tend to be more difficult as the impacts are either indirect or intangible. At present, the tools to calculate the indirect or intangible impacts are not well-developed in the field of flood risk management (F Messner and Meyer 2006; Veldhuis 2011).

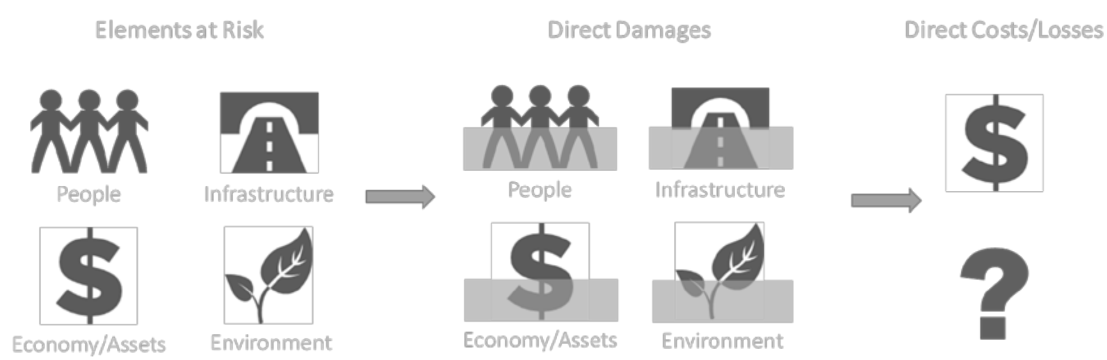

Figure 7: Estimating direct flood impacts

4. FLOOD IMPACTS IN THE CITY OF VANCOUVER

If we revisit the definition of flood consequence; it is a function of both the flood hazard and the vulnerability of the elements in the way of the flood (Figure 3). For the City of Vancouver, detailed hazard mapping has been developed as a major component of the CFRA project and is summarised below. Furthermore, key vulnerabilities have been fleshed out and are also summarised below.

4.1 Identified Hazards in the City of Vancouver

As described in the introduction, the City of Vancouver is surrounded on three sides by water: ocean coastlines to the north and west, and by the Fraser River to the south. All the shorelines are directly impacted by fluctuations in coastal water levels. The water level is a function of deterministic tidal fluctuations as well as probabilistic increases resulting from storm and wind surge and set-up (Figure 8). As we look to the future, water levels will also be affected by potential sea level rise, which at the moment is uncertain, but in Vancouver is expected to increase local water levels by 1 m (from year 2000 levels) by 2100 (Bornhold 2008). Although dependent on local topography, this 1 m increase can have a significant impact on the areal extent of the coastal floodplains (Figure 8)

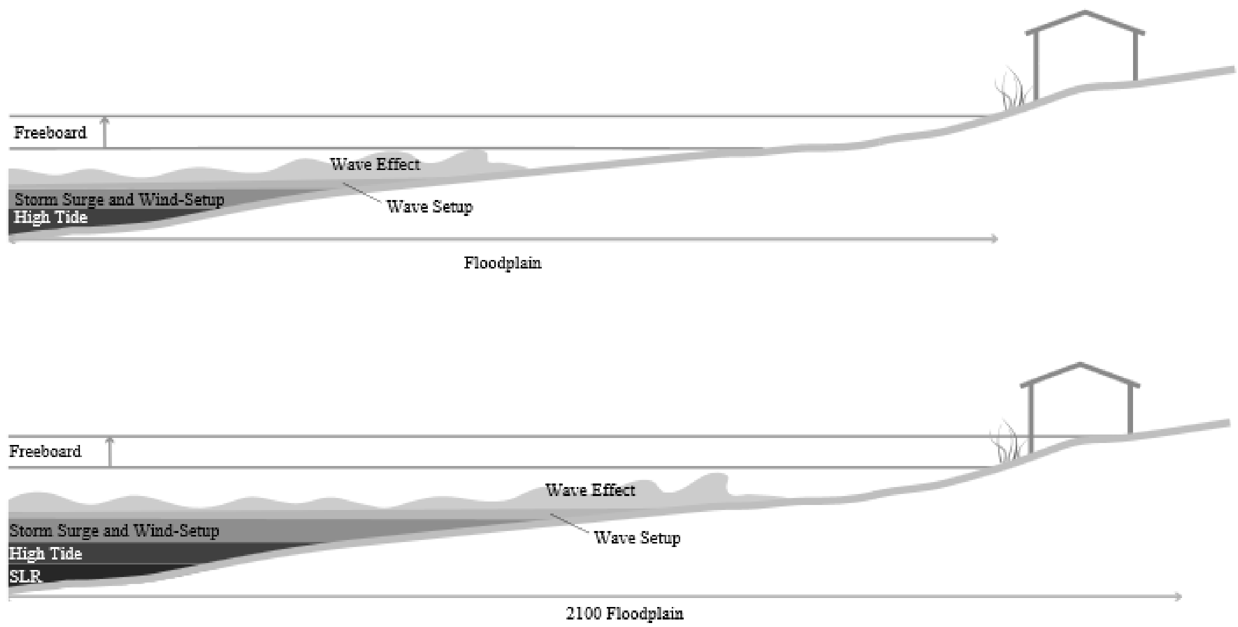

Figure 8: Coastal flood levels for present and with sea level rise (SLR)

In order to complete a true risk assessment that considers a spectrum of events with various probabilities and time scales, five coastal flood scenarios were selected and modelled as described in Table 2. Modelling and mapping efforts completed by the consulting team included coastal modelling of the Georgia Strait using a continuous simulation approach to capture the joint probability of the various coastal components occurring together. Inundation modelling on land was developed from a TELEMAC2D hydrodynamic model of the floodplains, using the coastal model outputs as a boundary condition. The model mesh was carefully designed to capture the urban nature of the floodplains; buildings and building groups were removed from the mesh, and breaklines were used to align flow along roads and other natural flow paths. Onshore waves were also modelled for affected coastal areas. The hazard modelling is based on the best available science and modelling techniques. It is however, like all models, subject to some error and uncertainty. Specifically, for the coastal modelling: the use of historic coastal conditions as a reflection of future conditions given climate change, the extrapolation of a relatively short data record (50 years) to estimate return periods up to 1 in 10,000 years, in addition to general modelling uncertainty related to bathymetry, mesh development and operator error. Similar uncertainties are found for the overland hydrodynamic modelling from topographic data, mesh optimisation and simplification, and operator error. Significant effort was made to minimise errors in the hazard modelling, and at this time it is not to be improved upon using existing data and techniques.

Table 1: Summary of hazard scenarios

Run	***Year***	***Sea Level Rise***	***Return Period for Surge, Set-up and Tide***
1	2013	-	1/500
2	2100	0.6 m	1/500
3	2100	1.0 m	1/500
4	2100	1.0 m	1/10,000
5	2200	2.0 m	1/10,000

4.2 Identified vulnerabilities in the City of Vancouver

Table 2: Summary of identified vulnerabilities to coastal flooding

Infrastructure	***Economy***	***People (Community)***	***People (Recreation and Culture)***	***Environment***
▪ Major rail lines ▪ Rapid transit tunnels ▪ Electricity substations and transmission lines ▪ Water and sewer pump stations, overflows and pipes ▪ Neighbourhood energy infrastructure ▪ City yards, fire halls and police stations ▪ Commercial and residential towers ▪ Commercial and residential low-rise buildings, some with basement suites ▪ Industrial buildings	▪ Transport hubs (train stations and yards, bus station, rapid transit stations) ▪ Port ▪ Tourist destinations (parks, beaches, major restaurants, hotels and hostels, cruise ship terminal, parks, beaches, Granville island) ▪ Commercial service centres ▪ Industrial zones including “green jobs zone” and produce depots ▪ Water dependant industry including marinas ▪ High-value real estate	▪ Community centres ▪ Homeless shelters ▪ Non-market housing ▪ Emergency shelters and mass refuges ▪ Seniors housing and day-centres ▪ Childcare and pre-schools ▪ Schools and educational facilities (including libraries) ▪ Food banks ▪ Social service centres ▪ Animal shelters	▪ Pools, rinks, sports fields ▪ Museums and archives ▪ Galleries and cultural destinations ▪ Heritage sites	▪ Ecological value of shoreline areas ▪ Potential contamination from hazardous waste storage and infill soils ▪ Parks and beaches

On the completion of the hazard assessment, with knowledge of what areas of the city might be under water in future, the project team conducted a high level vulnerability assessment to look at elements at risk on the floodplains. This effort involved reviewing the current land uses, available literature and reporting and most importantly conducting a stakeholder workshop. Several dozen diverse stakeholders were invited to illicit a list of "what's in the way" and "what do we care about" on the City's floodplains. A summary of key vulnerabilities is listed in Table 2.

There was significant diversity in the identified elements; they straddled the various receptor types of infrastructure, economy, people and environment. Many of the elements are indirect impacts (e.g. economic losses from the closure of tourist destinations), and many were intangible (e.g. the potential loss of heritage and cultural sites). Indirect and cascading impacts were also considered, but are not presented here for brevity.

As we transition from a period of flood planning and damage mitigation based on a standards based approach to a more holistic risk based approach to flood mitigation, there has been a significant increase in the knowledge base around flood impacts. Flood damage estimation has traditionally been the domain of engineers and as such as focussed on economic valuation of infrastructure and building losses, leaving a large gap in knowledge (F Messner and Meyer 2006). This gap has increasingly been acknowledged, but there is still very limited validated research available and tools to look at intangible impacts are large undeveloped. Given the identified elements at risk for the City of Vancouver, this is a clear and large gap in the CFRA outcomes for the City.

4.3 Calculating consequences in the City of Vancouver using Hazus Model

Hazus, a model initiated by FEMA in 1992, is a standardized methodology for the calculation of potential losses from natural hazards and is widely used across the United States. It was designed as a planning level tool for local governments and agencies to develop emergency management and mitigation plans (Department of Homeland Security. Federal Emergency Management Agency 2009a). Natural Resources Canada began adapting Hazus for use in Canada in 2011 (Nastev and Todorov 2013). The earthquake module was the initial focus of the effort; the addition of the flood module for Canada is still in the infancy stage, with the model currently in beta release. The Canadian version of Hazus is solidly based on the US version and is for the flood module virtually unchanged (Nicky Hastings 2014).

The City of Vancouver opted to use Hazus as the primary tool for flood consequence assessment for several reasons. First, because this tool had recently been adopted by the Federal government, and second because the City had already invested resources into developing the asset inventory for Hazus for earthquake assessment studies. At the outset, the project team recognised that there would be some limitations to Hazus as a tool.

Hazus, like most risk assessment tools, calculates only direct tangible and some indirect tangible damages and losses, providing a significant amount of information about buildings in particular. It also provides limited loss information pertaining to people as well as indirect economic losses. Most of the calculations are done based on large scale classifications of building stock and demographics, but there is also the opportunity to refine this information with user-defined facility information. Both approaches have been applied for the City of Vancouver assessment.

Damage and loss results are calculated based on an asset inventory – what's on the floodplain – and the hazard itself – where and how deep is the water. This information is then combined with damage and loss curves from the Hazus database to produce hazard and site specific consequence information (Figure 9). The City of Vancouver and national Statistics Canada databases were not designed with flood damage estimation in mind, and as such many proxies were required to populate the asset inventory. This is of course as source of additional uncertainty to the CFRA process.

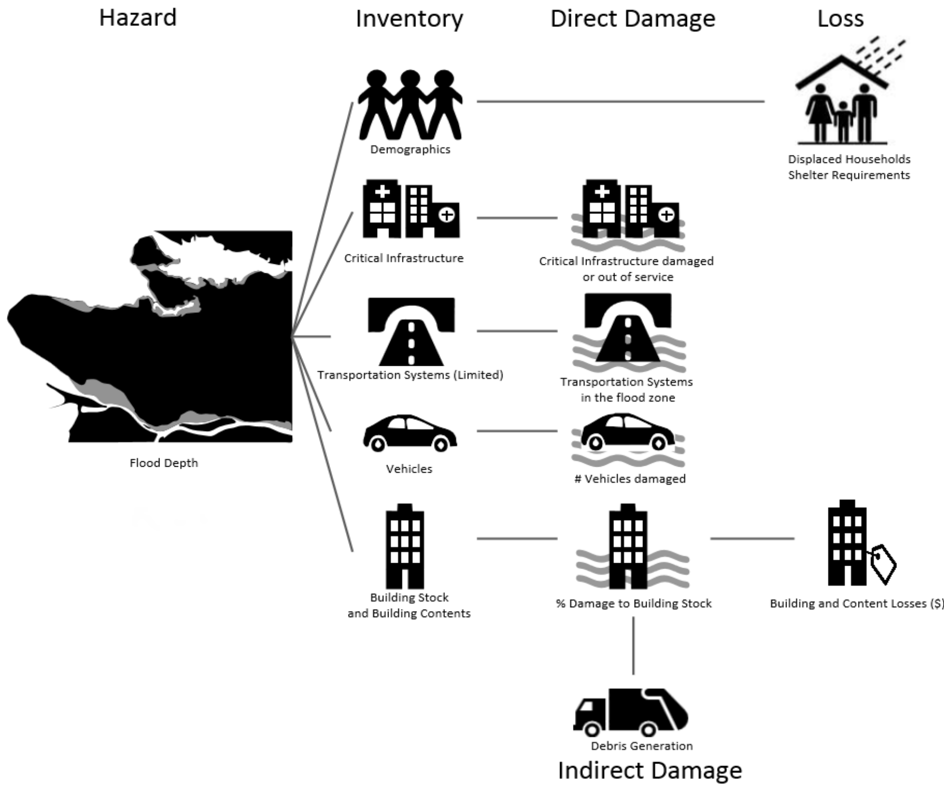

Figure 9: Hazus Structure (adapted from (Department of Homeland Security. Federal Emergency Management Agency 2009b)

Outputs for the CFRA from the Hazus model include spatial representations of potential displaced households and shelter requirements, numbers of damaged critical infrastructure buildings, a spatial representation of building (and content) damages and losses, as well as debris volumes from damaged buildings. The beta version of the Canadian flood module for Hazus does not have either the transportation systems or vehicle damages functioning for the project, and calculations for these damages were completed outside Hazus.

The Hazus model was run for each of the scenarios described in Table 1 and provides a rich resource of information on the relative damages and losses for each of the scenarios, especially for the building stock. However, over the course of the project we identified many uncertainties and gaps in the use of Hazus for a dense, urban, developed city like Vancouver. In particular, uncertainties in the applicability of the default stage-damage and loss curves emerged. Stage-damage curves are a key component of Hazus modelling and flood consequence modelling in general. Research has shown that along with information about the assets that depth-damage curves are the most important source of uncertainty in consequence modelling (Bubeck et al. 2011; Jongman et al. 2012) , and can affect the end results by a factor of 2 (Moel and Aerts 2010). A dozen concerns were identified, three of which are summarised below:

- ☐ **Transferability of stage-damage curves: R**esearch has shown that stage-damage curves aren't directly transferable, and that care should be taken to at least select curves from related regions with similar flood and building characteristics (Cammerer, Thieken, and Lammel 2013). The Hazus default curves are primarily based on empirical evidence from mid-western and southern U.S. towns (Department of Homeland Security. Federal Emergency Management Agency 2009b); these are anecdotally significantly different to the modern urban Vancouver.

- ☐ **Omission of velocity from damage curves:** Velocity is known to be a key factor in the damage of buildings in a flood, however few empirical databases exist that describe expected damages under a combination of depths and velocities (Kelman and Spence 2004; Middelmann-Fernandes 2010). And, no velocity is used in the default Hazus curves at this time. H. Kreibich et al. 2009 suggests that this may not be an oversimplification for damage to buildings, although road damage is highly sensitive to velocity. Road damage is not at this time considered in Hazus.

- **Wave damage omission:** Similar to velocity, intuitively it makes sense that waves would damage buildings more than slack water. Hazus does have a coastal damage feature enabled, however the relative difference in the damage curves for a riverine versus a coastal zone is negligible. This is a known problem with Hazus that has been recognised by the developers. For example, based on recent validations the coastal damage functions are incorrect, only estimating 33% of the actual loss - especially for high rise buildings such as those found in Vancouver (Todorov 2013). Fortunately, hazard mapping for this project has shown that only a few areas would be subjected to significant waves.

5. SUMMARY OF GAPS

Throughout the CFRA process, it became clear that there are many gaps in the development of a robust consequence and risk assessment for the City. In fact, if we look back at Table 2, which outlines the key elements at risk on the floodplain – elements "that we care about" – the only element that can be reliably calculated using the available data and risk methods is damage and loss to low-rise residential structures. Effectively, we only have one element at the centre of the Venn diagram that is proposed to understand the gaps in the process (Figure 10). But, this does not necessarily mean that there is no value in the assessment or the process that has been used to develop the CFRA.

Figure 10: Model to assess gaps in CFRA.

6. IDENTIFIED VALUE IN THE CFRA

Over the course of the project, the team has recognized the many uncertainties and gaps in the process of developing a CFRA for a modern, dense, vibrant, urban city such as Vancouver. Especially when considering the long planning horizons required to prepare for and adapt to sea level rise. This paper highlights the many obstacles and gaps in the assessment, but also alludes to the inherent value of the process and results, some of which are outlined below:

- **Increased knowledge of hazards:** Up until the development of hazard mapping for this project, the City of Vancouver lacked detailed floodplain maps. These provide high value to the city as they inform the current standards-based policies (e.g. flood construction levels). Furthermore, the hydrodynamic model results includes depths and velocities, which can be used for emergency management mapping.

- ☐ **Increased knowledge of relative difference between hazard scenarios:** One of the goals of this project was to look at the changes to the floodplain extents and depths over time with sea level rise. The inundation mapping clearly shows regions of the City that are currently 'safe' from coastal flooding, but that will 'tip' in future and become floodplains.

- ☐ **Increased knowledge of vulnerabilities:** The project included an assessment of vulnerable assets on the existing and future floodplains. Understanding the elements at risk will inform future planning and policy.

- ☐ **Increase in city engagement and capacity:** Many dozens of people were involved in the project (see acknowledgements). Each interaction with the stakeholders has hopefully resulted in increased awareness in the issues of climate change, and the need to prepare for and adapt for its impacts. Numerous maps (hazards, vulnerability hotspots, consequence hotspots) and other visual aids have been developed for this project that will continue to aid in engagement and education, which will hopefully lead to action.

- ☐ **Increased understanding of gaps:** The process of documenting the gaps and uncertainties associated with a CFRA will help the project team as it moves forward. Some of the gaps will be filled in time, others will merely be identified and acknowledged.

7. CONCLUSION

From the outset of the CFRA, the project team recognised that the problem of identifying future flood risk was fraught with uncertainty. The primary uncertainty being the unknown rate of local sea level rise over a 100 year planning horizon. Throughout the course of the project, it became clear that in addition to the uncertainty of sea level rise was the uncertainty associated with modelling flood hazard (Section 4.1). Layered on this were the many gaps between the elements at risk on the floodplain that were recognised priorities, and the team ability to estimate the consequence and risk of coastal flooding to these elements (Section 4.2 and 4.3). The team did however use the best available information and methods given time and resource constraints to complete a risk assessment for the City.

Despite the many gaps and uncertainties, there was considerable value in the process and results of the CFRA. These include increased understanding of vulnerabilities, knowledge about the relative difference between various hazard scenarios and the development of useful visual tools for engagement, planning and education.

As coastal cities grapple with climate change and sea level rise in particular, there is an urgent need to begin planning for adaptation and mitigation that will reduce our risk to coastal floods in future. This need far outweighs the risk of moving ahead with imperfect information. As practitioners, we need to recognize that we are not going to get the risk calculation perfectly right, or perhaps even close, but that we can use the best available tools and data to make informed decisions. These decisions will hopefully increase our resiliency to coastal flooding in a changing climate.

8. ACKNOWLEDGEMENTS

The authors would like to thank the large and diverse team involved in the City of Vancouver CFRA project. This includes City staff in the Sustainability Group, Engineering Services and in GIS and CADD services. Furthermore, the authors would like to acknowledge the work completed by the consultant team: Northwest Hydraulic Consultants Ltd. managed the project and completed the hazard modelling and mapping, and the Arlington Group Planning and Architecture Inc. completed the baseline vulnerability assessment. Project advice and review was provided by a broad spectrum of government bureaucrats and academics from Natural Resources Canada and the University of British Columbia.

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